Perpendicular Biased Ferrite-Tuned Cavities

R. L. Poirier
TRIUMF
4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3

Abstract

For varying the frequency of accelerating cavities in rapid-cycling rf systems for Synchrotrons, perpendicular biased yttrium garnet ferrites have gained popularity over the conventional parallel biased NiZn ferrites. An important milestone in fast cycling perpendicular biased ferrite tuners was reached at TRIUMF in the spring of 1991. To the best of our knowledge this is the first time that anyone has operated a fast ac perpendicular biased yttrium garnet ferrite tuner over such a large frequency swing at high rf power levels. A similar design is now being developed at SSCL for the Low Energy Booster. This paper will present a brief history of the development of perpendicular biased ferrite tuners, a comparison of the two biasing methods, magnetic field theory of perpendicular biasing, and the problem of eddy currents produced by the ac biasing circuit. A comparison will be made of the requirements and design features of the different tuner designs with special emphasis on the designs in the process of being developed and tested.

I. INTRODUCTION

Parallel biased NiZn ferrite tuners [1][2] have been well established for many years as a means of varying the frequency of accelerating cavities. NiZn ferrites have the disadvantage of very low electric Q's which limit the voltage that can be applied and very high saturation magnetization values which make it impractical to operate in the saturation region for obtaining high magnetic Q's. Also when parallel biasing NiZn ferrites, instabilities caused by dynamic loss effect and high loss effect were observed [3]. On the other hand, yttrium garnet ferrites have very high electric Q's and are available with very low saturation magnetization values, making perpendicular biasing practical for operating in the saturation region for high magnetic Q's. Operating in the saturation region also eliminates the ac dynamic loss effect, which occurs only at low values of bias field. The high loss effect, which is related to the stored rf energy in the ferrite for the case of parallel biasing NiZn ferrite, has not been observed in the case of perpendicular biasing yttrium garnet ferrite. However, the classical non-linear detuning of the resonance curve as a function of power level has been observed [4]. Yttrium garnet ferrites are normally used at microwave frequencies for such devices as isolators, circulators, phase shifters, attenuators and filters. These devices make use of the gyromagnetic resonance phenomena for their properties and never operate much above a bias field which causes a gyromagnetic resonance to occur. The history of perpendicular biased ferrite tuners operating at a bias field far above the gyromagnetic resonance is reviewed. The two biasing methods are based on different physics phenomena and are compared. Basic magnetic field theory and problems introduced by eddy currents, when perpendicularly biasing ferrites, is presented. A comparison of the different tuner designs is discussed.

II. DEVELOPMENT HISTORY

The idea of operating at a bias field far above the gyromagnetic resonance in order to take advantage of the low value of the dissipative component of the permeability in that region, was first tested at Los Alamos for the Proton Storage Ring [5] at 500 MHz with a 1% tuning range. When the LAMPF II rapid-cycling Synchrotron was proposed, the development of perpendicular biased yttrium garnet ferrite operating above the gyromagnetic resonance was continued at Los Alamos in the 50 MHz to 60 MHz range for a 20% frequency swing and a gap voltage between 130 and 140 kV [6][7]. These tests were with dc magnetic bias only but the principle of operating above the gyromagnetic resonance (lower frequency) was tested at high power. Concurrently TRIUMF was involved in an rf development program on accelerating cavities for a proposed KAON Factory and a collaboration was set up between TRIUMF and Los Alamos to further develop perpendicular biased ferrite tuners. Los Alamos shifted its efforts toward designing an off-axis tuner with a smaller tuning range for the main ring cavity using a radial bias scheme [8]. The radial bias scheme was aborted because of the difficulty in maintaining a uniform magnetic field. The Los Alamos Booster Cavity was shipped to TRIUMF where it was completely rebuilt for ac bias operation and the lower frequency limit extended to 46 MHz [9].

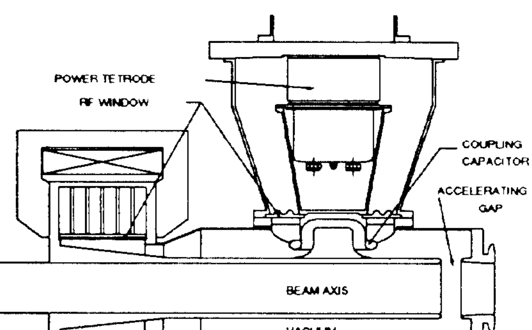

Figure 1. Typical cross section view of the type of ferrite tuned cavity used at Los Alamos, TRIUMF and SSCL with the ferrite tuner on the beam axis

The Los Alamos main ring cavity and RF amplifier was eventually shipped to SSCL for its development program and the collaboration initially set up between Los Alamos and TRIUMF has continued as a TRIUMF/SSCL collaboration.

SSCL has designed a liquid cooled tuner similar to the TRIUMF/LANL design [10] for the Low Energy Booster (LEB) and the Institute for Nuclear Physics in Novosibirsk (INP) has produced an alternative design [11] for the LEB similar to the TRIUMF design except the tuner is an epoxied assembly. A typical cross-section view of the type of ferrite tuned cavity used at Los Alamos, TRIUMF and SSCL is shown in figure 1. The different tuner designs will be discussed later.

The Institute for Nuclear Research (INR) in Moscow has also done extensive design work on perpendicular biased ferrite tuners [12] for their proposed Kaon Factory. Development work on perpendicular biased ferrite tuners was also done at AECL, Chalk River for the PETRA II [13] and HERA [14] RF systems in Hamburg but for much slower and smaller tuning ranges. A tuner using perpendicular biased ferrite was also developed at CERN for the 114 MHz electron accelerating system for the CERN PS [15] but again for a slow and small tuning range. A stripline type fast ferrite tuner with a small tuning range [16] was produced by ANT Bosch Telecom in Germany for BNL but is different from the other designs in that it uses ferrite tiles epoxied to copper cooling plates.

III. COMPARING OF BIASING METHODS [17]

Assuming that the operating rf frequency is sufficiently far below the frequency for gyromagnetic resonance and that the rf field is small compared to the bias field, the effective permeability [18] for parallel biasing is a function of the rate of change of the B-H curve as shown in figure 2 by the slope of the tangent lines at points A and C, while for perpendicular biasing it is a function of the ratio of B/H at any point on the B-H curve (e.g. slope of the lines B and D).

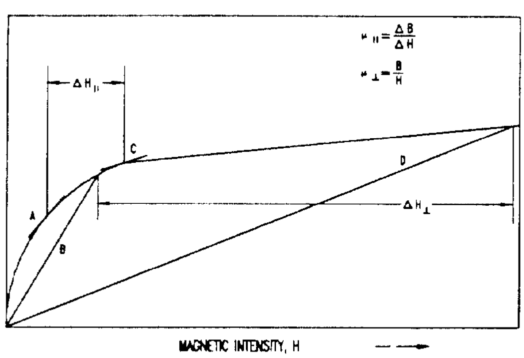

Figure 2 Plot of magnetic induction vs. magnetic intensity

The ΔH shown is for the same tuning range for each case for a particular tuner. For NiZn ferrites which have very high saturation magnetization values (3200 gauss for the NiZn ferrite used at Fermilab), operating in the perpendicular bias mode would require a significantly larger bias range and would make the design of the bias power supply very difficult and expensive. On the other hand yttrium garnet ferrites are available with very low saturation magnetization values (810g for the TRIUMF-KAON ferrites) making the design of the bias power supply comparable to the one used in parallel biasing NiZn ferrite and making them very attractive for perpendicular biasing.

IV. PERPENDICULAR BIAS THEORY [19][20]

If a dc magnetic field H is applied to a ferrite material and a small rf magnetic field h is applied perpendicular to the dc field, the rotating vector (H+h) of a magnetic field describes a cone and the magnetic moment M precesses around the cone. The condition for gyromagnetic resonance is when the rf is synchronized with the precession and occurs at

$$H = f/2.8$$

where H is the internal dc magnetic field in oersteds and f is the rf frequency in Megahertz. The permeability of the ferrite is of a tensor nature and has both a dispersive and a dissipative component and can be written as

$$\mu = \mu' - j\mu''$$

Figure 3 is an idealized plot of permeability vs applied magnetic field. The plot of the dissipative component μ'' shows the greatest loss at H_{res}, which is the condition for gyromagnetic resonance. The plot of μ' is the effective μ for the dispersive part of the permeability μ'. The cavity frequency is tuned in the optimum way by varying the dc bias from H_2 to H_1, thus varying μ' from μ_2 to μ_1. In the region above resonance the value of μ'' is lowest.

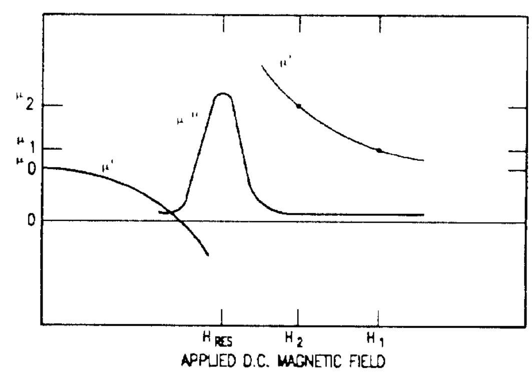

Figure 3. Plot of permeability vs applied magnetic field.

For low frequencies well below the frequency for gyromagnetic resonance [21] and small rf magnetic fields relative to the dc bias field, the expressions for u' and u" to some approximation are:

$$\mu' = 1 + \frac{4\pi\, Ms}{H} \qquad \mu'' = g\Delta H_k \frac{f}{f_o^2} \frac{4\pi\, Ms}{H}$$

where g is the gyromagnetic resonance ratio, ΔH_k the spinwave linewidth at the gyromagnetic resonant frequency f_0, f the operating frequency, $4\pi Ms$ the saturation magnetization and H the dc internal bias field. Since the magnetic Q is the ratio of μ'/μ'', then for a fixed frequency and a given value of μ' (i.e. the ratio of $4\pi Ms/H$ is constant),it can be seen that a low value of ΔH_k will give a higher magnetic Q. For the same μ' range a lower saturation magnetization will certainly reduce the demands on the bias power supply but care must be taken not to go too low in saturation magnetization because the Curie temperature of magnetic materials decreases with a decrease in saturation magnetization and will limit the maximum operating temperature of the ferrites.

V. AC BIASING CIRCUITS

With ac perpendicular biased ferrite tuners the magnetizing circuit becomes much more complicated [22]. In the parallel bias mode the magnetic path is a circumferential closed loop through the ferrite rings. In the perpendicular bias mode the magnetic path, as shown in figure 4, consists of a toroidal C-shaped return yoke, air gaps, metal walls and the ferrite rings.

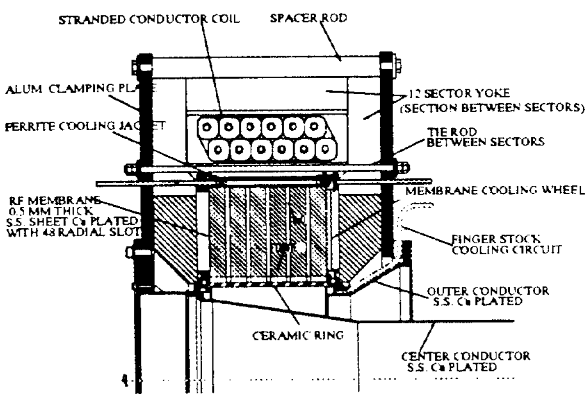

Figure 4. Cross-section view of the TRIUMF ac biased ferrite tuner.

It is desirable that all the components that make up the ferrite tuner be designed so that the induced eddy currents are as small as possible. A complete circular geometry represents a short circuit for the induced emf in the magnetic field so whenever such a geometry can be broken a significant reduction in eddy current losses can be achieved. In order to maintain vacuum integrity the inner circumference of the rf membrane wall forming a short circuit could not be broken. This made the reduction of eddy current losses in the rf membrane end walls very difficult. However, losses due to the eddy currents were minimized by extending 8 of the 48 radial slots in the rf membrane to its outer circumference and introducing 8 insulating breaks in the water cooling jacket in line with the 8 slots in the rf membrane wall. The complicated magnetizing circuit also makes it much more difficult to determine the magnetic parameters. The following formulae have been derived [23] for expressing the magnetic induction, magnetic field strength and ferrite permeability.

$$B_g = \frac{\mu_o NI + B_{sat} L_f}{L_g + L_f} \qquad H_f = \frac{\mu_o NI - B_{sat} L_g}{\mu_o (L_f + L_g)}$$

$$\mu_f = \frac{\mu_o NI + B_{sat} L_f}{\mu_o NI - B_{sat} L_g}$$

where B_g is the magnetic induction, H_f the magnetic field strength in the ferrite, μ_f the permeability of the ferrite, μ_o the permeability of free space, NI the applied ampere turns, B_{sat} the saturation magnetic induction of the ferrite material, L_g the magnetic path length in the air gap (including non-magnetic materials) and L_f the magnetic path length in the ferrite. Although these equations look rather simple they are very useful in reaching a conceptual magnetics design for perpendicular biased ferrite tuners.

From an rf control point of view the effect of the eddy currents on the bandwidth response of the tuner assembly and the magnetic field produced by the eddy currents must be considered[24]. The eddy currents induced in the end membranes of the ferrite tuner produces a pole and the extra inductance from the slots in the membrane produces a zero. The magnetic field produced by the eddy currents tends to cancel the field produced from the coil , reducing the effect of the coil current on the resonant frequency. All these effects must be taken into consideration in designing the tuning control loops.

VI. DESIGN COMPARISONS

There are many versions of different designs [25],[26] and [27] which are too numerous to mention in this paper. However table 1 is a comparison of some of the parameters of tuner designs which are being developed or are in operation.

The tuner for PETRA II is very slow and does not have to deal with eddy current losses. However the TRIUMF Booster and the SSCL LEB are fast-cycling machines and require special attention to eddy current losses.

The TRIUMF Booster operates at a repetition rate five times greater than the SSCL LEB tuner making the eddy current problems more severe. It also has an accelerating time five times less than the SSCL LEB which tends to make df/dt and di/dt larger, putting a greater demand on the rf control system and the ferrite bias power supply. However the SSCL LEB tuner operates with a higher RF power density dissipated in the ferrite putting a greater demand on efficient cooling of the ferrite material. Figure 5 is a cross-sectional view of the different types of tuners that have been designed. The PETRA II and HERA type tuners shown in figure 5(c), are water cooled via the tuner walls and BeO disks sandwiched between the ferrite rings. The tuners are inductively coupled to the accelerating cavity and are off the beam axis. The ferrite disks are rather small with an outer diameter of 13 cm and an inner diameter of 7 cm. The TRIUMF tuner is water cooled in a similiar manner but the ferrite rings are much larger with an outer diameter of 60 cm and an inner diameter of 30 cm.

Table 1. Comparison of different rf system requirements using perpendicular biased ferrite tuners

	TRIUMF Booster	SSCL LEB	PETRA 11 (AECL)
Min Frequency (MHz)	46.1	47.5	51.63
Max Frequency (MHz)	60.8	59.8	52.03
Peak RF at Gap (kV)	62.5	127.5	100
Accelerating Time (ms)	10	50	7e4
Repetition Rate (Hz)	50	10	0.01
Max RF df/dt (MHz/ms)	3.5	1.03	3e-5
Max Bias di/dt (A/ms)	311	39.2	1e-3
Max df/di (MHz/A)	0.03	0.065	----
Min Bias (AT)	8640	6437	----
Max Bias (AT)	31200	24632	----
Min H internal (AT/m)	19469	25956	40000
Max H internal (AT/m)	119292	136095	100000
Min H_{RF} (A/m)	358	670	----
Max H_{RF} (A/m)	656	3525	----
Ferrite Material	TT-G810	TT-G810	TT-G510
Min μ(rf) of Ferrite	1.48	1.4	1.3
Max μ(rf) of Ferrite	3.94	3.2	2.8
Pk power density (W/cc)	0.50	0.936	----
Avg power density (W/cc)	0.06	0.342	1.7
Cavity Q	2200-3600	2800-3420	----
Cavity R/Q	35	36	----

The INP alternative design for the SSCL LEB cavity is also water cooled in the same way, but only two BeO disks are used which are glued to the ferrite rings as shown in figure 5 (b). The outside surface of the outer ferrite rings and the edges of all of the ferrites at the outer circumference are glued to the tuner rf walls. The size of the ferrite rings are similiar to the TRIUMF tuner but only 5 rings are used instead of 6 because of the slightly smaller tuning range. The in-house LEB tuner design is a direct liquid cooled tuner with the ferrite rings totally immersed in the cooling liquid. This requires an additional structure to contain the liquid since the rf tuner walls are slotted to reduce eddy current losses and increase the bandwidth response of the tuner. This design also requires two ceramic windows, one to contain the liquid and the other for the vacuum, as shown in figure 5(a). The tuners for TRIUMF and SSCL are on the beam axis as part of the accelerating cavity and therefore the magnetic fields on the beam axis produced by the ferrite biasing field must be compensated for by mounting two cavities back to back to get first order cancellation of the magnetic field effect on the beam axis.

VII. STATUS OF TUNERS

The PETRA II and HERA tuners are in operation at the DESY labaratory and although they are having rf problems with the cavities, the ferrite tuners themselves are performing very well. The TRIUMF Booster Cavity has operated in a test stand for several one or two hour intervals at a 50 Hz repetition rate to the full design voltage and frequency swing but with no tuning loops or regulating loops [9]. The ferrite tuner program at TRIUMF is now focussed on developing a control system and proper ferrite bias power supply to implement the above control loops.The INP designed conduction cooled tuner at SSCL was tested under dc bias conditions and maintained 70 kV at 5% duty cycle (100 msecs) in 1 Mhz steps over the desired frequency range of 45 to 60 Mhz. However it failed after approximately 12 minutes at 80 kV gap voltage at 28% duty cycle. Their focuss now is on the assembly and test of the liquid cooled tuner [28].

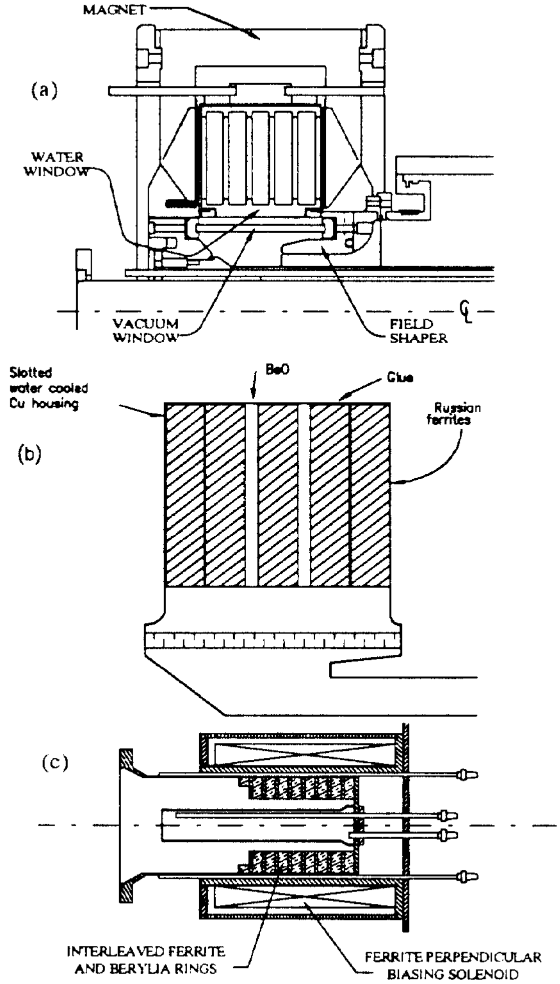

Figure 5. Cross-section view of ferrite tuners. (a) SSCL(LEB) direct water cooled tuner, (b) INP water/BeO cooled alternative for the LEB, (c) PETRA II & HERA type ferrite tuner. The TRIUMF tuner is already shown in figure 4.

VIII. CONCLUSIONS

The development work in the field of operating yttrium garnet ferrites in the region beyond the gyromagnetic resonance has progressed very well. To the best of the author's knowledge, TRIUMF was the first laboratory to operate a fast ac perpendicular biased yttrium garnet ferrite tuner over such a large frequency swing at high rf power levels. Hopefully in the future, ac perpendicular biased tuners will become as popular as the now well established parallel NiZn ferrite tuners.

IX. ACKNOWLEDGEMENT

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