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IMPROVING MAGNETIC MATERIALS FOR RCS CAVITY TUNERS*

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Abstract

Within the Lab Directed R&D (LDRD) Program at Fermilab, and in partnership with National Magnetics, we have recently begun to study and explore techniques to improve the loss parameter in garnet material. This could be used for fast tuner applications such as in rapid cycling synchrotrons.

INTRODUCTION

Normal conducting copper cavities used in rapid cycling synchrotrons require tuners to sweep over large frequency ranges. For example, in the Proton Improvement Plan II (PIP2) era at FNAL, the required tuning range is in the 10 to 20 MHz range. The swing in frequency is very rapid, typically on the order of 500 to 900 MHz per second. This means that mechanical tuners are not an option; only electromagnetic tuners respond at the rate necessary for the desired frequency ramp.

The tuners that are used worldwide commonly employ a magnetic bias scheme on a magnetic material like ferrite. [1]. The permeability of the ferrite material is dependent on the magnetic field. If the cavity is modelled as a parallel RLC circuit, its resonant frequency is simply given by $\omega_0 = 1/\sqrt{LC}$, where L is the inductance and C is the capacitance of the cavity respectively. The permeability, μ, of the ferrite can be divided into two parts:

$$\mu = \mu' - i\mu''$$

where μ' is the lossless part and $\mu''$is the resistive part of the permeability. If L_0 is the inductance of the inductor in air (i.e. without ferrite) then the lossless part of the inductance is

$$L = \mu'(B)L_0$$

where we have explicitly written that μ' is a function of the magnetic field B.

There are two schemes for biasing the ferrite, referred to as parallel and perpendicular bias. In the parallel bias case, the bias B field and the RF B field vectors are parallel. For the perpendicular bias case, the bias B field is orthogonal to the RF B field. The relationship between μ' and B, H in these two schemes are as follows:

$$\left.\begin{aligned} \mu'_{\parallel} &= \frac{\partial B}{\partial H} \qquad \text{parallel biased} \\ \mu'_{\perp} &= \frac{B}{H} \qquad \text{perpendicular biased} \end{aligned}\right\}$$

Nearly all cavities at Fermilab (and around the world) operate in the parallel bias scheme. There are no explicit arguments in the literature that state why parallel biased is dominant over perpendicular bias schemes. It may be because the engineering is less challenging: copper conductors are wound in the same way as a toroidal transformer around ferrite rings to form the bias magnet.

However, for low RF loss, the ferrite material must be operated close to saturation; $\partial B/\partial \mathrm{H}$ has a tiny change in slope and thus the achievable tuning range is very small. Therefore, to take advantage of low RF loss at magnetic saturation, the perpendicular bias scheme must be used because B/H still varies substantially, and thus the tuning range is adequate. In this case, the choice of ferrite material is critical. It must have low enough saturation magnetization so that a realistic bias magnet can be built. For example, the NiZn ferrite that is used in the FNAL Booster RF cavity tuner has a saturation magnetization of 3.2 kG, which is much too high. Garnet material (Y3Fe5O12 which in the case of this study is doped with aluminum) has a saturation magnetization less than 1 kG and is the preferred material for building perpendicularly biased devices.

The garnet material chosen for this study, National Magnetics Group (NMG) AL-800 [2], has a saturation magnetization of 800 G. The Curie temperature is 200°C which is needed because in practice, hot spots with temperatures exceeding 100 °C may be present in areas of locally low magnetic field.

The loss constant α (related to μ'') of AL-800 samples supplied by NMG has been measured at Fermilab as part of the quality assurance program for the Booster 2nd harmonic cavity [3, 4]. These measurements were performed with a magnetic system which was on hand. It was not ideal for such a measurement because the field was not sufficiently uniform. Due to this non-uniformity there are still large uncertainties in the measured values of α, especially at low bias. This is where knowing its value and reducing its error is most critical.

The goal is to reduce the error of α by at least 10% using the manufacturing processes that will be discussed in the next section. This will be useful not only for future RF cavities, but for other high power RF devices, such as tunable phase shifters.

RESEARCH PLAN

NMG had previously manufactured four lots of AL-800 for the 2nd harmonic cavity built for the FNAL Booster. In terms of the gyromagnetic line width, ΔH (which is proportional to α, c.f. Eq. 9 of Pozar [5]), their measured values were: 28.6 Oe, 29.0 Oe, 21.3 Oe and 19.98 Oe respectively. For the present study, NMG will make several new mixtures (lots) and improve the lot with the lowest ΔH by sintering under O2 and hot isostatic pressing. The goal is to reduce ΔH by at least 10%, i.e. to reduce ΔH to 18 Oe. Even though this improvement may be small, we know that an improved ΔH proportionately improves the Q of the cavity which in turn means less power is needed to drive it.

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This is especially important for future RCSs where the ramp rates will be in the realm of 20 Hz or more and beam currents will be much higher than at the present time. A 10% improvement results in a savings of hundreds of kilowatts, enabling significantly higher gradients.

NMG is manufacturing the improved garnets and performing their high frequency tests at each step. Fermilab will test the garnets at the frequencies that are useful for RCSs (tens of MHz range). The three steps for improving ΔH are as follows:

1. Three different trial compositions will be made to try to drive down ΔH while maintaining other parameters. At this stage, no changes will be made in the forming and sintering of the garnet. Fifteen rings of each composition will be made. NMG will test the garnet from each composition for ΔH, saturation magnetization, dielectric constant and dielectric loss tangent. The tests done there are at frequencies much higher than a typical accelerating cavity but are still useful as a benchmark.
2. New rings made from the three compositions (again 15 of each) outlined in (1) will be sintered under ~8 psi of pressurized oxygen. The goal is to reduce the porosity and increase the density of the garnet. NMG will perform their inhouse tests as in (1).
3. Hot isostatic pressing (HIP) will be performed by an external vendor on rings manufactured with the process outlined in (2). In this step, the sintered materials will be pressed at high pressure in an argon atmosphere and at elevated temperatures. NMG will perform their inhouse tests as in (1) and (2).

FNAL Test Plan

NMG does not have the capability of testing the garnet rings in the 30 MHz to 200 MHz range, which is the frequency range of interest for accelerators. Fermilab has experience testing garnet rings for the 2nd harmonic cavity project [3, 4]. Fermilab will measure μ' and the loss tangent $\tan\delta_m = \mu''/\mu'$, from which α is extracted. A critical step and part of this LDRD will be to improve the devices that Fermilab has used in the past to measure α and μ''.

Two batches of garnet have already arrived at Fermilab. We are currently in the process of constructing the test setup, and will begin testing soon. The OD and ID of each sample is 1.547” and 0.67”, respectively, and they are ½” thick. The test fixture is based on 1⅝” coaxial line, and partially custom sized coax surrounded by a solenoid. In the design of the coaxial sample holder and bias system, we have aimed to make the magnetic field in the garnet as uniform as possible. This is both difficult and important for a real cavity, but even more important for a measurement fixture. The coaxial test fixture is shown in Fig. 1. In order to make the magnetic field more uniform, the coax is surrounded by another piece of AL-800 garnet which is a permanent part of the test fixture. This same material is also inside of the center conductor (not in the RF volume). The walls surrounding the sample and the gap between the sample and the wall were made as thin/small as possible, also for field uniformity. They cannot be arbitrarily thin though, or the fixture would not be strong enough to withstand the forces needed to make good electrical contact.

To allow efficient testing of the garnet rings, one side of the test fixture can be removed to allow the sample to slide into place over a two-piece spring loaded connector. This silver-plated beryllium-copper connector houses the inner AL-800 garnet and maintains electrical continuity between the two inner conductors. When the fixture is re-assembled with the specimen inside, a small, precisely machined taper keeps the parts aligned and locks the specimen in place. A machined copper ring locates the specimen relative to the outer AL-800 garnet and provides a conductive path between the two outer conductors on either side of the specimen.

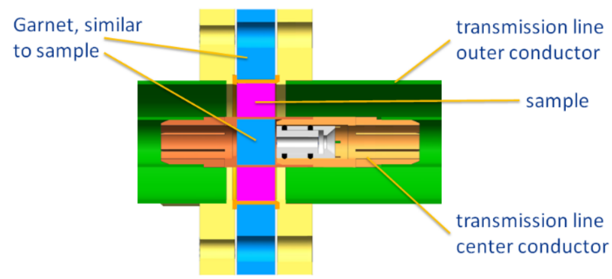

Figure 1: Coaxial test fixture without solenoid.

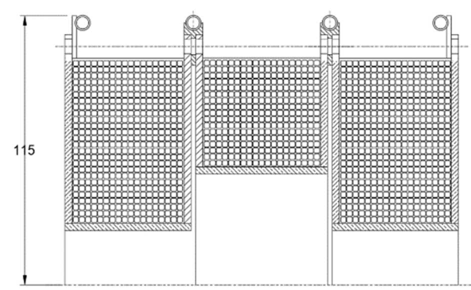

Figure 2: The solenoid which will surround the coaxial test fixture.

Figure 3: The solenoid which will surround the coaxial test fixture.

The solenoid, which surrounds the coaxial sample holder and sample and generates the adjustable bias field is shown

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in Figs. 2 and 3. This consists of three coils which are wound around bobbins and connected mechanically and electrically. The windings are impregnated with epoxy to facilitate heat transfer to the cooling lines located on the copper bobbin flanges. The coils are wound using #11 square copper wire; there are 468 turns on the outer coils and 323 turns on the center coil. Each coil and cooling plate can be easily removed from the assembly by undoing several bolts allowing access to the specimen holder to swap out samples. Alignment pins pressed into the flanges of each coil and an aluminum base plate keep the solenoid well aligned to the test fixture which ensures mechanical reproducibility.

A photograph of the parts for the coaxial fixture and one of the garnet samples is shown in Fig. 4.

Figure 4: Picture of the existing parts of the test fixture and one of the garnet samples which we have already received.

The magnetic parameters of the samples will be measured by adapting the larger coaxial line down to type N connectors and measuring the S-parameters on a network analyser. The fundamental magnetic parameters will be tuned in the simulation until the measurable quantities match that predicted by the simulation.

The general method to compute complex ε and μ from the measured complex reflection (S11) and transmission (S21) coefficients was proposed by Weir [6] and has been detailed in many following publications. Theoretically the method is considered both accurate and reliable, but technical problems require very cautious approach in its realization. The theory assumes a perfect RF field distribution in coaxial line with the sample. However, as it was shown in [7] that even small errors on the dimensions of coaxial line and sample can result in significant errors of complex ε and μ. In our case, the task of test set up design is much more complicated because of the presence of the bias static magnetic field, which also must be perfectly uniform over sample volume to assure a uniform distribution of μ in the sample as theory requires. So, development of the setup mechanical design was heavily based on the simulations, aimed to make the RF and bias field as close to the theoretical assumptions as possible. In our study we concluded that it was necessary to introduce "shieldings" outside the coaxial line that were made of the same material as the sample. This trick helped us to achieve a reasonable field quality (but still not perfect) - See Fig. 5. Unfortunately, it made the mechanical design tremendously complex.

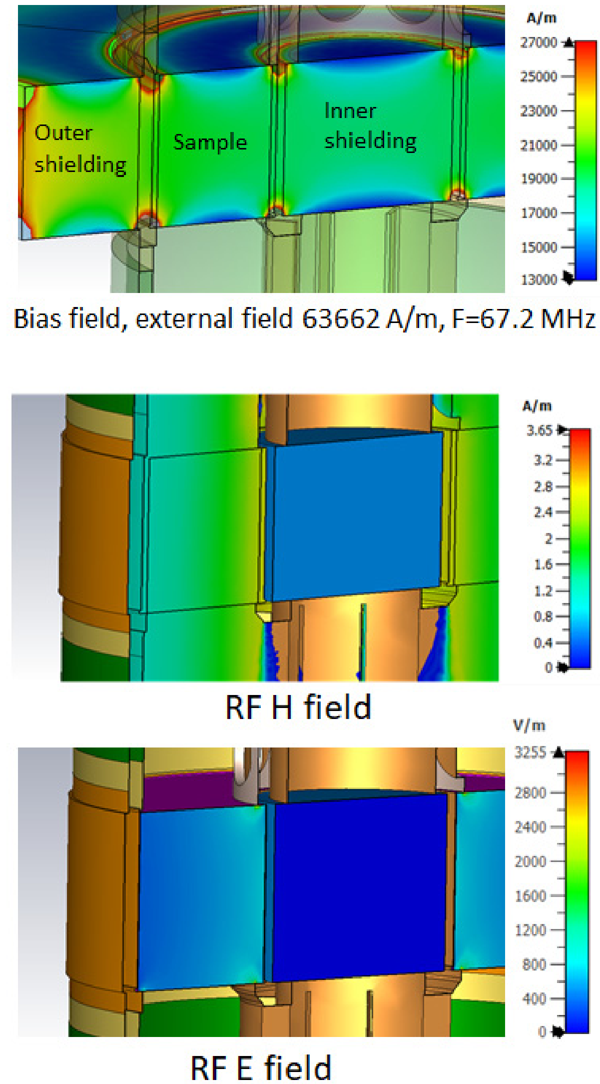

Figure 5: CST Simulation results showing the field uniformity.

CONCLUSION

We are in the process of building a test setup and will soon measure the magnetic properties of AL-800 manufactured under new conditions and techniques by National Magnetics Group.

ACKNOWLEDGEMENTS

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