The 11th Symposium on Accelerator Science and Technology, Harima Science Garden City, 1997

A NEW TYPE OF RF CAVITY FOR HIGH INTENSITY PROTON SYNCHROTRON

Y. Mori,E.Ezura,M.Fuzieda,K. Koba*,S.Machida,H. Nakayama,C.Ohmori,
K. Saito**,S.Sawada,A.Takagi,Y. Tanabe***,M.Toda, M.Yamamoto,M. Yoshii,T. Uesugi****
High Energy Accelerator Research Organization
3-2-1, Midori-cho, Tanashi-shi,Tokyo 188-0002, JAPAN
(*also Miyazaki Univ.,**also Hitachi Co.,***also Toshiba Co.,****also U.Tokyo)

Abstract

A new type of RF accelerating cavity using high permeability magnetic alloy (MA) is proposed for high intensity proton synchrotron. Because of its large accelerating efficiency compared with the conventional ferrite-loaded cavity, total length of the cavity can be reduced dramatically and stable operation under heavy beam loading becomes possible.

1. Introduction

In the intermediate energy proton synchrotron, the resonant frequency of the RF accelerating cavity has to be tuned with the particle velocity. Using high permeability materials such as ferrite, the resonant frequency can be varied by applying the static magnetic field. Performance of this type of cavity , therefore, depends largely on the characteristics of the high permeability materials.

In evaluating the RF cavity performance, it is necessary to consider the following two things: (1) acceleration efficiency and (2) beam induced effects.

The acceleration efficiency is defined as an effective field gradient (=accelerating voltage per cavity length). In ordinary normal conducting RF cavity, the acceleration efficiency is limited by electric breakdown and cooling. For the electric breakdown limit, the Kilpatrick's criterion has been widely used. In the case of using a cooper cavity, the maximum power density cooled by water is approximately several 100W/cm^3.

In the RF cavity using a high permeability material, the effective field gradient relates the material characteristics itself. It is rather complicated compared with an ordinary normal conducting RF cavity.

2. Power Density

In order to evaluate the performance of the RF cavity using a high permeability magnetic core, the product of the relative permeability(μ) and the quality factor (Q) of the material, so-called the μQf-product, has been used. When the toroidal shape of the core is used, this μQf-product corresponds the shunt impedance per unit length as follows.

$$R_p/l = \mu\, Qf\left(1+\frac{1}{Q^2}\right)\mu_0 \times \ln\left(\frac{r_o}{r_i}\right). \qquad (1)$$

Here, R_p is the core shunt impedance, l the core length, μ_0 the vacuum permeability, r_0 and r_i the outer and inner radius of the core, respectively.

If $Q>>1$, then, R_p/l is proportional to μQf. The μQf-product depends largely on the RF characteristics of the material, therefore, so many investigations on the μQf-product for the various composite of the ferrite cores have been carried out so far.[1]

As described above, the effective field gradient is limited by the electric breakdown and the cooling efficiency. There is no problem for the electric breakdown in this type of cavity because its maximum RF voltage is relatively low. The question is a cooling limit. In order to evaluate the cooling limit of the magnetic cores, the RF power density in the core is important.

The RF power dissipated in the magnetic core is given by,

$$W_L = \frac{\omega U}{Q}. \qquad (2)$$

Here, U is the stored RF energy in the cavity and ω the RF angular frequency. The stored energy U is described by,

$$U = \frac{\mu\mu_0}{2}\int_V H_{rf}{}^2 dv = \frac{1}{2\mu\mu_0}\int_V B_{rf}{}^2 dv. \qquad .(3)$$

Here, B_{rf} is the RF magnetic field strength in the core. Thus, the average power density for a toroidal core is given by,

$$\bar{\rho} = \frac{W_L}{V} = \frac{V_{rf}{}^2}{4\pi\mu\mu_0 Qf}\,\frac{1}{\frac{(r_0^2 - r_i^2)}{2}\times l^2 \times \ln\left(\frac{r_o}{r_i}\right)} \qquad .(4)$$

The effective RF field gradient is related to the power density as given by the following equation.

$$\left(\frac{V_{rf}}{l}\right)^2 = A \cdot \mu Qf \cdot \bar{p}, \qquad (5)$$

where

$$A = 2\pi\mu_0\left(r_0^2 - r_i^2\right)\ln\left(\frac{r_o}{r_i}\right). \qquad (6)$$

The power density ρ is proportional to $(V_{rf}/l)^2$ if μQf-product is constant. In the case of ferrite material, the μQf-product is not constant and decreases when the RF magnetic field strength, B_{rf}, is increased. In Fig. 1, closed squares show the dependence of the typical μQf-product on B_{rf} for the Ni-Zn type of ferrite which has been widely used in the proton synchrotrons.. According to eq. (5), the power density is calculated for this type of ferrite and the results is presented by a solid line of Fig. 2.

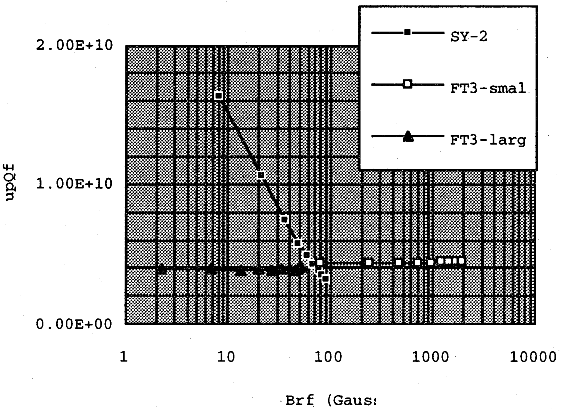

Fig.1 μQf-values vs. Brf.

As can be clearly seen from this figure, when the effective field gradient is more than ~20kV/m, the power density increases enormously. In other words, the ferrite has a limitation on the effective field gradient, which is less than 20kV/m. Since the stacking factor in fabricating the practical cavity is about ~0.7, the practical effective field gradient becomes ~14-15kV/m at maximum for the ferrite core.

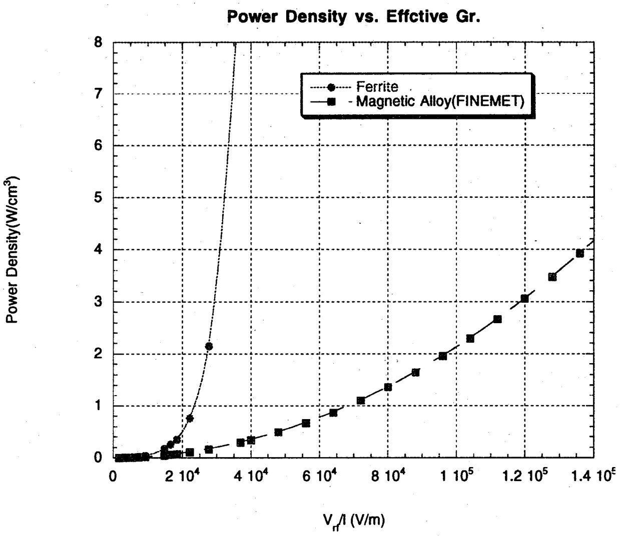

Fig.2:Variations of the power density as a function of the effective field gradient.

On the other hand, the amorphous type of the magnetic alloy(MA), which becomes available recently, does not have such behavior on the μQf-product because the saturation magnetic field strength of the MA is almost one order magnitude larger than that of ferrite and the hysteresis loss of MA is negligible small. A typical μQf-product of the MA (FINEMET) for different B_{rf} is also shown with closed triangles and open squares in Fig. 1. The μQf-product is fairly constant even at large Brf of more than 1kG. For MA, the power density as a function of the effective field gradient is calculated and the result is shown in Fig.2 with a broken line. The power density is just proportional to $(V_{rf}/l)^2$. Even when the field gradient is so high as V_{rf}/l=100kV/m, the power density is still less than 2.5 W/cm³. The practical field gradient will be 70kV/m if the sacking factor of the cores is assumed to be 0.7. This power density is marginal for cooling if proper cooling medium such as oil or even purified water can be used. Thus, the field gradient achieved by the MA core is more than 5 times higher than that of the ferrite core. This means that a total number of cores required for generating the same RF voltage is 5 times less and the total cavity length becomes also smaller by a factor of about 5. This is a big advantage in the RF system of the high intensity rapid cycling synchrotron. Of course, the required RF power increases. However, in high intensity synchrotron, the beam power is also huge. Therefore, the net increase of the total RF power becomes not so large. Moreover, the electric consumption power in the RF system is much less than that required by the ring magnets. The total impedance of the cavity seen from the beam becomes also small, which is good for stable acceleration. The

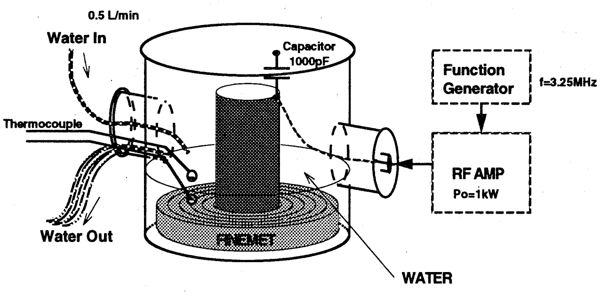

Fig.3: Schematic layout of the test cavity.

total cavity cost is, of course, reduced a lot..

3. High Gradient Cavity with Water Cooling

As a cooling medium for the core, various candidates such as insulating oils, some organic medium such as Fluorinate, some gases like SF$_6$, and purified water, are considered. Looking at an environmental condition in the ring, purified water seems to be one of the best. The problem of using water is that it has a large dielectric constant (*ε=80.36@20℃*). The capacitance contributed by water has to be included into the total capacitance of the resonator. Fortunately, the *Q*-value of the MA-loaded cavity is normally low (1~2), therefore, the control of the capacitance is not so difficult.

In order to estimate the water contributed capacitance, we have made an experiment using a small test cavity which is shown in Fig.3. The size of the MA(FINEMET) core is as follows: the inner radius is 50mm, the outer radius 170mm, and the width 25mm, respectively. The water was purified and its volume resistivity was more than 10MΩ.cm.The variations of the resonating frequency as a function of the purified water level from the bottom of the cavity were measured. The results are shown in Fig. 4 with closed circles. Once the water level exceeded the upper surface of the core, the resonating frequency decreased gradually. The water capacitance contribution to the resonant capacitance appeared when the electric field leaking from the gap saw the water. We have also made Superfish calculation to compare with the experiment. The calculated resonant frequency changes as a function of the water level are also shown with the closed squares in Fig. 4. Calculations agrees with the measurements nicely. From these results, it is found that we can estimate the capacitance contributed from the purified water by Superfish calculation.

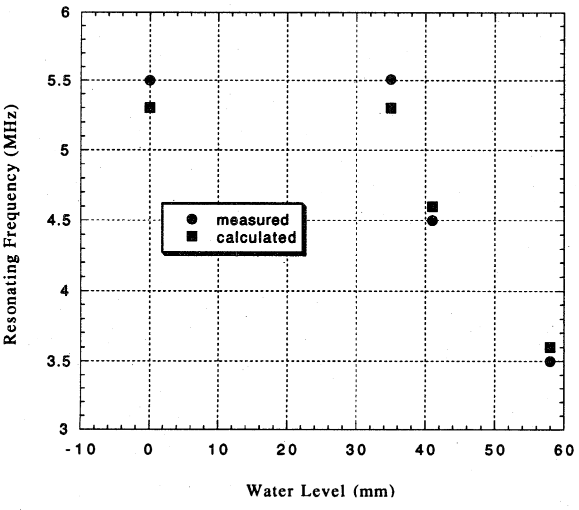

Fig.4 :Resonating frequecy vs. water level.

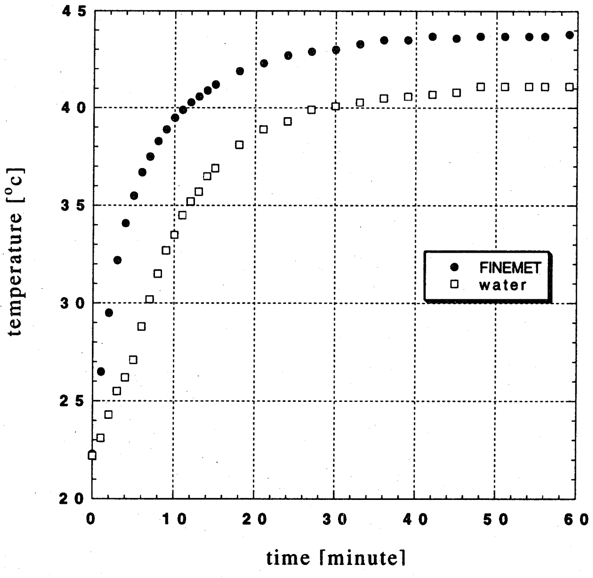

Fig.5:Variations of t water and core temperatures as a function of time.

We have also measured the effective heat transferring coefficient of the MA core by using the same test cavity. The MA core is made from thin MA tapes, whose thickness is ~20μm, winding around a spool. It is important to know the effective heat transferring coefficient of the core for making a cooling design properly. The RF power of about 1kW was fed into the cavity and measured the core and water temperature. The flowing rate of the purified water was 0.5l/min. Figure 5 shows the temperature configurations for both core and water as a function of time after the RF power is introduced. From this measurement, we obtain that the effective heat transferring coefficient is 20-30 W/m.K, which is a little larger than that of stainless steel. There seems to be no problem for cooling of the MA cores when the consumption RF power density is even more than 10W/cm^3.

4. Summary

A new type of RF cavity using a magnetic alloy for high intensity proton synchrotron is proposed. The effective accelerating field gradient of more than 70kV/m will be possible if it is properly cooled. The purified water cooling seems to be the most simple if careful design for water dielectric effect is accomplished.

REFERENCE

[1] T.Uesugi et al; JHP Report, JHP-31,1997.