

# LONGITUDINAL EMITTANCE MEASUREMENTS IN THE FERMILAB BOOSTER

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## Abstract

I have installed a system to measure the longitudinal emittance over the entire acceleration cycle in the Fermilab Booster Accelerator. Measured inputs to the system are the total beam current, the RF voltage per turn seen by the beam, and a diode-detected resistive wall signal. These signals are digitized by an oscilloscope and transferred to the Fermilab control system computers. The bucket area is calculated using the measured RF voltage per turn and the design synchronous phase and ramp rate. The bunch length is taken as the ratio of the total charge to the peak-detected current and, together with the bucket area, can be used to calculate the longitudinal emittance. This system can measure the emittance or bunch length over the entire booster cycle at a 1 KHz sampling rate or over shorter periods (for example, around extraction) at up to a 10 MHz rate. We discuss operational uses of this system.

## INTRODUCTION

Longitudinal beam dynamics play an important role in the Booster Synchrotron at Fermi National Accelerator Laboratory (FNAL). We desire the smallest longitudinal emittance ( $\epsilon_l$ ) possible. However, many processes occur naturally in the Booster acceleration cycle which can increase the  $\epsilon_l$ . The 400 MeV beam injected into the Booster from the Linac is debunched and must be captured in RF buckets. The Booster is a 15 Hz. resonant accelerator, so capture occurs while the RF and magnetic fields are ramping, making adiabatic capture difficult and possibly leading to phase space dilution. Transition occurs at 5.4 GeV, in the middle of the Booster ramp, and passage through transition can excite synchrotron oscillation. Finally, at high energies and intensities longitudinal coupled bunch motion is excited. If the coupled bunch motion leads to instabilities that filament within the Booster cycle,  $\epsilon_l$  will increase. Even if they do not filament and lead to a measurable emittance growth in the Booster, they can still lead to decreased efficiency in the Main Ring as the individual bunches are injected with different phase errors. In order to evaluate the effects of these processes, it is necessary to measure and understand the longitudinal emittance throughout the entire acceleration cycle.

The moving bucket area in a synchrotron is given by

$$\epsilon_l = 16 \left( \frac{R}{hc} \right) \sqrt{\frac{EV}{2\pi h\eta}} \alpha(\Gamma)$$

\*Operated by the Universities Research Association under contract with the U. S. Department of Energy

where  $R$  is the radius of the synchrotron,  $h$  the harmonic number,  $c$  the speed of light in vacuum,  $E$  the particle energy,  $V$  the RF voltage/turn,  $\eta$  the frequency slip factor, and  $\alpha$  is the function of the synchronous phase angle  $\Gamma$  that relates the stationary bucket area to the moving bucket area. The bunch area ( $\epsilon_l$ ) is the phase space area actually occupied by the beam and can be calculated from the bucket area if the bunch length is known [1].

In the rest of this paper I will describe a system which measures the Booster longitudinal emittance over the entire cycle.

## SYSTEM DESCRIPTION

The system I have designed requires knowledge of the bunch length and RF voltage throughout the cycle. The bunch length is calculated as

$$\tau = \frac{\text{total circulating charge}}{\text{peak current}},$$

so three quantities must be measured: the total circulating charge, the peak current, and the RF voltage. The peak current is derived from a diode-detected 5 GHz bandwidth resistive wall signal, the total charge from a DCCT, and the RF voltage is the phase-summed detected voltage from all gaps. These three quantities are digitized using an HP 54501A Digitizing Oscilloscope which is interfaced to the FNAL Accelerator Control System (ACNET) [2]. The system is shown in Fig. 1.

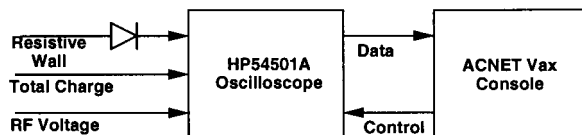


Figure 1. Schematic diagram of measurement system.

The HP 54501A scope is a 4-channel oscilloscope with 2 8-bit ADCs capable of digitizing at up to 10 MHz. On any given trigger, 2 of the inputs are digitized, and the other 2 are digitized on the next trigger. In principle it is important to measure all quantities simultaneously, but the RF voltage never changes with intensity as long as the anode voltage program is unchanged. The total charge and the peak current are measured on one cycle and the RF voltage on the next.

After digitization the data are read by an application running on an ACNET Vax where all further calculations are done.  $\tau$  as calculated above is in arbitrary units, and is converted to ns. by applying a calibration factor determined once by measuring the bunch profiles directly with a 500 MHz digitizing scope and

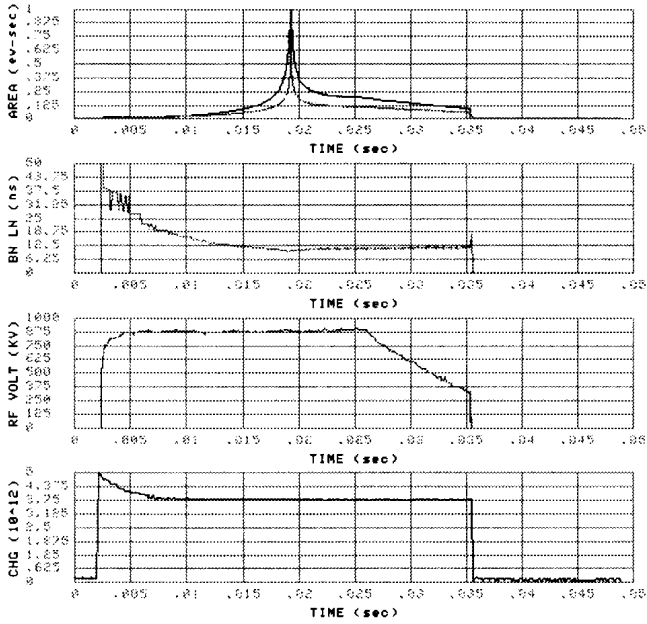


Figure 2. Data used in the  $\epsilon_l$  calculation.

comparing with  $\tau$  measured simultaneously. Calculation of the bucket area requires knowledge of the Booster energy gain/turn and the synchronous phase. These are determined assuming that the Booster excitation is a 15 Hz sine wave. An example of the calculation for a complete cycle is shown in Fig. 2. The plots are, from bottom up, the total charge, the RF voltage per turn, the bunch length, and the bucket and bunch areas (the bucket area is always larger). Note that the simple formula used to calculate the bucket area is singular at transition. More accurate approximations to the bucket area near transition exist [3] but have not been used in this work. The application allows zoom views and FFT calculations on any portion of the data.

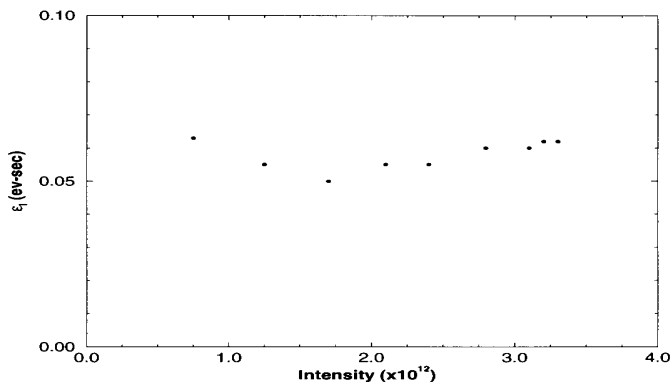


Figure 3. Intensity vs. Long. Emittance.

$\epsilon_l$  determined in this way is subject to few systematic errors. Errors due to the 8-bit resolution of the ADCs are negligible, and the RF waveform does not change from pulse to pulse with intensity. The Booster ramp is well approximated by a 15 Hz sine wave, and the only real source of error is the calibration of the diode-detected bunch length with the bunch length measured on a digitizing oscilloscope. The bunch profiles are non-gaussian,

and I have taken the bunch length to be the time during which the profile is above the baseline value. This leads to an error of about 1 ns, or 10%, in the bunch length. The function relating (bunch length/bucket length) to (bunch area/bucket area) has nearly unity slope over the region in which the Booster operates, so the 10% error in the bunch length calibration leads to a similar error in  $\epsilon_l$ .

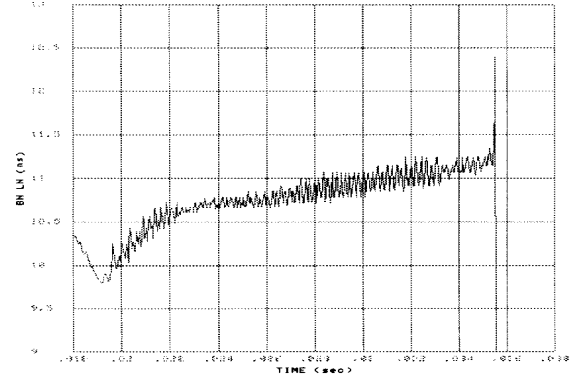


Figure 4. Bunch length oscillations at transition. Note the suppressed 0.

## MEASUREMENTS

In this section I will show examples of some of the phenomena which can be studied with this system. The phenomena of interest vary with time in the cycle. In studying extracted beam one examines  $\epsilon_l$  whereas oscillations at transition and the bunch rotation at the end of the cycle are best studied through the bunch length.

### Extracted Emittance

Figure 3 is a plot of the longitudinal emittance at extraction as a function of the extracted intensity. There seems to be a small decrease in  $\epsilon_l$  for intermediate intensities. This decrease in  $\epsilon_l$  is also observed in measurements made in a dispersive section of the extraction line [4], a measurement with completely different systematic and statistical errors. It is possible that at low intensities noise in the RF feedback loops leads to emittance growth, producing the anomalously large emittances.

Prior to 1994,  $\epsilon_l$  had increased rapidly with intensity, limiting the intensity to about  $2.5 \times 10^{12}$ . This growth was attributed to longitudinal coupled bunch instabilities which decohered during the Booster cycle. In early 1994 several narrow band dampers [5] operating on the unstable modes were installed, and the lower  $\epsilon_l$  is due to their successful operation.

### Oscillations at Transition

In Figure 4 I have zoomed in on the bunch length measurement from near transition to the end of the cycle. The frequency of the oscillations which appear after transition is roughly 4 KHz, or twice the synchrotron frequency of 2 KHz. Thus they are quadrupole synchrotron oscillations induced by the mismatching of the bunch and bucket before and after transition. The Booster has a  $\gamma_t$ -jump system which could be used to eliminate this os-

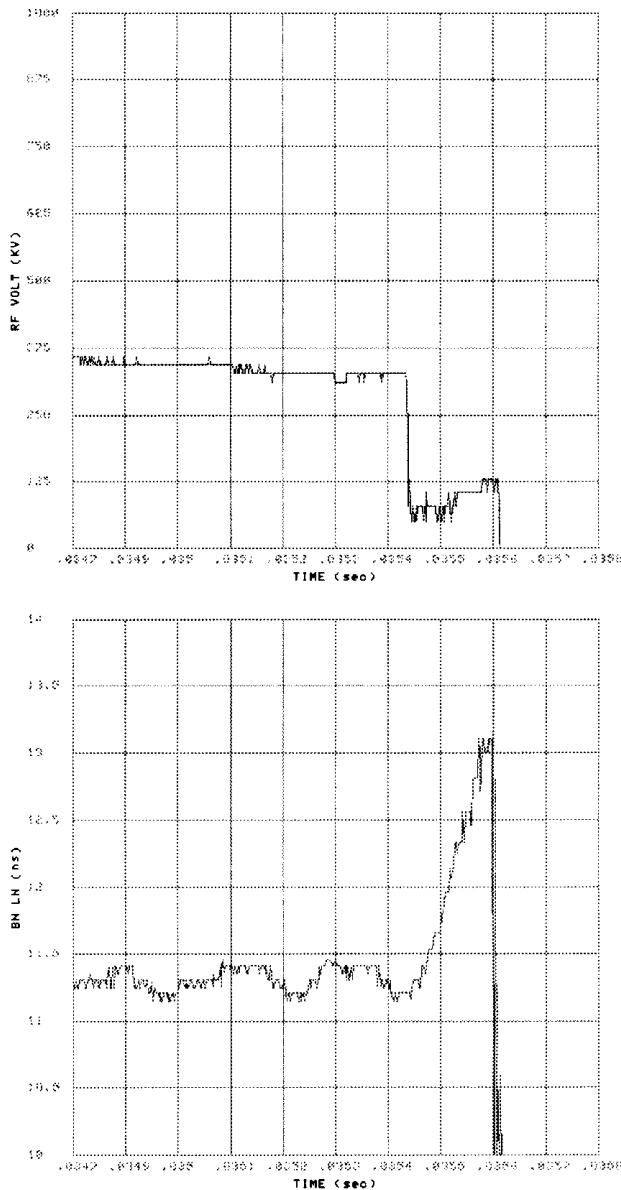


Figure 5. RF voltage (upper) and bunch length (lower) for the bunch rotation at extraction. Note the suppressed 0.

cillation, but since the oscillation does not lead to emittance growth, it is not used.

#### *Bunch Rotation at Extraction*

Extracted beam from the Booster is injected into the Main Ring. The momentum aperture of the Main Ring has long been known as a limitation, and as a result the Booster attempts to provide as low a  $\Delta p/p$  as possible.  $\Delta p/a$  is normally determined by the RF voltage, and throughout the last half of the Booster cycle the voltage is kept as low as possible to avoid beam loss. In addition, at the very end of the cycle a bunch rotation is performed to provide an even lower  $\Delta p/p$ . The rotation consists of a step drop in the RF voltage  $1/4$  of a synchrotron period ( $125 \mu\text{sec}$ ) before extraction. During this interval the bunch rotates in longitudinal phase space, exchanging energy spread ( $\Delta p/p$ ) for time (bunch length).

This process is illustrated in Fig. 5, the RF waveform for the bunch rotation, and Fig. 5b, the bunch length during the rotation. Immediately before the rotation one observes a bunch length of roughly 11 nsec, with a small quadrupole synchrotron oscillation. During the last  $1/4$  synchrotron, while the RF voltage has been reduced, one can see the bunch “tumble”, resulting in a larger bunch length and smaller  $\Delta p/p$ . After making this bunch rotation operational, the Main Ring intensity and pulse-to-pulse stability increased noticeably.

## CONCLUSIONS

We have developed a system capable of making detailed bunch length and longitudinal emittance measurements in the Fermilab Booster. This system allows us to make detailed studies of longitudinal beam dynamics.

## References

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