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PRELIMINARY DESIGN OF A PERPENDICULAR BIASED FERRITE LOADED ACCELERATING CAVITY

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Abstract

A ferrite loaded accelerating cavity with a frequency sweep of 18 to 40 MHz is studied for a possible upgrade of the CERN accelerator complex. The resonance frequency of a ferrite loaded cavity shifts by applying an external magnetic bias field to the ferrite material by means of changing the relative permeability. We present the electromagnetic design of such a cavity with a special emphasis on the modeling of the nonlinear, anisotropic and dispersive characteristics of the ferrite's relative permeability above magnetic saturation. For experimental crosscheck, a ferrite loaded resonant test setup was built which provides results for the material performance in a magnetic bias field. A comparison of numerical simulations and experimental measurements is shown and calculations are benchmarked by measurement data. Based on this study a preliminary design of a ferrite loaded accelerating cavity is described.

INTRODUCTION

The characteristics of ferrite loaded accelerating cavities are dominated by the properties of the ferrite material. During the development process it is essential to know the electromagnetic properties of the filling material. A measurement setup is described to investigate a possible resonance frequency swift, to measure the quality factor and to characterize the relative permeability of the ferrite material exposed to a perpendicular magnetic bias field. Moreover we model the measurement setup in an electromagnetic field simulation program and compare the results with the measurements. Based on this, we investigate an electromagnetic design of an accelerating cavity with a frequency sweep of 18 to 40 MHz.

FERRITE LOADED TEST SETUP

For the accelerating cavity, toroidal cores of the ferrite G-510 of 350 mm OD and 200 mm ID consisting of five segments were the largest size currently available by Trans-Tech Inc. [1]. The five segments were glued on top of an 3.3 mm thick *Al 995* toroidal carrier disc with the two component epoxy glue *Stycast 2850 FT*. *Al 995* provides high thermal conductivity of 29.3 W/m.K, a small dielectric loss factor of $\tan \delta_e = 2.9 \cdot 10^{-4}$ at 10 MHz and tight fabrication tolerances. Up to now, the large rings were only investigated in two resonant test setups with different purposes [2]. First, it was shown that doubling the resonance frequency of a measurement cavity is possible by changing a perpendicular magnetic bias field. But the frequency range achieved was well above the desired 18 to 40 MHz and a radiating open gap degraded the measured Q. Second, it was pointed out with another ferrite loaded resonant cavity that high quality factors of up to 5000 can be obtained, but the ferrite shift was limited due to a ferrite filling factor of ca. 25%. A dedicated test setup was developed to investigate the ferrite rings with two different measurement methods. A resonant measurement method is used to investigate the resonance frequency sweep dependent on the magnetic bias field and to measure the corresponding quality factor within the frequency range of interest. With the second method, a 1-port reflection measurement, we measured the complex permeability spectra, similar to the measurement setup presented in [3].

Resonant Measurement

The measurement cavity consists of a main cell, a top cover and a piston all made out of aluminum, see Fig. 1. A capacitive load of up to 1900 pF can be achieved by placing a 0.1 mm Teflon foil between top cover and the piston which reduces the resonance frequency of the empty cavity to 44.7 MHz.

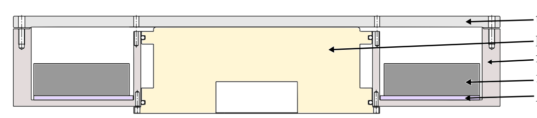

Figure 1: Resonant measurement setup.

The measurement setup is placed within the aperture of an H-dipole to apply a magnetic bias field which is perpendicular to the RF magnetic field. We could not detect resonances for magnetic bias fields below 35 mT, since in that range the losses of the ferrite material are rather high. With increasing magnetic bias field from 35 to 300 mT the resonance frequency shifts from 18.8 to 43.7 MHz due to the decreasing relative permeability of the ferrite, which is shown in Fig. 2.

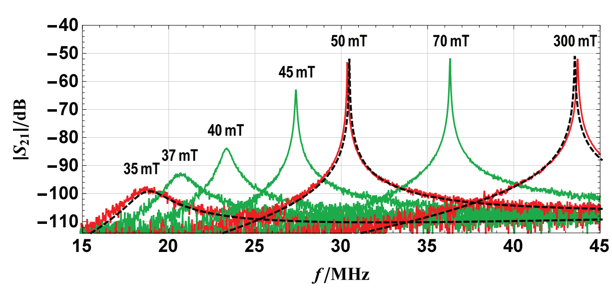

Figure 2: Measurement results (solid traces) of resonant ferrite filled setup in comparison with driven modal simulation results (dashed traces).

The unloaded quality factor can be measured via the 3 dB bandwidth of the transmission signal as a weakly coupling

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of S_{11} and S_{22} < 0.03 dB is used. The measured quality factor first increases to a maximum of 1371 which is well above the quality factor of the empty cavity of 1129 and then decreases with increases bias field, which is discussed later in detail. The measurement results are summarized in Tab. 1.

1-Port Reflection Measurement

The cavity setup is changed in order to perform a 1-port reflection measurement as shown in Fig. 3. The piston is rotated by 180 degrees and is connected to the inner conductor of an adapter to provide the transition to a 50 Ω type N connector. A different top cover is used to allow the mounting of the adapter.

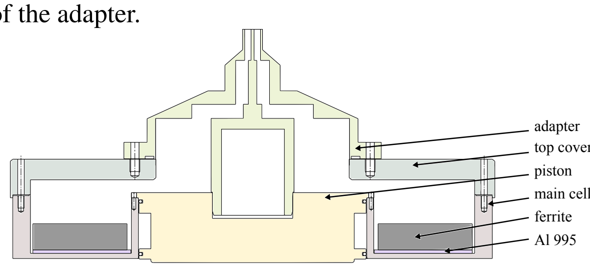

Figure 3: 1-port reflection measurement setup.

This setup is used to measure the reflection coefficient S_{11} of the ferrite filled sample holder in the range of 1 to 50 MHz. For known $\varepsilon' = 14.3$ and $\tan\delta_e = 2\cdot10^{-4}$, given by the manufacturer [1] we can compute μ' and μ'' from the results of the 1-port reflection measurement. With increasing magnetic bias field μ' gets more linear and decreases while μ'' reduces as shown in Fig. 4.

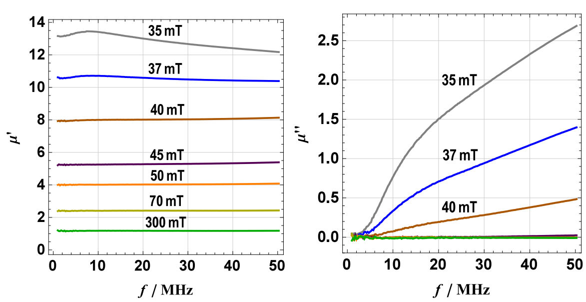

Figure 4: Measured complex permeability vs. frequency for different magnetic bias fields.

Above 40 mT bias field, μ'' is getting smaller than 0.01 and cannot be calculated accurately because the magnitude of S_{11} is getting too close to unity. For 35, 37 and 40 mT the calculated quality factor of the ferrite material from the 1-port measurement reads 9, 15 and 35 respectively, which is close to the resonant measurement results. In a next step the resonant measurement system is designed in an electromagnetic field simulation program to crosscheck the resonance frequency measurements and to investigate the quality factor of the ferrite loaded cavity.

NUMERICAL SIMULATIONS

It has to be mentioned, that the resonance frequency of the measurement cavity is sensitive to the capacitive load. Tightening the screws of the cavity leads to a bending of the top cover and a local air-gap occurs which results in a deviation of the resonance frequency. This effect can be compensated in the simulation model by adding an effective air-gap of 60 μm to the 0.1 mm Teflon foil, which leads to a matching of simulated and measured resonance frequency. Furthermore, only ohmic losses were taken into account for the simulation model of the empty measurement cavity. In reality, contact resistances between the different components of the measurement set-up have to be considered leading to a quality factor of the simulation model that is about 38% larger compared to the measurement. As a first measure, the surface resistance of the simulation model is reduced to bring the simulated quality factor in agreement with the measurement. The quality factor of the ferrite loaded measurement cavity can be expressed as:

$$\frac{1}{Q_{\text{total}}} = \frac{1}{Q_\Omega} + \frac{1}{Q_\varepsilon} + \frac{1}{Q_\mu} = \frac{1}{Q_\Omega} + \frac{2}{W_{\text{total}}}\left(\frac{W_{\text{el,Teflon}}}{Q_{\varepsilon,\text{Teflon}}} + \frac{W_{\text{mag,ferr}}}{Q_{\mu,\text{ferr}}}\right), \quad (1)$$

where Q_Ω, Q_ε and Q_μ refer to the ohmic, dielectric and magnetic quality factor, respectively. The magnetic energy stored in the Teflon foil, the electric energy stored in the ferrite toroid and in the *Al 995* carrier disc can be neglected due to the electromagnetic field distribution in the reentrant cavity. Hence, it is sufficient to take only the ohmic quality factor of the cavity Q_Ω, the dielectric quality factor of the Teflon $Q_{\varepsilon,\text{Teflon}}$ and the magnetic quality factor of the ferrite material $Q_{\mu,\text{ferr}}$ into account to express the total quality factor. Both, $Q_{\varepsilon,\text{Teflon}}$ and $Q_{\mu,\text{ferrite}}$ need to be multiplied with an energy filling factor to obtain the dielectric and magnetic Q of the cavity. $Q_{\mu,\text{ferrite}}$ is determined according to Eq. (1) by bringing the quality factor of the numerical simulation of the ferrite loaded cavity in agreement with the measurement (relative error < 5%).

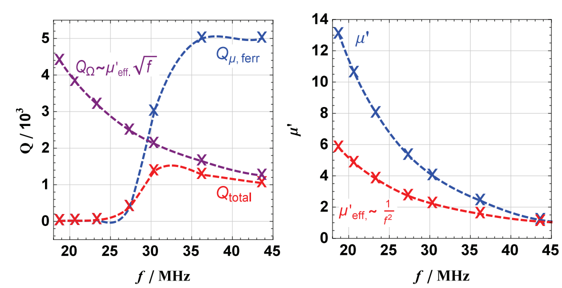

Figure 5: Left: Q_{total}, $Q_{\mu,\text{ferr}}$ and Q_Ω vs. frequency. Right: μ' and μ'_{eff} vs. frequency.

The different Q factors are compared in Fig. 5, left. $Q_{\mu,\text{ferr}}$ is small for low magnetic bias fields, but increases significantly up to a maximum of 5000 once magnetic saturation is reached. Q_Ω decreases with increasing frequency and can be considered to be proportional to the effective relative permeability of the cavity and the square root of the frequency with reasonable accuracy. The total quality factor of the cavity is first dominated by the magnetic quality factor of the ferrite for low frequencies. Once, the magnetic Q of the ferrite is greater than the ohmic Q, Q_{total} reaches a maximum, which is above the Q_{total} of the empty cavity and then decreases with increasing frequency. The relative

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permeability of the ferrite is modeled based on the 1-port reflection measurement results for a specific magnetic bias field. The effective relative permeability of the cavity μ'_{eff} is obtained by multiplying the relative permeability of the ferrite μ' with a filling factor, both are compared in Fig. 5, right. The Eigenmode simulation results of the resonant cavity are compared with the measurement in Tab. 1. The relative error between measured and simulated resonance frequency is smaller than 1.5%. The results of a driven modal simulation are compared to the measurement results in Fig. 2, beside the resonance frequency also the peak values of the transmission signal show good agreement. However, this investigation shows that a maximum $Q_{\mu,\mathrm{ferr}}$ of 5000 can be achieved, which agrees well with Hutcheons results [4] of a $Q_{\mu,\mathrm{ferr}}$ of 500 - 5000 for a relative permeability variation of 4 - 1.25 and also with the measured Q of 5000 for the ferrite loaded copper cavity presented in [2].

Table 1: Measurement and Eigenmode Simulation Results

B/mT	35	37	40	45	50	70	300
Results Resonant Measurement							
f_{res}/MHz	18.8	20.7	23.4	27.4	30.4	36.3	43.7
Q_{total}	9	16	40	396	1371	1274	1046
Input Simulation: $\mu'(f_{\mathrm{res}})$ from measurement, adapted $Q_{\mu,\mathrm{ferr}}$.							
$\mu'(f_{\mathrm{res}})$	13.0	10.6	8.00	5.30	4.00	2.40	1.17
$1/Q_{\mu,\mathrm{ferr}}$	1/8	1/15	1/35	1/396	1/3003	1/5000	1/5000
Results Simulation							
f_{res}/MHz	18.6	20.5	23.1	27.3	30.3	35.9	43.3
Rel. error/%	1.1	1.0	1.3	0.4	0.3	1.1	0.9

PRELIMINARY DESIGN OF FERRITE LOADED ACCELERATING CAVITY

To investigate the capability of the G-510 material for the usage as a perpendicular biased tuning ferrite, we designed a simplified ferrite loaded accelerating cavity. By means of an Eigenvalue simulation we calculated the power needed to achieve 1 kV accelerating voltage. For the cavity design, we used the geometry requirements of a previous study. In the design lattice, the maximum space foreseen per cavity was 1125 mm. Furthermore, an accelerating gap of 50 mm, a beam pipe of 2 mm thickness and 130 mm diameter are assumed. A ferrite stack of 20 rings with 2.54 mm thickness each is modeled by using the data taken from the measurements.

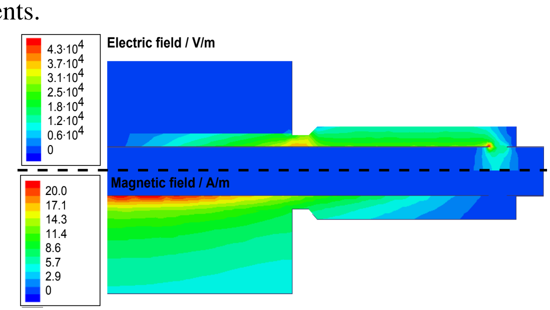

Figure 6: Preliminary design of accelerating cavity. Top: electric RF field distribution, bottom: magnetic RF field distribution for $\mu' = 8$.

The two operation points of the accelerating cavity are simulated with an Eigenmode solver, the results are listed in Tab. 2. For the low frequency operation point, a relative permeability of 8 and a corresponding $Q_{\mu,\mathrm{ferrite}}$ of 35 will lead to a resonance frequency of 17.6 MHz and a Q_{total} of 37. Note, that $Q_{\mu,\mathrm{ferrite}}$ is the magnetic Q of the ferrite and has to be scaled with an energy filling factor to obtain the magnetic Q of the cavity according to Eq. (1) which is greater than Q_{total}. With a R/Q of 213 calculated from the simulation results, 63.3 W power are required to achieve an accelerating voltage of 1 kV. For the high frequency operation point a relative permeability of the ferrite of 1.17 is set which leads to a resonance frequency of 40.9 MHz. The quality factor of the ferrite loaded cavity will be 4683, hence with and R/Q of 108, 1 W power will be needed per 1 kV accelerating voltage. By considering the aforementioned study, for example, an accelerating voltage of 62.5 kV would be needed at 40 MHz and 8.3 kV would be required at 18 MHz; in both cases about 4 kW of RF power would be needed. This rough estimate shows that the required frequency range of 18 to 40 MHz could be covered with reasonable power needs.

Table 2: Simulation Results of FLC and Estimated Power Needs for 1 kV Accelerating Voltage

Input Simulation		**Results Simulation**			
μ'	$Q_{\mu,\mathrm{ferr}}$	f_{res}/MHz	Q_{total}	$\frac{R}{Q}/\Omega$	P/W
8	35	17.6	37	213	63.3
1.17	5000	40.9	4683	108	1

CONCLUSION

We presented a test setup to investigate the resonance frequency shift based on a changing magnetic bias field which is perpendicular to the RF magnetic field and measured the corresponding quality factor. With a reflection measurement method, we characterized the complex permeability exposed to the magnetic bias field. We were able to reproduce the results of the resonant measurement with a simulation model which uses the measured relative permeability as input. Based on the results obtained, we studied a preliminary design of a ferrite filled accelerating cavity to achieve a frequency sweep of 18 to 40 MHz.

OUTLOOK

For measurement and simulation we assumed an homogenous relative permeability distribution within the ferrite volume. But in fact, for non-ellipsoidal ferrite shapes the internal magnetic bias field distribution is inhomogeneous, even if an uniform external bias field is applied, due to demagnetization fields. This results in an inhomogeneous distribution of the relative permeability. As a next step, this influence should be analyzed. Usually, the bias system of a perpendicular biased ferrite loaded accelerating cavity consists of a yoke, which leads to a nearly homogenous magnetic bias field distribution within the ferrite stack. Hence, the dependence of the magnetic losses of the ferrite on the magnetic bias field homogeneity has to be examined. Furthermore, the magnetic losses of the ferrite are considered to rise with increasing RF power and this relation has to be investigated.

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