R-SQUARE IMPEDANCE OF ERL FERRITE HOM ABSORBER*

H. Hahn, A. Burrill, R. Calaga, D. Kayran, Y. Zhao, BNL, Upton, NY 11973, USA

Abstract
An R&D facility for an Energy Recovery Linac (ERL) intended as part of an electron-cooling project for RHIC is being constructed at this laboratory. The center piece of the facility is a 5-cell 703.75 MHz superconducting RF linac. Successful operation will depend on effective HOM damping. It is planned to achieve HOM damping exclusively with ferrite absorbers. The performance of a prototype absorber was measured by transforming it into a resonant cavity and alternatively by a conventional wire method. The results expressed as a surface or R-square impedance are presented in this paper.

1. INTRODUCTION

A superconducting (SC) cavity for an Energy Recovery Linac (ERL) is being constructed at this laboratory [1]. The performance of the SC cavity can be severely impacted by the presence of higher order modes (HOM). A carefully chosen design minimizes their presence and remaining HOMs must be damped by HOM couplers attached to the cavity located in the liquid helium [2] or by ferrite absorbers at room temperature [3]. The ERL cavity will rely completely on ferrite absorbers.

Ferrite absorbers have proven successful in damping higher order mode (HOMs) in single cell cavities (CESR [4], KEKB [5]). The Cornell ferrite design is being adopted here for the ERL five-cell linac cavity.

The production ERL HOM absorber is obtained from ACCEL, using the nickel-zinc ferrite C-48 produced by Countis Industries. The ferrite blocks are cooled by water flowing through the copper tubes brazed onto the surface of the heat sink of the ferrite. The ERL test porcupine used for the HOM measurements in the copper cavity is shown in Fig.1. The unit has 18 sections in the 25 cm diameter spool, each assembled of two tiles with $2 \times 1.5 \times 0.125$ in. dimensions. A smaller 20 cm diameter unit with 8 tiles was also available for the R-square measurements.

The dipole modes were measured in the ERL copper prototype cavity both with and without the ferrite absorber. The measured data are compared with the Mafia predictions in Fig. 2. The dominant dipole modes are found around ~900 MHz so that the absorber properties need to be measured primarily in the frequency range around this strong dipole mode. The dipole mode

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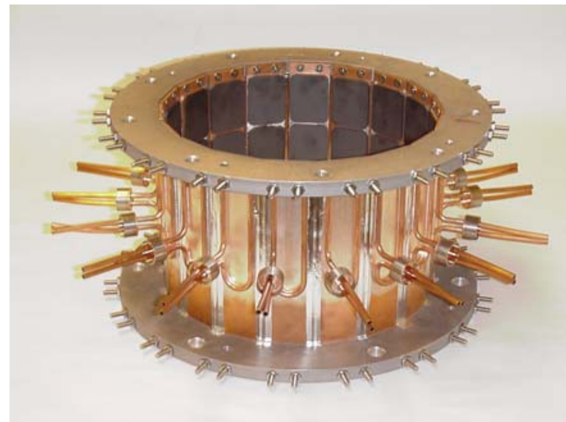

Figure 1: HOM ferrite absorber test porcupine

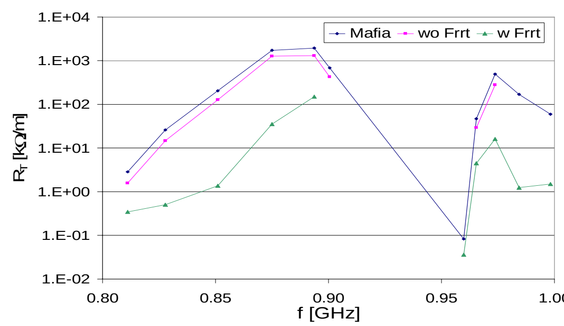

Figure 2: Dipole HOMs in ERL copper model

strength in the SC cavity will be equal to those shown in Fig. 2 with the ferrite absorber in place.

The RF properties of the ferrite absorber have typically been determined by measurements of the material permeability and permittivity in a waveguide or transmission line arrangement and subsequent theoretical calculation of the coupling impedance [6].

The measurement of RF properties of the ERL absorber are presented in this report in the convenient form of a R-square impedance (which is equivalent to the surface impedance of a metal) and provides the power loss per unit area by the relation

$$P = R_{SQ} H^2$$

This approach seems justified by the small radial dimensions of the ferrite and the assumption that the losses are primarily magnetic field induced. The advantage of this interpretation stems from the applicability of standard expressions for losses, impedances, attenuation length and similar quantities.

The R-square value is obtained here by independent measurements. In the first, the absorber is transformed into a resonant cavity by attaching end plates with loop couplers in preparation for a comparison with a metal spool of the same dimensions. The cavity measurements give results only for a few identifiable resonances. In a further measurement the ferrite absorber is placed into a transmission line setup and the change of the forward scattering coefficient due to the absorber versus the spool as reference is interpreted as impedance by the network analyzer.

2. RESONANT CAVITY

The ferrite absorber is transformed into a resonant cavity by attaching shorting end plates, and then is compared with a reference cavity of the same dimension. The reference cavity has an inner radius of $a = 12.5$ cm and a length of $d = 18.6$ cm. The end plates have stubs, 15 cm long with 4.8 cm i.d., to allow bead pulling for use in other experiments. The ferrite is treated as a thin layer on the same inner radius but covering axially only $d_{Fe} = 10$ cm (4 in.) of the cylinder.

The cavity was analyzed with SUPERFISH (SF) to compare it with a pill box cavity. The SF frequencies of the TM010 and TM011 resonances of the model cavity are 937.3 and 1252 MHz versus 917.8 and 1222 MHz of a pill box with the same inner dimensions. The SF geometry constants are 280 and 264 Ω versus the pill box values of 271 Ω. In view of considerable measurement errors and for the sake of simplicity, the interpretation of the measurements will be based on a pill box geometry.

The cavity is excited by two equal loops located in the shorting plates at the upper most radial position. The primary measurement of frequency and quality factor of a resonance is by means of the transmission coefficient S21 with a network analyzer. The S21 for the reference and the ferrite absorber cavity are shown in Fig.3. The R-square impedance of the ferrite absorber will be determined for these two resonances.

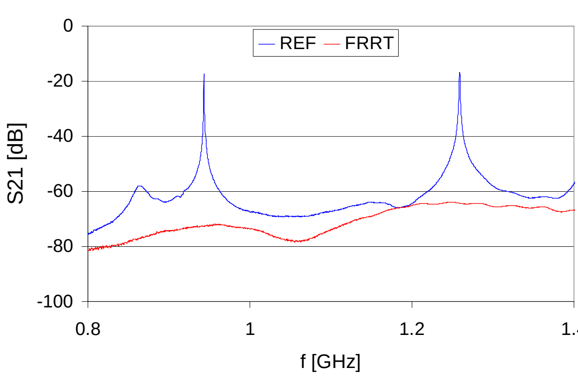

Figure 3: S21 in reference and absorber cavity

In principle, the S21 measurement yields the loaded Q but the measuring loops are here only weakly coupled. Thus, the unloaded quality factors of the reference cavity are obtained directly. The absorber cavity was measured with two sizes of the coupling loop. The loop area was reduced from ~ 45 to 25 mm^2 to move a stray resonance away from the TM011 resonance.

2.1 The ferrite absorber at the resonance frequencies, 955 MHz

The interpretation of the Q measurement in the absorber cavity is based on the fact that the losses are for all practical purposes generated by the surface impedance of the ferrite located only on the cylinder, implying a geometry factor of

$$G = \frac{d}{2d_{Fe}} Z_0 j_{01} \approx 838\ \Omega$$

The R-square impedance must now be found from the quality factor as $R_{SQ} = G/Q$.

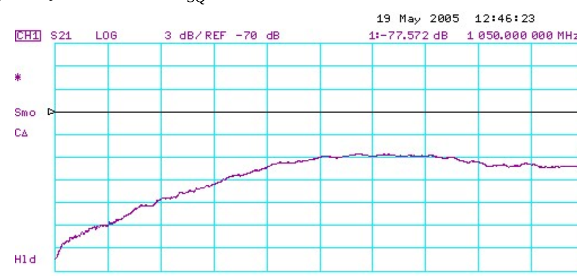

Figure 4: S21 in ferrite absorber with coupling loops

The S21 transmission in the ferrite absorber at the TM010 resonance is shown in Fig. 4. However, the signal to noise ratio is low and massaging of the raw data by smoothing over 5 MHz is appropriate. The data are fitted to the normalized resonance curve in Fig.5 with Q = 6.5 and the center frequency shifted to 955 MHz.

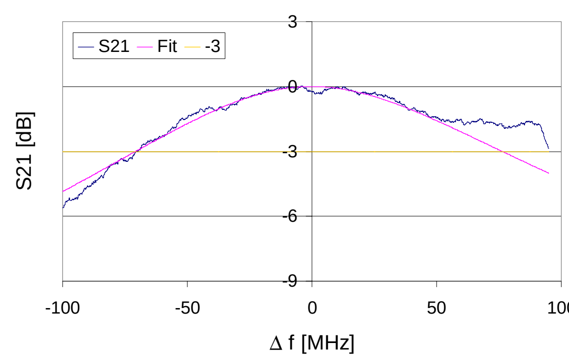

Figure 5: Fitted S21 with Q = 6.5 at 955 MHz

Application of the same interpretation to the data from the large coupling loops yielded a fitted Q ≈ 9 instead of the 11.62 indicated by the instrument.

Summarizing the measurements on the ferrite absorber, one can take <Q>≈ 8 from which follows the R-square impedance at 955 MHz as, $R_{SQ} \approx 100 \pm 35$ Ω, indeed an increase of 4,500 over copper.

2.2 The ferrite absorber at the resonance frequencies, 1255 MHz

The S21 transmission coefficient, taken with the large coupling loops in the ferrite absorber cavity at the TM011 resonance is shown in Fig.6. Note the ~40 kHz wiggles above the resonance, which were confirmed by other measurements, and are believed to be caused by resonances within the ferrite tiles. Fitting of the curves at -3 dB yields a quality factor of Q ≈ 7.4 versus the instrument value of 6.3.

The geometry constant for the TM011 mode, again under the assumption that all losses are located in the ferrite at the cylinder, is $G = 838\ \Omega$ leading to the R-square impedance $R_{SQ} \approx 113 \pm 20\ \Omega$ at 1.255 GHz

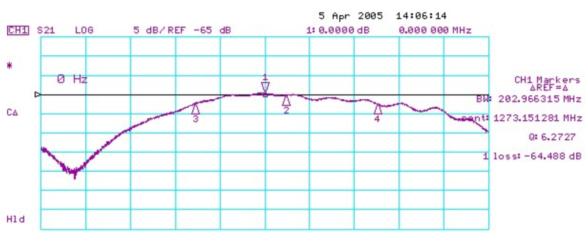

Figure 6: S21 in ferrite absorber with coupling loops

4. TRANSMISSION LINE

Conventional transmission line measurements of the ferrite absorber losses are performed by assembling the small 8-tile "porcupine" between coaxial lines, formed from long tubes and a 2 mm center conductor.

The ratio of the forward scattering coefficients of the device and of a metal spool is directly interpreted by the network analyzer as a transmission impedance, Z_T, from which follows $\Re_{SQ} = 2\pi Z_T a / d_{FE}$. The measured transmission Z_T of the small 8-tile prototype is shown in Fig. 7. The Z_T impedance again exhibits strong superimposed amplitude oscillation, the source of which are believed here to be caused by a mismatched setup of the reference cavity. The sharp discontinuity at ~1.2 GHz could be due to a resonance of the 20 cm dia cavity in the 15 cm tube. This measurement was performed in part to establish the sensitivity of the ferrite to a magnetic field. A solenoid coil was wound over the cavity and Z_T was found at $H = 0$ and $H = 100$ G. The results in Fig. 7 show an increase of the absorber losses in the present of a magnetic field, a welcome result, since no special absorber shielding will be required.

5. FERRITE ABSORBER ATTENUATION

A major objective for the present measurements is to get an estimate of the attenuation constant, α, of wave propagation in the presence of the ferrite absorber. Containment of HOM into the cavity region is achieved if $\alpha d_{Fe} \geq 1$. With the ferrite length of $d_{Fe} = 10$ cm, one would need $\alpha \gg 0.1$/cm. The attenuation due to the surface impedance, $\Re = R_{SQ}$, can be found in text books for circular wave guides with radius *a* [7].

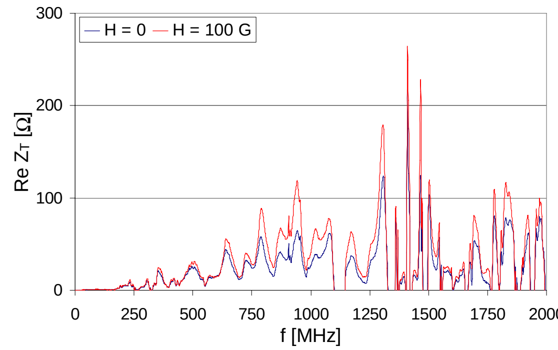

Figure 7: The effect of a magnetic field on Z_T

The E_{mn} (TM_{mn}) mode attenuation constant is

$$\alpha = \frac{\Re}{Z_0 a} \frac{1}{\sqrt{1-(\lambda/\lambda_{mn})^2}}$$

where $\lambda_{mn} = \frac{2\pi}{j_{mn}} a$ and $J_m(j_{mn}) = 0$.

The H_{mn} (TE_{mn}) mode attenuation constant is

$$\alpha' = \frac{\Re}{Z_0 a}\left[\frac{m^2}{j'^2_{mn} - m^2} + \left(\frac{\lambda}{\lambda'_{mn}}\right)^2\right] \frac{1}{\sqrt{1-(\lambda/\lambda'_{mn})^2}}$$

where $\lambda'_{mn} = \frac{2\pi}{j'_{mn}} a$ and $J'_m(j'_{mn}) = 0$.

The absorber sits at a beam tube with 25 cm diameter in which all HOM can propagate, $\lambda < \lambda_{mn}$, suggesting an order-of-magnitude $\alpha, \alpha' \approx \Re/(Z_0 a)$. The estimated R_{SQ} for $\alpha =$ 0.1/cm is thus $R_{SQ} \geq 500\ \Omega$, whereas the experimental result of $R_{SQ} \simeq 100\ \Omega$ indicate that e.m. waves are in most cases not sufficiently damped by one ferrite ring and propagate beyond the present absorber.

Adding more ferrite length represents a possible solution but is unattractive due to increased cost and loss of real estate. Terminating the absorber with a sharp step, from 25 to 10 cm, increases the local magnetic field and HOM losses and will be tested in the ERL cavity. The added longitudinal energy loss is seen as part of the linac cavity.

6. REFERENCES

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