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# A DEDICATED WAKE-BUILDING FEEDBACK SYSTEM TO STUDY SINGLE BUNCH INSTABILITIES IN THE PRESENCE OF STRONG SPACE CHARGE

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*Abstract*

Recent advances in the theoretical understanding of beam stability in the presence of strong space charge, has suggested a new class of instabilities known as convective instabilities. A novel approach to excite and study these instabilities will be to install a 'waker' system, a dedicated wake-building feedback system. The System was installed in the Fermilab Recycler and commissioned during 2021. The first results are presented.

## INTRODUCTION

The transverse mode coupling instability (TMCI) is known to be one of the main intensity limitations for bunch stability in circular machines. For many years, space charge was thought to have a stabilizing effect on TMCI raising the instability threshold to higher intensities. However, recent advances in the theoretical understanding of beam stability in the presence of strong space charge has led to the suggestion of a new class of instabilities, convective instabilities [1–4]. Numerical simulations [5] taking into account space charge also see these instabilities. It is believed these instabilities have been observed [6, 7] before but are often attributed to TMCI.

In order to study these instabilities, a new experimental program making use of Fermilab's existing accelerator complex is underway. The primary objective of the proposed research will be to characterize these instabilities in the presence of varying space charge and varying wake amplitudes. Usually, the wake amplitudes which drive instabilities are machine dependent and are determined by the impedance of the components installed within the machine. A novel approach to control instabilities will be to install a 'waker' system, a dedicated wake-building feedback system.

## WAKER CONCEPT

One of the advantages of simulations, is that the user can vary the wake parameter however they please. If this could be accomplished in actual machine, it would open the door to many exciting studies that could not normally be performed. The waker system is a novel concept which tries to mimic this approach and allow the user to define their own wake.

The system design will be similar to a traditional damper system however, used to excite instabilities rather than damp them. The concept of the system is as follows;

- The user defines a wake, W(s).
- The system will measure the position and intensity of the bunch at different time slices along the bunch in a single turn given by $x_j$ and $q_j$ respectively.
- On the next turn, the system applies multiple kicks along the bunch where the kick size, $K$ is determined by the convolution of transverse offsets of the upstream time slices with the wake function of the longitudinal position difference

$$K_i \propto \sum_{j=1}^{i-1} x_j q_j W(s_j - s_i) \qquad (1)$$

The bandwidth of the system should be much bigger than the inverse bunch length i.e.

$$\Delta\omega >> 1/\sigma_b \qquad (2)$$

For standard operation in the Recycler, the beam is bunched at 53 MHz. A typical bunch length is 2 ns, which would require a bandwidth larger than 500 MHz which would not be feasible to build. However, the beam can be re-bunched to 2.5 MHz which is routinely performed for the Muon program. In this case, a typical 1-sigma bunch length of 30 ns can be expected and so, a bandwidth larger than 30 MHz would be needed. Assuming a full bunch length equivalent to 4-sigma of 120 ns, a 100 MHz system would provide 12 time slices across the bunch and a 200 MHz system would provide 24 time slices. Based on this, the bandwidth of the system will be designed to be at least 100 MHz.

## WAKER SYSTEM

The waker system is installed in the Fermilab Recycler. The main components are as follows:

**Kicker** A 0.5m vertical stripline kicker is used to provide the kicks that mimic a wakefield. The length is chosen based on the frequency response in order to meet a bandwidth of 200 MHz.

**Pickups** Two split plate BPMs are used. Ideally, the two BPMs would be separated by 90° in betatron phase advance. The two signals from these BPMs can be combined with the correct coefficients to control the phase to the kicker. The pickups used are located at 206 and 208 in the Recycler and are separated in phase by 82°.

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**Amplifiers** Two amplifiers are used to drive each plate of the kicker.. Each amplifier is a R&K-A010K221-6464R which has a broadband frequency range of 10kHz-225MHz. The output power at saturation is 2.5kW from 10kHz - 100MHz and at least 2kW from 100MHz-225MHz. Two RF loads/attenuators are also used.

**Digital Feedback Board** The board is needed to process the signals, apply the wake and output the kick signal to the amplifiiers. The current board allows a bandwidth of 100 MHz [8].

## COMMISSIONING

In order to commision the system in, two important parameters need to be determined. The first is time delay needed such that kick is applied at the correct time. The two are the coefficients needed to combined the bpms signals to simulated a pickup signal that is 90° from the kicker. These parameters can be found by using performing an open loop transfer function measurement.

Figure 1 shows a schematic of an open loop BTF measurement. The circuit is broken between the board and the amplifiers. A vector signal analyzer (VSA) sends out a white noise signal in the bandwidth of interest to the kicker. The beam response is then measured by the bpms and sent to the VSA via the board.

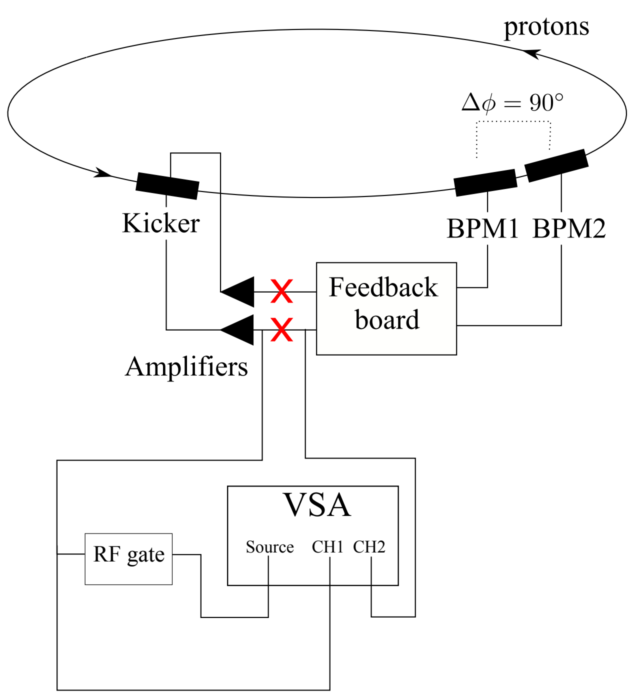


Figure 1: BTF schematic.

If the driving term from kicker is proportional to $\cos(2\pi\nu f_0 t)$, then the signal from the detector is proportional to

$$\cos[2\pi n f_0(t-t_d)+\vartheta]\cos[2\pi\nu f_0(t-t_d)+\phi] \quad (3)$$

which can be separated into the upper and lower betatron sidebands.

$$\cos[2\pi(n+\nu)f_0(t-t_d)-\vartheta+\phi] \quad (4)$$
$$+\cos[2\pi(n-\nu)f_0(t-t_d)+\vartheta-\phi] \quad (5)$$

where the phase of the upper and lower sidebands is given by:

$$\theta_{lsb} = \vartheta+\phi-2\pi f_{lsb}t_d \quad (6)$$

$$\theta_{usb} = \vartheta-\phi-2\pi f_{usb}t_d \quad (7)$$

From this, the sum and difference of these two phases can let us determine all the information needed to time in the system.

$$\theta_{lsb}-\theta_{usb} = 2\phi+2\pi(f_{usb}-f_{lsb})t_d \quad (8)$$
$$\theta_{lsb}+\theta_{usb} = 2\vartheta+2\pi(f_{usb}+f_{lsb})t_d \quad (9)$$

By the measuring the sum of the sideband phases at multiple frequencies, we can find a time delay used by the board that simulates $t_d = 0$. Figure 2 shows an example measurement. Once the correct delay is found, the difference phase equals twice the phase advance from the pickup to the kicker. However, the board uses a numerical notch filter i.e. the board is looking at the position difference between revolutions rather than absolute difference. The result of this notch filter is that the upper betatron sidebands phase are flipped 180°. This means that in order to simulate a pickup signal that's 90° from the kicker, the bpm coefficients are chosen such that the phase of upper and lower sidebands are the same.

Once the delay and bpm coefficients were found, the timing was tested by trying to damp and antidamp the beam. This was performed on both 53 MHz bunched beam and 2.5 MHz bunched beam. The next step is to try a wake. A theta (Heaviside step function) wake was used. The initial test was done use moderate intensity and beam fallout was observed. The intrabunch motion was captured using a set of stripline pickups connected to an oscilloscope and is shown in Figure 3. The integrated sum signal from the pickups shows the longitudinal profile. The difference signal is proportional to both position and intensity. The head of the bunch is on the left and tail on the right. The instability appears to show signs of being a convective instability as intrabunch motion seems to be slightly more tail dominated.

Successful excitation of an instability using the waker system meant that instability studies could begin. However, two important measurements needed to be made first. The

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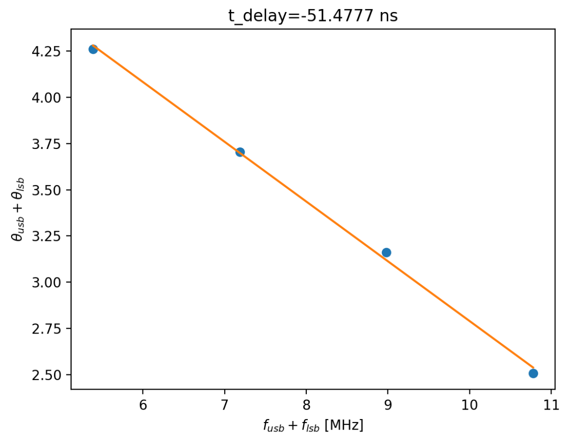


Figure 2: The sum of the upper and lower betatron sideband phases at different frequencies. The gradient is proportional to the time delay.

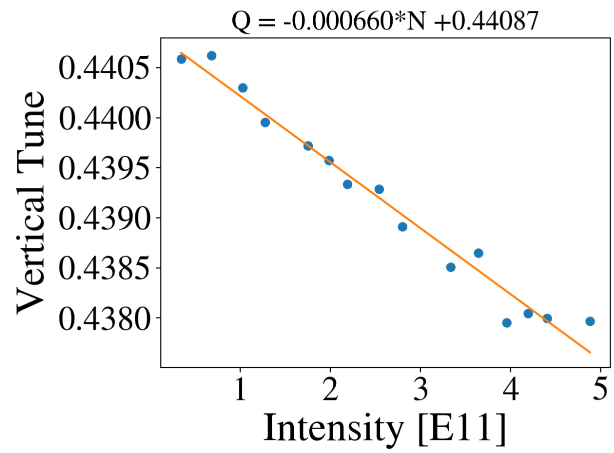


Figure 4: The vertical tune shift due to increasing bunch intensity.

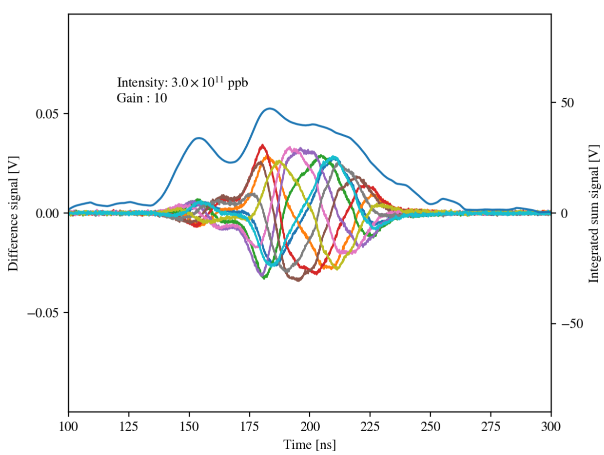


Figure 3: Snapshot of first instability observed using waker system. The integrated sum signal from the pickups shows the longitudinal profile. The difference signal is proportional to both position and intensity.

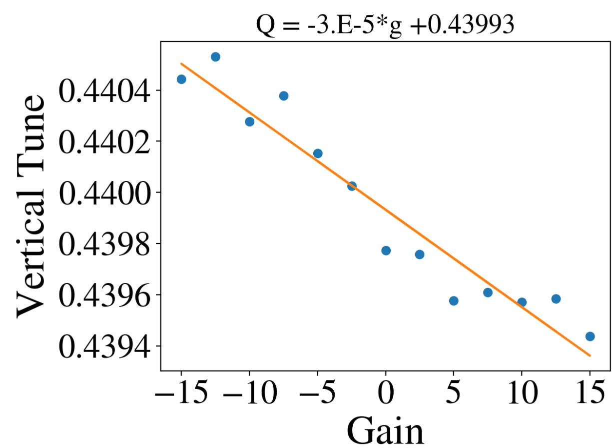


Figure 5: The vertical tune shift as a function of gain of the system. Positive gain results in a negative tune shift i.e. it follows the natural tuneshift of the machine. Note: There is some large uncertainty in the tune measurements but the sign of the slope is believed to be correct.

natural tune shift due to intensity without the waker and the tuneshift caused by the waker itself.

The first measurement needed is to determine the natural tune shift vs intensity for the Fermilab Recycler. The result is shown in Figure 4.

The next measurement is to see how the waker affects the tune shift. Figure 5 shows how the tune varies as the gain is changed well below the intensity threshold. It can be seen that at positive gain, the tune shifts down. i.e. it follows the natural tune shift of the machine. A negative gain results in a positive tune shift. There is some large uncertainty in the tune measurements and so the magnitude of the slope may not be correct however the sign of the slope is believed to be correct.

## INSTABILITY STUDIES

The first study was to find the instability threshold at varying intensities. After the beam was injected and rebunched to 2.5 MHz, the waker system was run for 50000 revolutions. Typical parameters during the study are shown in Table 1. At each intensity, the gain of the waker was gradually increased until an instability was observed. Figure 6 shows instability snapshots at 3 different intensities at the minimum gain needed to cause an instability. It can be seen that as the space charge parameter increases, a strong amplification from the head of the bunch to the tail is observed and looks like a convective instability predicted by [1].

The last measurement was to compare the instability threshold with positive and negative gain. Figure 7 shows the result. It can be seen that significantly more gain is

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Table 1: Typical Parameters Used for Instability Measurements in the Fermilab Recycler

| Parameter | |
|---|---|
| $Q_s$ | 0.0005 |
| $\xi_x$, $\xi_y$ | 0.03,-0.15 |
| $\Delta p/p$ | 0.0005 |
| $\sigma_l$ | 30 - 40 ns |
| $\epsilon_{n,95\%}$ | 15 $\pi$ mm mrad |
| $\beta$ | 0.9944 |
| $R$ | 528 m |

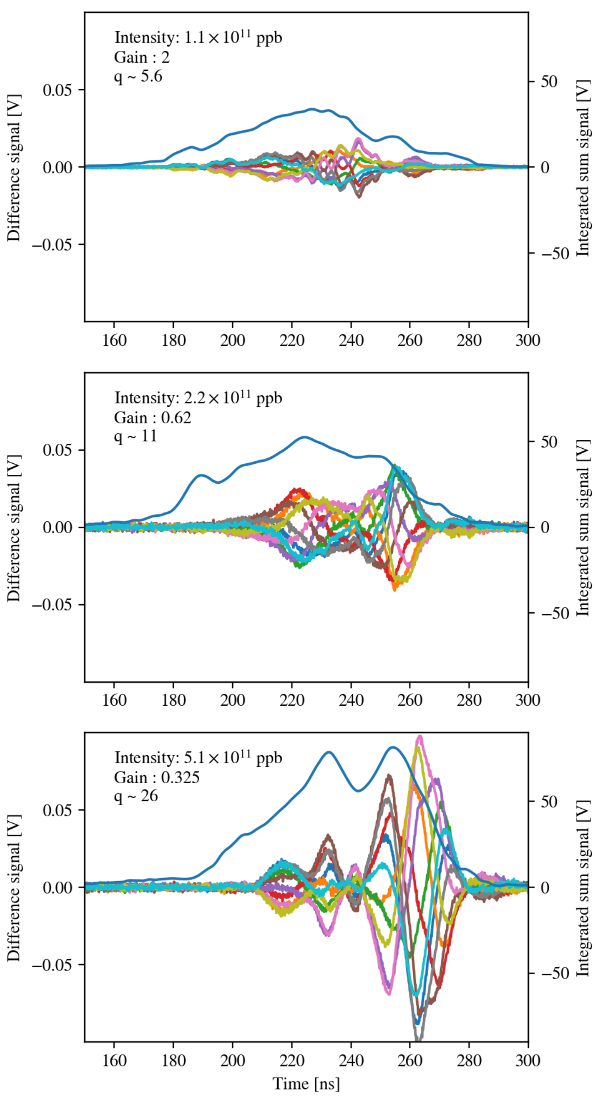


Figure 6: Instability snap-shot taken at three different intensities. The difference signal is proportional to position and intensity. The integrated sum signal shows the longitudinal profile. As the intensity and space charge is increased, huge amplification is observed from the head to the tail.

required when attempting to couple to the +1 mode vs coupling to the -1 mode. One possible reason for this is due to the natural tune shift of the Recycler. At high intensity, the tune has already shifted and so a small amount of gain is needed to push it become unstable. However, large negative gain is needed to result in an instability as the waker needs to counter the natural tune shift. The snapshots also agree well with theoretical predictions. From the theory on convective instabilities, we should expect to see large amplification from the head to the tail when following the natural tuneshift however, the intrabunch motion should be much more symmetric when coupling to the positive modes.

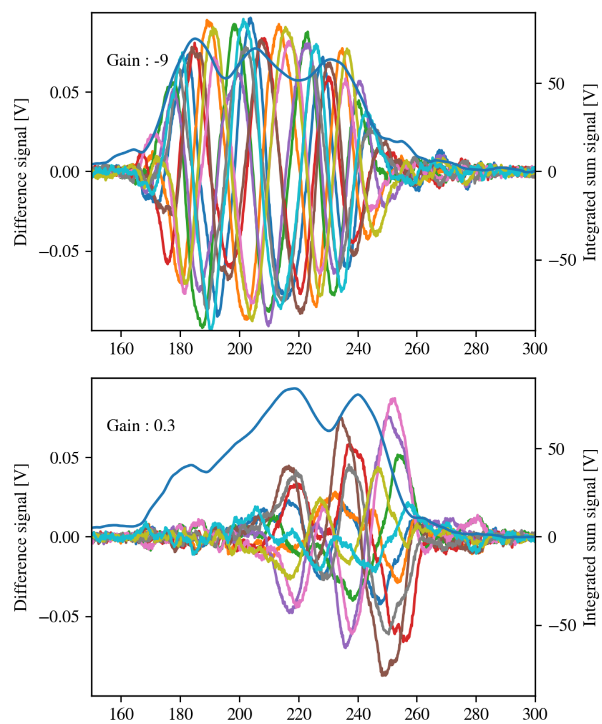


Figure 7: Instability snap-shop taken at three different intensities. The difference signal is proportional to position and intensity. The integrated sum signal shows the longitudinal profile. As the intensity and space charge is increased, huge amplification is observed from the head to the tail.

## SUMMARY

A new hardware system has been commissioned in the Fermilab Recycler to study beam instabilities. It has successfully excited single bunch beam instabilities. As space charge was increased, huge amplification from the head to the tail is observed which agrees well with the theory relating to convective instabilities. The initial measurements show a good qualitative agreement but more studies are needed for a more quantitative agreement. Studies in the Recycler will continue for another 1 to 2 years before the system is move to IOTA. A new digital feedback board is in development

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which will increase the bandwidth of the system by a factor of 2.

Work is also ongoing to upgrade the board of the system which will allow the bandwidth to be increased to 200 MHz.

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