

# TRANSIENT BEAM LOADING COMPENSATION IN THE FERMILAB MAIN RING

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## Abstract

A requirement for bunch coalescing and bunch rotation for antiproton production in the Fermilab Main Ring is that the net rf voltages be reduced below  $\sim 1$  kV. At high beam intensities, the fields generated by the beam in a single pass through the rf cavities will exceed this limit. The new compensation system monitors the component of the beam current at the fundamental rf frequency as a function of time. This information is then delayed by a single turn and fed back into the high level rf system to cancel the beam-induced fields. The system has compensated the beam-induced voltage generated by a single booster batch to 5% of its initial value.

## Introduction

The Fermilab Main Ring will serve three roles in the Tevatron p- $\bar{p}$  collider. It must provide a source of p's for  $\bar{p}$  production, accelerate and coalesce a small number of p and  $\bar{p}$  bunches into single high intensity bunches, and act as an injector into the superconducting Tevatron ring. All of the operations have in common the fact that only a small fraction of the ring is filled with charge. In the case of  $\bar{p}$  production a single booster batch of 80 proton bunches is circulating in the ring and for bunch coalescing only nine bunches.<sup>1</sup> This partial filling of the ring combined with the high shunt impedance of the 18 Main Ring rf cavities produces large transient beam-induced voltages in the cavities. In the case of 80 bunches the shapes of the last few bunches in the batch are severely deformed. At high bunch intensities, the beam loading for nine bunches may become large enough to actually stop the coalescing process.<sup>2</sup> In response to these two cases, two similar beam loading compensation techniques have evolved, one for an entire booster batch and a second for the nine bunch coalescing. Both rely on measuring the 53 MHz component of the beam current on each turn and on the following turn applying a correction signal to the low level rf drive.

## Beam Loading Calculations

Under the assumption that a bunch of charge  $q$  is short compared to an rf cycle of frequency  $\omega$ , the magnitude of the cavity voltage change due to the passage of the bunch through the cavity is given by<sup>3</sup>

$$\Delta V_b = \frac{R}{Q} \omega q \quad (1)$$

Here  $Q$  is the unloaded cavity  $Q$  and  $R$  is the cavity shunt impedance which relates the peak cavity voltage  $V$  to the power  $P$  dissipated in the cavity through  $P = V^2/2R$ . If the voltage changes  $\Delta V_b$  are small so that the cavity does not detune significantly, the total cavity voltage induced after the passage of  $N$  bunches spaced by a time interval  $\tau$  is just the sum of the voltages induced by the individual bunches.

$$V_N = \sum_{n=0}^{N-1} \Delta V_{bn} e^{-\frac{\omega n \tau}{2Q}} \quad (2)$$

Each of the terms in Eq. (2) correspond to the exponential decay of the cavity voltage,  $\Delta V_{bn}$ ,

induced by the passage of the  $n$ th bunch which traversed the cavity a time  $n\tau$  before.

Using the above results, it is now possible to calculate the expected beam loading in a single cavity for a bunch of  $10^{10}$  protons. The Main Ring cavities have an  $R/Q=104$ ,  $Q \sim 5000$ , and operate at  $\omega=2\pi \times 53$  MHz.<sup>4</sup> Substituting these values into Eq. (1) yields  $V_b=55.4$  V. From Eq. (2), the total voltage induced by nine identical bunches or an entire booster batch of 80 identical bunches spaced by  $\tau=2\pi/\omega$  is very nearly equal to  $N$  times the single bunch value,  $V_9=497$  V and  $V_{80}=4.32$  kV. Since there are 18 Main Ring rf cavities, the above values need to be multiplied by 18 to obtain the total beam loading voltage for the entire ring.

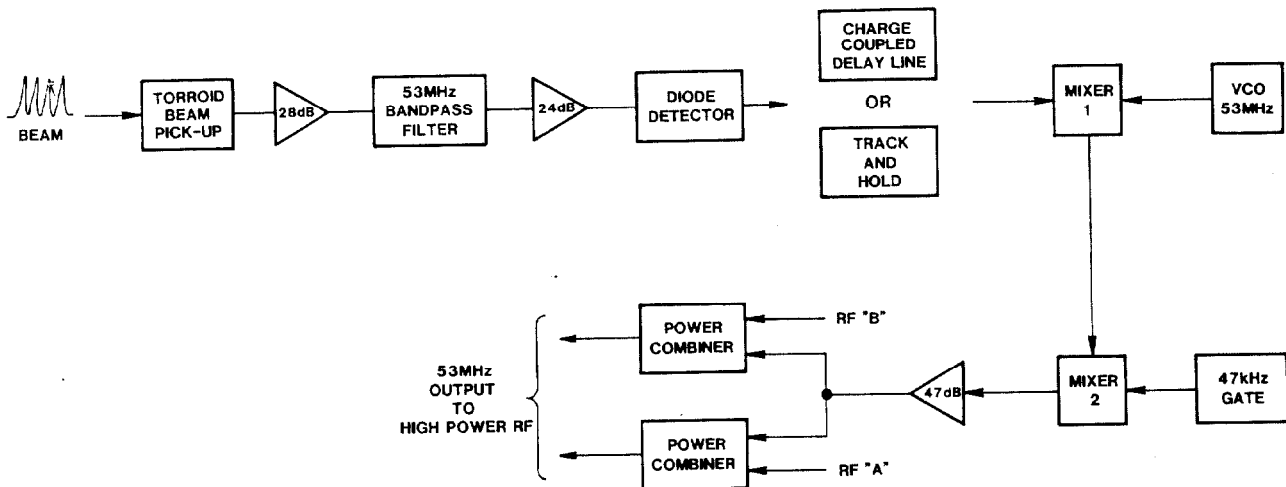
## Design Consideration for Beam Loading Compensation

The first step in the design of the beam loading compensation is to specify the conditions under which the system must operate. First, it must function over the entire energy range of the Main Ring from 8 GeV to 150 GeV which corresponds to an rf frequency change from 52.813 to 53.104 MHz. Secondly, it must be able to function for both the nine bunch coalescing process and the 80 bunch  $\bar{p}$  production cycle. Thirdly, it must have a dynamic range of approximately an order of magnitude from the highest machine intensity to a level where the beam loading is no longer significant. Finally, it should be compatible with the existing Main Ring high level rf system.

The ideal compensation system would measure the exact bunch shape of the beam current as the bunch entered an rf cavity and apply a current pulse to the cavity with the same identical shape but  $180^\circ$  out of phase with the beam current. This would provide a bunch-by-bunch compensation of not only the fundamental component of the beam current but also all higher harmonics. Such a system would be difficult to incorporate into the Main Ring rf cavities due to the flight time delay through the power amplifiers and their limited bandwidth. Fortunately this is not necessary since the higher harmonics of the beam are sufficiently damped in the accelerating cavities and only the effect of the fundamental component of the beam current on succeeding bunches needs to be considered.

The Main Ring rf distribution system in its present form precludes an exact bunch-by-bunch beam loading compensation over the entire acceleration cycle. Unlike the Tevatron rf in which a single proton bunch is accelerated in each cavity by the same rf cycle from the low level oscillator, the Main Ring distribution system tries to equalize the time delay to each cavity. This is necessary because of the large frequency range ( $\sim 300$  kHz) that the system must sweep. A signal originating at the low level oscillator will arrive at each cavity with the correct rf phase with respect to the beam but not synchronous with the passage of a single bunch through the cavities. The beam loading compensation signal has been summed into the low level rf drive in two groups of nine cavities, group A and group B, with a phase delay of four wavelengths at

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TRANSIENT BEAM LOADING COMPENSATION BLOCK DIAGRAM

Figure 1

150 GeV between the two groups. Using this procedure a single bunch can transverse the entire 18 cavities being accelerated by the same four rf cycles. The phase and amplitude errors introduced into the beam loading compensation signal at injection due to the  $4\lambda$  delay are  $4^\circ$  and 0.5% respectively. This inherent error was considered to be acceptable especially since the most demanding case, bunch coalescing, takes place at 150 GeV where the phase error due to the  $4\lambda$  delay is zero.

Although the compensation phase and amplitude errors are zero at 150 GeV, the compensation intended for a single bunch is still distributed between the intended bunch and its three neighboring bunches. Calculations using the cavity positions and the time delays show that the early bunches will be slightly over-compensated and the final bunch will be under-compensated. After realizing this constraint, the compensation method described below was adopted since it is compatible with the existing Main Ring rf system and capable of providing the degree of compensation required.

#### The Beam Loading Compensation Circuit

A block diagram of the compensation circuit is shown in Fig. 1. The beam current is monitored with a 2 GHz bandwidth torroid placed just upstream of the rf accelerating cavities. The amplified signal from this pick-up is then filtered by a low Q passband filter centered at the rf cavities' resonant frequency of 53 MHz. The 53 MHz output is amplified again and detected by an HP-8471A point contact detector operated in its linear response region. The diode detector output, representing the time varying amplitude of the 53 MHz component of the beam current, is then delayed by approximately one machine revolution period ( $\sim 21\mu\text{s}$ ). For the 80 bunch case this is accomplished with a 5 MHz bandwidth charge coupled analog delay line (Reticon SAD-100). The analog delay line is followed by two HP-10514A double-balanced mixers in series. Mixer #1 is used as a variable attenuator to adjust the amplitude of the 53 MHz signal from the VCO. Care was taken to operate the mixer in a region where the response was linear and the phase shift with amplitude was less than  $\pm 2^\circ$  over a 20 dB range. Mixer #2 is used as a gate to apply the compensated rf burst at the proper time and

essentially eliminates any feedthrough from the VCO through mixer #1. Mixer #2 also has the option of being used as another variable attenuator to adjust the compensation amplitude for different anode program levels (high power rf amplitudes). The 47 kHz timing gate to mixer #2 is obtained from a gate triggered by the Main Ring beam synch countdown which divides the 53 MHz rf frequency by the harmonic number  $h=1113$  to obtain the revolution frequency. This insures that the timing pulse is correct for all beam energies. The compensating rf bursts are then amplified, divided into two equal signals, and combined with the two low level distribution signals A and B. Correct phasing is achieved by making the compensation and A signals differ by  $90^\circ$  when the Main Ring synchronous phase angle  $\phi_s = 0^\circ$ .

For operation with nine bunches, in place of the analog delay line, a simple integrating circuit followed by an Analog Devices HTC-300 high speed track and hold circuit is used. The flight time delays in the system are such that the integrated output of the diode detector can be tracked during the passage of the beam and held at its maximum value for 20  $\mu\text{s}$ . This signal is then used to set the VCO amplitude from mixer #1. Before the beam reappears at the beam pick-up (500 ns), mixer #2 is gated on and the compensation signal is sent to the low level distribution system. The HTC-300 is then returned to the track mode to sample the next turn of beam.

The method of measuring the amount of beam loading and the degree of compensation uses a fast phase detector ( $\sin\theta$  output response) which compares the phase difference between the low level drive signal to the cavities and the rf sum from the cavity gap voltage monitors. The low level drive signal is obtained from either the phase-shifted VCO output or the flattop oscillator delayed by 973 ns of cable. This delay equals the round trip delay time to the cavities and back on the gap monitor cables. It insures that in the absence of beam loading, the two inputs to the phase detector maintain a constant phase difference as the frequency of the Main Ring sweeps from 52.813 to 53.104 MHz. The fast phase detector output is displayed on an oscilloscope whose sweep is triggered at the 47 kHz machine revolution frequency. Early attempts at mea-

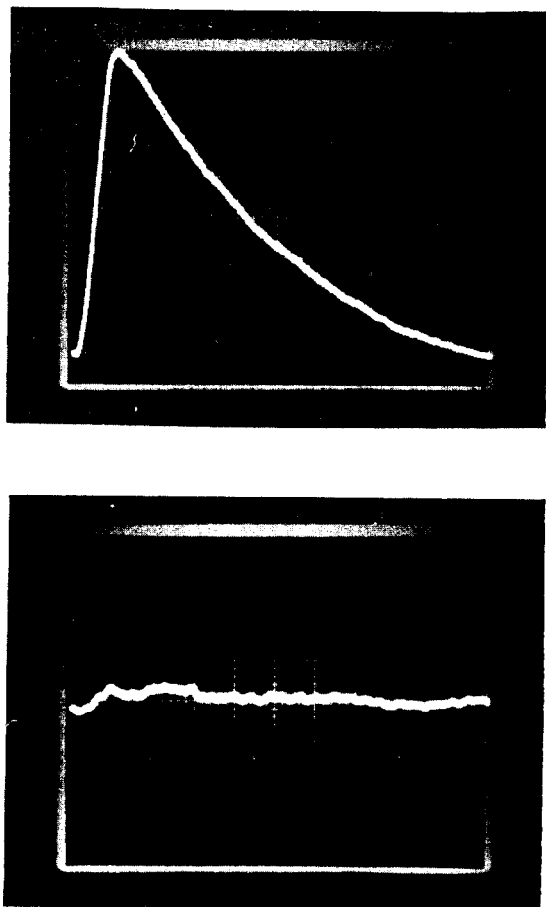


Figure 2. Beam-induced phase shift with beam loading compensation disabled (top trace) and active (bottom trace). Vertical scale  $0.8^\circ/\text{div}$ . Horizontal scale  $2 \mu\text{s}/\text{div}$ .

During the beam-induced phase shifts were hindered by a 600 kHz oscillation of a few tenths of a degree appearing at the phase detector output. This problem was later traced to the sidebands produced by the VCO whose intensity was 60 dB down from the center frequency. To observe a cleaner signal for initially setting the compensation level and time, the 8 GeV injection reference oscillator which has a much cleaner spectrum was used in place of the low level drive input to the fast phase detector. The example shown in Fig. 2 was taken using the reference oscillator.

#### Experimental Results

Two oscilloscope traces of the fast phase detector output are shown in Fig. 2 for a single booster batch of 80 bunches with a total intensity of  $8.5 \times 10^{11}$  protons. The top trace was taken with the beam loading compensation disconnected, while in the bottom trace the compensation was active. Both traces were taken at the 8 GeV injection energy on two different booster batches of approximately the same intensity. In the upper trace, the almost linear phase shift during the  $1.5 \mu\text{s}$  passage of the batch through the cavities is observed followed by the long exponential decay of the induced cavity fields due to the high cavity Q. During injection the Main Ring rf was producing a net voltage of 900 kV with a synchronous phase angle of  $0^\circ$ . The observed phase shift of  $5.6^\circ$  at the end of the passage of the 80 bunches corresponds to a total beam-induced voltage of 88 kV. This result is in good agreement

with the value of 83 kV calculated using Eqs. (1) and (2). The lower trace shows that the beam loading effect has been reduced to less than 5% of its previous value or less than 4.5 kV.

The compensation circuit utilizing the charge coupled analog delay has also performed surprisingly well with a small number of beam bunches. With only 10 bunches circulating in the Main Ring, the compensation has reached the 10% level. More accurate compensation with fewer than 10 bunches will require the track and hold version which is currently being tested.

#### Paraphasing and Beam Loading Compensation

For achieving very low voltages ( $\sim 1$  kV) in the Main Ring, the two A and B groups of cavities must be operated  $180^\circ$  out of phase from each other. This is done by simultaneously lowering the rf amplitude and rotating the low level rf drive signal to groups A and B  $90^\circ$  in opposite directions. The rate at which this rotation is made determines the net rf voltage as a function of time. Once this paraphasing is completed, the net voltage of the B group of cavities is in phase with the beam induced voltage. Unlike the normal operation of the compensation circuit which produces both phase and amplitude changes in the high level rf, this situation requires that the compensation be accomplished by an amplitude change alone. Data obtained during the paraphasing time shows that the beam induced voltages can be compensated to 25% of their initial value. It is proposed that once the A and B groups are  $180^\circ$  out of phase, both the A and B groups should be rotated  $90^\circ$  in the same direction. The net voltage would still be near zero but both A and B would be  $90^\circ$  from the direction of the beam induced voltage. The beam loading compensation circuit would then operate as it does during injection and reproduce the 5% level of compensation illustrated in Fig. 2.

#### Acknowledgements

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#### References

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