A&T Sector Note

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Keywords: Cavity resonators, ferrimagnetic materials, ferrites, particle accelerators, permeability

Summary

Cavities that are partially filled with ferrite material provide a tunable resonance frequency by making use of the changing μ -characteristics of ferrites when exposed to an external magnetic bias field. The concept of using either parallel or perpendicular magnetic biasing to reach a certain resonance frequency of a cavity has been known for many years. However, a cavity based on superposition of perpendicular and parallel magnetic fields to obtain improved ferrite characteristics was suggested in W. R. Smythe "Reducing ferrite tuner power loss by bias field rotation," IEEE Trans. Nucl. Sci., vol. 30, no. 4, pp. 273–275, 1983, but to our knowledge was neither tested nor built. Such a 2-directional biasing is expected to provide a reduction in RF losses for an identical tuning range as compared with the classical 1-directional magnetic bias. We have successfully tested this theory with a measurement set-up consisting of a ferrite-filled cavity, exposed to external biases that allow the clear separation of the two orientations of superposed magnetic bias fields. The outcome is an enlargement of tuning range with high cavity Q and the possibility of fast tuning. In this paper, we describe the measurement set-up and present the tuning ranges that we attained by applying different bias schemes.

The Effect of 2-Directional Magnetic Biasing Used for Tuning of a Ferrite-Loaded Re-entrant Cavity

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Abstract—Cavities that are partially filled with ferrite material provide a tunable resonance frequency by making use of the changing μ -characteristics of ferrites when exposed to an external magnetic bias field. The concept of using either parallel or perpendicular magnetic biasing to reach a certain resonance frequency of a cavity has been known for many years. However, a cavity based on superposition of perpendicular and parallel magnetic fields to obtain improved ferrite characteristics was suggested in W. R. Smythe “Reducing ferrite tuner power loss by bias field rotation,” *IEEE Trans. Nucl. Sci.*, vol. 30, no. 4, pp. 273–275, 1983, but to our knowledge was neither tested nor built. Such a 2-directional biasing is expected to provide a reduction in RF losses for an identical tuning range as compared with the classical 1-directional magnetic bias. We have successfully tested this theory with a measurement set-up consisting of a ferrite-filled cavity, exposed to external biases that allow the clear separation of the two orientations of superposed magnetic bias fields. The outcome is an enlargement of tuning range with high cavity Q and the possibility of fast tuning. In this paper, we describe the measurement set-up and present the tuning ranges that we attained by applying different bias schemes.

Index Terms—Cavity resonators, ferrimagnetic materials, ferrites, particle accelerators, permeability.

I. INTRODUCTION

IN the concept of changing the resonance frequency of a cavity by using ferrites in a magnetic bias, it is distinguished between parallel and perpendicular magnetic biasing according to the orientation of the external bias field with respect to the magnetic RF-field. Depending on the chosen biasing method, different ferrite types (e.g. Ni-Zn or ferrite garnets) are used. A comparison of ferrite properties, namely the magnetic Q as a function of the bias field orientation was demonstrated in [2]. In addition to the two conventional methods, a superposition of perpendicular and parallel magnetic bias fields was suggested by Smythe [1] already in 1983. The goal of a combined biasing is to obtain a reduction in RF losses for an identical tuning range as compared with a 1-directional bias. To our knowledge, this concept was never tested and no RF cavity equipped with a 2-directional biasing unit was ever built. The scheme of a 2-directional bias works as follows: First the ferrite is exposed to a perpendicular bias that brings the material in a magnetized state,

this way fixing an operating point where the ferrite is in a state of reduced losses. Then, the actual tuning is carried out by applying an additional magnetic bias oriented parallel to the magnetic RF-field.

It is a side effect that with an appropriate choice of the operating point, parallel biasing becomes rather efficient. This way, a small variation of the parallel bias should have a large effect on the permeability and thus allow for a fast tuning. We have tested this method and compared the results with tuning ranges obtained from ferrite-tuned cavities with classically perpendicular biased ferrites. To this purpose, a transmission measurement is carried out on a cavity resonator for different bias schemes. Further, the Q -factor is determined via the 3-dB-Method [3] from the measured resonance to quantify ferrite losses: $Q = f_{\text{res}}/\Delta f_{3\text{ dB}}$.

II. PERMEABILITY DESCRIPTION

The relevant quantity for RF applications is the so-called differential permeability μ_{rf} that characterizes the material in a rapidly alternating field and the presence of a magnetic bias. Following [1], this differential permeability is a function of parallel and perpendicular bias fields:

$$\mu_{\text{rf}} = 1 + \frac{4\pi M_s}{H} \left(\frac{H_{\text{perp}}}{H} \right)^2 \left[1 - \exp \left(-\frac{(\mu - 1)H}{4\pi M_s} \right) \right] + (\mu - 1) \left(\frac{H_{\text{par}}}{H} \right)^2 \exp \left(-\frac{(\mu - 1)H}{4\pi M_s} \right) \quad (1)$$

where $4\pi M_s$ denotes the saturation magnetization, μ is the initial relative permeability of the material, and $H = \sqrt{H_{\text{perp}}^2 + H_{\text{par}}^2}$ is calculated from the two components of external biasing. The resonance frequency f_{res} depends on μ_{rf} :

$$f_{\text{res}} \sim 1/\sqrt{\mu_{\text{rf}}}. \quad (2)$$

In the case of 1-directional biasing, we expect μ_{rf} to reduce for increasing magnetic bias causing an increase of the resonance frequency.

In the case of 2-directional biasing, the dependence is more complicated. Fig. 1 shows a contour plot of μ_{rf} as a function of perpendicular and parallel bias field components. The plot is normalized to the saturation magnetization and the values are given for an initial relative permeability of 20. The dashed lines

Manuscript received December 05, 2012; revised February 22, 2013; accepted March 27, 2013. Date of publication May 23, 2013; date of current version June 12, 2013.

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Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TNS.2013.2256148

Fig. 1. Contour plot of constant differential permeability μ_{rf} as a function of perpendicular and parallel bias field components.

Fig. 2. Drawing of the cross-section of the re-entrant cavity resonator.

indicate the tuning schemes that we have measured and that we will refer to in the next sections.

III. MEASUREMENT SET-UP

Fig. 2 shows the drawing of the cross-section of the test cavity. The cylindrical, re-entrant type cavity is filled with rings of ferrite garnet of 127 mm outer diameter and 70 mm inner diameter. Without ferrite rings, the cavity has a resonance frequency of 600 MHz for the fundamental mode. For the ferrite rings, we used G-510, a microwave garnet from Trans-Tech Inc. which has a saturation magnetization of 55 mT and an initial permeability $\mu = 37$ (see data sheets for material details [4]). Since the magnetic RF-field in this cavity resonator is azimuthal with respect to the cavity's symmetry axis, a toroidal coil is added to provide the parallel bias in azimuthal direction as can be seen in Fig. 3. The inner stem of the cavity has a bore diameter of 50 mm which allowed to put $n = 19$ toroidal windings. We powered the toroidal coil with a bias current I_{bias} corresponding to an azimuthal bias field

$$B_{par} = \mu_0 \frac{n I_{bias}}{2\pi r_m}, \quad (3)$$

where $r_m = 49.3$ mm is the arithmetic mean of the radius of the ferrite ring. The cavity resonator is sufficiently small to fit into the aperture of a laboratory magnet that will provide the perpendicular bias field. With a Vector Network Analyser

Fig. 3. Picture of the re-entrant cavity resonator with toroidal coil windings in the aperture of a laboratory magnet.

(VNA), we carried out transmission measurements of S -parameters on the cavity for a frequency sweep of 180 ... 400 MHz for each bias setting. The signals were picked up via two pins each mounted over the cavity gap on two opposite points of the gap. The measurement lines were only weakly coupled to the cavity such that the resonance frequency was not disturbed (i.e. loaded $Q_L \approx$ unloaded Q_0 with a relative error below 2%). For this purpose, adjustable coupling capacitors with capacitances in the picofarad-range were mounted on the measurement lines, keeping the reflection coefficient of the input port $|S_{11}| < 0.1$ dB. The measurements are carried out with VNA-RF power levels of 1 mW. The non-linearity of the material as a function of high RF-power levels is not taken into account. Via transmission measurement of S_{21} , the exploitable tuning range in different settings of external magnetic bias can now be determined taking into consideration a Q_{min} that is required for a specific application.

IV. 2-DIRECTIONAL BIAS, PART I

We tried different combinations of the two orientations of the magnetic bias field. Firstly, we kept the perpendicular bias field constant at values $H_{perp} = 15 \dots 50$ mT and varied the parallel bias. For each value of perpendicular bias, we ran the same range of parallel biasing to allow a direct comparison of the graphs. For the parallel bias, we quote the biasing current in A instead of the field strength as there is the $1/r$ -dependence of the azimuthal bias field in the ferrite, as indicated in (3). Fig. 4 shows the measured magnitude $|S_{21}|$ for different values of perpendicular biasing. Graph (a) (blue) is taken with zero parallel biasing whereas graph (b) (red) corresponds to a bias current of 350 A. The different values of perpendicular biasing provide the operating point for the tuning. In order to be able to compare tuning ranges at different operation points we want to keep $Q_{min} = 150$ at start and at end of the tuning range which would roughly correspond to a magnetic loss tangent $\tan \delta_\mu = 0.007$. Note that in the first case of $H_{perp} = 15$ mT, no resonance could be detected for 0 A parallel biasing current, hence no peak for graph (a) is visible. In addition, the Q -values drop fast with decreasing bias current. From these measurements, several conclusions can be drawn:

Fig. 4. Measurement of S_{21} with constant perpendicular magnetic biasing and varied parallel bias. Perpendicular magnetic biases from top to bottom: 15 mT, 40 mT, 50 mT. The range of parallel biasing is identical in all plots.

1) Comparison of the three plots in Fig. 4 shows that with a perpendicular biasing of 15 mT, and a parallel bias current of 0...350 A, only a small change of resonance frequency of 12 MHz could be reached with $Q > 150$. For the case of perpendicular biasing of 50 mT with the same parallel bias current of 0...350 A, a change of f_{res} from 225...300 MHz could be obtained with Q -factors above 150. Table I gives exact numbers obtained with $H_{\text{perp}} = 15$ mT and $H_{\text{perp}} = 50$ mT that demonstrate how a change in the perpendicular biasing allows to **increase** the exploitable tuning range by proper choice of the operating point. In the case of perpendicular bias $H_{\text{perp}} = 15$ mT and I_{bias} below 150 A, the Q -factor is smaller than the requested $Q_{\text{min}} = 150$. An increase of Q with increasing bias current is observed. However, a certain level of perpendicular bias is required, otherwise no satisfactory tuning range is reached with low perpendicular bias, even if the parallel biasing current is set to 0...350 A. Indeed,

TABLE I
MEASURED RESONANCE FREQUENCY f_{res} AND Q -FACTORS FOR CONSTANT PERPENDICULAR AND VARYING PARALLEL MAGNETIC BIAS

$H_{\text{perp}}/\text{mT}$	I_{bias}/A	Q	$f_{\text{res}}/\text{MHz}$
15	170	168	322
	190	200	325
	250	239	330
	350	256	334
50	30	204	225
	50	249	232
	130	272	255
	170	180	265
	350	200	300

for optimal tuning, an operating point close to the saturation magnetization (here: 55 mT) should be chosen. This test confirms that it is possible to keep the ferrite highly magnetized with perpendicular biasing and carry out the actual tuning by superposition of a parallel bias [1].

- 2) Working at an operation point that is set with perpendicular bias while the actual tuning is resulting **only** from parallel magnetic biasing could also be carried out considerably faster than a system with pure perpendicular biasing, if applied to a cavity design. However, in the regions of 240 MHz and 280 MHz of the example with $H_{\text{bias}} = 50$ mT, we observe a decrease in Q which could impede the exploitation of the achieved tuning range if it cannot be compensated by other means. It is likely that this reduction of Q results from an interference with a higher order cavity mode which then would have to be damped for a tuning cavity application;
- 3) Following (2), we observe a drop in resonance frequency at maximum bias fields, leading to a shift of the graph (b) towards smaller values, e.g. from $f_{\text{res}}(H_{\text{perp}} = 15 \text{ mT}, I_{\text{bias}} = 350 \text{ A}) = 334 \text{ MHz}$ to $f_{\text{res}}(H_{\text{perp}} = 50 \text{ mT}, I_{\text{bias}} = 350 \text{ A}) = 300 \text{ MHz}$;
- 4) From Fig. 1, it appears that a large tuning range could be obtained if the biasing path is chosen such that a maximum number of *different* μ -contours is cut by following the shortest path. This would be possible in the area of low perpendicular bias. However, we observed rather low Q -factors on the G-510 material for perpendicular bias fields $H_{\text{perp}} < 12 \text{ mT}$, i.e., for $H_{\text{perp}}/4\pi M_s < 0.2$ making this region unexploitable for tuning. Therefore, this region was not further investigated.

Note that while the tuning ranges shown in Table I give an indication of the dependency on the selected operation point, in the case of a cavity design also other parameters, as e.g. ferrite ring size would define the final resonance frequencies that can be obtained. It should also be noted that the values of Q measured here are limited due to the open (radiating) gap of the test cavity.

V. 2-DIRECTIONAL BIAS, PART II

Alternatively, it is possible to keep the parallel magnetic bias constant and carry out the actual tuning by superposing a perpendicular bias. Fig. 5 shows the resulting measurements for

Fig. 5. Measurement of S_{21} with varied perpendicular magnetic biasing and constant parallel bias current; top: at 350 A corresponding to path I in Fig. 1; bottom: at 210 A. The perpendicular biasing range is identical in the plots.

TABLE II
MEASURED RESONANCE FREQUENCY f_{res} AND Q -FACTORS FOR CONSTANT PARALLEL AND VARYING PERPENDICULAR MAGNETIC BIAS

I_{bias}/A	$H_{\text{perp}}/\text{mT}$	Q	$f_{\text{res}}/\text{MHz}$
350	12.5	156	337
	15	256	335
	30	299	321
	50	200	300
210	12.5	237	331
	15	227	327
	30	218	302
	50	162	276

constant parallel bias currents of 350 A and 210 A. A bias current of 350 A corresponds to path I indicated in Fig. 1 (path for 210 A is not shown). It can be seen from the graphs in Fig. 5 and the numbers given in Table II that a tuning range between 300 MHz and 337 MHz is reached by varying the perpendicular bias from 12.5 mT to 50 mT and at the same time keep the Q – factor ≥ 150 during the entire tuning. For the same perpendicular variation, but with a bias current of 210 A, a tuning range between 276 MHz and 331 MHz could be reached, this time with slightly lower Q -factors for higher perpendicular bias fields. It should be pointed out that in the two cases shown, the resonance frequency **drops** with an increasing total bias field (whereas with 1-directional biasing, μ_{rf} reduces with increasing bias and thus f_{res} increases as well). With a powering scheme as indicated by path I, an increasing perpendicular bias field results in a permeability increase and thus, following the relation given in (2), we observe a drop in resonance frequency.

Fig. 6. Measurement of S_{21} with varied perpendicular magnetic biasing and constant parallel bias current at 110 A corresponding to path II in Fig. 1.

Fig. 7. Measurement of S_{21} where both magnetic biasing orientations are shifted, corresponding to path III in Fig. 1.

Fig. 6 gives $|S_{21}|$ for 110 A constant parallel bias current, i.e. a biasing scheme according to path II shown in Fig. 1. Similarly to the graphs shown in Fig. 5, the current for parallel biasing is kept constant, merely on a lower value. This way, an increase in the perpendicular bias field first causes an increase in permeability and thus a reduction of f_{res} until about 247 MHz are reached. Any further increase of perpendicular bias results in a μ_{rf} -reduction and this way, f_{res} increases again. This behaviour of the resonance frequency occurs when the tuning path is chosen such that identical μ_{rf} -contours are cut more than once. Such a biasing scheme is undesirable for cavity tuning and should be avoided. Further, it can be seen that the Q -factors for $I_{\text{bias}} = 110$ A are considerably lower than what has been measured with higher parallel bias currents (compare Figs. 5 and 6).

Finally, Fig. 7 shows a biasing scheme according to path III where the parallel bias current increases while the perpendicular biasing is reduced. This could be reached with a combination of the biasing schemes of Fig. 5. In the example shown, the parallel bias current reduces from 350 A to 210 A, while at the same time the perpendicular bias increases from 12.5 mT to 50 mT (as indicated by the arrows in Fig. 5). Such a biasing scheme produces a larger tuning range than what could be reached with path I, Fig. 5, albeit with lower Q -factors. In comparison with the schemes following path I, and path II in Fig. 5, it can be considered an alternative tuning option that demonstrates the potential of the 2-directional biasing methods.

VI. 1-DIRECTIONAL BIAS (CLASSICAL ORTHOGONAL)

For the sake of completeness, we exposed the test cavity to a purely perpendicular magnetic bias to determine the available

Fig. 8. Measurement of S_{21} with pure perpendicular magnetic biasing. A magnetic bias of 0.1 . . . 0.2 T yields a tuning range of approx. 28 MHz.

TABLE III
MEASURED RESONANCE FREQUENCY f_{res} AND Q -FACTORS FOR PURE PERPENDICULAR (ORTHOGONAL) MAGNETIC BIAS

$H_{\text{perp}}/\text{mT}$	Q	$f_{\text{res}}/\text{MHz}$
40	29	185
60	146	241
80	55	268
100	135	283
110	277	288
150	456	302
200	396	311

tuning range obtained with classical perpendicular (orthogonal) biasing. It can be seen from Fig. 8 and Table III that either considerably higher magnetic biases are required for tuning than in the settings with 2-directional biases presented above, or a drop of Q -values during tuning has to be accepted. For instance, with perpendicular bias fields $H_{\text{perp}} = 40 \dots 80$ mT, a tuning range of 83 MHz could be reached, albeit with Q -factors considerably below the requested 150, whereas a magnetic bias above 100 mT would be required to reach a cavity $Q > 100$ for tuning with the G-510 material which is in use here. It can also be seen from Table III that high Q -values can be obtained with higher perpendicular bias fields, however, in this case, only a small tuning range of approx. 28 MHz, could be achieved.

VII. CONCLUSION

We presented a method that allows tuning of the resonance frequency of a ferrite-loaded cavity by means of applying a superposition of an axial and independently azimuthal external magnetic bias (2-directional external magnetic bias field). To this purpose, we built a re-entrant cavity that is partially filled with ferrite rings, and exposed to a superposition of perpendicular and parallel biasing in a way that a clear separation of the two orientations of the applied bias fields is possible. The objective of this procedure is the augmentation of the total tuning range for an operational regime with high Q -factors. To our knowledge, this particular technique has never been tested or applied in practice. We proposed a particular set of combinations of axial and azimuthal tuning field to achieve an enlarged tuning range for high- Q application for the experimental verification of this hypothesis. From our measurements, it could be seen that a frequency tuning by means of a 2-directional external bias field can be advantageous in comparison with classical 1-directional biasing methods as it allows to enlarge the available tuning range and/or to improve the Q -factor over a given tuning range. Depending on the application, this method would also allow a very fast tuning since the levels of the applied biasing fields in the 2-directional case are considerably smaller than what is required for the same tuning in the classical case of orthogonal biasing.

ACKNOWLEDGMENT

The authors would like to thank A. Gamp from DESY/Germany for kindly providing the ferrite rings and to F. Bergsma and P. Blanc from CERN for providing access to the laboratory magnet for our measurements.

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