MEASUREMENTS OF THE PROPERTIES OF GARNET MATERIAL FOR TUNING A 2ND HARMONIC CAVITY FOR THE FERMILAB BOOSTER*

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Abstract

A perpendicularly biased 2nd harmonic cavity is being designed and built for the Fermilab Booster, to help with injection and extraction. Tunable accelerating cavities were previously designed and prototyped at LANL, TRIUMF, and SSCL for use at ~45-60 MHz (LANL at 50-84 MHz). The required frequency range for FNAL is 76 - 106 MHz. The garnet material chosen for the tuner is AL-800. To reliably model the cavity, its static permeability and loss tangent must be well known. As this information is not supplied by the vendor or in publications of previous studies, a first order evaluation of these properties was made using material samples. This paper summarizes the results of the corresponding measurements.

INTRODUCTION

A perpendicularly biased (as opposed to parallel biased) design of a second harmonic cavity has been pursued because the former should have a substantially higher shunt impedance. The cavity design and status is discussed in [1]. Various types of garnets are available and the choice of National Magnetics AL-800 (aluminum doped garnet) was based on a balance between an acceptable saturation magnetization ($4\pi M_s$) and Curie temperature. In the case of perpendicular bias, operation is in the saturation region and this results in much lower power loss than in the case of the "traditional" parallel biased ferrite.

As the magnetic bias is achieved by using a realistic solenoid, non-uniformity of the magnetic field in the garnet can have a significant impact on the local permeability and the loss tangent. If a local working point is near gyromagnetic resonance, significant local power loss can render the device non-operational if the temperature exceeds the Curie temperature, and even result in mechanical damage due to temperature gradient induced stress.

Knowing the local working point of the garnet over the whole tuning range requires reliable information about the permeability (μ), permittivity (ϵ), and loss tangents $\tan\delta_\mu$ and $\tan\delta_\epsilon$. This paper presents results of first studies of the static permeability and RF losses that were performed using existing material samples and a biasing solenoid which was already on-hand. This approach helped to deliver the necessary information, but required an elaborate (and iterative) approach. More precise measurements are planned, using witness samples of the material fabricated for the cavity.

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MATERIAL PROPERTIES

The ability to accurately model the cavity is key to the success of the design. In particular, it is necessary to know the permeability as a function of magnetic field. The real and imaginary parts μ' and μ'' determine the tuning range and losses, respectively. The magnetic field in the tuner is never perfectly uniform, and in order to properly model the device, these properties must be known at every point in the tuner for all bias settings. In the following sections, we describe our measurements of the static permeability and the loss tangent using the available set of AL-800 garnet rings (3.0" OD, 0.65" ID, and 0.5" thick).

STATIC PERMEABILITY

The static magnetization curve was extracted by iteratively adjusting the magnetization curve used in the simulation of the setup, until the simulation results matched measurements. The initial $\mu(B)$ curve was a guess based on the vendor's data for the initial permeability (~ 50) and a theoretical value for large B.

A sketch of the setup is shown in Fig. 1. The ten stacked rings are placed inside of the solenoid, which has a flux return on the bottom and sides, made from CMD-10 and G4 ferrite. The solenoid's length, ID and OD are 177.8 mm, 100 mm, and 305 mm, respectively. The number of turns is 112. A steel plug was inserted on top to improve the uniformity of the magnetic field within the samples.

Three different magnetometer/hall probe pairs were available for measurement, and they were cross calibrated inside of the solenoid with no garnet. The hall probes were placed between rings, on the top, bottom, and middle of the stack. Magnetic field was measured with each probe as a function of solenoid current.

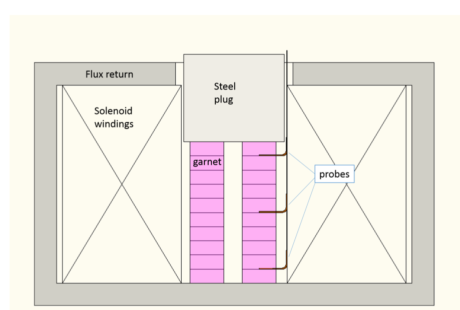

Figure 1: Setup concept for the measurement of the static magnetization.

The iteratively obtained magnetization curve was gradually changed starting with low current. At each new current level, changes to the magnetization curve used at the previous level were made until the modeling result matched the measurement data. The existence of 1 mm gaps between rings (due to the presence of the probes) had a significant impact on the field distribution within the sample material, especially near the edges of the rings; it was necessary to take this into account in the modeling. The iterative modeling was accepted as converged when changes to the curve $\mu(B)$ become smaller than the spread in the measurement data. The final magnetization curve is shown in Fig. 2. A comparison between the magnetic probe readings and the simulated magnetic field at the same locations (using the final magnetization curve) is shown in Fig. 3.

Note that for the real cavity being designed and discussed in [1], the maximum (averaged over the garnet) value of μ' is ~3.5. Although this is the average value, the local value of the permeability, being a function of the local magnetic field, can be significantly greater. Thus the full magnetization curve is needed for the cavity modeling, unless one can make sure that the magnetic field is sufficiently uniform.

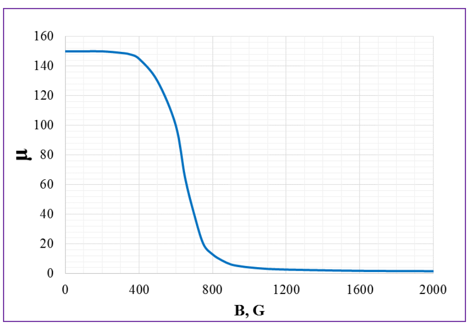

Figure 2: Extracted magnetization curve $\mu(B)$

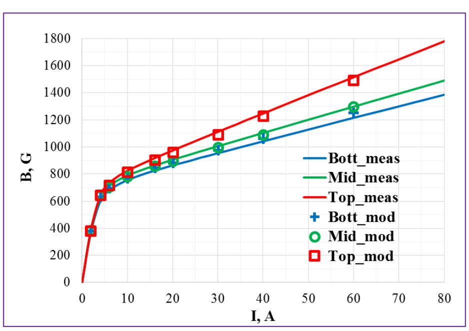

Figure 3: Comparison between measured values and values predicted by a model, using the extracted magnetization curve. Values are B as a function of solenoid current.

LOSS TANGENT

To measure the magnetic loss tangent of the garnet, a test resonator was constructed using the same set of garnet rings used for the static permeability studies. The measurement setup is shown in Fig. 4. The cavity was the quarter-wave coaxial type with the garnet rings as a filler material. The resonator is placed inside of the same solenoid that was used for the static permeability measurements, which allowed measurements for a range a frequencies. Again a steel plug was placed on top of the cavity, to help with the field uniformity. The quality factor Q of the cavity was measured at various settings of the bias current. As the Q is an integrated quantity, and the loss tangent depends on the magnitude of the magnetic field and the frequency, an iterative approach was used (as before) since the field in the sample is not uniform.

Weakly coupled probes were used for the excitation and for measurement of S_{21} with a network analyzer.

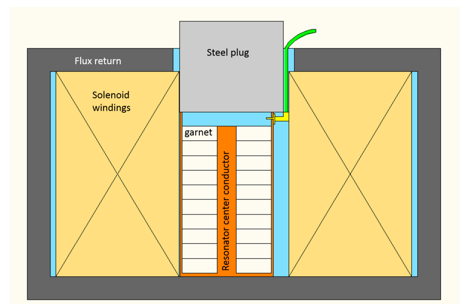

Figure 4: Measurement setup for $\tan\delta_\mu$.

Figure 5 shows a field map in the sample for 30 A current in the solenoid (I_{sol}). The frequency of the cavity is 84 MHz, where the gyromagnetic resonance would occur at 30 Oe. The minimum field in the sample is ~ 50 Oe. Note that, without the steel plug, even for I_{sol} = 40 A, a large fraction of the sample was in gyromagnetic resonance, and similar resonances were observed (though in smaller volumes) up to near the maximum value of the current.

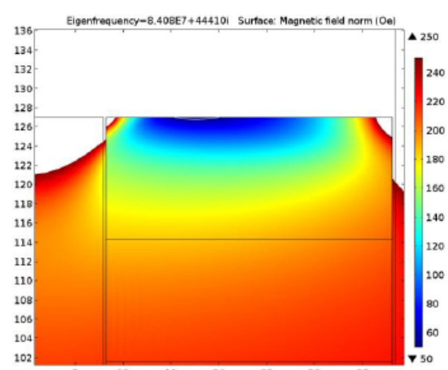

Figure 5: Field map in the sample for I_{sol} = 30 A. The x axis is the radial coordinate, and the y axis is the axis of the cavity and cylindrical ring stack. Only one half of the cavity/sample (in the radial direction) is shown.

Figure 6 shows measured values of Q as a function of I_{sol}. Resonant frequencies of the cavity range between 78 and 121 MHz. The significant increase in power loss at currents below 35 A can be attributed to onset of gyromagnetic resonance somewhere in the sample. Power losses in the cavity are resistive (copper), dielectric (garnet $\tan\delta_\epsilon$), and magnetic ($\tan\delta_\mu$). The resistive losses are calculable without difficulty since the conductivity of copper is well known. National Magnetics has supplied a measurement of $\tan\delta_\epsilon$=0.0001.

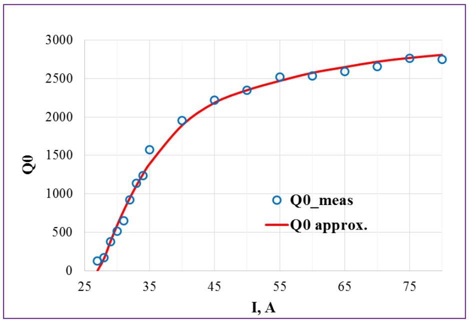

Figure 6: Measured and modeled Q of the resonator as a function of I_{sol}.

Magnetic power losses are traditionally characterized by the loss coefficient α [2]. Since $\alpha \ll 1$, neglecting terms proportional to α^2:

$$\tan\delta_\mu = \frac{\mu''}{\mu'} = \frac{\alpha\omega\omega_M(\omega_0^2+\omega^2)}{(\omega_0^2-\omega^2)(\omega_0^2-\omega^2+\omega_M\omega_0)} \quad (1)$$

where $\omega = 2\pi f$ is the RF frequency, $\omega_0 = \mu_0\gamma H_0$ is the precession frequency given H_0, the magnetic field in the material, $\gamma = e/m_e$ is the gyromagnetic ratio, $\omega_m = \mu_0\gamma M_s$, and M_s is the saturation magnetization. For AL-800, $\mu_0 M_s \approx$ 0.08 T ($4\pi M_s$ = 800 G).

Note that for the expression to be valid $\omega_0 > \omega$ and this imposes a lower limit on H_0. Given that this requirement is satisfied, for a material with properties parameterized by ω_m at a point with field given by ω_0, and RF frequency ω, the loss tangent is proportional to α. It is unclear as to whether α itself has a dependence on magnetic field. Some sources argue that it is a constant [2], while others dispute this [3].

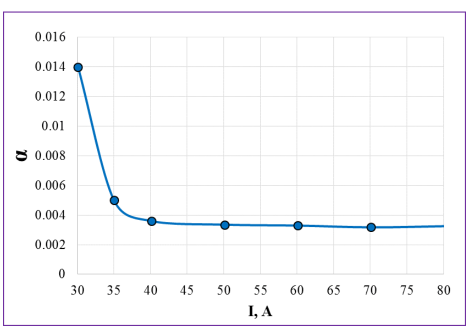

Figure 7: Extracted value of the loss coefficient α as a function of solenoid current. The rise at lower currents is likely due to an onset of gyromagnetic resonance.

Values of α for the AL-800 sample were determined for each value of I_{sol} by adjusting its value in the model until the model predicted the same values for Q and f as were seen in the data. Copper and dielectric losses are easily calculated by simulation. Inputs to the simulation were manufacturer measured values of dielectric constant (ϵ = 13.8), $\tan\delta_\epsilon$ = 0.0001, and $4\pi M_S$ = 764 G. In addition, the static permeability curve described in the previous section was used. Results are shown in Fig. 7. The sharp rise of α at low current can be explained by the onset of the resonant condition in some (initially small) parts of the sample. With the relatively low excitation current in the current experimental setup, local power loss can be orders of magnitude higher than the averaged one. Results can be trusted only for the cases were resonance is nowhere within the material, $I_{sol} \geq$ 40 A.

SUMMARY

The static permeability and RF loss tangent of the garnet material AL-800 were evaluated using an iterative modeling approach. The obtained static magnetization curve differs significantly from initial assumptions. In the authors' opinions, the loss coefficient α (used in Eq. (1) to calculate $\tan\delta_\mu$) should be considered constant over a wide range of frequencies, where α = 0.0033. The increase in this quantity at lower current is likely due to the onset of gyromagnetic resonances within the material. This value of the loss coefficient agrees to within 10% of the value calculated (α = 0.0036) based on the vendor's data for the line width of 24 Oe, giving confidence in the measured value.

Given the above mentioned onset of gyromagnetic resonance, the biasing field equipment for devices using such garnet should be designed to avoid field non-uniformity and the resulting onset of this resonance. Taking this into consideration, a more refined setup for permeability measurements is currently being constructed. This will be used to measure parameters in witness samples of the material that will be used in the 2nd harmonic cavity. In addition, a test system (a cavity and a bias magnet) is being designed to perform measurements on larger pieces of the actual garnet which will be used in the cavity.

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