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REDUCING FERRITE TUNER POWER LOSS BY BIAS FIELD ROTATION*

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Summary

It has been suggested that ferrite tuners for rf cavities with the magnetic bias field perpendicular to the rf magnetic field would have greatly reduced rf losses. Recent measurements at Los Alamos National Laboratory appear to confirm this effect. A simple model proposed here allows the calculation of tuning characteristics for a variety of bias schemes. The model shows that the perpendicular bias scheme mentioned above requires very much larger bias levels than does the parallel bias scheme in order to achieve the same tuning range with a particular ferrite tuner. However, further investigation with the model has led to the discovery that the use of perpendicular bias at low frequency and parallel bias at high frequency requires only a modest increase in the bias field. In effect, the ferrite is kept highly magnetized, reducing ferrite losses, and is tuned primarily by rotating the bias field direction with respect to the rf field direction. The resulting reduction in dissipation can significantly reduce the amount of ferrite required per cavity.

Introduction

A rapid cycling synchrotron such as LAMPF II (60 Hz, 16-32 GeV) requires a large energy gain per turn (12-24 MeV) and a large tuning range (19%). If ferrite tuners are considered, it is found that the amount of ferrite required is very large and is proportional to the power dissipated in the ferrite, assuming that power density is the limiting factor. Therefore it is important to minimize the energy lost in the ferrite. Tuners topologically similar to the one shown in Fig. 1 have been used with a variable azimuthal bias to tune rf cavities of a number of synchrotrons.[1] To reach low frequencies (high permeability), bias fields which are well below saturation are used. Under such conditions the Q of the ferrite is much lower than it is when the dc magnetization is near saturation. The low Q region can be avoided by orienting the bias field in a direction which is perpendicular to the rf field, as has been done for the LAMPF proton storage ring tuner cavity.[2]

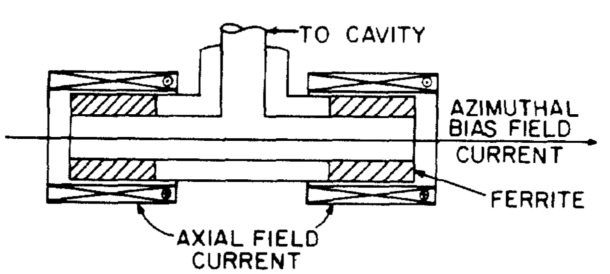

Fig. 1. A sketch of a ferrite tuner, consisting of a coaxial line which tees into two coaxial shorted stubs containing annular ferrite cylinders. The rf magnetic fields and the parallel bias field are in the azimuthal direction in the ferrite. An axial bias field which would be perpendicular to the rf magnetic field could be produced by the solenoidal coils.

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A simple model is used here for calculating the characteristics of ferrite tuners with the magnetic bias field perpendicular to the rf magnetic field. Based on the assumption that the radio frequency is far enough below the ferromagnetic resonance frequency so that the magnetization in the ferrite will be parallel to the magnetic field intensity, a very simple expression for the effective permeability is obtained. It is shown that larger bias fields are required to operate a tuner in this mode, relative to the parallel bias field case. However, the rf losses in this mode are much smaller because the ferrite is at or near saturation over the entire frequency range of the tuner.

The Assumptions

The first assumptions are that the frequency is sufficiently far below the ferromagnetic resonance frequency so that $\vec{B}$ is parallel to $\vec{H}$ and that hysteresis is not important, so $\vec{B}$ (in gaussian units) may be written as:

$$\vec{B} = \vec{H}\left(1 + \frac{4\pi M_s}{H} f(H)\right) \quad , \tag{1}$$

where f(H) is a function which approaches unity at saturation and characterizes the particular ferrite, and $4\pi M_s$ is the saturation magnetization. It is further assumed that the rf field is small compared to the bias field so that the effective rf permeability may be found from:

$$\mu_{ij} = \frac{\partial B_i}{\partial H_j} \quad . \tag{2}$$

The Effective Permeability

If we choose one axis (say the x-axis) parallel to the bias field, then the tensor μ_{ij} is diagonal and has only two distinct values. To find them we write:

$$\vec{B} = B_x\hat{i} + B_y\hat{j} = (H_x\hat{i} + H_y\hat{j})\left[1 + \frac{4\pi M_s}{H} f(H)\right] \quad , \tag{3}$$

where:

$$H = \sqrt{(H_x^2 + H_y^2)} \quad .$$

For the parallel bias ($\vec{H}_{rf} \parallel \vec{H}_{dc}$) case the effective rf permeability is the well known result:

$$\mu_{xx} = 1 + \frac{4\pi M_s}{H} f'(H) = \frac{\partial B}{\partial H} \quad , \tag{4}$$

while in the perpendicular bias case ($\vec{H}_{rf} \perp \vec{H}_{dc}$) the effective permeability reduces to the surprisingly simple expression:

$$\mu_{yy} = 1 + \frac{4\pi M_s}{H} f(H) = \frac{B}{H} \quad . \tag{5}$$

Graphical Interpretation

In the parallel bias case the rf permeability is simply the slope of the B-H curve at the operating point, as is well known. Although not well known, there is an equally simple graphical interpretation for the transverse rf permeability, namely, it is the slope of the straight line from the origin to the operating point, as may be seen from Eqn. 5.

Implications of these Results

Consider now a tuner of the type illustrated in Fig. 1. If a current is passed along the axis, the ferrite is biased in the azimuthal direction and the bias field is parallel to the rf magnetic field. On the other hand, if the solenoidal coils are energized a bias field perpendicular to the rf field is produced. Now consider the bias fields necessary to tune the tuner over the same frequency range in these two cases. This situation is illustrated in Fig. 2. It is seen that the minimum bias in the perpendicular case is large, which is desirable because it magnetizes the ferrite raising the Q without lowering the permeability very much. However, it is seen that it requires very high perpendicular bias to reach the high frequency end of the range. When the situation is viewed from this perspective, it becomes obvious that the complete tuning range could be achieved by going from condition B to condition C, that is, by rotating the bias field from being perpendicular to being parallel to the rf field. This would avoid both the low bias condition (A) which involves high ferrite losses and the very high field bias condition (D) which involves very large coils, power supplies and power consumption.

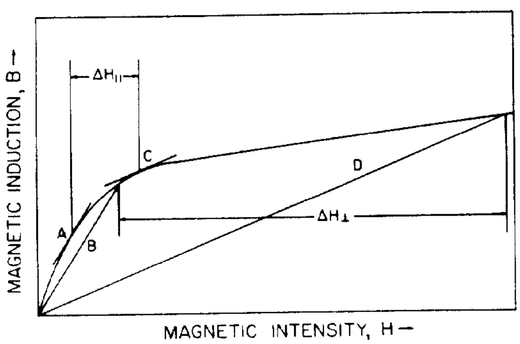

Fig. 2. A typical ferrite B-H curve. The effective rf permeability for the parallel bias case is given by the slope of the tangent line, for example A and C. In the perpendicular bias case the effective permeability is the slope of the line to the operating point, such as lines B and D, respectively. A particular tuner with parallel bias might provide the desired tuning range with the change in magnetic intensity indicated by $\Delta H_{\parallel}$. To provide the same tuning range with the same tuner operating in the perpendicular bias mode requires the significantly larger bias indicated by the range labeled $\Delta H_{\perp}$.

Diagonal Bias Fields

From the conclusions of the preceeding paragraph it is clear that the effective permeability for bias conditions in between parallel and perpendicular bias may be of interest. To investigate this we add to our previous assumptions a specific assumption of the form of f(H). We assume the plausible, explicit form:

$$B = H + 4\pi M_s\left[1 - \exp\left(-\frac{(\mu-1)H}{4\pi M_s}\right)\right] \quad , \tag{6}$$

which is qualitatively similar to the curve shown in Fig. 2, and where μ is the initial (small H) permeability. We take the field $\vec{H}$ to have components H_x and H_y, and then define the effective rf permeability in the y direction as:

$$\mu_{rf} = \frac{\partial B_y}{\partial H_y} \quad , \tag{7}$$

obtaining:

$$\mu_{rf} = 1 + \frac{4\pi M_s}{H}\left(\frac{H_x}{H}\right)^2\left[1 - \exp\left(-\frac{(\mu-1)H}{4\pi M_s}\right)\right]$$
$$+ (\mu-1)\left(\frac{H_y}{H}\right)^2 \exp\left(-\frac{(\mu-1)H}{4\pi M_s}\right) \quad . \tag{8}$$

A contour plot of μ_{rf} as a function of the bias field components H_x and H_y is given in Fig. 3 for an initial permeability (μ) of twenty. With the aid of Fig. 3 it is possible to examine various tuning arrangements. The two possibilities described in Fig. 2 correspond to trajectories along the x or y axes in Fig. 3. Points A, B, C and D are the same in both figures. Looking at the contour plot suggests that a good practical arrangement would be to use a combination of fixed perpendicular bias with variable parallel bias which would result, for example, in tuning along the line from B to E. It has been pointed out by J.E. Griffen of Fermilab[3] that the dc perpendicular bias might be supplied by permanent magnets, effecting an additional saving of power.

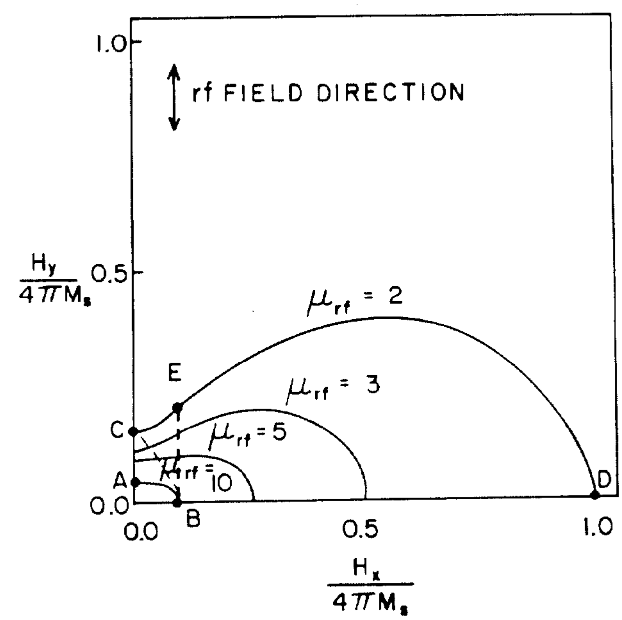

Fig. 3. A contour plot of the differential permeability in the y direction as a function of H_x and H_y, the magnetic bias field components. Values were calculated from Eqn. 8 with an initial permeability (μ) equal to 20. It is seen that tuning from B to C along the dashed path requires much smaller bias fields than tuning from B to D. Another alternative would be to apply a dc bias field in the x direction and a variable bias in the y direction, tuning from B to E.

A Cavity for Testing Ferrite

A cavity has been conceptually designed which will facilitate the testing of ferrite samples under conditions of both parallel and perpendicular bias at high rf fields. The cavity will fit between the poles of a conventional iron core laboratory magnet which supplies the large number of ampere turns needed to explore perpendicular bias tuning. It will have toroidal windings to supply the azimuthal bias (Fig. 4). The rf oscillation involves the transfer of energy stored in a large volume annular capacitor into the

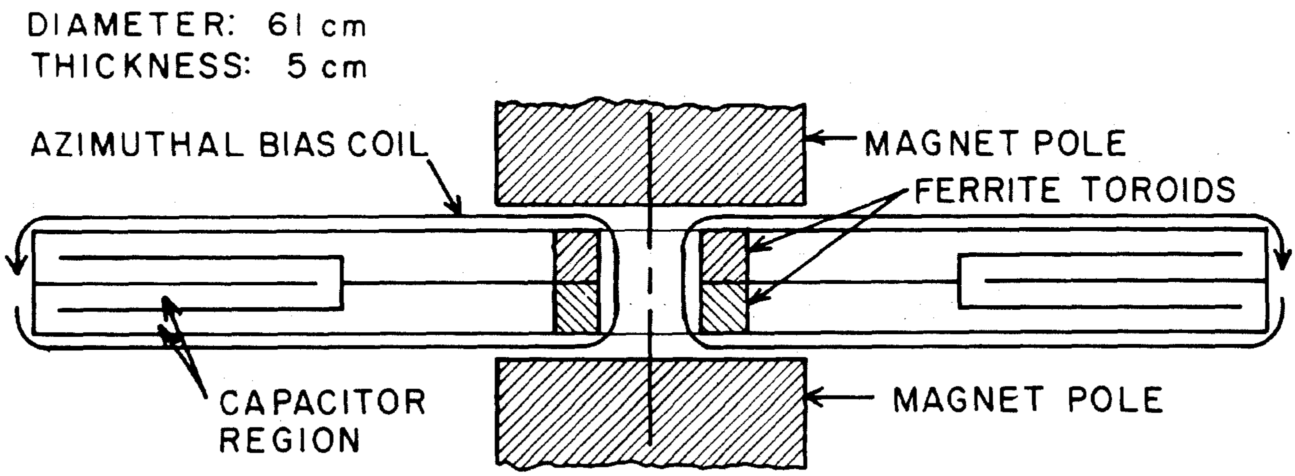

Fig. 4. Cross section of a cavity for testing ferrite. The thin, annular cavity is bisected by a conducting disc on the median plane. The disc carries the rf current from the capacitor region to the center of the cavity, passing between the two ferrite toroids.

much smaller ferrite volume, and is thus capable of subjecting the ferrite samples to high rf magnetic energy density. Table I lists some of the calculated characteristics of the cavity, including its resonant frequency as a function of the effective rf permeability. The power and the Q listed were calculated from copper losses alone, assuming lossless ferrite. Q' is the cavity Q calculated assuming that the ferrite has a Q of 2000. It is clear that the cavity Q is very sensitive to the ferrite Q, even when it is quite high.

TABLE I

Calculated Properties of the Copper Cavity Shown in Fig. 4, with 3.0 kV (peak) Excitation

Ferrite μ_{rf}	Freq. (MHz)	Q	Q'	Power (watts)	H_{rf} pk (A/m)
1	77.4	2350	1740	728	2,700
4	56.0	3840	1720	338	2,000
8	43.8	5560	1760	187	1,600
12	37.2	7130	1780	122	1,300

Conclusions

A magnetic bias field perpendicular to the rf magnetic field is relatively ineffective in changing the rf permeability of the ferrite, therefore it can be used to magnetically saturate the ferrite, greatly reducing ferrite rf losses while retaining a relatively large rf permeability. A bias field parallel to the rf field is far more effective in changing the rf permeability. Thus a superposition of the two bias fields can be used to achieve a wide tuning range and at the same time avoid the high loss region usually encountered at low frequencies with parallel bias and also avoid the very high bias power required to reach high frequencies with purely perpendicular bias.

References

1. J.E. Griffen and Q.A. Kerns, "NAL Main-Ring Cavity Test Results," IEEE Trans. on Nucl. Sci. NS-18 241 (June 1971).

2. L.M. Earley, G.P. Lawrence, and J.M. Potter, "Rapidly Tuned Buncher Structure for the Los Alamos Proton Storage Ring (PSR)", Bull. Am. Phys. Soc. 28 106 (1983)

3. J.E. Griffen, private communication.