

## MEASUREMENTS OF $\epsilon$ AND $\mu$ OF LOSSY MATERIALS FOR THE CRYOGENIC HOM LOAD

Valery Shemelin, Matthias Liepe, Hasan Padamsee  
 Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853

### INTRODUCTION

In high current storage rings with superconducting cavities strong broadband HOM damping has been achieved by using beam-pipe ferrite loads, located at room temperature [1]. Adopting the same damping concept for the ERL with RF absorbers between the cavities in a cavity string will require operating the absorbers at a temperature of about 80 K. This temperature is high enough to intercept HOM power with good cryogenic efficiency, and is low enough to simplify the thermal transition to the cavities at 2 K. However, the electromagnetic properties of possible absorber materials were not well known at cryogenic temperatures. Therefore, we performed a measurement program at Cornell to find possible absorbers for HOMs in the ERL. First results for ferrites TT2-111R, HexM3 and HexMZ in the frequency range from 1 to 17 GHz were presented earlier [2, 3]. Now we have results of measurements for 10 different materials up to 40 GHz.

### MATERIALS

We examined materials listed in the Table 1. Not all of them were measured in the whole frequency range because of absence of some samples with the necessary shape; they are marked by “minus” (-) in the table. Some materials appeared to be very brittle (C48-E1, C48-E2) and cannot be recommended for further usage in our project.

Table 1. Materials and frequency ranges where they were measured.

Freq., GHz \ Material	1-12.4	12.4-18	18-26.5	26.5-40
TT2-111R	+	+	+	+
C48-E1	+	-	+	+
C48-E2	+	-	+	+
HexM1	+	+	+	+
HexM2	+	+	+	+
HexM3	+	+	+	+
HexMZ	+	+	+	+
ZR10CB5	-	+	+	+
ZR20CB5	-	+	+	+
Z7YL	-	+	+	+

The tested materials fall into 3 groups: ferrites TT2-111R, C48-E1, C48-E2, hexagonal phase ferrites M1, M2, M3, and MZ [4, 5], and Ceradyne ceramics ZR10CB5, ZR20CB5, Z7YL [6, 7].

### MEASUREMENTS

The measurement procedure is described in [2, 3]. For measurements of  $S$ -parameters in the region 12.4-40 GHz the network analyzer Agilent E8363B was used. So, the whole range from 1 to 40 GHz was covered by measurements with a coaxial line (7/3.05 mm, 1-15 GHz, HP8720 network analyzer), and with waveguides: WR62 (12.4-18 GHz), WR42 (18-26.5 GHz), and WR28 (26.5-40 GHz). Transmission lines used for measurements and samples to be measured are shown in Fig. 1.



Figure 1: Transmission lines for 4 frequency ranges.

We used the TRL calibration as giving the most accurate results of measurements.

Schematic of measurement is shown in Fig. 2. A coaxial line or two long waveguides with a short waveguide section between them were used. Shorter waveguide, with a sample, helped to decrease the errors related to evaluation of the phase shift for the complex  $S$ -parameters at higher frequencies. Reproducibility of results was improved when the connecting bolts were tightened with a torque wrench (10 or 15 N·m). To compensate contraction after cooling, spring washers were used. The thickness of the used samples was less than half-wave length in the material, to avoid the resonance and decrease errors. Calibration of the analyzer before measurements of cold samples was also performed with cold waveguides joined to warmer adapters with coaxial cables connected to the analyzer. So, the procedure of calibration became more complicated because we needed three times cool down and then warm up the waveguide line for changing calibration standards.

Though the changes of the line length and of the dielectric constant of  $N_2$  (data for air were used) partly compensated each other at 80 K, in a definition of the phase advance both effects should be taken into account especially for the long coaxial line. Position of the sample in the line, "insertion distance", was defined by numerical comparison of complex reflections from each side:  $S_{11}$  and  $S_{22}$ . Before cooling, the waveguides were blown through with dry nitrogen and the experiment was housed under positive pressure of nitrogen atmosphere (inside a plastic bag) to prevent ice formation on the cooled parts (water has  $\epsilon \approx 80!$ ). Only the central part of the waveguide line with a cooled short waveguide was immersed into the bath with liquid nitrogen. Small holes in the waveguides were needed because, when being cooled down, the pressure in them drops more than a half of atmosphere, and, if leakage is uncontrolled, the sample moves in the waveguide like a piston. Temperature of the central part (that was about 78÷80 K) and of the

waveguide ends (190÷200 K) was checked by thermocouple thermometers.

Temperature equilibrium was assumed to be achieved in 15 minutes after the start of cooling. The measured  $S$ -parameters were converted to complex  $\epsilon$  and  $\mu$  values following the algorithm outlined by Hartung [8].

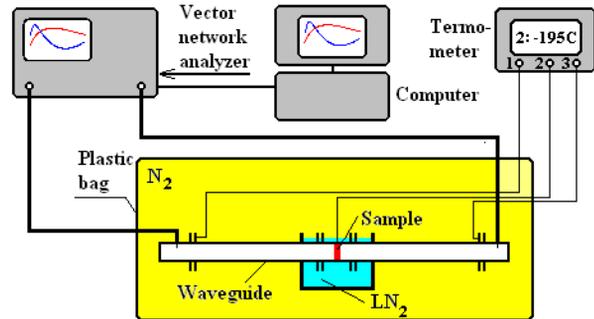


Figure 2: Schematic of test setup.

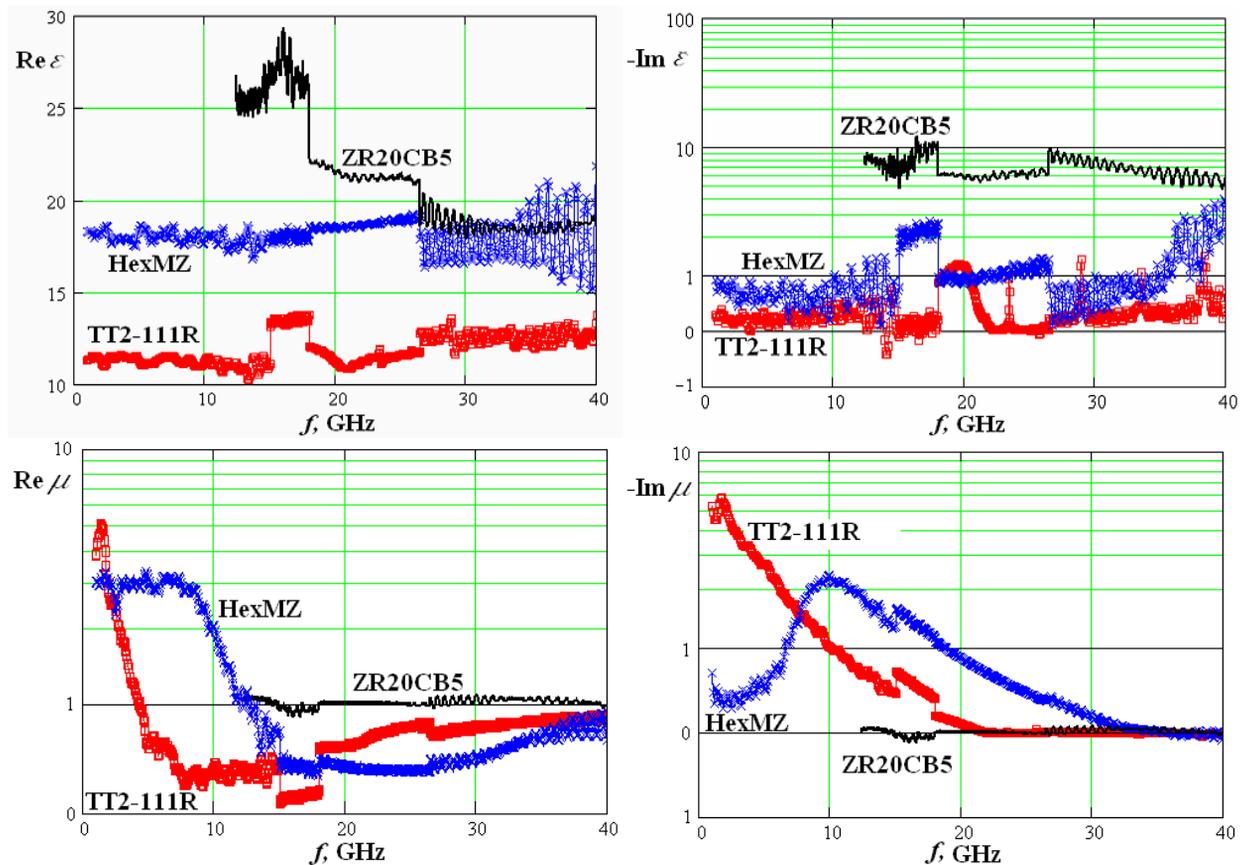


Figure 3: Real and imaginary parts of  $\epsilon$  and  $\mu$  for 3 materials from 1 to 40 GHz at 80 K. The ordinates scale is logarithmic for values more than 1 and linear otherwise.

## RESULTS

We present here only a small part of obtained results (Fig. 3) for reason of space; some data were presented elsewhere [9]. The imaginary parts of both  $\epsilon$  and  $\mu$  should be negative, this means that material absorbs, not gives off, power. If our results show positive  $Im \epsilon$  or

$Im \mu$ , this shows limits of our accuracy only. The level of accuracy can be also seen from deviation of  $Im \mu$  from 0 and  $Re \mu$  from 1 for Ceradynes. Some data do not butt together at the ends of frequency ranges. This can be related not with the errors of measurements only but with difference of properties for different batches of materials.

Such a behavior was observed in data by M. Dohlus [7] for Ceradynes at a room temperature. Some errors can be caused by irregular shape of samples; it is hard to keep right shape for so small sizes. Influence of these shape deviations was studied on computer models.

In the measurements of  $S$ -parameters, we revealed some resonant peaks that do not correspond to half-wave length of the samples: we used sufficiently short samples to avoid these resonances. The observed peaks are clearly seen in Fig. 3 for  $\text{Im } \epsilon$  of TT2-111R. Analysis has shown that these are ghost-modes described by Forrer and Jaynes in 1960 [10]. "A ghost-mode is a resonant electromagnetic field configuration, existing in the vicinity of certain waveguide obstacles, such as dielectric windows. Its transverse field configuration is that of an ordinary waveguide and its resonant frequency lies below cutoff frequency of the particular mode in the unperturbed guide... Since these modes are orthogonal, no coupling would be expected under ideal conditions. However, imperfections, such as slight tilt of the window, uneven thickness, or inhomogeneous dielectric may provide the modal coupling." Not all the calculated ghost-modes manifested themselves, this indicates that thoroughly prepared and installed samples can provide smoother results.

Behavior of different materials changes at 80 K, compared to room temperature, in different ways. Magnetic losses of C48-E1 and C48-E2 decrease at lower frequencies when cooled, and they change only slightly for TT2-111R. Resonant losses of hexagonal ferrites shift about 10 GHz to higher frequencies. Losses of ceramics practically do not change on cooling.

A simplified absorption model for a plane wave has been calculated for a 3 mm thick absorber, see Fig. 4. The measured at 80 K  $\epsilon$  and  $\mu$  data have been used as input for this model. Peaks of absorption at 35 and 38 GHz are related to resonant thickness of the layer, not to the peaks of  $\epsilon$  or  $\mu$ . Real geometry of the absorber will be more complicated.

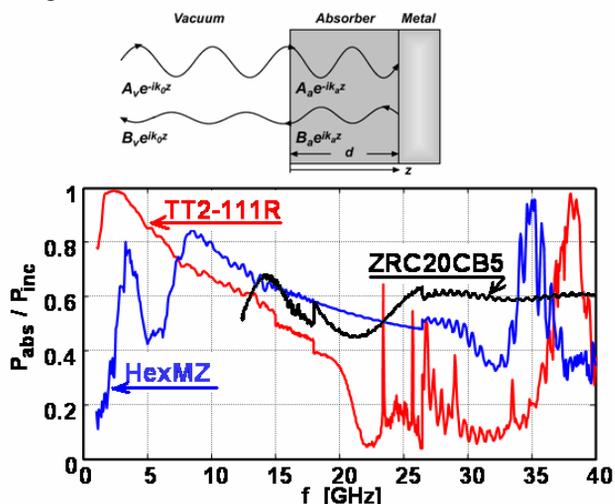


Figure 4: Absorber model calculation ( $d = 3$  mm) based on measured  $\epsilon$  and  $\mu$  at 80 K.

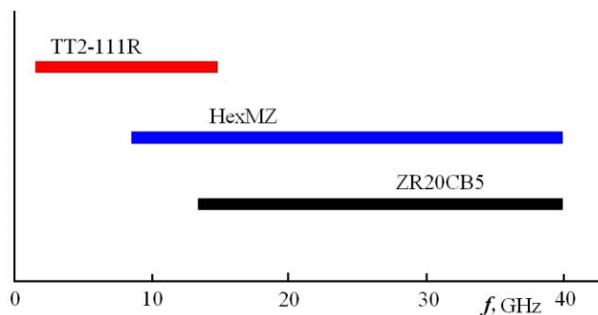


Figure 5: Regions of application for 3 chosen materials.

## CONCLUSION

We have now a general notion about the properties of examined materials at room temperature and at 80 K, and here are presented the most promising of them. Ferrite TT2-111R can be proposed as absorber at 80 K in the lower part of the frequency range, and ceramics like ZR20CB5 can work at higher frequencies, Fig. 5. Ferrite HexMZ can work in the mean and higher frequencies. In the mean frequencies 15–30 GHz both HexMZ and ZR20CB5 will complement each other because the losses in them are magnetic and electric, respectively. This should help to suppress different types of HOMs.

We thank Martin Dohlus from DESY for providing Ceradyne samples, and our colleagues from LEPP for help.

## REFERENCES

- [1] D. Moffat et al. Proceedings of the 1993 Particle Accelerators Conference, Washington DC, p. 977, 1993.
- [2] M. Liepe, B. Barstow, H. Padamsee. First studies for a low temperature higher-order-mode absorber for the Cornell ERL prototype. Proceedings of the 2003 Particle Accelerators Conference, Portland, OR, May 12-16, 2003.
- [3] B. Barstow, M. Liepe, H. Padamsee. Engineering a light source for the future. 11<sup>th</sup> workshop on RF superconductivity, SRF 2003, September 8-12, 2003. Lübeck, Germany.
- [4] Trans-Tech Inc., <http://www.trans-techinc.com>
- [5] Countis Laboratories, <http://www.countis.com>
- [6] Ceradyne, Inc., <http://www.ceradyne.com>
- [7] [http://tesla.desy.de/new\\_pages/TESLA\\_Reports/2002/pdf\\_files/TESLA200213/hom\\_absorber\\_dohlus.pdf](http://tesla.desy.de/new_pages/TESLA_Reports/2002/pdf_files/TESLA200213/hom_absorber_dohlus.pdf)
- [8] W. Hartung. PhD Thesis. Cornell University, Ithaca, NY, 1996.
- [9] V. Shemelin, M. Liepe, H. Padamsee. Characterization of ferrites at low temperature and high frequency. Workshop ERL 2005, Newport News, VA, March 19 - 23, 2005.
- [10] M.P. Forrer and E.T. Jaynes. Resonant modes in waveguide windows. IRE Trans. on Microwave Theory and Techniques. March, 1960.