FERMILAB-Conf-02/221 September 2002

Fermilab

Induction Inserts at the Los Alamos PSR

K.Y. Ng

Fermi national Accelerator Laboratory, P.O. Box 500, Batavia, IL 60540

Abstract. Ferrite-loaded induction tuners installed in the Los Alamos Proton Storage Ring have been successful in compensating space-charge effects. However, the resistive part of the ferrite introduces unacceptable microwave instability and severe bunch lengthening. An effective cure was found by heating the ferrite cores up to $\sim 130°$C. An understanding of the instability and cure is presented.

INTRODUCTION

Inductive tuners were installed into the PSR to cancel the space charge effects of the intense proton beam at 799 MeV. Each tuner consists of a stainless steel pill-box cavity closely packed with 30 Toshiba M_4C_{21A} ferrite cores, each 1.0 in thick, 5.0 in I.D. and 8.0 in O.D. When two tuners were installed in 1997 with the intention of two-third space-charge compensation, clear and consistent evidence was observed, including shorter bunch length, cleaner bunch gap, and smaller rf voltage required for stable operation. After an upgrade when 3 tuners were installed in 1999 and the beam intensity was raised, a longitudinal instability was observed. Figure 1 shows a chopped coasting beam accumulated for 125 μs and stored for 500 μs recorded at a wide-band wall current monitor. The ripples at the beam profile indicate a longitudinal microwave-like instability at 72.7 MHz, which is roughly the resonant frequency of the pill-box cavities housing the ferrite cores. The resonance also showed up as ripples at the rear half of a 250 ns (left) and 100 ns bunch (middle) in Fig. 2. Apparently, the instability is tolerable for the 250 ns bunch because the bunch shape distortion is small. However, the $\sim$100 ns bunch is totally disastrous because it was lengthened to 200 ns.

CAUSE OF INSTABILITY

To incorporate loss, the relative permeability of the ferrite can be made complex: $\mu \to \mu_s' + i\mu_s''$, where the subscripts denote "series". The impedance of the ferrite is therefore

$$Z_0^{\parallel} = -i(\mu_s' + i\mu_s'')\omega L\,, \tag{1}$$

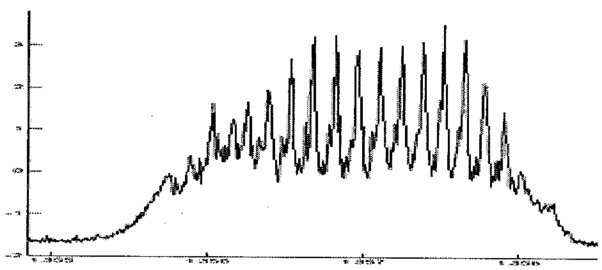

FIGURE 1. Longitudinal microwave-like instability recorded by wall-gap monitor of a coasting beam driven at 72.7 MHz.

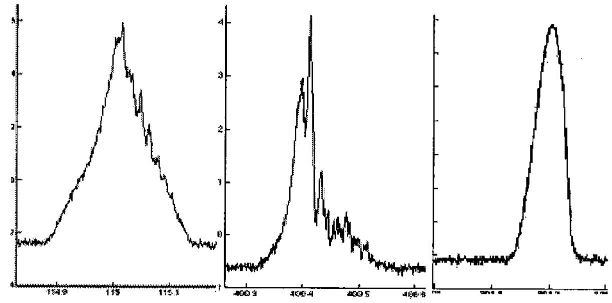

FIGURE 2. Instability perturbation on profiles of bunches with full width 250 ns (left) and 100 ns (middle). Right: Upon heating the ferrite to 130°C (see Sec. 4), the profile of the 100 ns bunch is no longer distorted.

where L denotes the inductance of the ferrite and ω the angular frequency. It is clear that μ_s' and μ_s'' must be frequency-dependent. The simplest circuit model is an inductor L_p in parallel with a resistor R_p. However, whenever ferrite is used, like the cores packed inside a pill-box cavity, there is an accompanying capacitor C_p in parallel. The impedance of the inductor tuner can then be represented by

$$Z_0^{\parallel}(\omega) = \frac{R_p}{1 - iQ\left(\omega/\omega_r - \omega_r/\omega\right)}\,, \tag{2}$$

where ω_r is roughly where μ'' peaks. If we denote μ_L' as the value of μ' at low frequencies and μ_R'' the value of μ'' at resonant frequency $\omega_r/(2\pi)$, we readily obtain $\mu_R'' = Q\mu_L'$. Note that Q here is the quality factor describing the μ'' peak and is *not* the usual industrial-quoted Q. For a space-charge dominated beam, the actual area of beam stability in the complex $Z_0^{\parallel}/n$-plane (or the traditional U'-V' plane), where n is the revolution harmonic, is somewhat different from the commonly quoted Keil-Schnell estimation [2]. In Fig. 3, the heart-shape solid curve 1 is the threshold for parabolic distribution in momentum spread, where the momentum gradient is discontinuous at the ends of the spread. Instability develops and a smooth momentum gradient will result, changing the threshold curve to that of a distribution represented by 2. Further smoothing of the momentum gradient at the ends of the spread to a Gaussian distribution will change the threshold curve to 3. On the other hand, the commonly known Keil-Schnell criterion is denoted by the circle of unit radius in dots. This is why in many low-energy ma-

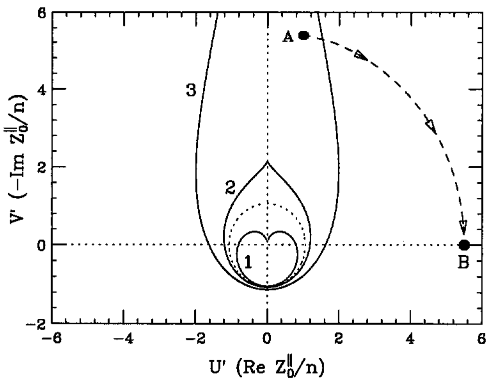

FIGURE 3. An intense space-charge beam may have impedance at A outside the Keil-Schnell circle (dots) but is stable inside the stability curve 3 for Gaussian distribution. Ferrite inserts compensating the space charge completely will lead to a resistive impedance roughly at B, which introduces instability.

chines the Keil-Schnell limit has been significantly overcome by a factor of about 5 to 10.

At the PSR, the space charge is almost the only source of the impedance, $\mathrm{Re}Z_0^{\|}/n$ typically orders of magnitude smaller. As an example, if the impedance of the Los Alamos PSR is at A, the beam is within the microwave stable region if the momentum spread is Gaussian like, although it exceeds the Keil-Schnell limit. Now, if we compensate the space-charge potential-well distortion by the ferrite inductance, the ferrite required will have an inductive impedance at low frequency equal to the negative value of the space charge impedance at A, for example, about −5.5 units according to Fig. 3. However, the ferrite also has a resistive impedance or $\mathrm{Re}Z_0^{\|}/n$ coming from μ''. Although $\mathrm{Re}Z_0^{\|}/n$ is negligible at low frequencies (for example, the rf frequency of 2.796 MHz of the PSR), it reaches a peak value near $\omega_r/(2\pi)$ (about 50 to 80 MHz for the Toshiba M_4C_{21A} inside the pill-box container) with the peak value the same order of magnitude as the low-frequency $\mathrm{Im}Z_0^{\|}/n$.

Thus the ferrite will contribute a resistive impedance denoted roughly by B ($\sim$5.5 units) when $Q\sim 1$. This resistive impedance of the ferrite will certainly exceed the threshold curve of any momentum distribution and we believe that the longitudinal instability observed at the PSR is a result of this consideration. In order to avoid this instability, we must search for a ferrite sample having a small $\mathrm{Re}Z_0^{\|}/n$ to $\mathrm{Im}Z_0^{\|}/n$ ratio.

HEATING THE FERRITE

Past experience indicates that when a piece of ferrite is heated up, μ_s' will increase and loss at high frequencies will decrease, thus having exactly the same properties we are looking for.

A measurement has been made by sending a sinusoidal wave from one end of the ferrite tuner via an antenna and receiving it with an antenna at the other end, while the loss is recorded as a function of frequency of the wave [3]. The results are shown in Fig. 4 and reveal that the resonant peak drops by a factor of about 6 when the ferrite cores are heated from the room temperature of 23°C to 100°C. At the same time the resonant frequency moves to lower frequencies.

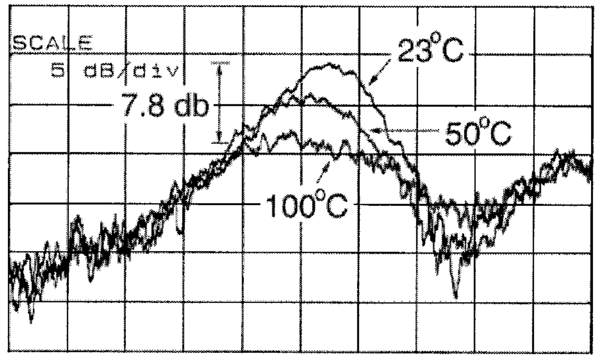

FIGURE 4. (color) As the ferrite cores are heated from room temperature to 100°C, the loss at the resonant peak reduces by almost 6 times. Abscissa: center 75.0MHz, span 149.4MHz. Ordinate: 5 db/div.

A measurement of the permeability of the ferrite has also been made on a single Toshiba M_4C_{21A} ferrite core as a function of core temperature [4]. To provide both a good electrical circuit path and a uniform core temperature, the core was encased in an aluminum test fixture before being placed on a hot plate. The top half of the test fixture consisted of a machined aluminum disk, 9 in in diameter and 1.25 in thick. The inner section of the disk was machined out 0.005 in undersize to accommodate the ferrite core. The disk was then heated and the core was slipped into the disk. Upon cooling, the aluminum disk contracted and made a good thermal contact with one side and the outer edge of the ferrite core. The aluminum fixture and core were then flipped over onto a flat aluminum plate so that only the inner edge of the core was exposed. A good electrical connection between the aluminum disk and flat plate was made using strips of adhesive backed copper tape. The test fixture was placed on a hot plate and covered with two fire bricks. The test fixture was then heated to 175°C and allowed to cool slowly. The impedance measurement was made by placing the probe of an HP4193A vector impedance meter directly across the inner edge of the ferrite core. Impedances were measured from 10 MHz to 110 MHz in 10 MHz steps from 150°C to 25°C. The temperature of the core was monitored by a Fluke 80T-150U temperature probe inserted into a small hole in the aluminum disk portion of the test fixture.

The capacitor C_p in parallel to the ferrite core was determined by adding additional fixed 100 pf capacitors

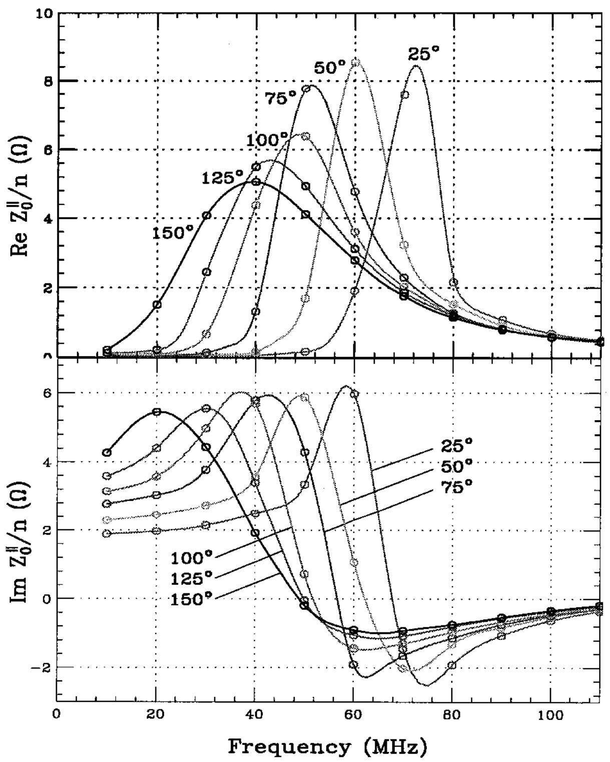

FIGURE 5. (color) Fermilab measurement of real and imaginary parts of impedance per revolution harmonic $Z_0^{\|}/n$ of a ferrite core inside a snugly fit pill box cavity.

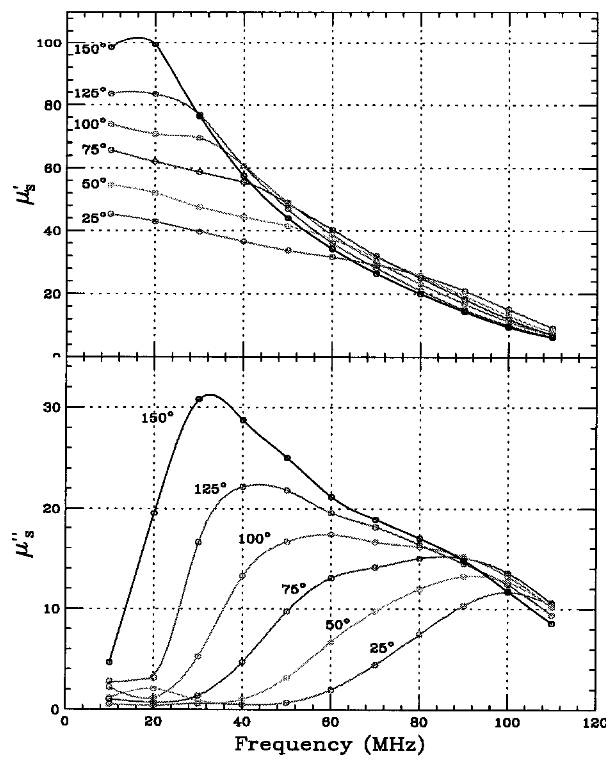

FIGURE 6. (color) Real and imaginary parts, μ_s' and μ_s'', of the permeability of the ferrite core as functions of frequency at different temperatures as derived from Fermilab measurement.

across the inner edge of the ferrite core and observing the change in the resonant frequency of the structure from 41 to 28 MHz, a frequency range in which the μ_s' of the ferrite is known to be relatively constant. In this manner, a capacitance of $C_p = 75$ pf was chosen to represent the equivalent parallel capacitance of the test circuit. There was also a residual resistance of $R_r = 0.55\ \Omega$ in the probe in series with the *RLC* parallel equivalent circuit. This residual resistance introduces a large error at low frequencies (below ~ 10 Hz) when the resistive part of the *RLC* circuit is small. From the measurements of the input impedance, R_p and L_p were computed. The real and imaginary parts of $Z_0^{\|}/n$ for one ferrite core encased in a cavity as seen by the beam are shown in Fig. 5. It is clear that the resonant peaks of $\mathrm{Re}\,Z_0^{\|}/n$ decrease twice as the temperature increases and the resonant frequency moves towards lower frequencies. At the same time, $\mathrm{Im}\,Z_0^{\|}/n$ increases by more than twice. If one plots $\mathrm{Re}\,Z_0^{\|}$ versus frequency instead, the decrease with temperature becomes more rapidly. For a coasting beam, the area under a $\mathrm{Re}\,Z_0^{\|}$ curve represents the energy loss to the ferrite assembly. We find that this loss is in fact temperature independent within 10%.

The real and imaginary parts of the series permeability of the ferrite core derived from the measurement are shown in Fig. 6. It is interesting to see that μ_s'' actually increases with temperature. However, an increase of the series resistance inside the ferrite core implies a decrease of the resistance R_p in the *RLC* parallel circuit, and therefore leads to a decrease in $\mathrm{Re}\,Z_0^{\|}/n$ of the resonant peak as depicted in Fig. 5.

APPLICATION TO THE PSR

When the induction tuners at the PSR are heated to 130°, the longitudinal microwave instability seen in Fig. 1 disappears. The profile of the 100 ns bunch now becomes as depicted in the right plot of Fig. 2, no longer distorted and lengthened. Further beam studies with the heated ferrites demonstrated other benefits of the inductor tuners without unmanageable operational impacts.

REFERENCES

1. M.A. Plum, et. al., *Phys. Rev. ST Accel. Beams*, **2**, 064201 (1999).
2. E. Keil and W. Schnell, CERN Report TH-RF/69-48 (1969); V.K. Neil and A.M. Sessler, Rev. Sci. Instr. **36**, 429 (1965). D. Boussard, CERN Report Lab II/RF/Int./75-2 (1975).
3. M. Popovic, private communication.
4. D. Wildman, private communication.

Acknowledgement

Operated by Universities Research Association Inc. under
Contract No. DE-AC02-76CH03000 with the United States Department of Energy.

Disclaimer

Distribution

Copyright Notification