A NEW TYPE OF RF CAVITY FOR HIGH INTENSITY PROTON SYNCHROTRON USING HIGH PERMEABILITY MAGNETIC ALLOY

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Abstract

A new type of rf accelerating cavity using a high-permeability magnetic alloy (MA) core is proposed for a high-intensity hadron synchrotron. The prototype of a single-gap high gradient cavity whose total length is only 40cm is under development and a maximum rf voltage of 20kV has been obtained so far.

1 INTRODUCTION

Recently, demands have increased for high intensity and intermediate energy proton synchrotrons(PS) like the 3-GeV booster or the 50-GeV main ring of the JHF project [1]. Various intense secondary beams such as neutron beams for spallation neutron source, and kaon, muon and neutrino beams for nuclear and particle physics are produced by the PS. In order to increase average beam current in the PS, high repetition rate in operation is essential. This requires inevitably a higher accelerating rf voltage. In the 3-GeV booster of the JHF project, for example, operation at a 50Hz repetition rate is expected and the requested total rf voltage exceeds 800kV. In the intermediate energy PS, the resonant frequency of the rf accelerating cavity has to be tuned with particle velocity and the ferrite-loaded rf cavity has been used so far. By applying a static magnetic field, the permeability of the ferrite can be varied and the total inductance of the cavity is changed.

In evaluating the rf cavity performance, it is necessary to consider the following two things: (1) the accelerating field gradient and (2) the beam induced effect. The accelerating gradient is defined as the accelerating voltage per cavity length. Since space for the rf cavity in the ring is normally limited, it is desired that the rf voltage per unit length, the so-called accelerating rf field gradient, should be increased as high as possible. When the total length of the cavities becomes short, the impedance seen by the beams also becomes small. The accelerating field gradient of the conventional ferrite-loaded accelerating cavity is limited to less than 15kV/m because of its large nonlinear hysteresis loss at high RF magnetic field.

Recently, high-permeability soft magnetic alloys (MA) , such as FINEMET, METGLAS and the other amorphous types of soft magnetic alloy [2] have become available and development of the rf cavity using these materials has been carried out at KEK. for the JHF synchrotrons. Compared with ferrite, these materials have the following characteristics:

(1) The μQf-value of the MA core remains constant at a high rf magnetic field. In the case of FINEMET, the μQf-value is still constant, even at an rf magnetic field of 2 kG. The rf power density in the material is still low enough for cooling (~4 W/ cm^3) at a relatively high effective rf field gradient (~100kV/m),.

(2) A high Curie temperature, typically 570°C for FINEMET, makes the cavity possible to operate at a high effective field gradient.

(3) The intrinsic Q-value of the MA core is relatively small. Because of its low Q-value (Q~1), no frequency tuning loop is necessary in the cavity control system. This substantially widens the stable operating region of the cavity loading phase angle under heavy beam loading. Longitudinal coupled-bunch instability may also be reduced, since the Q-value of the cavity is low.

(4) Although the intrinsic Q-value is small as described above, the Q-value can be increased up to more than ~10 by a radial gap with cut-core configuration. Thus, the R/Q value can be decreased to less than 100 Ω/gap and it allows stable operation under large transient beam loading.

(5) Fabrication of a large core is possible because the core is formed by winding very thin tapes.

One of the interesting characteristics of the MA cores is that the core is completely stable at the high rf magnetic field and, therefore, a high gradient accelerating cavity can be realized with MA cores. Recently, a prototype of the high gradient cavity with FINEMET cores has been developed at KEK for the JHF synchrotrons and an rf voltage of about 20kV was obtained. The total length of this cavity is only 40cm and an effective accelerating gradient of about 50kV/m has been achieved.

2 CHARACTERISTICS OF HIGH PERMEABILITY MAGNETIC ALLOY

2.1 *μQf-product on the rf magnetic field strength*

In order to evaluate the performance of the rf cavity using high permeability magnetic cores, the product of the relative permeability(μ) and the quality factor (Q) of the material, the so-called the μQf-product, has been used. When the toroidal shape of the core is used, this μQf-product corresponds to the shunt impedance per unit length. The μQf-product depends largely on the rf characteristics of the material, so many investigations of the μQf -product for various compositions of the ferrite core have been carried out at KEK so far.

The accelerating field gradient is related to the power density(ρ)as given by the following equation.

$$\left(\frac{V_{rf}}{l}\right)^2 = A \cdot \mu Qf \cdot \bar{\rho}, \qquad (1)$$

where A is a geometrical factor of the core configuration.

The power density (ρ) is proportional to $(V_{rf}/l)^2$ if the μQf-product is constant. In the case of ferrite material, the μQf-

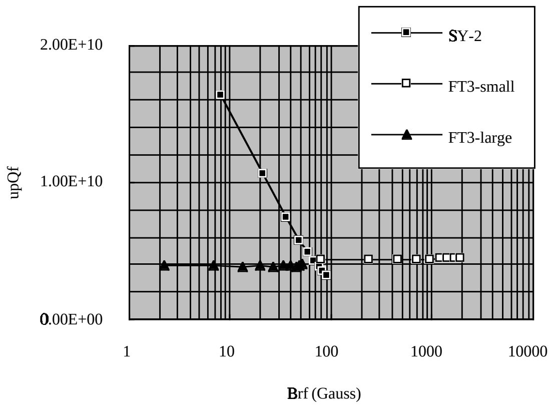

Fig.1 Dependence of mQf values on the rf magnetic field strength(Brf) for Ni-Zn ferrite(SY-2) and magnetic alloy (FINEMET:FT3) cores.

product is not constant but decreases when the rf magnetic field strength (B_{rf}) is increased. In Fig. 1, the 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 proton synchrotrons. The power density was calculated for this type of ferrite according to eq. (1), and the results are shown by the solid line of Fig. 2.

As can be clearly seen from this figure, when the accelerating field gradient is more than ~20kV/m, the power density increases enormously. In other words, the ferrite limits on the effective field gradient to less than 20kV/m. Since the stacking factor in fabricating a practical cavity is about ~0.7, the practical effective field gradient should be less than 15kV/m at most for the Ni-Zn type of ferrite core.

On the other hand, the high permeability magnetic alloys (MA), which have become available recently, do not show such a behavior of 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 negligibly small. We have measured the characteristics of the μQf-product on B_{rf} for several types of the MA core such as FINEMET, METGLAS and other amorphous types of MA core. A typical μQf-product of the MA (FINEMET) for different B_{rf} is also shown by closed triangles and open squares in Fig. 1. The μQf-product is fairly constant, even at a large Brf of more than 2kG. For

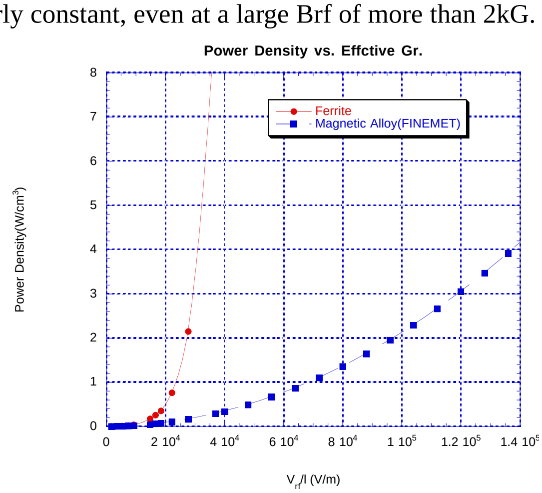

Fig.2 Variation of the power density of the power density as a function of the effective field gradient.

MA cores, the power density as a function of the field gradient is calculated; the result is shown in Fig.2 by the broken line. The power density is just proportional to $(V_{rf}/l)^2$. Even when the field gradient is as high as V_{rf}/l=140kV/m, the power density is still less than 4 W/cm^3. The practical field gradient will be 100kV/m if the stacking factor of the cores is assumed to be 0.7. This power density is manageable for cooling if a 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 10-times higher than that of the ferrite core. This means that the total number of cores required for generating the same rf voltage is 10-times less and the total cavity length also becomes smaller by a factor of about 10. This is a big advantage in the rf system of the high intensity rapid cycling PS.

2.2 Increase of Q-value with radial gap

The intrinsic Q-value of the MA core is normally small (0.5~1) because the main rf loss is caused by eddy current loss. When the beam current becomes relatively large, the R/Q-value of the cavity should be small to minimize the beam loading effect. We found that the Q-value of the MA

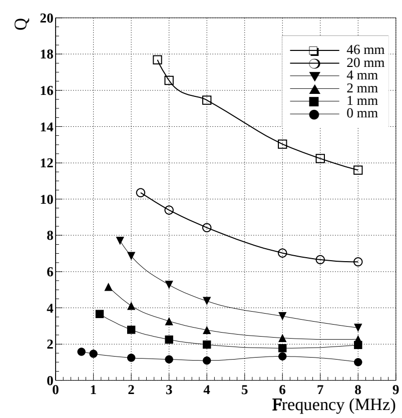

Fig.3 Q-value depence of the FINEMET core for various radial gap lengths.

core can be increased greatly by use of a radial gap in cut-core configuration without having a large deterioration of the μQf-product. Figure 3 shows the Q-value dependence of the FINEMET core for various radial gap lengths. The outer and inner diameter of the core are 550mm and 300mm, respectively and the core thickness is 25mm. As can be seen from this figure, the Q-value can be increased up to about 16 at 3.4MHz. If the total shunt impedance of the cavity is chosen to be 1kΩ, then the R/Q-value becomes about 60 Ω/cavity, which is small enough even under large beam loading. For example, in the JHF 50-GeV main ring, the peak beam current reaches more than 100A because the bunch width becomes less than 20 ns at the top energy. Even under such heavy beam loading conditions, the voltage drop caused by the beam is only 1-2kV per cavity with such a small R/Q-value.

3 HIGH GRADIENT MA-LOADED CAVITY

3.1 Test cavity with single MA core[3]

One of the advantages of using a magnetic alloy (MA) core is its μQf stability at the very high magnetic rf field of

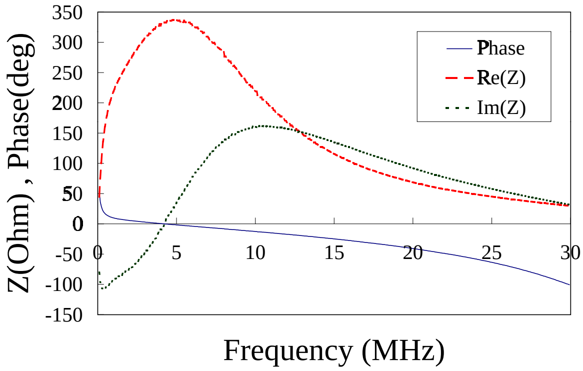

Fig. 5 Impedance curve of the prototype of the high gradient cavity. Total impedance is two times of the value presented in this figure.

more than 2kG, where the ferrite cores are completely saturated and difficult to use. In order to demonstrate this advantage experimentally, a high gradient test cavity has been developed. In this test cavity, only one large core was installed in the λ/4 cavity. The cavity was driven by a push-pull amplifier. The core was cooled directly by water. The problem of using water is that it has a large dielectric constant (*e=80.36 @20℃*). The water capacitance contribution to the resonant capacitance appeared when the electric field leaking from the gap saw the water. We have made a Superfish calculation to compare with the experiment. The calculated resonant frequency changes as a function of the water level and agrees with the measurements nicely. The maximum rf voltage of about 5.5kV per core(=220kV/m), which is the limit of the maximum plate voltage of the rf amplifier, was obtained. Using a different small cavity, the effective heat transfer coefficient was measured. The measured coefficient was 20-30 W/m.K, which is a little larger than that of stainless steel. There seems to be not large problems for cooling of the MA cores even when the absorbed rf power density is more than 10W/cm^3.

3.2 High gradient prototype cavity

Based on the R&D work described above, a prototype of the rf cavity for the JHF synchrotrons has been developed. In this cavity shown in Fig.5, three FINEMET cores are installed into each water tank which is surrounded by stainless steel and FRP insulators. The size of each core is 250mm(i.d.) x 670mm(o.d.) x 2.5cm (w). The total length of the cavity including vacuum flanges at the both ends is only 40 cm. In the case of using ordinary cores without radial gaps, the total shunt impedance of the cavity is about 500-600Ω at the wide frequency range around 5 MHz and the Q-value is about 0.6 as shown in Fig.5. If there is no requirement for a wide range of frequency in operation but severe beam loading like in case of the 50-GeV main ring of JHF, cut-cores with radial gaps will be used. In this case, the R/Q-value will be reduced to less than 100W/cavity. Figure 6 shows a picture of the prototype of the high gradient cavity under development.

Fig.6 Prototype of the high gradient cavity. The rf voltage of 20kV has been obtained with this cavity.

The rf cavities are driven by amplifiers using two tetrodes (4CW150000E) with a push-pull type design. The output impedance depends not only on the cavity itself, but also on the ways to couple the rf amplifiers to the rf cavity. Since the L coupling has a large output impedance, the C coupling was used. The required rf voltage per gap is 16kV.

With this prototype of the high gradient cavity, we have succeeded in obtaining a stable rf voltage of 16kV at relatively high duty factor (~40%) operation. An rf voltage of 20kV, which was limited by rf amplifier, has been also achieved at small duty factor operation. Such a high rf voltage at small duty factor operation would be also very attractive for the "barrier bucket" operation.[4]

4 CONCLUSION

A new type of rf accelerating cavity using high permeability magnetic alloy (MA) core has been proposed for high intensity hadron synchrotron and developed at KEK for the JHF proton synchrotrons. We have measured various characteristics of the different types of MA core and found that a large accelerating field gradient of more than 100kV/m is possible with the MA cores. This is because the maximum allowable rf magnetic flux of the MA core is more than 2kG which is ten times larger than that of the ferrite core. Based on these measurements, the prototype of the single-gap high gradient cavity whose total length is only 40cm has been developed. With this cavity, a maximum voltage of 20kV, which is limited by the rf amplifier, has been obtained so far.

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[4]C.Ohmori;"MA-loaded cavity for barrier bucket experiment", contributed to this conferece.