Ferrite-Loaded Higher-Order-Mode Absorbers for the MIT-Bates South Hall Ring[1]

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Abstract

Higher-order-mode (HOM) absorbers have been designed, fabricated and tested at Atomic Energy of Canada Limited's Chalk River Laboratories for the Bates Linear Accelerator Center South Hall Ring 2856 MHz RF cavity. The absorbers are 25 mm long sections of 61 mm diameter beam pipe lined with 3 mm thick TT2-111 ferrite from Trans-Tech Inc. This paper describes the techniques used to calculate the mode damping properties, and to assemble and test the absorbers.

1. INTRODUCTION

The MIT-Bates South Hall Ring (SHR) [1] is an electron beam storage ring designed for a circulating current of 80 mA, with a bunch frequency of 2856.000 MHz and all (1812) RF buckets full. The short time between bunches precludes using any standard longitudinal-bunch RF feedback techniques for suppressing coupled-bunch beam instabilities. The only method available to minimize the growth of these instabilities is to minimize the RF amplitude of all longitudinal higher-order modes around the ring, which may drive these instabilities.

Careful RF design of all ring components can significantly reduce the total longitudinal impedance over most frequencies that can cause trouble. However, the RF cavities usually have instrinsically high longitudinal impedance at frequencies other than the design operating mode. For RF cavities, external damping of the undesirable modes is essential, in addition to any other technique used to reduce the magnitude of the HOM excitation.

The design of a high-power single-cell 2856 MHz cavity for the SHR was described in an earlier paper [2]. The key feature of the SHR cavity is that all significant higher-order modes have frequencies above cut-off in the beam pipe, and the cavity profile is designed to maximize the coupling of these modes from the cavity to the pipe. The result is very low Q's for higher-order modes within the cavity. Nevertheless, power lost by beam bunches into these modes is not absorbed anywhere within the cavity, so standing-wave RF fields may be produced between beam-pipe impedance discontinuities, with the RF cavity being one of the largest discontinuities. Thus a beam-pipe HOM damper was developed to absorb RF fields on either side of the cavity. These absorbers do not significantly affect the HOM RF distribution in the cavity, but prevent the growth of RF standing-wave fields in the beam-line that may cause coupled-bunch instabilities.

2. ABSORBER CHARACTERISTICS

A number of important requirements must be considered in selecting any material used as a HOM absorber. These include:

1) High electric or magnetic loss factors are needed at the HOM RF frequencies.

2) Relatively low dielectric constant and permeability at HOM RF frequencies are useful to allow adequate penetration of the RF fields into the absorbing material. Many materials that rely upon an electrical conductivity for RF absorption also have high dielectric constants that reduce the RF fields within the material, reducing the efficacy of the RF absorption.

3) The dissipated RF power in the damper must be removed to prevent excessive heating of the material. Consequently, materials with good thermal conductivity are preferred.

4) Any significant heating of the absorbing material, or its substrate during fabrication or operation, can result in substantial mechanical stress from thermal gradients. The material must tolerate these stresses without cracking or fracturing.

5) The material must have a low out-gassing rate, so that the material may be used inside the high-vacuum systems.

No material meets all these requirements perfectly, and engineering compromises are necessary for any particular application. Ferrite ceramics can be very good RF absorbers, with high magnetic loss factors, while the magnitudes of the dielectric constant and permeability remain sufficiently low to permit good penetration of the RF fields into the material. However, most ferrites have low tensile strength and poor thermal conductivity, posing significant engineering problems for manufacture and operation. High-density ferrites are usually suitable high-vacuum materials with low out-gassing rates at typical operating temperatures (below 200°C). After substantial review, the TT2-111 ferrite from Trans-Tech Inc., also selected by Cornell for a HOM load for CESR-B [3], was

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chosen as a suitable absorbing material for the SHR HOM load.

3. FERRITE PROPERTIES

The properties of TT2-111 ferrite must be known to permit detailed engineering analysis of the load. The thermal and mechanical properties [4] are compared to those of Oxygen-Free High-Conductivity (OFHC) copper and 304 stainless steel in Table 1, since both copper and stainless steel were considered as possible materials to use as substrates on which to mount the ferrite in the vacuum.

Table 1 Comparison of thermal and mechanical properties of TT2-111 Ferrite to 304 Stainless Steel and OFHC Copper

	304 Stainless Steel	OFHC Copper	TT2-111 Ferrite
Thermal Conductivity (W/m/K)	16.0	390.8	5.4
Thermal Expansion Coefficient (K^{-1})	14.4×10^{-6}	17.0×10^{-6}	8.2×10^{-6}
Specific Heat (J/g/K)	0.502	0.385	0.712
Density (kg/m^3)	8.03×10^3	8.94×10^3	5.27×10^3
Modulus of Elasticity (MPa)	193×10^3	118×10^3	150×10^3
Yield Strength (MPa)	207	69	----
Tensile Strength (MPa)	552	221	49
Compressive Strength (MPa)	-----	-----	245 to 1962

The RF properties of the ferrite are needed as well for the absorber design. The complex dielectric constant and permeability of TT2-111 were measured using a cavity perturbation method [5,6] over a frequency range from 400 MHz to 2500 MHz. These measurements are in agreement with results from Cornell [7] over a wider frequency range using a different technique. Since the absorbed RF power will increase the ferrite temperature, the temperature dependence of the RF properties was measured from 20° to 200°C over the same frequency range. The results for 2500 MHz are given in Table 2.

Table 2 Temperature dependence of TT2-111 RF properties at 2500 MHz

Temperature (°C)	ε'	ε''	μ'	μ''
23	14.0	0.76	1.07	5.1
100	14.0	0.73	0.80	4.7
200	14.0	1.26	0.50	3.4

4. FABRICATION

The two SHR HOM dampers consist of short, beam-line spool pieces, 62 mm inside diameter, with 12 pieces of ferrite (3 mm thick, 12.5 mm wide, and 25 mm long) bonded around the inside circumference of each piece. This design is very similar to that used by Cornell in HOM dampers for the superconducting cavities for CESR-B [3].

The biggest challenge to using ferrites as HOM absorbers is to develop ferrite-to-substrate bonding techniques suitable for ultra-high-vacuum (UHV) applications. The bond must provide good thermal contact with the substrate, withstand typical UHV bakeout temperatures (approximately 200°C), minimize mechanical stress, and avoid materials unsuitable for UHV such as hydrocarbons (common in glues), or lead (used in some solder alloys). A common technique for other ceramics, e.g., alumina, often used in RF applications is metallization followed by high-temperature brazing. Initial attempts to develop a similar technique for TT2-111 failed for several reasons: metallization procedures often did not bond adequately; the difference in thermal expansion coefficients between the ferrite and substrate produced stress in the ferrite that caused the ferrite to fracture during cool-down from brazing temperatures of ~800°C; and, measurements of the ferrite RF properties after a typical braze temperature cycle showed that the ferrite's dielectric constant became very large, with a large imaginary (absorptive) component. The change in the RF properties was attributable to changes in the ferrite stoichiometry at high temperatures in vacuum, or to the reducing atmosphere necessary for brazing.

After considerable experimentation, a suitable technique was developed [8] for bonding TT2-111 to 304 stainless steel. The ferrite, 12.5 mm by 25 mm, was metallized using a commerical silver ceramic metallization compound (Silver Metallization Paste 3524 from Metech Corp.). The silver metallization was nickel plated approximately 25 μm thick, to provide a good adherence layer during later steps, while inhibiting diffusion of silver away from the ferrite surface. The ferrite was then soldered, in vacuum at 350°C, to a nickel-plated 304 stainless steel substrate using Mattisol E (87% tin, 10% silver, 3% copper) foils approximately 50 μm thick. This technique resulted in bond strengths that usually exceeded the tensile strength of the ferrite; i.e., the ferrite fractured before the bond broke. This final step also serves as a UHV vacuum bakeout. The temperatures used in this process were sufficiently low that no changes in the RF properties were observed and mechanical stresses from thermal expansion were reduced.

5. PERFORMANCE

Several measurements were performed on the HOM damper assemblies to assess the damper RF characteristics under low-power and high-power conditions. A coaxial-wire technique, similar to that used to determine the SHR cavity coupling impedance [9], was used to measure the attenuation of beam-pipe RF modes by the damper. A comparison of the

RF-transmission properties of a 50 Ω coaxial line was made using the HOM damper as the outer conductor to a beam-pipe section with the same length as the HOM damper. The 3 mm thick layer, 25 mm long, of TT2-111 ferrite effectively acts as an attenuator for TEM-like modes, with an attenuation varying smoothly from -2.5 dB at 2.85 GHz to -1.5 dB at 5 GHz, with only a few degrees shift in RF phase. Measurements above 5 GHz were not possible, since mode conversion in the coaxial line occurred at higher frequencies. These results were in agreement with calculations of the attenuation using SEAFISH [10] to model the coaxial line and damper.

The same coaxial-line configuration was used to perform high-power tests on the dampers at 2.45 GHz. An industrial, magnetron-based, rf system delivered up to 540 W forward power into the coaxial-line, HOM-damper assembly. The reflected power was minimized using a coaxial stub tuner, and 340 W was trasmitted through a damper, indicating an attenuation of -2.0 dB. The 200 W absorbed power corresponds to an average power flux of 5 W/cm^2. The dampers were intentionally not cooled during this test and, after a few minutes, the damper outside surface temperatures exceeded 100°C. Nevertheless, the ferrite-to-substrate bonds remained unaffected by these temperatures, and the dampers were not damaged.

Performance of the dampers in the SHR is not yet known. As mentioned in the Introduction, the SHR RF cavity has all significant higher-order modes heavily damped by radiation into the beam-pipe, making HOM dampers potentially unnecessary. Nevertheless, the SHR is an ideal case to study the effectiveness of these HOM dampers. The primary reason for damping the higher-order modes is to increase the beam-current threshold for coupled-bunch instabilities. During the SHR commissioning studies, the coupled-bunch instability limit will be examined with, and without, the dampers in place, to determine the effectiveness of these HOM dampers with the SHR cavity.

6. CONCLUSION

The design, fabrication and testing of ferrite-loaded HOM absorbers for the MIT-Bates SHR RF cavity have been described. These absorbers are suitable for UHV cavity and beam-line applications, and serve as rf mode attentuators with approximately -2 dB attenuation. Similar HOM damper designs may also be suitable for other beam-line devices, such as beam position monitors, which can also have significant HOM impedance.

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