ENGINEERING A LIGHT SOURCE FOR THE FUTURE

Studies of a Higher Order Mode Absorber for Cornell's Energy Recovery Linac

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Abstract

An X-Ray source for the future will need to produce brilliant, ultra-short and coherent pulses of light to allow exploration of new biology and material science. Engineering this light source will push the envelope of accelerator engineering. Cornell proposes the construction of an energy recovery linac (ERL) based light source [1]. One crucial challenge in the design is the control of the higher order mode spectrum in the main linac and injector cavities spanning from 1.3 to over 40 GHz.

Presented here are results of continuing investigation into the electromagnetic properties of three promising microwave absorbing ferrite materials from 1 to 17 GHz at room and liquid nitrogen temperatures [2].

The ε and μ parameters of the materials TT2-111R, Hexagonal M3 and Hexagonal Z were measured with a vector network analyzer, and will be used in numerical models of the ERL's superconducting cavities.

TT2-111R shows strong absorption at low frequencies, peaking at around 1 GHz, while M3's absorption only begins at 10 GHz, and persists until past 20 GHz. Z shows absorption at high and low frequencies. Knowing this, we have decided to construct a higher order mode absorber using at least two ferrite types.

INTRODUCTION

What motivates the construction of the energy recovery linac light source? What is on an X-Ray user's wish list for the future? One of these is the ability to track the motion of atoms on ultra-short timescales, to make molecular movies. Another is the ability to work with very small protein crystals. The X-Ray source may even allow the crystallographer to dispense with the crystal altogether.

Making molecular movies will require ultra-short X-Ray pulses, while working with very small samples will require a very stable X-ray beam. Hard X-Ray microscopy, producing and interpreting the diffraction pattern from non-crystalline objects will require a highly coherent X-Ray beam.

High quality electron bunches are needed to produce such high quality X-Ray beams. For beam stability, a highly stable electron orbit is required. For ultra-short pulse production the ERL must be able to accelerate, and decelerate ultra-short electron bunches at a very high repetition rate, and do so stably for many hours at a time. Finally, production of coherent X-Ray light demands that the electron bunch be highly mono-energetic.

The most important obstacle to producing an electron bunch that orbits stably through the ERL, while remaining mono-energetic and ultra-short is its interaction with the higher order modes (HOMs) of the accelerating microwave field in the in the injector and main linacs. These modes must be removed from the linac cavities, while carefully preserving the accelerating fundamental.

To achieve this, the ERL's cavities have been carefully shaped to trap the fundamental while allowing the higher order modes to propagate out of the cavity cells into the beam pipe, where they are absorbed by a microwave absorbing ferrite material [3]. A schematic of this idea is shown in figure 1.

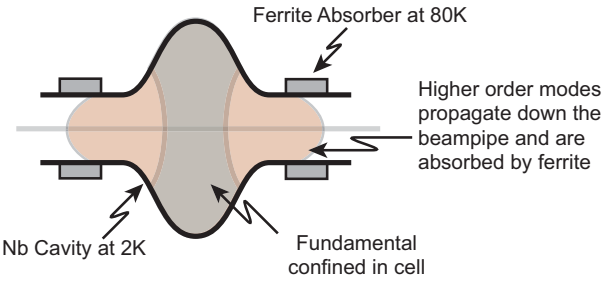

Figure 1: Schematic of Higher Order Mode absorber.

The superconducting Niobium cells are maintained at 2K. It is undesirable to deposit the heat from the absorption of the HOM radiation into the 2K heat bath. At the same time is impractical to have a thermal transition from 2K to room temperature and back to 2K over a distance as short as the spacing between the cells. Thus, an intermediate temperature of 80K was chosen. The heat from absorption of the HOMs is deposited into a liquid nitrogen heat bath.

Unfortunately, when this scheme was proposed, the electromagnetic behavior of ferrite materials was unknown. It was unclear how the frequency dependence of the ferrite's microwave absorption would change. Thus, a program of measurement to establish the ferrite properties was initiated. The first results of this program were reported by Liepe and Barstow [2]. These measurements showed that the well characterized ferrite, TT2-111R, exhibits enhanced absorption at low frequency, while its absorption resonance shifts to higher frequencies.

Unfortunately, its absorption becomes too low at frequencies above approximately 20 GHz. Thus, a second

series of measurements was started to find a ferrite that absorbs strongly in the range of 20 to 40 GHz.

Trans-Tech [4] and Countis Laboratories [5] responded to our requests for ferrite materials that absorb at higher frequencies. Trans-Tech produced 4 hexagonal phase ferrites, M1, M2, M3 and Z, while Countis Laboratories produced two variants on their C48 material, C48 E1 and C48 E2 fired at elevated temperatures to increase microwave losses by electron hopping.

The complex ε and μ parameters of these materials were tested in a coaxial waveguide set up identical to the one described by Liepe and Barstow [2] in the frequency range 1 to 14 GHz. Above these frequencies, the coaxial method becomes unreliable, and the coaxial waveguide sample holder was replaced by rectangular waveguide. This allowed very reliable measurements to be made on the ferrites from 12.4 to 18 GHz.

MEASUREMENT PROCEDURE

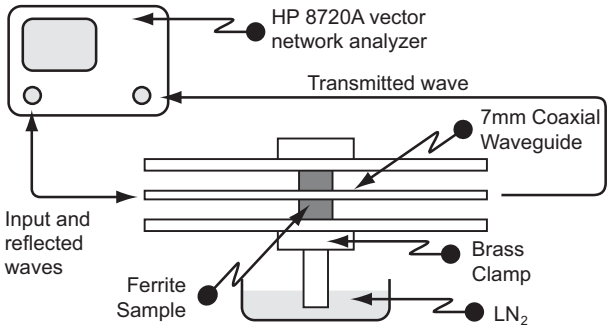

Figure 2: Coaxial waveguide version of the ε and μ experiment.

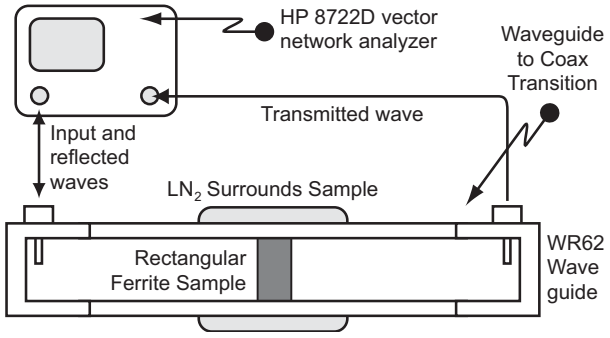

Figure 3: Rectangular waveguide version of the ε and μ experiment.

Systematic errors were reduced in the waveguide measurement equipment with the use of calibration routines that measured the reflection and transmission of microwaves by known standards.

An HP8720A network analyzer was used to make measurements in the 1 to 14 GHz range. This was calibrated with an onboard 2 port calibration routine, using a set of terminators, opens and shorts.

For higher frequency measurements, from 10 to 18 GHz, measurements were made in a WR62 waveguide. The Thru Reflect Line (TRL) calibration procedure was used. This algorithm was implemented in the HP8722D network analyzer used to make these measurements. The calibration kit was included a shorting plate and quarter wavelength thru. The kit was provided by Space Machine & Engineering Corp [6].

RESULTS

A good way to get an intuitive understanding of the behavior of an absorbing material is to plot the fraction of the S parameters neither transmitted nor reflected by the sample as a function of frequency. This produces the dimensionless number[*†];

$$\frac{\text{Absorbed Power}}{\text{Incident Power}} = 1 - \sqrt{S_{nm} \cdot S_{nm}^{*} + S_{mm} \cdot S_{mm}^{*}} \quad (1)$$

This tells us how much radiation is absorbed the by the material in the case of normally incident radiation confined to a waveguide. It is worth noting that this only allows the comparison of like with like. For example, the only comparison that can be made is between measurements that were made of samples of a particular thickness in particular waveguide. For instance, it is meaningless to compare S parameters measured in a rectangular WR62 waveguide and those measured in a 7 mm coaxial guide.

It is possible, however, to convert the S parameters measured by the network analyzer in a waveguide to more general parameters, the complex permittivity, ε, and complex permeability, μ, of the sample. These values can be used as an input to a computer program such as CLANS to calculate the damping of modes in an accelerating cavity.

The conversion of the S parameters measured by the network analyzer and the ε and μ parameters was detailed in HP product note 8710-3 [7]. For completeness we have detailed the conversion here. Starting from a set of complex S parameters, the following algorithm is followed, to calculate ε and μ.

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[*] A * denotes complex conjugation.

[†] The S parameters are marked with subscripts. Snm is a transmission parameter, and is used to stand for S_{12} (transmission from port 2 to port 1) or S_{21} (transmission from port 1 to port 2). S_{mm} can stand for S_{11} or S_{22}, which means that the signal was transmitted from port 1 and received at port 1, or transmitted from port 2 and received at port 2.

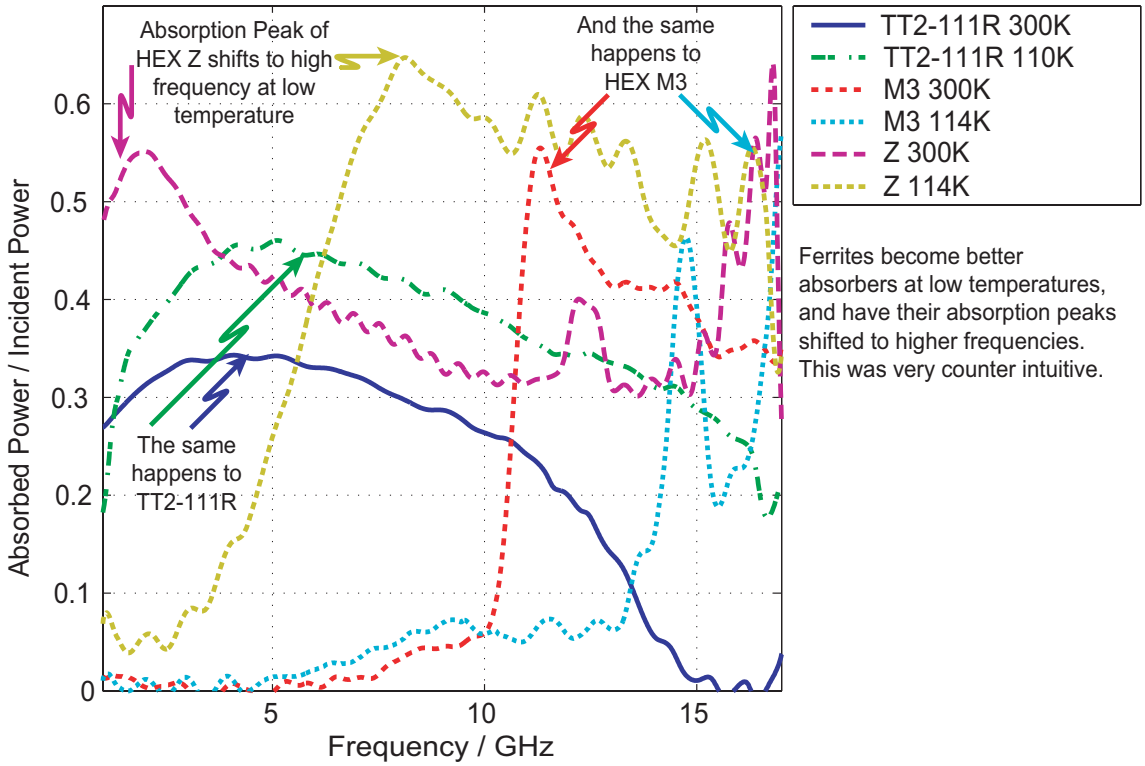


Figure 4: Absorption of candidate materials in coax at room temp and in the cold.

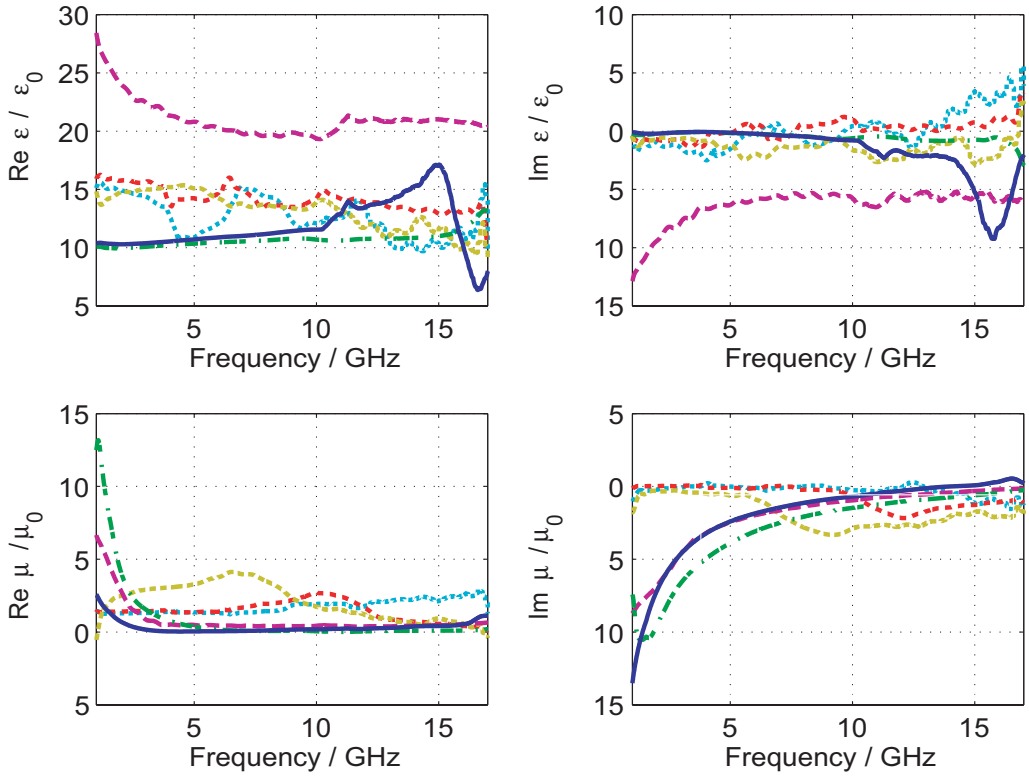
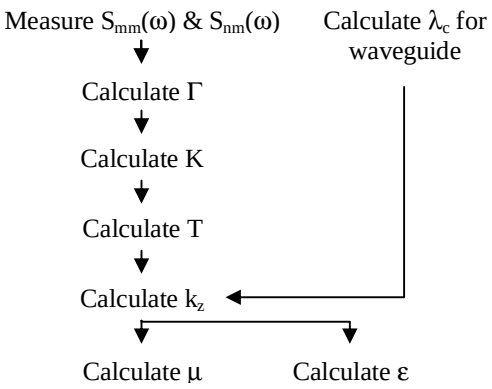


Figure 5: ε and μ properties of HEX Z at room temperature and at cryogenic temperatures with TT2-111R for comparison and HEX M3 at room temperature from coax data.



$$K = \frac{\left\{S_{mm}^2 - S_{nm}^2\right\}+1}{2S_{mm}}$$

$$\Gamma = K \pm \sqrt{K^2 - 1}$$

$$T = \frac{\left\{S_{mm} + S_{nm}\right\} - \Gamma}{1 - \left\{S_{mm} + S_{nm}\right\}\Gamma}$$

$$k_z = \frac{i \ln T + 2\pi N}{d}$$

Unfortunately, as discussed by Hartung [8], calculation of the wavenumber, k_z, is complicated because one does not know the number of integral wavelengths, *N*, in the sample of length *d*. At low frequencies, around 1 GHz, *N* was assumed to be 0. It is incremented by 1 unit each time k_z makes a jump from $-\pi$ to $+\pi$.

$$\frac{\mu}{\mu_0} = \frac{1+\Gamma}{1-\Gamma} \frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \frac{k_z}{2\pi}$$

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\mu_0}{\mu} \lambda_0^2 \left\{ \left\{ \frac{k_z}{2\pi} \right\}^2 + \frac{1}{\lambda_c^2} \right\}$$

The wavelength in the guide is altered from that in free space. They are related by

$$\lambda_g = \mathrm{Re}\left\{ 1 \Big/ \sqrt{\frac{\varepsilon_r \mu_r}{\lambda_0^2} - \frac{1}{\lambda_c^2}} \right\}$$

λ_c = Cutoff wavelength for the waveguide. λ_0 = Free space wavelength at a given frequency.

The most striking feature of our observations is that ferrites become better microwave absorbers at lower temperatures. At first this struck us as counter intuitive, but repeated measurement of the effects made us more comfortable with it. We speculate that lower temperatures allow larger magnetic domains to form in the ferrite. These have larger surface areas, allowing greater friction between neighboring domains, allowing greater energy dissipation. Also, the peak of absorption shifts from the low to higher frequencies in all observed cases.

We noted that while the well characterized TT2-111R material has desirable absorption properties at low frequencies, it tails off at high frequencies. Fortunately, the absorption of Hex M3 suddenly switches on at 10 GHz and stays high until at least 20 GHz.

REFERENCES

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[2] *First Studies for a Low Temperature Higher-Order-Mode Absorber for the Cornell ERL Prototype*, M. Liepe *et al.*, Proceedings of PAC2003.

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[8] Hartung, W.H., PhD Thesis, Cornell University, Ithaca NY, 1996.

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