PSR TECH NOTE 02-007

Longitudinal Instability Caused by Ferrite Inductors in Los Alamos Proton Storage Ring

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ABSTRACT

The longitudinal impedance caused by the Ferrite Inductors has been identified and quantified both theoretically and experimentally. The frequency dependence of the complex μ of the ferrite, growth time of instability, and impedance of ferrite inductors are discussed.

1. Introduction

Two Ferrite Inductors are installed and operational as of October 2000 in the Los Alamos Proton Storage Ring (PSR) to compensate the large Space Charge effect. This unfortunately lead to a longitudinal instability at ~75 MHz that was mitigated by heating of the Ferrite. Presented herein is a description of the Space Charge compensation, the complex permeability of the Ferrite as a function of frequency, the impedance of the Inductors, and the growth time of the instability (both theoretical and experimental) for a DC coasting beam.

2. Space Charge Compensation

The first issue to discuss is the effect of space charge. The Space Charge Impedance for the PSR is given by [1]:

$$\left(\frac{Z_0^{\parallel}}{n}\right)_{spch} = i\frac{Z_0 g_0}{2\gamma^2\beta} \approx i196\Omega,$$

where we use γ=1.85, β=0.84, n representing the revelotion harmonic number, and the geometric factor $g_0 \approx 3.0$. Since the beam energy in the PSR is below transition (γ_t =3.1), the space charge impedance is repulsive, and therefore tends to de-bunch the beam.

The space charge compensation benefit of the Ferrite is due to their inductive nature, which combats the capactive nature of space charge in the PSR. The frequency dependence of the μ′ and μ″ for the Ferrite cores installed in PSR was determined by matching the S_{11} parameters from Browman's [2] measurements of a jig containing a sample core of ferrite to a calculation using MAFIA. In MAFIA, the Debey parameters were systematically changed until the simulated S_{11} parameters matched those of Browman's measurement. From the Debey parameters, the complex permeability could be determined at different frequencies. Figure 1 shows this result, for two different temperatures (25°C and 125°C), up to 120MHz.

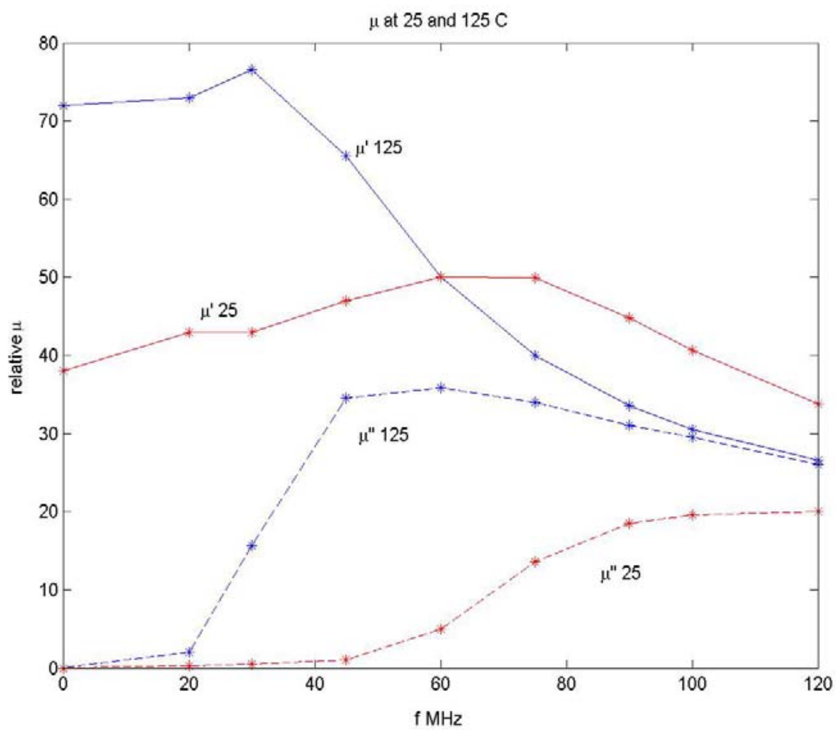

Figure 1. Relative μ′ and μ″ for 25°C and 125°C as a function of frequency as determined by MAFIA simulation.

Note that μ′=38 at the revolution harmonic (ω_0 =2.795 MHz) at 25°C, the impedance of the Ferrite is [1];

$$\left(\frac{Z_0^{\|}}{n}\right)_{ferrite} = -i\frac{Z_0\omega_0 t n_f}{2\pi c}\mu'\ln\frac{d_o}{d_i} = -i1.59 n_f \Omega .$$

There are two Ferrite Inductors consisting of 30 Ferrite cores each (giving n_f=60), with each core having an inner diameter d_i =12.7 cm, and outer diameter d_o =20.3 cm, and thickness t=2.54 cm. This leads to an impedance of – ™95.4 Ω (given the impedance of free space Z_0 =377Ω, and c is the speed of light). This compensates ≈50% of the space charge impedance (™196 Ω– ™95.4 Ω≈ ™100 Ω). When the Ferrite Inductors are heated to 125°C, μ′ is increased to 70, thus the Ferrite impedance increases to – ™176 Ω, compensating about 90% of space charge. Currently the PSR is operated with the Ferrite heated to approximately 160°C.

3. Longitudinal Instability at Room Temperature

The reason for heating the Ferrite is not for additional compensation of the Space Charge impedance, but to eliminate the longitudinal instability that was observed when the Ferrite was at room temperature (25°C).

a) b)

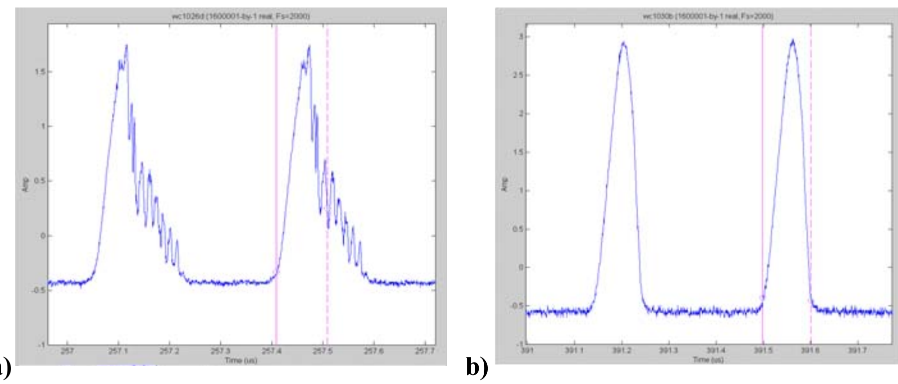

Figure 2. 100 ns pulse with inductors with 3.3 μC Inductors **at a)** 25°C, and b) 130°C.

The Ferrite Inductors were modeled in MAFIA to find their resonant frequencies. At room temperature, the resonant frequency (TM_{010} mode) of a Ferrite Inductor was found to be 80.6 MHz, with a Q of 3.3. This result is found given a μ′=48.4 and a μ″=15.0, which is their value at 80 MHz. Using these parameters, a MAFIA simulation gives a peak impedance of 16 kΩ at just below the Inductor resonance (~78 MHz → n=28).

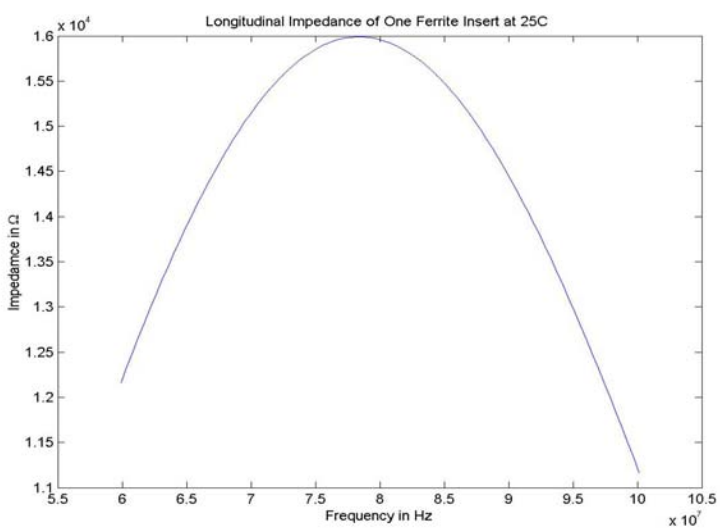

Figure 3. MAFIA Simulation of the Longitudinal Impedance of one Ferrite Inductor around the resonance frequency of the cavity.

Given 0.89 μC in a DC coasting beam with a Lorentzian distribution with a full width at half max momentum spread of 1.62 x 10^{-3} [3], this leads to a calculated growth time of 33.4 μs using the following equation [4];

$$\tau^{-1} = \sqrt{\frac{2\pi N r_o \,|\,\eta\,|\,n\,|\,Z^{\parallel}\,|}{\gamma T_0^3}} - n \frac{\Delta p}{p_0}_{FWHM} \,|\,\eta\,|\,\omega_0 \,.$$

The second term is the Landau Damping term. For this calculation one uses Gaussian units, giving $Z^{\parallel}$=42.4 $\frac{4\pi}{c}$ (note unit conversion 377Ω= $\frac{4\pi}{c}$), $\frac{\Delta p}{p_0}_{FWHM} = 1.62x10^{-3}$ [3], |η|=0.187, ω_0=2.795 MHz, r_0=1.5x10^{-18}, T_0 = 358 ns, and γ=1.85. A 0.89 μC DC coasting beam (giving N=5.6x10^{12}) is used to match with the experiment conducted on September 12, 2002 (file wc410912_c) and a Lorentzian longitudinal beam distribution was used because of its similarities to the actual longitudinal beam spectrum (sum of 2 Gaussians [3]). Experimentally it was found that at room temperature with a 0.89 μC DC coasting beam, the longitudinal instability was peaked at ≈79 MHz with a full width at half max (of the power) of approximately 16 MHz. This leads to a Q of 5.

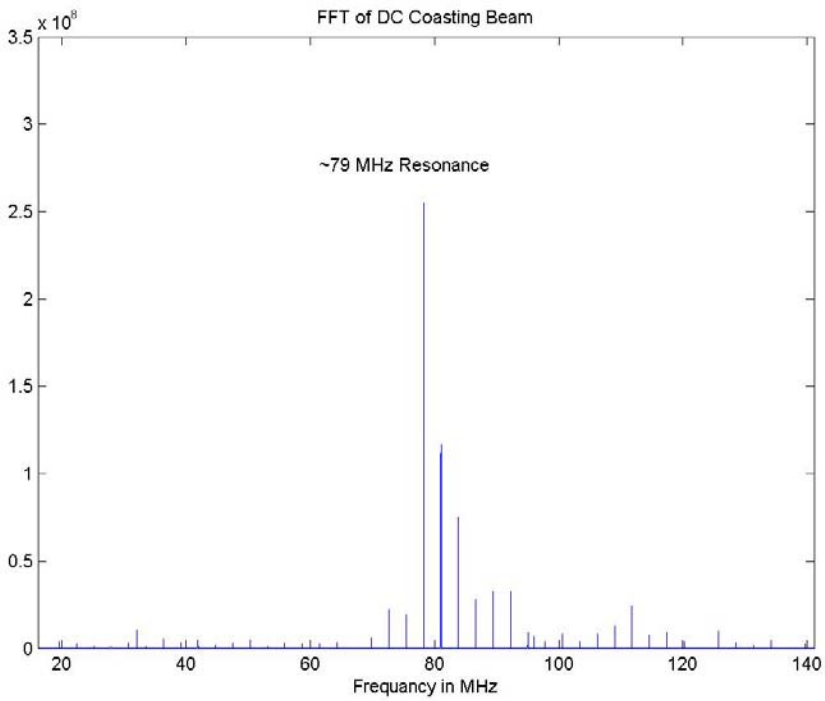

Figure 4. FFT of a DC Coasting Beam with the Inductors at room temperature.

The growth of the instability is not constant, but rather it appears to be the beating of two very near frequencies. The growth time was determined by summing the absolute value of the FFT spectrum turn by turn around 64-98 MHz (n=23-35). The growth times are all very similar, τ_1, τ_2, and τ_3 are all ≈30 μs, τ_4 is 26 μs, and τ_0 is ≈50 μs. 50 μs is also the growth time one obtains by taking the slope of the straight line formed by connecting the start of τ_0 and the peak at the end of τ_3.

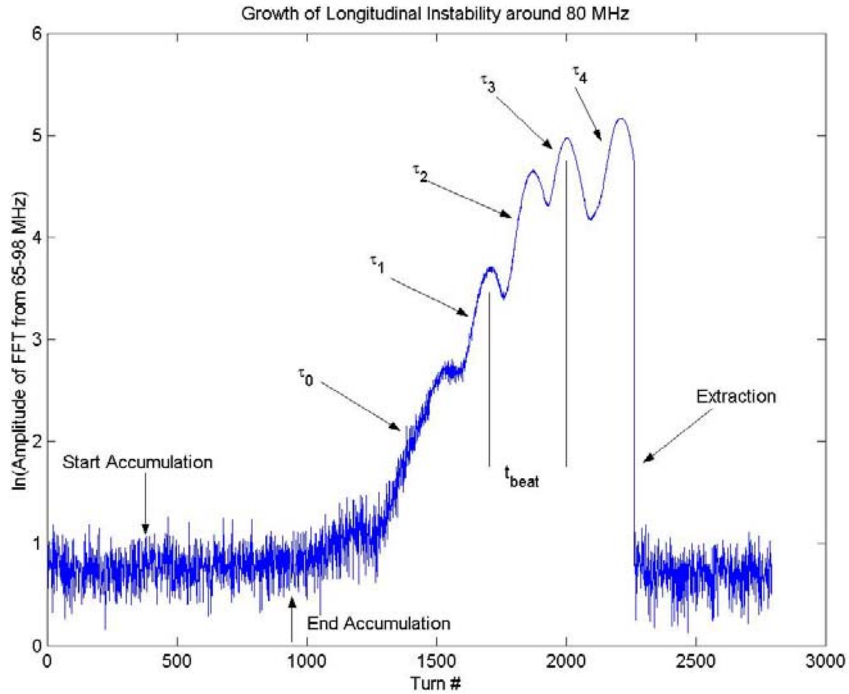

Figure 5. Growth times (τ) of the longitudinal instability caused by the Ferrite Inserts can be determined by the growth of the FFT spectrum near the resonance of the cavity.

Close examination of the spectral lines (from FFT) just above and below 80 MHz shows that they are each split in two. The separation of the spectral lines near 78 kHz is about 7 kHz, and the separation of the spectral lines near 81 MHz is about 6 kHz. The time interval between two successive peaks in figure 5 is t_{beat}≈108 μs, which leads to a beat frequency of f_{beat}=18.5 kHz.

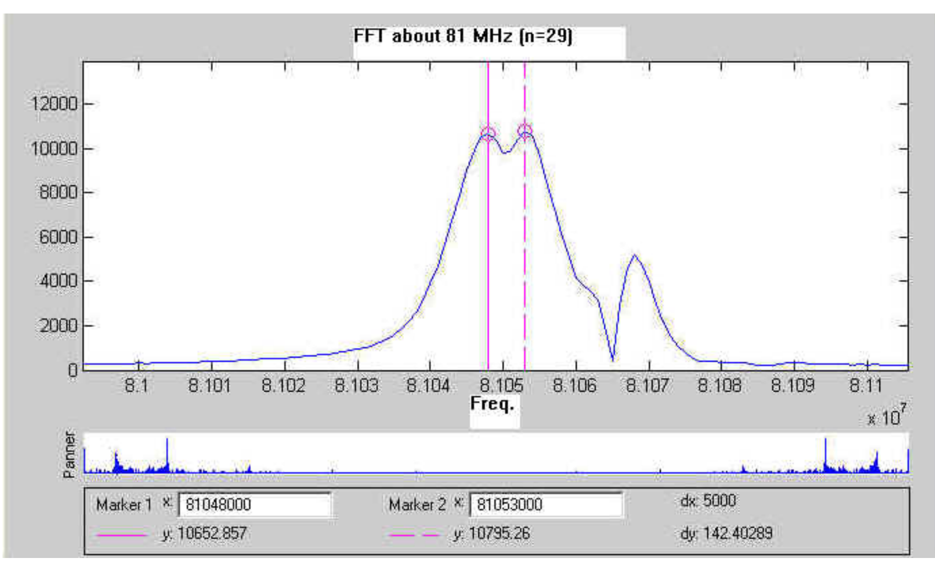

Figure 5. FFT about n=29. Note the separation of the two large peaks is about 5-6 kHz.

4. Longitudinal Instability at 125°C

At 125°C, the cavity resonance was found to be 75.6 MHz, and the Q to be 1.3. This was done using a MAFIA simulation, given a μ'=40.0 and a μ''=34.0. Using these parameters, a MAFIA simulation gives a peak longitudinal impedance of 9,400 Ω at a frequency of ~71 MHz. This is approximately 60% of the longitudinal impedance at room temperature.

Given 0.89 μC in a DC coasting beam with a Bi-Lorentzian spectrum, this leads to a growth time of 43.5 μs. Experimentally, at 160°C, there is no longitudinal instability observed that can be attributed to the Ferrite Inductors.

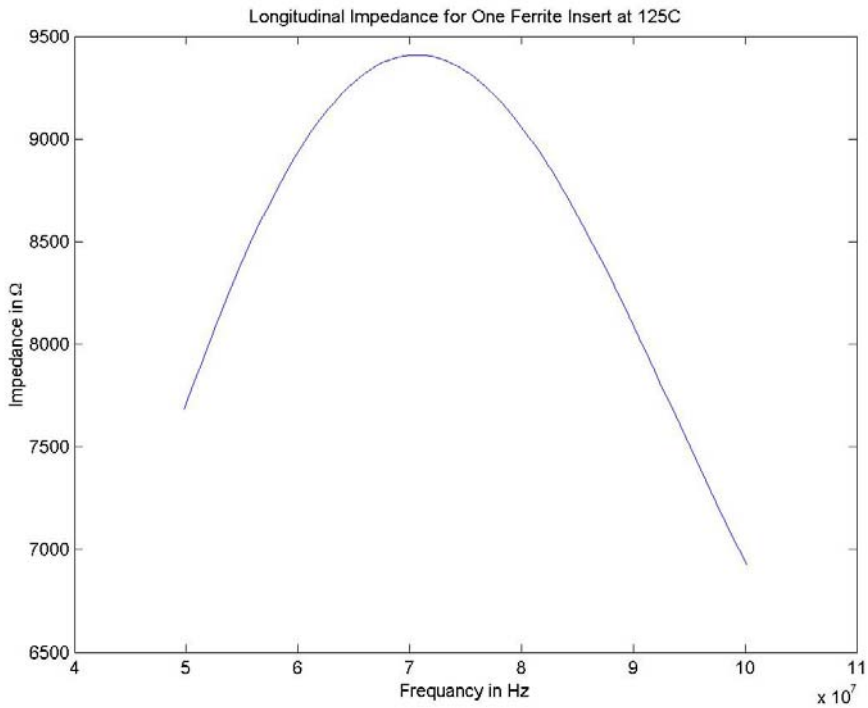

Figure 6. MAFIA Simulation of the Longitudinal Impedance around the Resonance Frequency of the cavity.

More experiments must be done to compare the theory to experiment at 125°C, and to compare experiment to theory at 160°C (the current operational temperature).

5. Conclusion

The MAFIA simulation of the cavity agrees well with experiment, namely the frequency of the instability, its growth time, and to a slightly lesser extent the Q. This leads one to have confidence that the frequency dependence and values of the relative μ' and μ'' shown in Figure 1 are correct. More is needed to be done, namely pin down the momentum spread for a DC coasting beam with the Inductors at room temperature, conduct an experiment at 125°C to compare experimental and theoretical prediction, investigate and identify the source of the beating phenomenon, and investigate the instability on a chopped coasting beam.

6. References

[1] Ng, King-Yuen; "Physics of Collective Beam Instabilities"; FERMILAB-Conf-00/142-T; Chapter 4.5.
[2] Browman, Andy; Private Communication Concerning Ferrite Measurements; LANL.
[3]Macek, Bob; Private Communication Concerning Momentum Distribution; Fit in July 13, 1996 using November 1995 data.
[4] Chao, Alexander; "Physics of Collective Beam Instabilities in High Energy Accelerators"; Chapter 5.4.