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Some Design Considerations for Perpendicular Biased Ferrite Tuners

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Abstract

Recently remarkable progress has been achieved in the development of perpendicular biased ferrite tuned rf resonators for fast cycled synchrotrons [1,2]. Compared with the broadly used parallel biased rf cavities they provide higher resonator quality factor Q. However when designing perpendicular biased cavities, special attention should be paid to the methods to provide eddy current suppression in the resonator walls, the ferrite nonlinearity influence, the generated heat removal, the fast self resonant frequency control. The prospective of a faster additional biasing system are discussed and conclusions are drawn.

1 INTRODUCTION

Ferrite materials have been used for many years to provide a frequency modulation in charged particles accelerating structures. The frequency variation is obtained by a change in the biasing current controlling the magnetic permeability of the ferrite. If the direction of the biasing magnetic field is parallel to the direction of the rf field in the structure, the biasing is known as "parallel"; if those fields are orthogonal, it is "perpendicular".

The difference in operating in the parallel or perpendicular biasing mode [1], projected on the magnetizing curve B(H), is that in the first case the induction B changes in a range below the saturation magnetization B_{sat} and the permeability μ is determined by the slope - the derivative dB/dH - at the working point; in the second case B changes in a range above B_{sat} and μ is determined by the ratio B/H at the corresponding working point. For the same μ change parallel biasing requires a bigger change in the induction flux Φ. Because of the operation above B_{sat} the ferrite ac dynamic (hysteresis) losses are practically absent for perpendicular biasing. The non-linear effects by perpendicular biasing are also much less pronounced compared to the parallel case [2]. But the main advantage of the perpendicularly biased cavities when using yttrium garnet ferrites is their high magnetic quality factor[1] Q_m and their high electric quality factor Q_e [3,4,5] meaning low rf losses.

In spite of that, the rf losses in the perpendicular biased ferrite tuned cavities are not negligible for real operational conditions and due to the ferrite's poor thermal conductivity the heat removal presents a serious problem, especially in the case of a large relative frequency variation $\Delta f/f$.

The field H is controlled by the current I_b flowing through a biasing coil (Fig. 1). Since the ferrite is inside the resonator, the penetrating magnetizing flux induces an emf e,

$$e = -(\Delta\Phi/\Delta t) \qquad (1)$$

(Δt is the time of modulation) and causes the flow of eddy currents in the walls. The resonator walls should have a low resistivity to bring down the surface rf power losses and should be thick enough for mechanical and thermal stability, but they should also have high electric resistance to reduce the eddy current losses. These contradictory requirements are met differently depending on the particular designs.

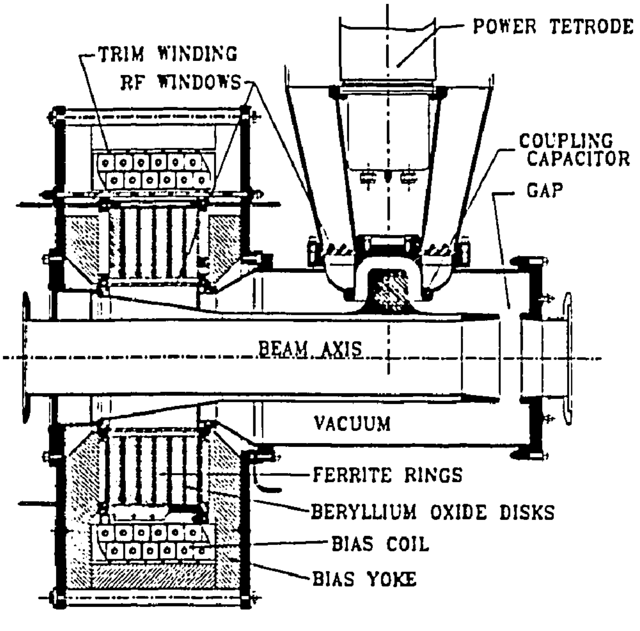

Fig. 1. Cross-section of the TRIUMF Prototype Ferrite Tuned Cavity

The resonator wall circuit acts as a secondary shorted winding coupled by a mutual magnetic flux to the primary biasing coil and loading its power supply. It determines to a large degree not only the energy consumption and the cooling requirements, but also the dynamic magnetic field distribution in the ferrite and the response time of the biasing system.

The increasing rotating frequency of the particles in ring accelerators is determined by the average magnetic field along the orbit, slightly differing from cycle to cycle. The driving frequency of the resonators follows the rotating frequency, but the self-resonant frequency of the acceler-

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[1] The magnetic quality factor Q_m is defined as a ratio of the dispersive and the dissipative (the real and the imaginary) components μ'/μ'' of the tensor of the magnetic permeability [5].

ating resonators is controlled by a pre-determined biasing current as a function of time. If these frequencies deviate from each other, the cavity impedance drops and the required power from the rf generator increases. To prevent the enormous power demands a fast control system should react during the accelerating cycle to bring the self-resonant frequency close to the driving frequency.

2 MAIN BIASING SYSTEM

The design of the main biasing system is based on the rf conceptual design of the cavity having as starting parameters the frequency range from f_1 to f_2, the gap voltage and a chosen geometric configuration. It could be based on line theory, SUPERFISH, MAFIA or other code computations. As an output result the range of the relative ferrite magnetic permeability ($\mu_{f1,2}$) is obtained to provide the frequency modulation. Then [1], the induction variation $B_{g1,2}$ in the ferrite is determined.

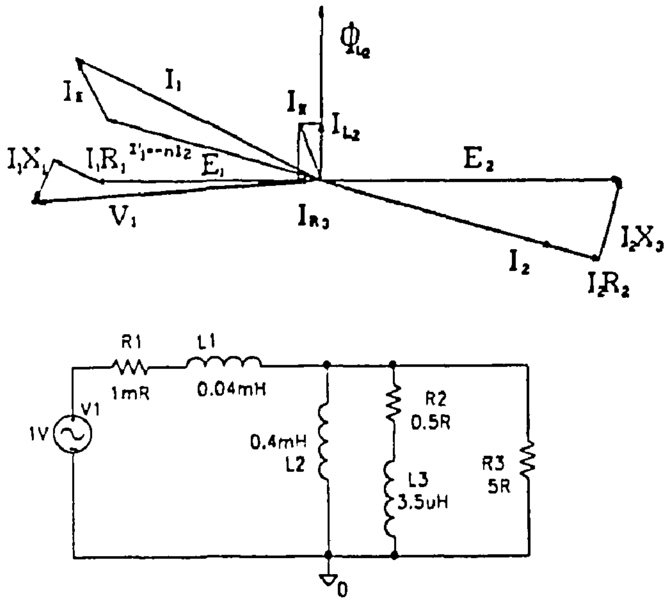

Fig. 2. Equivalent schematics and vectorial plot

The electromotive force e is producing eddy-currents in the cavity construction, depending on its electric and geometric parameters. These induced currents tend to produce a flux opposing to the initial penetrating flux.

Assuming all other parameters are fixed, the expression (2) determines μ_f as a function of B_{sat}, namely

$$\mu_f = (\mu_o NI + B_{sat}L_f)/(\mu_o NI - B_{sat}L_g)\ . \tag{2}$$

where NI is the ampere-turns, μ_o is the permeability of the free space, L_g is the magnetic path length in the non-magnetic materials, and L_f is the magnetic path length in the ferrite. Since B_{sat} is temperature dependent then μ_f is also temperature dependent. This means that a temperature stabilization is required to reproduce the pre-defined frequency curve from one cycle to another.

The contradiction between the requirements for the rf and eddy currents flowing on the resonator walls could be resolved at least partly by providing the shortest possible low resistive paths for the rf currents and longest high-resistive – for the eddy-currents [1,2,4].

3 EDDY-CURRENT CIRCUITS

In principle the circuit for the eddy currents includes all constructive elements in the biasing system, but its characteristics are determined mainly by the resonator walls. Its impedance in most cases is considered as consisting of its self inductance and resistance. Due to the strong magnetic coupling between the main magnetizing coil and the above circuit, the loaded transformer theory may be used [6] as a physics model.

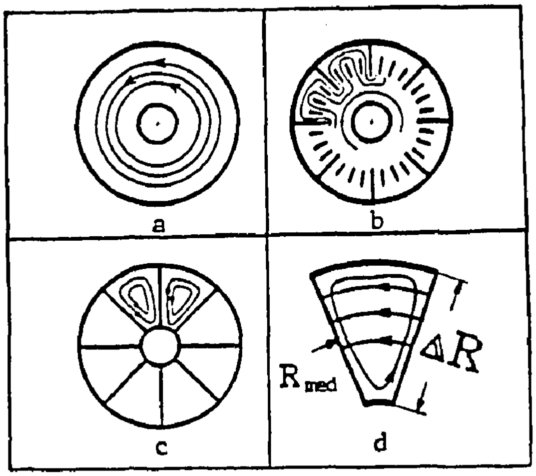

Fig. 3. a. concentric structure, b. partial radial cutting, c. complete radial cutting, d. detailed subsection of c.

Some of the main properties of the combined system including the magnetizing coil and the loading eddy-current circuit, acting as one turn fixed short-circuited secondary winding, are visible on both equivalent schematics and vector diagram presented in Fig. 2. This diagram allows one to consider the power requirements as well as the main transient characteristics of the system, remembering that the real control voltage in time represents a spectral sum. On the schematics drawn the primary winding resistance R_1 is connected in series with the primary leakage inductance L_1 and a group of two other impedances in parallel: (1) the parallel connection of the magnetizing inductance L_2 and of the resistor R_3, representing the ac losses in the main system; (2) the series connection of the resistivity and the leakage inductance of the secondary (eddy-currents circuit) winding, transformed to the primary side, R_2/n**2 and L_3/n**2 correspondingly, where $n = N_2/N_1 = 1/N_1$ is the ratio of the secondary and primary turns . If the reaction of L_3 is negligible compared with the resistivity R_2, the shunting action of the load will be stronger for lower R_2 and N_1 values . At higher frequencies of the spectra all inductive reactances will increase and influence the shunting. More accurate consideration may require taking into account the capacity of the elements as well.

As an illustration Fig. 3 shows different disc resonator wall configurations, penetrated by the same axially symmetric flux.

All structures essentially provide the same conductivity for the rf currents flowing in the radial direction. The different type radial slots create different resistive paths for the eddy-currents. The coupling with the main flux for the case (a) and (b) is the same, but because the longer path over the same surface, the equivalent parallel resistance in the case (b) will be higher. In the case (c) a complete slot in the radial direction is provided. Each of the total of m equal sectors is coupled with 1/m part of the total flux, its average resistance along the path of the currents (driven by the same equal proportional part of the total induced emf) compared to the average resistance of the same sector as a part of the structure (a), illustrated on (d), is (m**2). $(\Delta R/R_{med})$**2 times higher . The eddy-current loss power in the wall will be lower by the same coefficient.

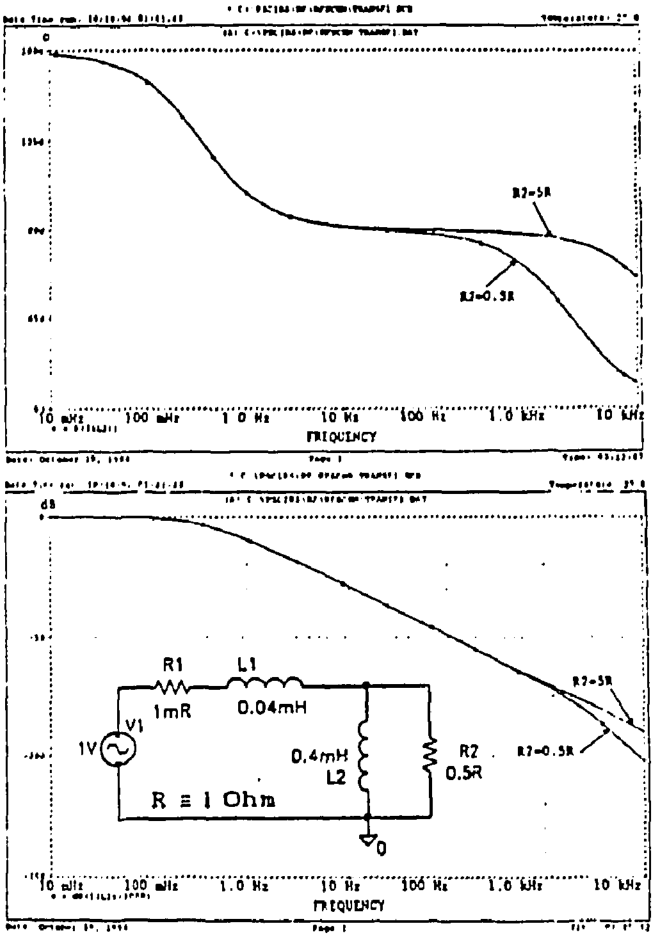

Fig. 4. Equivalent schematics with the amplitude and phase frequency response

For the equivalent schematics the combined action of this slotting is represented by a chain of m series impedances of the individual sectors shunting the main magnetizing inductance. On the other hand, the above consideration can also work in a reverse direction, for example, to use an additional loop in one of the legs of the return yoke to regulate this proportional part of the flux. In this case the primary impedance will be transformed to this loop, divided by (1/n)**2 and by the flux dividing ratio m. The same considerations may be expanded for any additional loop.

4 FREQUENCY RESPONSE

The equivalent scheme allows one to estimate the frequency response of the cavity when keeping constant the input biasing ac voltage amplitude. This could be done either by determining the time constant or by calculating the amplitude and phase dependence on frequency of the magnetizing current on this condition, because its value determines the ferrite μ and, consequently, the self resonant frequency of the cavity. Figure 4 demonstrates the calculated frequency response characteristics and their dependence on some parameter changes. Combined calculated and measured data of the TRIUMF/KAON Factory Booster Prototype Cavity with some simplification of the equivalent schematics, are used as input.

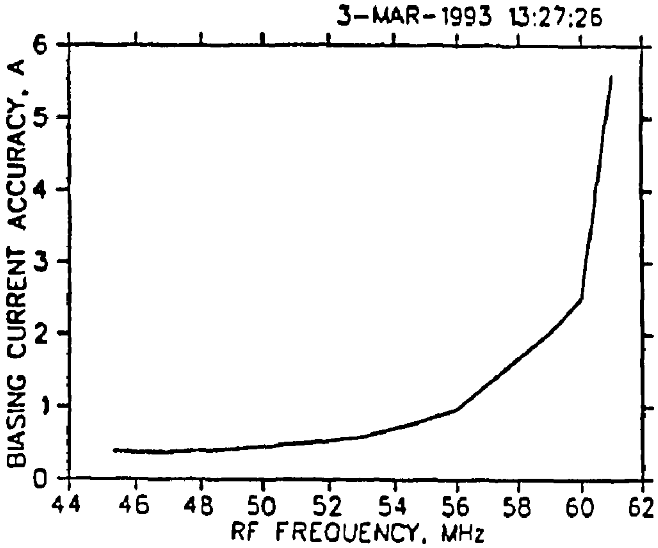

Fig. 5. Required main biasing current deviation for fast tuning

5 ADDITIONAL REGULATING LOOPS

If at a fixed biasing current I_b the temperature changes, then through B_{sat} the rf self resonant frequency of the resonator will also change according to the following relationship

$$\partial f/\partial t^\circ \;=\; (\partial f/\partial \mu).(\partial \mu/\partial B_{sat}).(\partial B_{sat}/\partial t^\circ)$$

The experiments showed that the frequency drift during the time of thermal stabilization is quite big, approaching 200 $kHz/^\circ C$ at the lowest frequency of the 46-61 MHz range and exceeds substantially the frequency range Δ f = 12 kHz, required for the fast frequency correction (see below). In addition to the temperature stabilization, one turn current correctional loops may provide the equivalent stabilization and correction of the biasing current components, if it supplies N times bigger current, than would be needed for the correction from the main biasing coil. A similar loop can be used also to fast tune the self resonant frequency of the cavity when it differs from the driving frequency. Additional trimming loops have the advantage of independence from the main biasing system, as well as avoiding the necessity to control currents of few Amperes at an average current level of 1500 A. Its dc power supply must be protected from the induced emf from the variable main flux by suitable filtering. Estimations based on the measured quality factor Q and on a limiting phase difference of 45° between the cavity self resonant frequency and the driving frequency show, that the fast correction requires up to a 7 A deviation of the main biasing current (Fig. 5), resulting in rf frequency correction between 8 and 12 kHz.

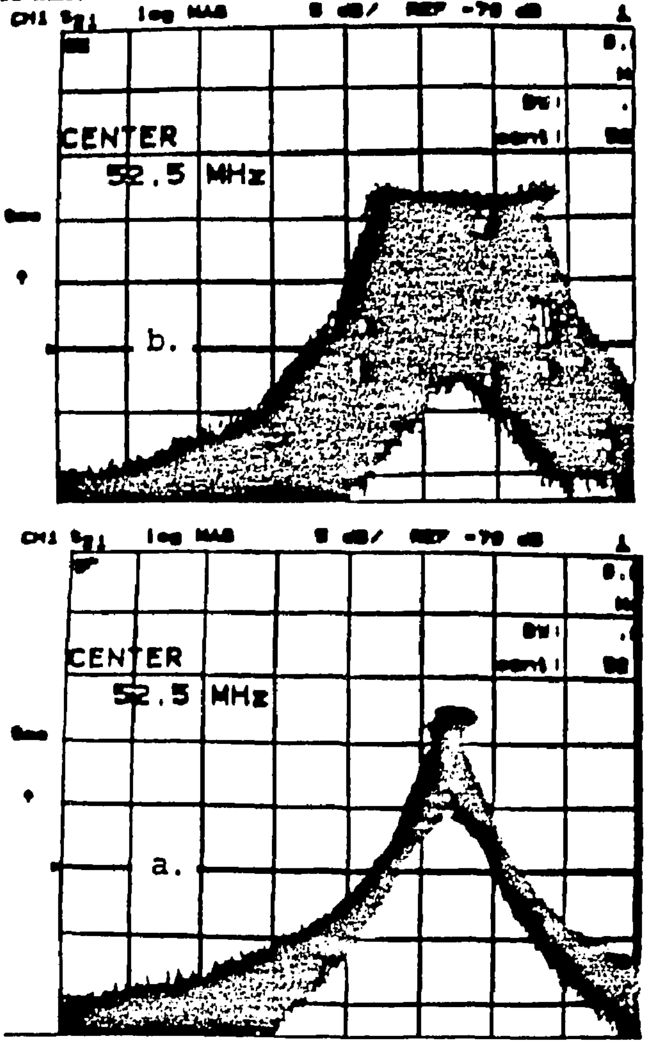

Fig. 6. a. self- modulated resonance curve, b. curve, modulated by one loop current. One horizontal division corresponds to 50 kHz.

When acting in an active ac mode, the correctional loop should be considered as a primary loop. It is loaded by the cavity eddy-currents circuit and by the main biasing coil circuit in parallel. The later includes not only the leakage inductance of the main biasing system, but also the inductance of the feeding cables and the capacity of the biasing power supply filter. These loads are transformed to the correcting loop impedance, depending on the mutual flux coupling and the winding number ratio n ($n = 1$ for the Eddy-current load and $n = N_{main}$ for the main biasing system). This system gives additional possibilities to vary its properties by changing the value of its different parameters, including the active resistivity of the correctional loop. It is a proposal to use as a correctional loop the eddy-current circuit itself [8], but then its properties are determined mainly from other requirements and the freedom of their variation is greatly limited.

In all cases it should be taken into account, that an emf is induced in the correctional loop by the main biasing variable flux. If the loop is closed by a controlled switch through a regulated resistor, it could be used as a passive element, removing energy, stored in the main biasing system, and then its impedance is acting as additional shunt-loading; if the correctional loop is fed by a separate current source, a compensation of the above emf is required to have a pure action of the correctional loop source.

6 EXPERIMENTAL RESULTS

To illustrate experimentally the possibility of a separate correctional loop, in the prototype cavity an additional loop - actually, 6 winding in parallel - was installed. Because of the high noise level in the biasing system in dc mode a method of photo-accumulation was proposed and used. At fixed main dc biasing the rf system was run in self excited mode at signal level. Due to the noises and the biasing system instability, the spectrum analyzer indicated some jitter of the resonance frequency, which has been recorded by increasing the exposure time and keeping the photo-camera focused to the analyzer screen. The photos on Fig. 6 show clearly that the recorded frequency swing of 125 kHz (b) with a sinusoidal modulating current of $I_m = 140$ A overlaps substantially the frequency jitter of 25 kHz (a) without modulation. The net frequency modulation is $\Delta f = 125 - 25 = 100$ kHz, much higher the needed estimated correction of 12 kHz. The dc biasing current during the measurements was $I_b = 1266$ A, the self resonance frequency of the cavity after the thermal stabilization was 52.525 MHz. Under these conditions the sensitivity of the frequency swing to the modulating current is about 0.7 kHz/A.

The measured loaded equivalent one-loop impedance (having the main biasing dc on) was 0.00333 Ohms , compared to the estimated equivalent impedance of the primary coil at the same frequency (60 Hz) of 0.017 Ohms. The measurement accuracy was about 5%.

The ratio of the ac voltage transformation from the modulation to the main loop was close to 2, when the main coil was biased with a dc current $I_b = 1166$ A at a modulation current amplitude of about 140 A. The reason is that at this conditions due to the leakage inductance and the ac load, which the main coil and the output impedance of the biasing power supply represent, this ratio is different from the ratio of the turns. If the dc power supply is turned off, or disconnected, the same ratio is close to 4.

With no biasing, the load impedance measured from the one loop primary when the main coil is disconnected from the power supply, was 0.004015 Ohms with a phase angle of 1.093 rad, while with the secondary disconnected from its power supply the impedance of the main coil was 0.24 Ohms with a phase angle of 1.28 rad. This measurement shows, that while the influence of the additional loop on the cavity frequency is strong enough, its disturbing influence on the main biasing system supply is weaker than it could be expected from the winding transformation ratio. The one-loop time constant is lower, compared to the corresponding one for the main coil (based on the above complex impedances measurements). Besides this, varying the loop parameters, the frequency response may be optimized in certain degree.

7 CONCLUSIONS

Perpendicularly biased frequency modulated cavities can already be designed with well defined parameters. Although the detailed design of the biasing system may be performed by using specialized computing programs, it makes sense to first do a conceptual design, based on feasible physics models. These models not only allow one to do fast estimation with reasonable accuracy, but are able to give hints for optimization when using the specialized programs. It also seems, that together with the means to provide thermal stabilization, the use of a low inductance fast acting system, separate from the main biasing one, makes sense.

8 ACKNOWLEDGMENTS

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