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Measurement of the Interaction Between a Beam and a Beam Line Higher-Order Mode Absorber in a Storage Ring*

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"Underneath this chilly gray October sky,
We can make believe the SSC is still alive;
We've shootin' for the Higgs,
An' smilin' Hazel's drivin' by." [1]

I. INTRODUCTION

A phased luminosity upgrade of the CESR e^+e^- storage ring has been initiated [2]. The upgrade program calls for the eventual installation of superconducting cavities with strongly damped higher-order modes (HOMs). The cavity is designed to allow all HOMs to propagate into the beam pipe, so that they may be damped by a layer of microwave-absorbing ferrite. RF measurements with a full-size copper cavity and loads made of TT2-111R ferrite[1] indicate that the design gives adequate HOM damping [3]. The coupling impedance of the ferrite loads and the consequences for beam stability in a high-current ring have been predicted [7]. Prototypes for the cavity, cryostat, and HOM loads were subjected to a beam test in CESR [4, 5, 6]. To further test our understanding of the beam-ferrite interaction, beam measurements were done in CESR in December 1994 on a ferrite load of magnified coupling impedance. This test is described herein.

II. LOAD FABRICATION

We designed a test structure with a beam tube diameter 2.5 times smaller and a ferrite-bearing length 6 times larger than an actual "porcupine" HOM load [6]. The predicted coupling impedance of this test structure is ~ 2 times the predicted monopole impedance and ~ 10 times the predicted dipole impedance of the 8 porcupine loads to be installed in CESR. The structure was split into three units, with sections of straight beam tube (with pumping ports) between them. Each unit consisted of a copper tube with 40 TT2-111R ferrite tiles soldered to the inside and water cooling on the outside (Fig. 1), incorporating features from both the original full-size HOM load [8] and the redesigned porcupine HOM load [6]. A total of four ion pumps, each rated at 140 L/s, were adjacent to the ferrite sections during the vacuum bake and the beam test.

A prototype unit with only 10 tiles was made first for evaluation in a high power density RF test with a 500 MHz klystron. For this test, the ferrite-lined tube became the outer conductor of a coaxial line, with a short placed to produce relatively uniform dissipation in the ferrite. An average surface power density of 15 W/cm^2 was reached without visible damage to any of the tiles. The maximum (measured) tile surface temperature was 96°C.

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[1]A product of Trans-Tech, Inc.

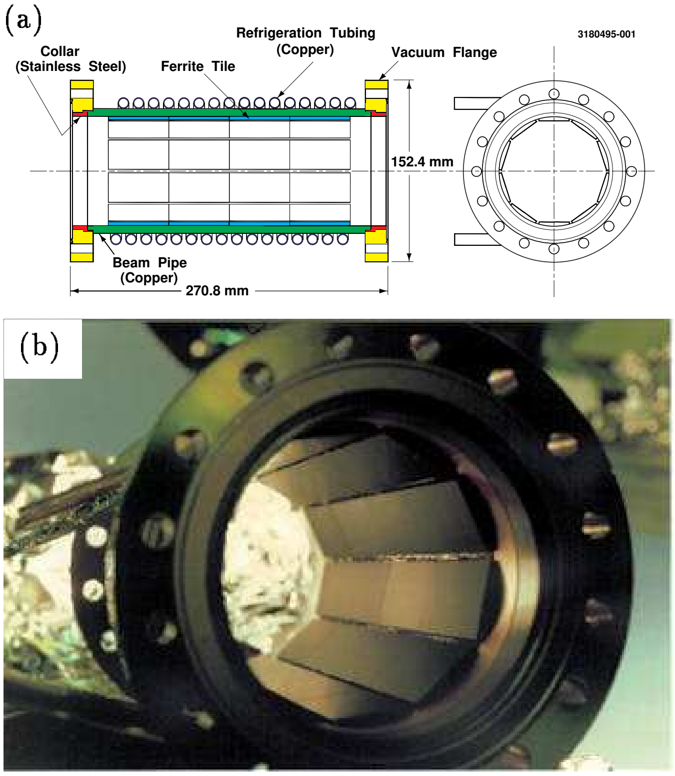

Figure 1. (a) Drawing and (b) photograph of one unit of the ferrite structure. The ID of the Cu tube is 92.1 mm; the ferrite tiles are $50.8 \times 25.4 \times 3.175\,\mathrm{mm}^3$ before radiusing.

III. BEAM TEST RESULTS

The beam measurements on the ferrite section were done over several days, interleaved with machine start-up activities following a down period. Some measurements were done with 9 bunches, in addition to the 1- and 2-bunch measurements discussed herein. Positrons were used almost exclusively, because we did not have complete masking for direct synchrotron radiation from the electron beam. The predictions mentioned in this section are based on the same type of coupling impedance calculations as was done for the HOM loads, *i.e.* using the AMOS program [9] and an analytic approximation [7]. In the calculations, we assumed an axisymmetric geometry with a 3.175 mm layer of ferrite, and did not split the ferrite into three sections.

A. Calorimetric Measurements

The power dissipation in each unit was obtained calorimetrically via the flow rate, inlet temperature, and outlet temperature of the cooling water (the volume flow rate of water was ~ 50 mL/s per unit for most of the test). The monopole loss factor $k_0^{\parallel}$ of the ferrite units can be obtained directly from the total power dissipation P_d and total beam

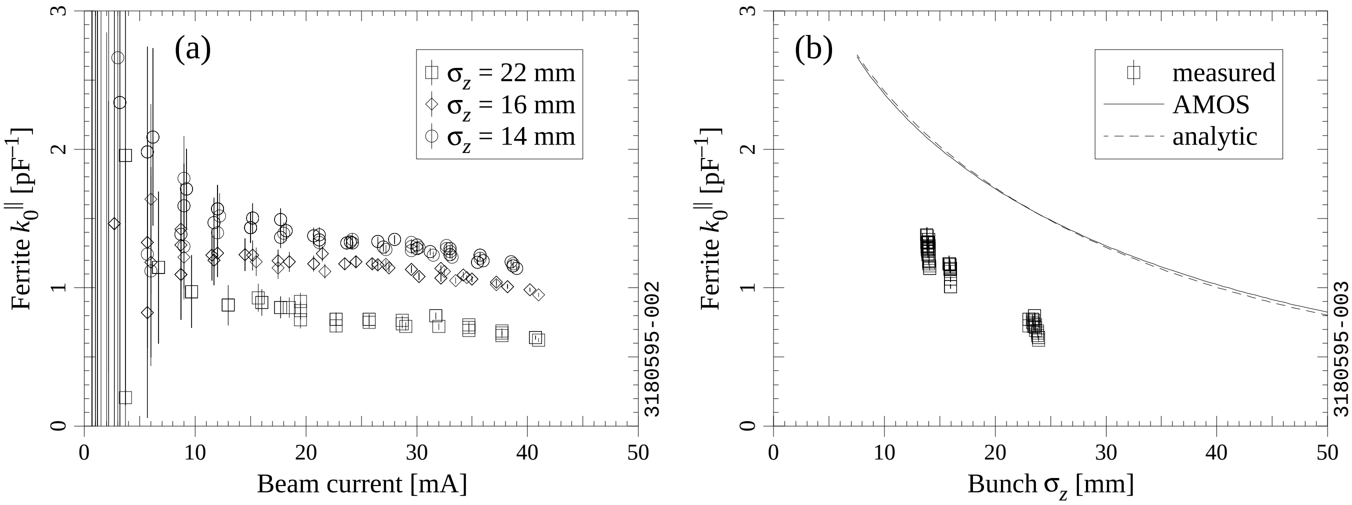

Figure 2. Calorimetrically measured single-bunch loss factor (summed over all 3 units) of the ferrite section as a function of (a) beam current, and (b) bunch length (with predictions). The RF voltage was adjusted to vary the bunch length. Noisy low-current points ($I < 20$ mA) are omitted in (b).

current I. The measured $k_0^{\parallel}$ as a function of I is shown in Fig. 2a for a single bunch. The noise in the data at low I is due to the poor resolution of the small ΔT values. At higher I, a slight decrease in the measured $k_0^{\parallel}$ as function of I is visible. Possible explanations for this effect include (i) systematic error in the calorimetry, (ii) non-linearity in the ferrite response to the RF field, or (iii) the ferrite properties' temperature dependence.

Fig. 2b shows the single-bunch data plotted as a function of the longitudinal bunch size σ_z, calculated from the measured synchrotron frequency f_s (we did not have any means to measure the bunch length directly), along with the predicted $k_0^{\parallel}$. It can be seen that, inasmuch as f_s is a reliable indicator of the bunch length, the decrease in $k_0^{\parallel}$ with I cannot be explained as being due to changes in σ_z as a function of I. The measured $k_0^{\parallel}$ is smaller than predicted by about a factor of 2, perhaps because of the afore-mentioned idealisations in the model.

We used the Temnykh method [10] to sample the wake field: with two bunches of equal charge (I_b = current per bunch = 20 mA for each), we measured the power dissipation in the ferrite as a function of the spacing Δz between the bunches. In terms of a power loss factor

$$P_0^{\parallel} \equiv \frac{P_d f_0}{N_b I_b^2} ,$$

where N_b = number of bunches and f_0 = revolution frequency, we should have[2] $P_0^{\parallel} = k_0^{\parallel}$ if the wake fields have vanished by the time the second bunch arrives and $P_0^{\parallel} \to 2k_0^{\parallel}$ as $\Delta z \to 0$. The results are shown in Fig. 3, along with a prediction obtained by integrating the calculated coupling impedance with the appropriate form factor. The measurement suggests that the ferrite section's wake fields endure longer than predicted; for $\Delta z >$ one RF bucket, however, the measurements and predictions seem to agree that the wake field has decayed to zero.

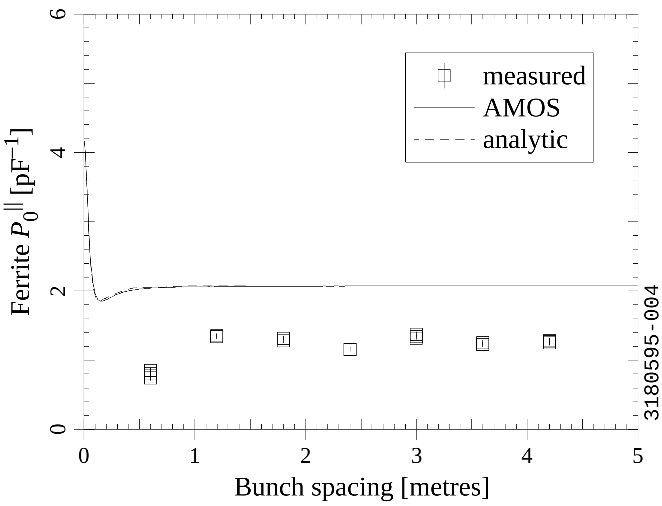

Figure 3. Calorimetrically measured and predicted 2-bunch power loss factor of the ferrite as a function of spacing, with σ_z = 14 mm (from f_s). Because the RF frequency is 500 MHz, the smallest measurable Δz is 0.6 m.

We used magnetic and electrostatic elements to produce a transverse displacement of the beam in the ferrite chamber and its vicinity. The measured calorimetric single-bunch loss factor as a function of displacement is shown in Fig. 4, along with a prediction based on the calculated monopole and dipole loss factors. Though the measurement suggests that there is some dependence on displacement, the signal-to-noise ratio is not very favourable.

B. RF Power Measurements

It is possible to infer the total loss factor of a storage ring by applying the appropriate book-keeping methods to the cavity RF power and synchrotron radiation power [11]. We applied this technique with and without the ferrite in order to get an independent measure of the power loss due to the

[2] we are (justifiably, we think) treating the single-bunch $k_0^{\parallel}$ and the single-pass $k_0^{\parallel}$ as synonymous.

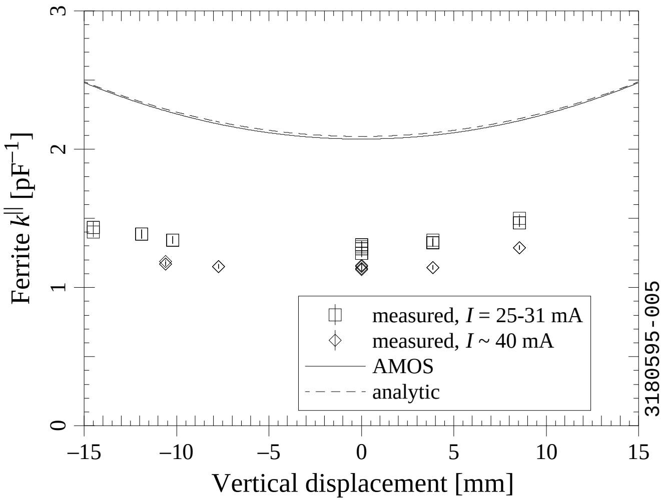

Figure 4. Calorimetrically measured and predicted loss factor of the ferrite section as a function of the vertical displacement of the beam, with $\sigma_z = 14$ mm (from f_s).

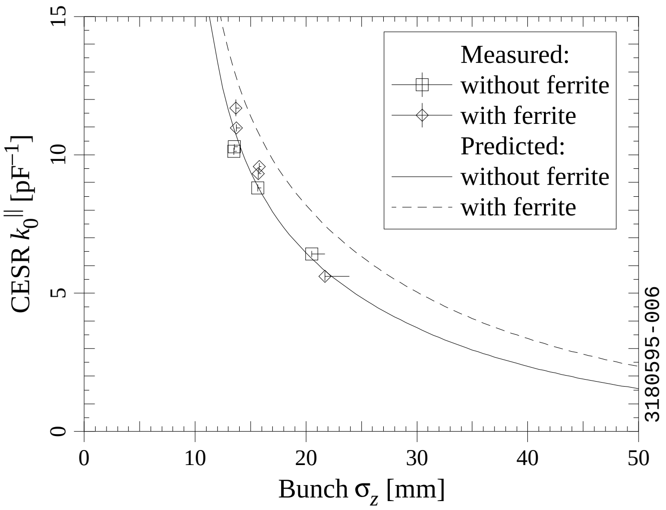

Figure 5. Measured and predicted single-bunch loss factor of CESR, with and without ferrite present.

ferrite. The results are compared in Fig. 5. The predicted $k_0^{||}$ of CESR shown in Fig. 5 was obtained from scaling laws for various machine elements [12] (updated to account for recent modifications). The total $k_0^{||}$ measurement gave less accuracy than the calorimetric measurement, but the results do not overtly contradict each other.

C. Tune Shift And Damping Rate Measurements

According to theory, the total ring impedance should produce shifts in the frequencies and damping rates of coupled-bunch modes. In the "effective impedance" approximation, the shift in the frequency f and damping rate α should be proportional to I. We used established techniques [13] to measure the lowest-order single-bunch transverse mode frequencies (*i.e.* the horizontal and vertical betatron frequencies) and corresponding α's as a function of I, with and without ferrite. We did the measurements with the CESR distributed ion pumps turned off, in order to eliminate anomalous growth effects [13]. We believe that measured differences in slope ($\Delta f' = 0$ to 13 kHz/A and $\Delta\alpha' = -4$ to -6 ms^{-1}A^{-1}) are below the reproducibility threshold of the measurement.

IV. LOAD PERFORMANCE

The maximum (total) power dissipation in the ferrite was was 5.8 kW according to calorimetry (average power density = 3.8 W/cm^2); this was obtained with $I = 142$ mA in 9 bunches. At this current, the pressure gauges read ≤ 30 pbar, although pressures as high as 50 pbar were recorded (at lower I) during an earlier "beam processing" shift. Several vacuum "spikes" occurred in the course of the test, with the pressure rising to 100–200 pbar or higher. Prior to installation, the pressure in the ferrite assembly reached 1 pbar at 17°C after a vacuum bake-out to 150°C.

A brief inspection of the ferrite chamber after removal from CESR revealed that one corner of one tile had broken off; it was found lying on the bottom of one of the ferrite sections. The piece appeared to have been unsoldered except along one edge. The remaining tiles have not yet been closely inspected for cracks.

V. CONCLUSION

CESR beam measurements with a ferrite-lined section of magnified impedance indicate that the loss factor is a factor of ~ 2 smaller than predicted; the measured wake field endures longer than predicted, but is not visible for $\Delta z \geq 4.2$ m, which is planned for CESR. The signal-to-background ratio made it difficult to pick out effects from the ferrite via measurements on the beam only. We are working on predictions which model the actual load geometry more closely.

We wish to thank all of the Laboratory staff who helped to make this beam test possible.

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