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A Review of Some Dynamic Loss Properties of Ni-Zn Accelerator RF System Ferrite

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Introduction

The Fermilab booster and main accelerator rf cavities are tuned through their operating ranges (30 to 53 MHz) by varying the reactance of Ni-Zn ferrite rings using low frequency biassing fields up to 45,000 AT/m. All rings are 8 inch O.D, 5 inch I.D, and 1 inch thick (volume 502 cm^3, weight ≈2kg). The rf power loss properties of three types of ferrite, labeled A, B, and C, have been studied. These ferrites have remanent field incremental permeabilities of about 10, 20, and 40 respectively. During the initial fixed frequency ferrite testing an anomalous rf loss mechanism "high loss effect" was observed[1,2,3]. In subsequent tests with swept dc bias fields another loss mechanism, "dynamic loss effect" was identified in this laboratory and elsewhere[4,5,6].

The purpose of this paper is to review the nature and extent of these two loss mechanisms and their effects on accelerator operation.

Test Procedures

Tests of the three types of ferrite were made on a standard booster accelerating cavity coupled to specially built "tuners" assembled with one of the ferrite types or a combination of several types. Each tuner contained approximately 28 cores and a cavity could be operated with 1, 2, or 3 tuners attached. The exact number of cores in any specially built tuner was dictated by the permeability range of the cores to be tested, the number of tuners to be used, and the frequency at which the test was to be done. The cores in a tuner are interleaved with 1/4 inch thick copper "washers" which are in tight thermal contact with each core face so that the ferrite temperature can be controlled accurately by water cooling the copper. The cores in the tuners were, in each case, linked by ten turns of bias current carrying buss bars which were driven by a programmable 0-2500 A current supply. No significant tests were done on unbiased, or remanent state, ferrite. Variable amounts of rf power were supplied to the testing cavity through a direct coupled 100 kW tetrode which constituted a reasonably good rf current source. The tuners constitute essentially the entire inductance of the cavity-tuner resonator and consequently the time averaged stored energy in the ferrite is about one half of that in the entire resonator. The Q of the resonant structure is essentially that of the ferrite. By measuring the Q of the resonator and the rf voltage one can infer from geometry the rf flux, rf stored energy, and the power dissipated in any core.

High Loss Effect

The test cavity, fitted with a particular type of ferrite, was operated at a fixed frequency in the range 20 to 50 MHz for 10 ms. Frequencies were selected by adjusting the ferrite dc biassing current, which remained fixed during most of the tests. Figure 1 shows an rf envelope with well developed high loss effect. The effect is characterized by a short period of normal operation followed by a decrease in rf voltage for a given input power. At higher initial drive levels the period of normal operation becomes shorter but it is always observable. During the high loss period the rf amplitude has a characteristic noisy appearance. The lower trace is a signal representing the phase angle between the resonator drive current and the rf voltage (sensitivity, 30 degrees per division). Although the phase error signal becomes more noisy at the onset of high loss no net phase shift is observed, indicating that the real part of the permeability does not change.

The effect is observed in all three types of ferrite and it can be induced at any dc bias level (and hence any rf drive frequency) within the experimental capability. Measurements on type c ferrite at 25, 30, and 35 MHz showed no significant difference in threshold level between 35 and 80 degrees C. In examining the high loss threshold of all three kinds of ferrite at different frequencies and bias currents only one perameter appears to remain constant. The onset thresholds always occur at about the same stored energy per unit volume, $3\pm1\times10^{-7}$ Joules per cubic centimeter.

An additional characteristic of high loss effect is shown in figure 2a and b. In part a the trailing edge of the rf envelope is shown at a sweep rate of 100 μs per division at an excitation level just below the high loss threshold. Part b shows the trailing edge with well developed high loss effect. There is clear evidence of a "follow-on" burst of rf in the resonator which occurs after the removal of excitation from the power amplifier. The pulse shape has the form

$$V(t) = V_0(1-e^{-t/T_1})e^{-t/T_2}.$$

The rf frequency, measured during the follow-on burst, is the same as the original excitation frequency (resonant frequency of the cavity). The rise time constant T_1 is about 2.2 μs and the decay time constant T_2 is about 21 μs. The measurement was done at 35 MHz where the Q of the resonator was measured to be 245. The cavity time constant $2Q/\omega$ is precisely consistent with the rise time of the follow-on burst. The longer decay time constant is consistent with a Q of 2300 and a bandwidth of about 15 kHz. It appears that the ferrite is storing energy in a highly coherent, narrow bandwidth, mode similar to the spin wave exchange field coupling which has been described for microwave ferrites[7,8]. If something like this mechanism is at work it should be possible to destroy the coherence by introducing a small tune spread (Landan damping) in the excitation frequency.

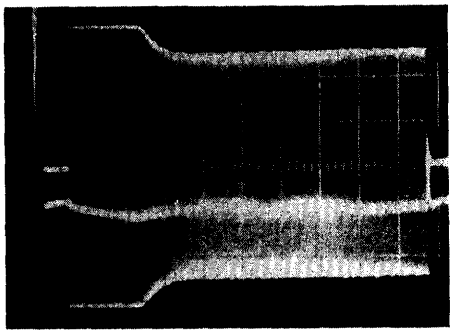

Fig. 1. Cavity rf envelope with well developed high loss effect. Sweep rate is 1 ms per div.

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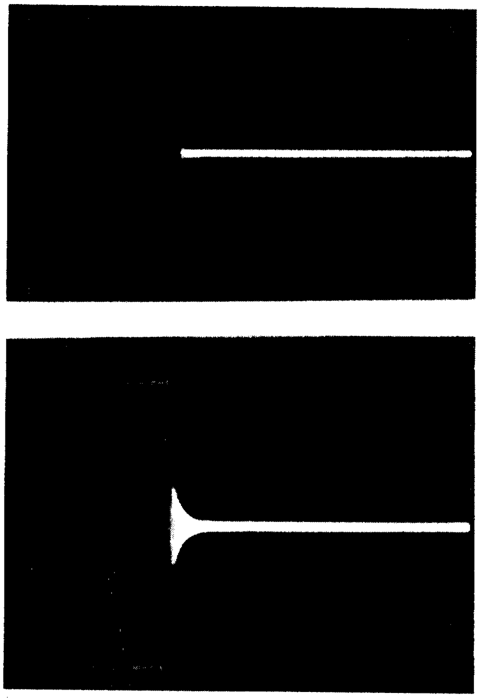

Fig. 2.a) Trailing edge of rf envelope with no high loss, b) Trailing edge with well developed high loss showing "follow-on" pulse.

In figure 3 the rf envelope of figure 1 is shown when the excitation frequency (near 35 MHz) is frequency modulated ±5 kHz at a rate of about 1 kHz. This results in a resonator phase error of about ±5 degrees. At this fm level the high loss effect begins to disappear. At fm levels with larger deviation the high loss effect disappears completely and the ferrite can be excited to much larger rf levels, limited only by other effects (such as sparking, cooling capacity, etc.). If the rf frequency is swept monotonically and the tuner bias current is simultaneously swept such that the cavity is always at resonance the high loss effect is similarly eliminated. A sweep rate of 20 kHz per ms was sufficient to eliminate the high loss effect entirely.

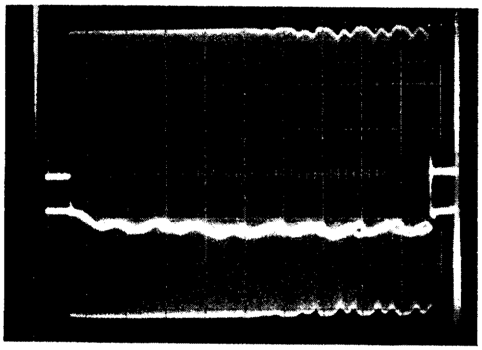

Fig. 3. RF envelope with frequency modulation just sufficient to destroy high loss effect.

Dynamic Loss

When the rf frequency and the ferrite biassing current are swept as described above at very high rates a dynamic loss occurs which is dependent on the rate and duration of introduction of bias field intensity into the ferrite. The effect is seen clearly by exciting the cavity at fixed frequency at constant current and observing the rf voltage developed as the bias current is raised through resonance at varying rates. The biassing sweep rate is always sufficiently slow so that reduced rf amplitude response at resonance cannot be accounted for by cavity filling time.

In figure 4 a, b the cavity is excited at 32.7 MHz while the biassing field is driven through resonance at 1000 AT/m-ms and 18000 AT/m-ms. The rf amplitude developed at the higher sweep rate is reduced by a factor of 0.6. Accurate measurements of Q degradation can be made by measurement of the required increase in rf drive power necessary to regain the unswept rf amplitude under various rates of bias. The Q degradation is a function not only of the rate of bias field change, but also of the duration of time previous to reaching resonance during which the bias has been changing. This can be seen in figure 5 where the Q degradation for type B $(\mu_\delta \sim 21)$ ferrite is shown as a function of time delay for constant ramp rate. Figure 5 also contains some indication of the temperature dependence of the effect. Other data indicate that dynamic Q degradation improves linearly from 0.55 to 40 deg. C to 0.65 at 80 deg. C (type B ferrite with resonance at 1960 AT/M, 23 MHz, and slope 1960 AT/m-ms).

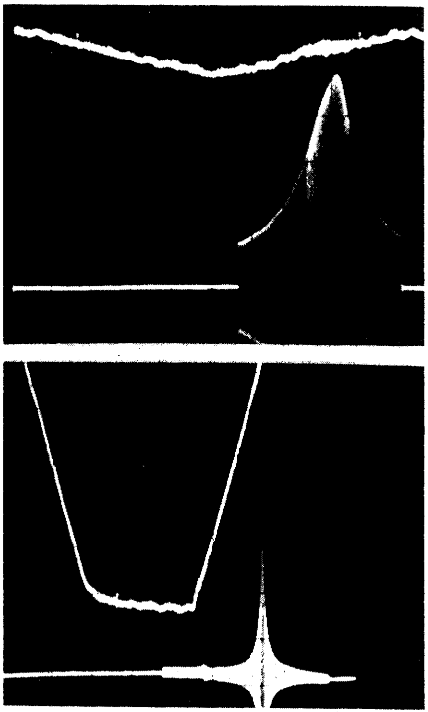

Fig. 4. Cavity response to constant excitation when biassing field is introduced at a) 1000 AT/m-ms and b) 18000 AT/m-ms.

The magnitude of dynamic loss effect increases slightly with rf excitation level but, unlike high loss effect, it occurs at any level of rf excitation. The loss occurs only at relatively low values of bias field and apparently becomes negligible, regardless of field time dependence, for fields greater than

15000 AT/m. In figure 6 the Q degradation factor is shown for three types of ferrite for varying bias rates. In each case the bias ramp was started 2 ms ahead of resonance and the loss was inferred by the power increase necessary to reach the zero slope value. RF flux in the ferrite was about 30 G for the three lower curves and 15 G in the upper curve.

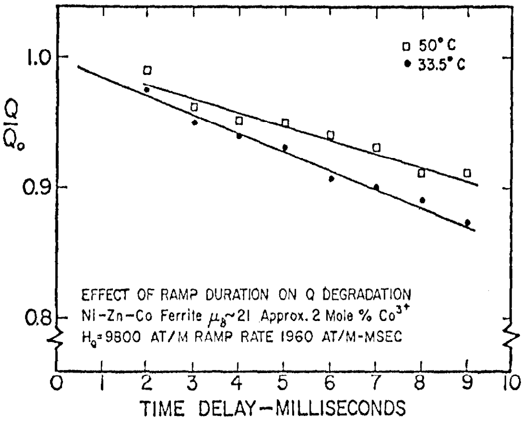

Fig. 5. Q degradation factor as a function of time duration of application of biassing ramp previous to reaching resonance.

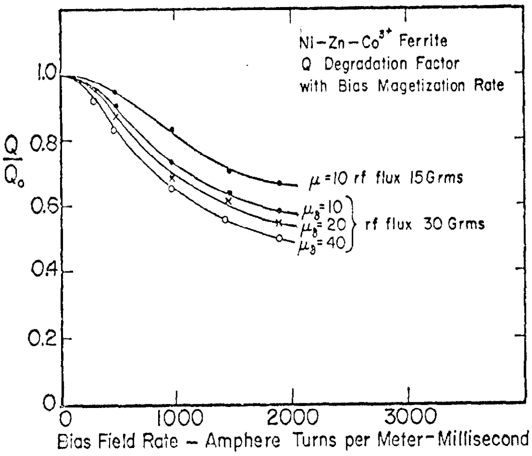

Fig. 6. Q degradation factor as a function of bias rate.

Ni-Zn ferrites for use with relatively large fluxes of high frequency rf typically contain small quantities of divalent and trivalent cobalt. The cobalt ions tend to reduce the power loss resulting from domain wall motion in high frequency rf fields[9]. However, domain wall displacement resulting from application of low frequency fields causes a decrease in Q which, in the case of Co^{2+} may be permanent, and in the case of Co^{3+} is responsible for the observed dynamic loss. Types B and C ferrite described here contain approximately 2 mole percent Co^{3+}. If the Co^{3+} content is removed entirely the dynamic loss disappears but the rf properties of the ferrite will be seriously degraded at flux levels above a few gauss. By including only about 0.6 mole percent Co^{3+} and careful adjustment of grain size and sintering temperature ferrite material which is superior to any in use at this laboratory can be produced[10,11].

Conclusions

While "high loss effect" clearly exists in Ni-Zn ferrite operated at high rf power levels, it is a fixed frequency phenomenon and does not contribute to degradation of Q in accelerator resonators which are swept in frequency.

The introduction of low frequency biassing fields, required for frequency sweeping, does introduce a degradation of Q which affects accelerator operation. The Q degradation depends on the detailed manner in which the frequency is swept and it can, in some cases, be as large as 50 percent. This degradation is caused by the trace presence of Co^{3+} ions in the ferrite and it can be minimized by reduction of the quantity of Co^{3+}. Such a reduction has an adverse effect on the linearity of the ferrite at rf frequencies if large rf fields are to be used. There is evidence that adjustments of grain size and sintering temperatures can offset these adverse effects and that a superior ferrite for accelerator use can be produced.

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