

Measurement of the Fermilab Main Ring Longitudinal Impedance

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Abstract

The Fermilab Main Ring provides a variety of services to the accelerator complex. High current pulses containing 1000 proton bunches are accelerated from 9 GeV/c to 150 GeV/c for fixed target operations. Single, intense proton and antiproton bunches are produced in the coalescing operation at 150 GeV/c just before injection into the Tevatron collider. At 120 GeV/c the bunch length of proton bunches are shortened using the bunch rotation process just before targeting for antiproton production. In all of these beam manipulations longitudinal stability is crucial. In order to improve present performance and predict beam behavior in future upgrades, the longitudinal impedance of the Main Ring must be measured. Results of such measurements are presented.

I. INTRODUCTION

The performance of a high intensity accelerator is often affected by impedances. In the Main Ring, the offending impedances seem to be both transverse [1] and longitudinal [2]. For example, during Tevatron Collider operations bunch coalescing [3] inefficiencies are responsible for excessively long bunches, lowering the luminosity. It has been hypothesized that the source of this inefficiency is longitudinal impedance generated by a low-Q, low frequency resonator [4].

In the past a number of methods have been applied to the Main Ring to measure either Z_L/n or R/Q . Their results are reviewed, as well as their strengths and weaknesses. The method of closed loop transfer function measurements on a coasting beam [5,6] has recently been attempted on the Main Ring. Preliminary results are presented.

II. TRADITIONAL METHODS

A. Z_L/n by Sudden Debunching

A beam with a few intense bunches is accelerated to a momentum of 150 GeV/c. The RF voltage, which is running at a high enough magnitude to create short bunches, is then turned off abruptly. Particles with different momenta have revolution periods different from the design value by the amount [7]

$$\frac{\Delta T}{T_0} = \eta \frac{\Delta p}{p} \quad (1)$$

where η is the slip factor (equal to 0.00281 at 150 GeV/c). Therefore, the longitudinal phase space ellipse enclosing the beam distribution begins to tilt. The momentum spread is invariant, but the bunch length increases. In order for the longitudinal area to remain invariant, the instantaneous momentum spread of the distribution shrinks.

If the bunched beam microwave stability criteria [8]

$$Z_L/n \leq (2\pi)^{3/2} \frac{|\eta| \sigma_p^2 \sigma_\tau}{N e E \beta^2} \quad (2)$$

is violated during this period of debunching, microwave instability should occur. The signature of this instability should be excitation of high frequency revolution harmonics in the beam spectrum. The time between the start of debunching and the observation of the microwave signals is used to calculate the value of Z_L/n [9].

This experiment was performed in the Main Ring before and after the insertion of bellow shields. A typical measurement used a HP8568B spectrum analyzer in zero span mode to record the power in the specified resolution bandwidth at a specific center frequency as a function of time [10]. Before and after shielding the bellows the results were 8 Ω and 2 Ω .

The implementation of this scheme suffered from two experimental problems. First, since the beam signals at or above 1 GHz are quite small, the measurement of the time at which microwave instability commences is very uncertain. Second, the beam loading of the RF cavities tends to decelerate the bunches in a quasi-bucket, rather than allowing linear shearing of phase space. This experiment needs to be repeated with better instrumentation and the cavities shorted during the debunching period.

2. Z_L/n by Adiabatic Debunching

Instead of snapping the RF voltage off, in this method the RF voltage is adiabatically reduced to different minimum levels, and then adiabatically increased again [11]. In this Main Ring experiment the RF voltage started at and returned to 150 kV while coasting at 150 GeV/c. Photographic double exposures of a bunch profile as detected by a resistive wall monitor before and after the adiabatic debunching were made. If no instability took place during this operation the bunch length would remain unchanged. Figures 1 and 2 show such

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double exposure photographs for two different minimum voltages. In the case of $V_{\min}=72$ kV (figure 1), no instability was observed. On the other hand, the beam went unstable during the adiabatic debunching process in figure 2.

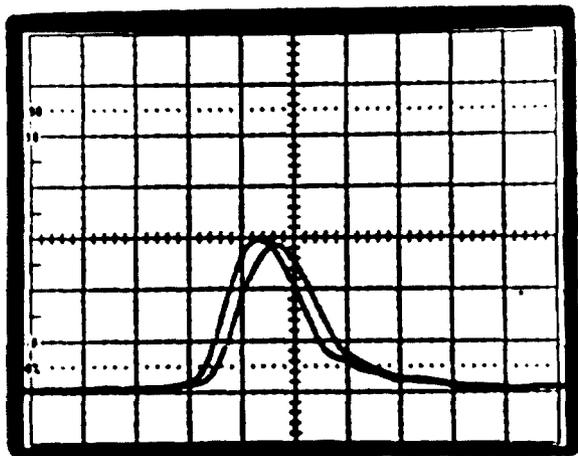


Figure 1: Bunch profile before and after reducing the RF voltage to a minimum value of 72 kV/turn. The scales are 100 mV/div and 1 nsec/div.

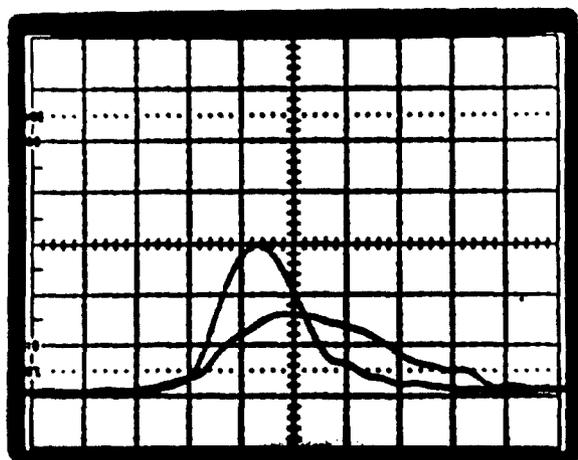


Figure 2: Bunch profile before and after dipping to a minimum RF voltage of 6 kV. Note that after the RF voltage program the bunch length has increased.

To analyze this data, one uses the bunch length at 150 kV to calculate the longitudinal emittance. So now the bunch length and momentum spread are known at all voltages (especially at V_{\min}) in the absence of longitudinal emittance dilution. Applying equation (2), limits can be placed on Z_L/n depending on whether or not instability occurred. Since an unstable beam will stabilize after its momentum spread has overshoot [12] the criterion in equation (2), by calculating the final longitudinal emittance and extrapolating it back to V_{\min} it is possible to place another upper limit on the impedance.

The minimum RF voltages that yielded useful information were 6, 12, and 72 kV. Table 1 contains the above calculations of the longitudinal impedance criterion based on

before and after bunch lengths. The conclusion is that the effective Z_L/n for long bunches in the Main Ring falls between 6 and 16 Ω .

RF Voltage (MV)	Z_L/n Before (Ω)	Z_L/n After (Ω)
6	5	36
12	6	17
72	16	16

Table 1: Longitudinal impedance criterion before and after reducing the RF voltage to the specified minimum value.

C. Observations of Resonators

In general the parameterization of the longitudinal impedance in terms of Z_L/n is inadequate due to the existence of prominent high-Q resonators scattered in frequency. These resonators tend to be single objects, like RF cavities and specialized beam signal pickups. In order to cure an instability or calculate the behavior of the accelerator after future intensity upgrades, it is important to identify and characterize resonators.

A bunched beam method of searching for and identifying resonators was applied in the Main Ring with good success. It involved the observation of the longitudinal coupled bunch oscillation spectrum [13]. After filling the Main Ring with 1×10^{13} protons distributed into 12 equally spaced batches of 84 bunches, the beam was accelerated. A longitudinal coupled bunch oscillation will appear in the longitudinal beam spectrum as pairs of sidebands on either side of harmonics of the RF frequency. The RF frequency in the Main Ring ramps from 52.8 to 53.1 MHz as the beam is accelerated. If the resonator has a fixed frequency, the coupled bunch spectrum will shift during acceleration. By looking for the RF harmonic interval in which the coupled bunch mode frequency is constant, the frequency of the resonator is found. In the case of the Main Ring, two prominent coupled bunch modes generated by resonators at 119 and 130 MHz were observed. Detailed observation of the width of these modes yielded the resonator Q. It turned out that the resonators were higher order modes in the RF cavities [14]. In fact, the cavities were modified to damp the 128 MHz mode because of its adverse effects on the beam during resonant extraction [15].

Because the RF cavities were fitted with gap monitors, it was possible to measure the voltage of these modes. The current at these frequencies was extracted from the spectrum analyzer data. Therefore, the shunt impedance could be calculated. Since the Q was determined from the width of the coupled bunch mode, R/Q was found for each mode:

$$R/Q(119) = 0.5 \text{ k}\Omega \quad R/Q(128) = 5.0 \text{ k}\Omega$$

In general a gap monitor is not available, so the shunt impedance may not be measurable with this method. On the other hand, it is good for identification of offending resonators.

III. SYSTEMATIC IMPEDANCE MEASUREMENT

A more general method of measuring the longitudinal impedance as a function of frequency is based on the external excitation of a coasting beam. Unlike the case in the Tevatron [16] where the beam can be stored for many hours, the maximum storage time in the Main Ring is about 60 seconds. Therefore, techniques which do not require a fixed momentum distribution or long measurement times are required.

Figure 3 is an example of a closed loop longitudinal transfer function measurement in the Main Ring. The apparatus is identical to that used in the Tevatron. After injection and acceleration to the desired energy, the RF must be adiabatically reduced to zero before the voltage is turned off and the cavities shorted. If the beam is not debunched when the RF voltage is turned off, the beam loading voltage decelerates the beam into the aperture, where it is lost. Once the RF is off, the beam must be allowed to distribute itself uniformly around the aperture. This time depends on the momentum spread and the value of η at that momentum.

In the future the longitudinal impedance of the Main Ring will be systematically measured. To prepare, the debunching technique will be modified in order to minimize the extensive momentum distribution structure apparent in figure 3. Alternatively, a new algorithm for determining the impedance from transfer function measurements will be tested [17].

Finally, interest has been expressed in trying to repeat the measurements performed in the Tevatron diagnosing the origins of the ghost lines [16]. Besides having much more available time for studies, the Main Ring has the advantage of being able to store beam both above and below transition. For example, it has been hypothesized that below transition the ghost lines should propagate upward in harmonic number, instead of downward as is the case in the Tevatron.

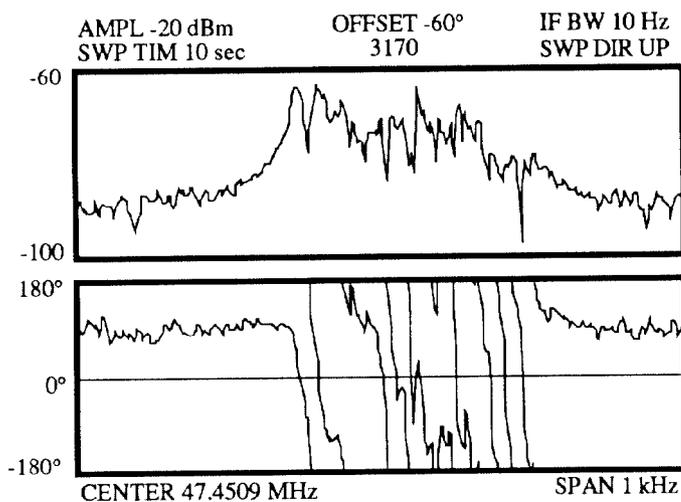


Figure 3: Example of a preliminary closed loop longitudinal transfer function in the Main Ring at 9 GeV/c. The beam intensity was 0.15×10^{12} .

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