# A BUNCH LENGTH MONITOR BY DETECTING TWO FREQUENCY COMPONENTS OF THE BEAM[1]

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## Abstract

The bunch length is measured by detecting two revolution frequency harmonics of the beam and taking the ratio of their amplitudes. The measurement was tried at the Fermilab Main Ring. Two heterodyne receivers have been made to detect them, one at 53 MHz and the other at 159 MHz. These signals are picked-up by a stripline detector. An analog circuit provides a signal proportional to the bunch length. The monitor measures variation of the bunch length as a function of time. The measured signal, which sometimes shows that the bunches are tumbling in phase space, can be damped by feedback to the RF amplitude modulator.


## Introduction

The new bunch spreader project[3],[4] for the Main Ring is in progress. The project increases the longitudinal emittance, and hence the bunch length, in order to raise the threshold beam current of instabilities in fixed target mode. A bunch length monitor is needed to measure the effect of the bunch spreader. Variations of the bunch length must be easily and clearly read from the monitor in real time.

The bunch length measurement from a mountain range photograph is unsuitable, because the measurement is not clear or real time. The bunch length is also measured from a stored bunch shape using a computer[5]. This measurement is adequate for a single bunch, but not for multi-bunch operation in the Main Ring. Therefore, a new type of the bunch length monitor should be designed.

## Principle[6]

Let us model the N bunches (N >> 1) as Gaussian longitudinal charge distributions of rms width $\sigma_t$, separated by a fixed time ($T_0 = 1/f_0$). The Fourier transform of the response on an ideal beam pickup is

$$V(m\omega_0) = 2V_0 \,\mathrm{EXP}\left[-\frac{2\pi^2 m^2 \sigma_t^2}{T_0^2}\right] , \qquad (1)$$

where $V(m\omega_0)$ is the voltage per unit bandwidth at the mth harmonic of the RF angular frequency $\omega_0 = 2\pi f_0$ and $V_0$ is the DC response of the beam. Solving for $\sigma_t/T_0$ in the case of DC vs. m = 1 yields

$$\frac{\sigma_t}{T_0} = \sqrt{\frac{1}{2\pi^2} \,\mathrm{LN}\left[\frac{2V_0}{V(\omega_0)}\right]} \qquad (2)$$

When detecting the frequencies of m = 1 vs. m = $\lambda$, the normalized bunch length ($\sigma_t/T_0$) is given as

$$\frac{\sigma_t}{T_0} = \sqrt{\frac{-1}{2\pi^2(\lambda^2 - 1)} \,\mathrm{LN}\left[\frac{V(\lambda\omega_0)}{V(\omega_0)}\right]} \qquad (3)$$

In an actual measurement, the 95 % interval of the beam distribution, referred to as the full bunch length $4\sigma_t$, is the quantity of interest. Since $T_0$ is almost constant in the Main Ring,the rms bunch length can be replaced by the full bunch length. Therefore, we use the full bunch length instead of the rms bunch length in all measurements.

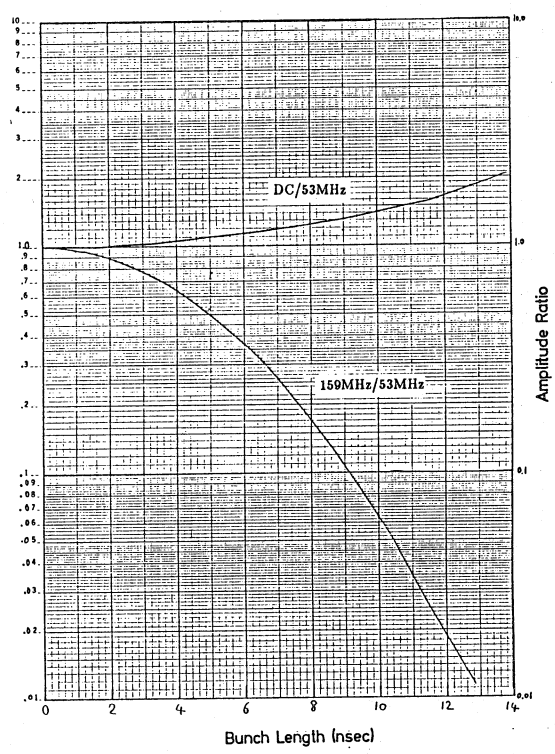


Figure 1 Amplitude ratio of the frequency components as a function of bunch length for DC/53 MHz and 159 MHz/53 MHz cases.

## Design

Selection of Detected Frequencies

In the frequency response of actual pickups, the sensitivity at each frequency is different. So, the range of detected frequencies is limited and the gain factor between two detectors must be compensated. Two detection schemes are considered using pickups already installed. One is DC/53 MHz detection. The DC component is available from a DCCT[7]. The 53 MHz signal comes from a BPF RF module[8]. The other is 159 MHz/53 MHz detection. The stripline electrode installed at E48 has resonant frequencies of 53 MHz, 159 MHz, 265 MHz and so on.

Fig. 1 shows the amplitude ratio of the two frequency components as a function of the bunch length. The interesting bunch length in the Main Ring is in the range of 1 to 10 nsec. When the bunch length is short enough, the amplitude ratio is almost one in both cases. The DC/53 MHz case requires more severe linearity and stability for detections than the 159 MHz/53 MHz case. At the bunch length of 10 nsec, the ratio becomes 0.063 in the 159 MHz/53 MHz case, which requires a dynamic range of at least 24 dB to detect both amplitudes. If we select the DC/53 MHz case, however, we will have trouble with different transient responses because of the different types of detectors. Therefore, the 159 MHz/53 MHz case is selected for the bunch length monitor in the Main Ring.

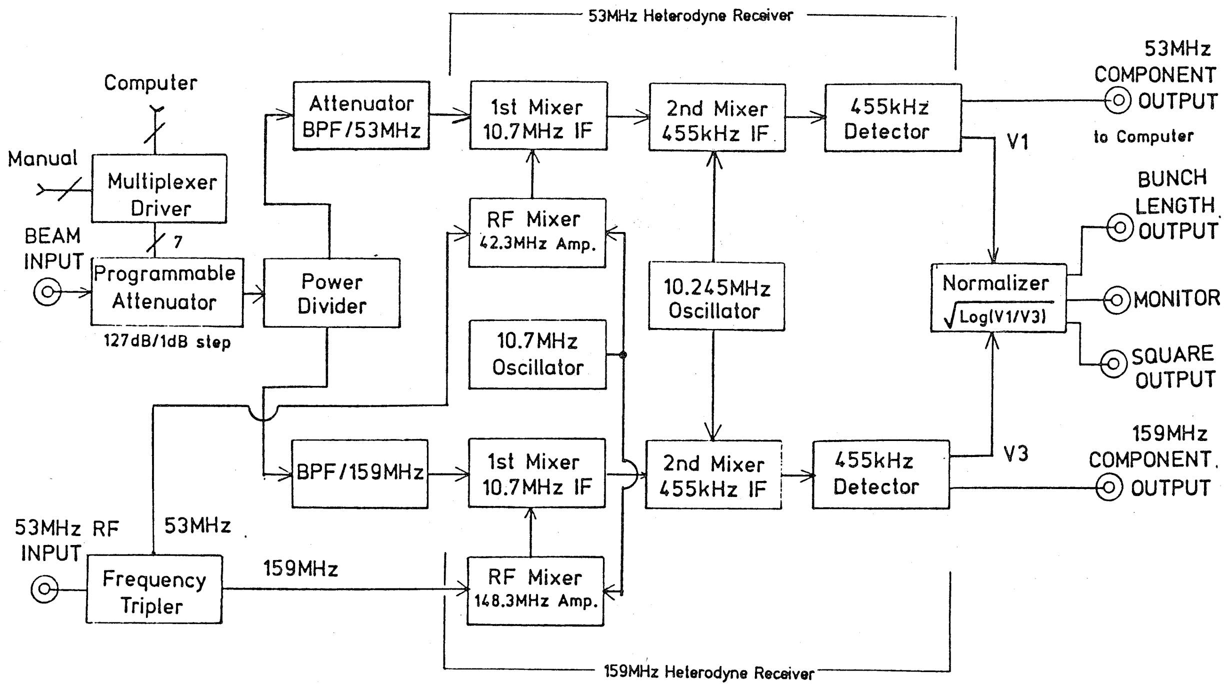


Figure 2 Block diagram of the bunch length monitor.

Sepcifications

The Main Ring handles various numbers of bunches. The proton bunches are almost fully occupied in 1113 RF-buckets in the fixed-target mode. When the bunches are coalesced and transfered to the Tevatron, only 11 proton and antiproton bunches are accelerated. Beam intensity per bunch is different between protons and antiprotons. The dynamic range of the beam intensity is about 60 dB.

In order to measure the bunch length in the Main Ring, the following specifications for two detectors with the same performance would be required.

| | | |
|---|---|---|
| 1. minimum detectable level | -80 | dBm |
| 2. dynamic range | 90 | dB |
| 3. accuracy | 1 | % |
| 4. frequency response | 10 | kHz |

The minimum signal is observed in the 159 MHz component during antiproton coalescing. The dynamic range of 90 dB is caused by the beam intensity variation plus the amplitude ratio between two components. The accuracy of at least 1 % is needed to detect a short bunch length of 1 nsec. The 10 kHz response comes from detecting harmonics of the synchrotron frequency and measuring transient beam response at such time like bunch rotation.

## Performance

Heterodyne Receivers

Two heterodyne receivers are employed to detect the 53 and 159 MHz components of the beam. The main advantages of a receiver are high sensitivity and wide dynamic range, and its disadvantage is the need for a complicated circuit. Fig. 2 shows the block diagram of the bunch length monitor composed of two heterodyne receivers and an analog circuit named a normalizer. The heterodyne receivers have two stages of frequency mixing to get high sensitivity. The intermediate frequencies (IFs) of 10.7 MHz and 455 kHz are used since cheap and small ceramic filters are commercially available[9].

The beam signal coming from the stripline pickup in the tunnel to the F0 RF building is split after passing through a programmable attenuator, one half passes through the 53 MHz Band Pass Filter (BPF) and the other half through the 159 MHz filter. The bandwidth of the BPFs are matched at 1 MHz to get comparable transient responses.

The performance of the receivers is summed up in Table 1.

Table 1 Performance of Heterodyne Receivers

| | | |
|---|---|---|
| 1. RF Mixer | | |
| RF Input Level | -5 dBm | @ 53 MHz |
| | -10 dBm | @ 159 MHz |
| 2. 10.7 MHz I.F. Amplifier | | |
| Gain | | 21.5 dB |
| Bandwidth | 280 kHz | @ -3 dB |
| Maximum Linear Output | | 0 dBm |
| Output Noise Level | | -60 dBm |
| 3. 455 kHz I.F. Amplifier | | |
| Gain | | 23 dB |
| Bandwidth | 22 kHz | @ -3 dB |
| Maximum Linear Output | | + 23 dBm |
| Output Noise Level | | - 43 dBm |
| 4. 455 kHz Detector | | |
| Linear Range | | 40 dB |
| Response Time | 40 μsec | @ 98% value |
| Maximum Input Level | | + 13 dBm |

Normalizer

The normalizer section is composed of two logarithmic amplifiers (B.B., 4127s), a differential amplifier and a square rooter (AD534). The log amplifiers accept a signal of 60 dB range (10 mV - 10 V) and provide an output signal with frequency response of more than 5 kHz. The calculated transfer function of this section is

$$Y = 8.17\sqrt{\mathrm{LOG}\left[\frac{V_1}{V_3}\right]} \quad , \qquad (4)$$

where Y is the output voltage of the normalizer in volts, $V_1$ is the amplitude of 53 MHz component and $V_3$ is that of 159 MHz one. The measured output voltage agrees with the calculated value within 5 %, but maximum Y is 10 V. From Eq. (3) with $\lambda = 3$ and Eq. (4), the relation between the bunch length and Y is given as

$$4\sigma_t\,(\mathrm{nsec}) = 1.12\,Y \quad . \qquad (5)$$

The output is also available for square of the bunch length, which is proportional to the longitudinal emittance[10] assuming that the frequency dispersion function and the RF voltage are constant.

## Beam Observation

Fig. 3 shows a typical measured bunch length during acceleration of 81 bunches, which agrees with the expected full bunch length[4]. The noise in the measured bunch length is dominated by real bunch length fluctuations.

The frequencies of the bunch length fluctuations can be measured with a spectrum analyzer (hp 3562A). Two main components are observed clearly. The measured frequency of the highest amplitude agrees with twice the small amplitude synchrotron frequency ($2f_s$). This phenomenon shows that the bunches rotate in phase space and modulate the bunch length with the frequency of $2f_s$. The second peak corresponds to $f_s$, which is 10 dB below the 1st peak, and may be due to asymmetric $2f_s$ oscillations.

The detected $2f_s$ oscillations can be suppressed by feedback to the RF amplitude program, because the bunch length oscillation is mainly caused by mismatch between an RF bucket and the bunch. The output signal of the monitor passes through a High Pass Filter to eliminate DC component and its phase shifted by 90 deg. to make a damping force. After the signal is amplitude modulated and gated by analogue multipliers (AD534), the resultant signal is summed with RF amplitude control voltage and sent to the RF amplifiers. The feedback test was done at flattop of a three-batch operation cycle, where $2f_s$ is constant at 160 Hz. Fig. 4 demonstrates the effect of this damping. The damping time was 30 msec or five oscillations. When the feedback gain is raised to get faster damping, an anti-damping occurred. Further study is needed when this feedback is used in daily operation.

## Conclusion

A prototype of the bunch length monitor has been made and successfully tested. Our concluding remarks are as follows.

(1) The monitor measures not only the average bunch length over many bunches, but also the quadrupole oscillations with a response of 10 kHz.
(2) The detected quadrupole oscillations can be used for damping by feedback to the RF amplitude.
(3) This monitor is indispensable for the bunch spreader.
(4) This is a useful tool for monitoring a longitudinal behavior of bunches in daily operations.

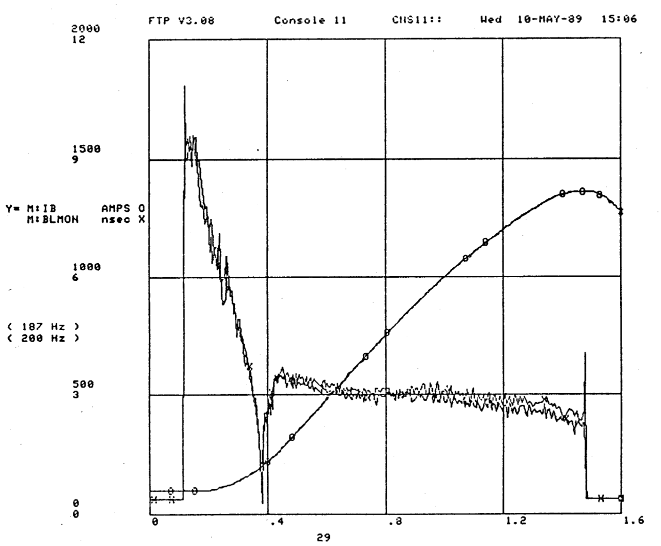


Figure 3 Measured bunch length as a function of time with the current of the dipole bus, H: 0.4 sec/div, V: 3 nsec/div.


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## References


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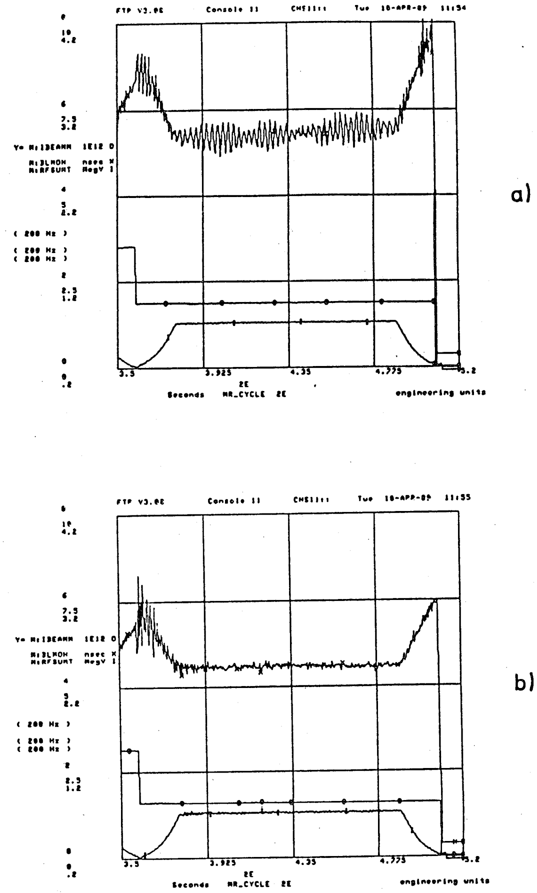


Figure 4 Damping the $2f_s$ oscillations at flattop of three-batch mode, with beam current and the RF voltage.
H: 425 msec/div, bunch length: 2.5 nsec/div.
a) without feedback.
b) with feedback on between 3.8 – 4.8 sec.