A PERPENDICULAR-BIASED FERRITE TUNER FOR THE 52 MHz PETRA II CAVITIES

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Abstract

Traditional ferrite loaded cavity frequency tuning systems are operated with the ferrite dc bias magnetic field parallel to the rf magnetic field. In this mode large permeability changes ($3 < \mu < 25$) are possible but the magnetic loss factor is high (ferrite $Q_M \leq 200$), generally resulting in an unloaded cavity Q of less than 2000. Also the ferrite must be located in a region with very low electric field, as the dielectric Q_E is ≈ 50. Recent studies of the perpendicularly biased ferrite mode have demonstrated much lower magnetic and dielectric losses ($Q_M > 1000$, $Q_E > 5000$), although over a narrower permeability range ($1.25 < \mu < 4$). This permits the use of ferrite tuners in high efficiency structures and reduces rf power requirements. The tuner system for the PETRA II cavities is ideal for the perpendicular bias application.

Introduction

The frequency of the 51 MHz PETRA II cavity must be increased by ≈ 0.4 MHz during the acceleration sequence. In such applications a biased ferrite tuning system has traditionally been used. The small frequency shift suggests an external tuner, the easiest form of which is a loop coupled section of transmission line. By changing the ferrite permeability, one changes the circulating current in the coupling loop which changes the magnetic stored energy.

The external tuning line may either be so short as to be essentially a lumped inductor (non-resonant) or long enough that, together with the coupling loop, it forms a $\lambda/2$ shorted transmission line resonator. In the latter case the circulating current in the loop can be increased above the "short-circuit" value and a larger frequency shift obtained. Including temperature changes and safety margins, a 500 kHz tuning range is required. A non-resonant tuner with this frequency range would require an unreasonably large coupling loop, so the resonant tuner concept was chosen.

Recently a collaboration between the University of Colorado and the Los Alamos and Sandia laboratories[1-3] has pioneered the use in low frequency accelerator applications, what was traditionally a microwave ferrite, namely the aluminum doped yttrium-iron-garnet ferrites manufactured by both TDK and Trans Tech. These ferrites operate with bias fields perpendicular to the rf magnetic field and close to or well above the saturation magnetization value. The rf permeability of the ferrite is given by

$$\mu_{rf} = 1 + \frac{Ms}{H} \qquad (1)$$

where Ms is the saturation magnetization of the ferrite and H is the perpendicular bias magnetic intensity inside the ferrite.

The perpendicularly biased ferrites have the following properties:

1) μ_{rf} varies between 4 and 1.25 over the practical low-loss operating region.
2) the magnetic Q varies between 500 and 5000 over this permeability range.
3) the saturation magnetization may be chosen to match a particular application, minimizing bias field requirements.
4) they have a high electric Q ($Q_E \gg 1000$).
5) the properties have only a weak dependence on bias field slew rate and on rf amplitude (for up to 1.5 watt/cc peak power dissipation).

Design of an External Resonant Coaxial Tuning Cavity, Loaded with Perpendicularly Biased Ferrite

The resonant tuner concept (Fig. 1) consists of a shorted piece of two-wire transmission line (i.e., the coupling loop) connected to another piece of shorted coaxial line which is loaded with ferrite. The two pieces, when coupled together, conceptually constitute a half wavelength resonator which is coupled to the main accelerating cavity by the open structure of the two-wire transmission line (i.e., what one normally calls the coupling loop).

The operation of the system may be understood in the following way: When the ferrite permeability is low the $\lambda/2$ "coupling loop-tuner line" resonator frequency is much higher than that of the accelerating cavity and only weakly influences it. However, increasing the permeability (by lowering the bias field) decreases the "loop and tuner" resonant frequency, and as the two resonators interact, the accelerating mode frequency is pushed down.

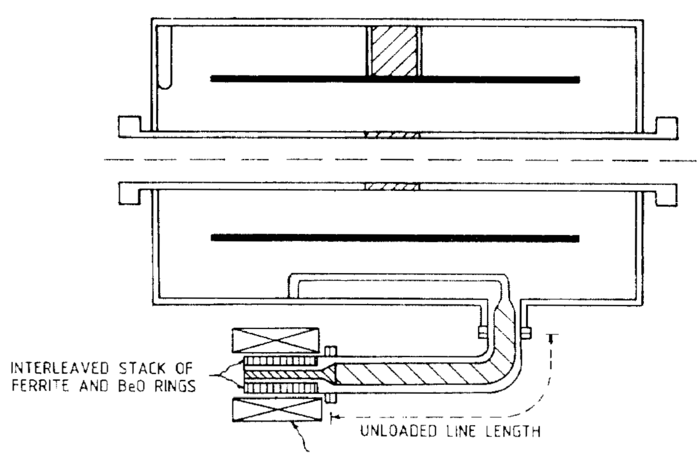

Fig. 1 Schematic layout of the PETRA II 50 MHz cavity with the loop coupled, external perpendicular biased ferrite loaded frequency tuner.

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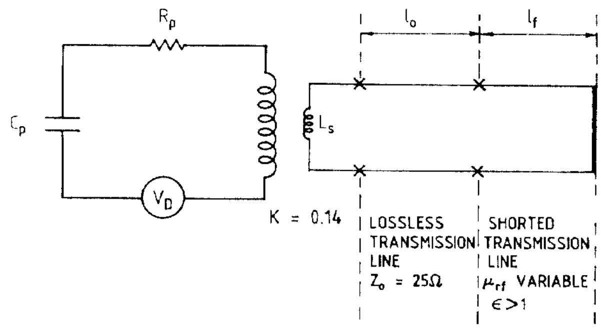
(a) Equivalent Circuit Modeling

The combined system was mathematically modeled using the equivalent circuits shown in Fig. 2. A lumped element representation of a mutually coupled main accelerating cavity and coupling loop was used, with the impedance of the external line, Z_L, reflected into the main cavity. Measured values of the coupling loop self inductance and coupling constant were used.



R_p = 0.0075 Ω (Q - 8380)

C_p = 52.0 μμf

L_p = 187 nH

L_{loop} = 200 nH

$K_{p,loop}$ = 0.14

M (mutual inductance) = 26.2 nH (i.e., $K_{p,loop} * L_p$)

Fig. 2 Equivalent circuit of the main cavity, tuner loop and ferrite loaded shorted transmission line.

The external tuner consists of a length of unloaded coaxial line terminated by a shorted coaxial line loaded with interleaved ferrite and beryllium oxide rings. The impedance of the ferrite loaded line was used as the terminating impedance for the piece of unloaded transmission line that attaches to the coupling loop.

The distributed impedance and admittance per unit transmission line length are written as $Z = R + j\omega L$ and $Y = G + j\omega C$, where for the loaded line

$$C\left(\frac{\mu\mu f}{meter}\right) = \frac{2\pi\varepsilon_o}{\left(\frac{\varepsilon_o}{\varepsilon_1}\right)\ln\left(\frac{r_m}{r_1}\right) + \frac{\varepsilon_o}{\varepsilon_2}\ln\left(\frac{r_2}{r_m}\right)}, \qquad (2)$$

$$L\left(\frac{nH}{m}\right) = \frac{\mu_o}{2\pi}\left[\frac{\mu_1}{\mu_o}\ln\left(\frac{r_m}{r_1}\right) + \frac{\mu_2}{\mu_o}\ln\left(\frac{r_2}{r_m}\right)\right] \qquad (3)$$

with μ_o = 1257 nH/m, ε_o = 8.85 μμf/m.

The measured Q value for a ferrite loaded test line may be used to infer an effective value of $R = \omega L/Q_M$, under the assumption that G = 0. The Q_M for the ferrite was assumed to be the same as the TDK-Y5 ferrite as measured by Smythe and Brophy[2].

The tuner system shown in Fig. 1 was modeled with $(\mu_1/\mu_o) = (\varepsilon_1/\varepsilon_o) = 1$, $(\varepsilon_2/\varepsilon_o) = 14$, and (μ_2/μ_o) variable between 1.25 and 4.0. The calculated dependence of the PETRA II cavity frequency on the ferrite permeability is shown in Fig. 3, and the loss in the tuner as a function of frequency is shown on Fig. 4. The required tuning range is readily achieved with reasonable power losses.

Electrical and Mechanical Design of the Ferrite-Loaded Frequency Tuners for PETRA II

The mechanical and electrical design of the tuner relied heavily on the computer modeling, as full scale test samples of the ferrite are expensive and have a long delivery time. The coupling loop is as large as possible with the restriction that the natural loop resonance is well above the operating frequency. The ferrite rings are interleaved with beryllium oxide cooling rings and the sandwich is encased in a copper cylinder which forms the outer conductor of the coaxial line. The copper is annealed to be soft and is mechanically squeezed into good contact with the BeO rings by a non-conducting outer wrapping material. As both the accelerator operating requirements and the ferrite functional characteristics had some uncertainties, the length of the ferrite loaded section and the volume and type of ferrite were chosen to provide conservative operating limits on critical parameters such as total line length and power loss per unit volume in the ferrite.

Calculations showed that, for the required frequency shift, the maximum voltage on the tuner line would be ≈ 15 kV. As the line will be operating in air, an upper limit for the gradient is 10 kV/cm. A conservative limit of 6 kV/cm is assured by choosing an inner-to-outer conductor gap of 2.5 cm.

Calculations indicated that a 25 to 30 cm length of ferrite loaded line was required to reasonably cover the frequency swing for a permeability ranging between 3.5 and 1.5. This range ensures a low-loss operating regime for the ferrite. The calculations showed a maximum peak power loss of ≈ 1 kW in the ferrite. Choosing ferrite rings of 12.7 cm OD and 7.0 cm ID yields a ferrite volume of ≈ 2500 cm^3 and a conservative peak power dissipation of ≈ 0.5 W/cm^3.

The choice of a specific ferrite is a compromise between bias magnetic field and operating Q. To achieve a very high Q a ferrite with a high saturation magnetization is required, which then demands commensurately high bias magnetic fields. Experience with water cooled solenoids suggested that a maximum field of ≈ 0.15 Tesla would be practical for the required bore size. A value of μ_{rf} = 1.5 would then be obtained with a saturation magnetization of "750 gauss". As the loss characteristics of "500 gauss" ferrite seem adequate, this value was chosen to provide safety margins. The TRANS-TECH ferrite type G-510 aluminum doped yttrium-iron garnet with a Curie temperature of 155°C and a saturation magnetization of $\mu_o M_s$ = 0.055 T ("$4\pi M_s$" = 550 gauss) at 60°C was chosen.

The bias magnetic field is produced by a 267 mm long solenoid with a 146 mm diameter bore and a peak magnetic field on axis of 1.4 mT per ampere current. The solenoid has an inductance of ≈ 1.8 mH and a room temperature resistance of 0.25 ohms (τ = L/R ≈ 8 ms). A rapid variation in the solenoid current must result in a rapid change in the bias field seen by the ferrite rings. Normally, the copper outer conductor would shield the ferrites (via induced azimuthal eddy currents) so two longitudinal slots run the length of the copper shell preventing azimuthal current flow and turning it, in effect, into two half cylinders (which are clamped onto the ferrites).

Measured Low Power Operating Characteristics

At the time of writing, the system had not been operated at high power. The measured low power properties suggest no serious problems. The commissioning of the system consisted essentially in adjusting the physical length of both the external line and the ferrite stack to find an operating point with sufficient tuning range and low enough power loss in the ferrite.

After initial assembly and tuning, the ferrite loss was found to be substantially higher than predicted. The ferrite stack initially was slightly longer than the physical solenoid dimensions, placing the outer rings in a lower magnetic field. Since ferrite in low bias field regions is very lossy, the stack length was decreased to 244 mm producing a marked decrease in ferrite losses. Although the losses remained higher than predicted, the initial cooling calculations yielded such low thermal gradients that the number of beryllia cooling rings was halved, slightly increasing the amount of ferrite in the stack.

The measured characteristics of the present tuner configuration are shown as experimental points on Fig. 3 and 4. The theoretical line length required to achieve the measured tuning response is within 5% of the actual line length, confirming the basic design principles. The ferrite losses are larger than predicted, but the predicted maximum temperature difference between the ferrite and the outer rim of the beryllia rings is ≈ 20°C with a power loss of 1.75 kW in the tuner.

The perpendicular biased ferrite loaded external line described here seems to provide a mechanically and electrically simple system for electronically slewing the frequency of a main cavity. The components are readily available, the overall cost is reasonable, and assembly and tuning is straightforward.

References

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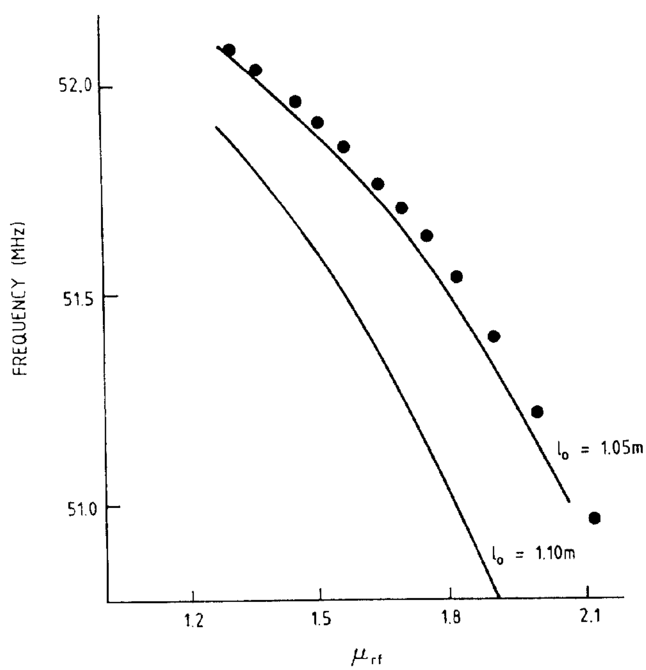

Fig. 3 Measured and calculated tuning characteristics of the combined main cavity and perpendicularly biased ferrite external tuning line. The value of the unloaded line length, ℓ_o, is given for each curve (see Fig. 1).

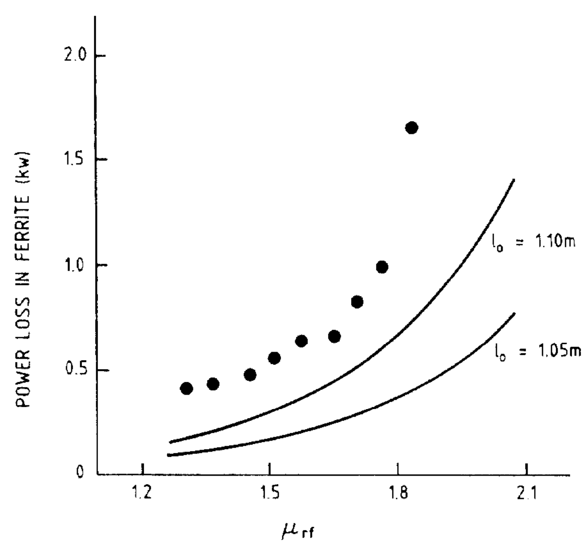

Fig. 4 Measured and calculated power loss in the ferrite for 50 kV acceleration voltage in the main cavity. The value of the unloaded line length, ℓ_o, is given for each curve.