ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA33

WAKER EXPERIMENTS AT FERMILAB RECYCLER RING

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Abstract

Attaining high-intensity hadron beams is often limited due to the transverse collective instabilities, whose understanding is thus required to see and possibly extend the intensity limitations. To explore such instabilities, a novel artificial wake system, the waker, has been built and tested at the Fermilab Recycler Ring (RR). In this report, we show recent upgrades of the waker. Also, we present experimental studies of instabilities at various space charge and wake parameters.

INTRODUCTION

As physics experiments demand more beam power, limitations in the intensity and beam quality are often encountered. It is important to understand the existing beam limitation and to try to overcome them to achieve the required beam parameters for future experiments.

Transverse Mode Coupling Instability (TMCI) is one of the main limitations of high-intensity beams in circular machines [1]. The dependence of the TMCI threshold on Space Charge (SC) has been considered previously. For instance, it was shown in several analytical models that at large SC tune shifts compared to the synchrotron tune, the threshold of TMCI increases [2–4]. It was also suggested that, although the threshold of TMCI increases, a new form of instabilities takes place [5]. Such instabilities, namely *convective instabilities*, may require different treatment than the traditional feedback system which damps the bunch center of charge. Thus, experimental verification of these new instabilities and the development of novel methods to mitigate them are essential at higher beam intensities.

To explore transverse instabilities further, a new program at the Fermilab Recycler Ring has been established. The program uses a dedicated feedback system, hereafter referred to as *the waker*, to induce instabilities in circulating beams. It does so by mimicking the equivalence of a wakefield kick to the beam. Such a system can explore the SC-wake parameter space and study their effect on beam instabilities simultaneously. In this work, we present the waker design, its recent upgrades, and commissioning. Moreover, we present the initial experimental results of the program and we give a brief description of possible upgrades to the current design.

DESIGN

The waker system, depicted in Fig. 1, is designed similar to a damper system [6]. However, by applying multiple kicks along the bunch, the waker induces instabilities rather than damping them. The system consists of a stripline kicker, split-plates Beam Position Monitor (BPM) pickups, two amplifiers, and a digital feedback board system. The kickers provide the kick to the beam that mimics the applied wake. The BPMs, separated in phase advance by 90°, are used to measure the beam position and intensity which acts as turn-by-turn feedback to the kicker through the digital board. The two amplifiers (R&K-A010K221-6464R) are used to drive each plate of the kicker providing up to 2.5 kW of power each. Typically, the BPMs measure the position x_i and intensity q_i along different slices of the bunch. This information is used to apply multiple kicks along the bunch in the following turns. The signal from the BPMs as well as the applied kick through the kicker are both analyzed and applied through the feedback board system. The bandwidth requirement of such a system is given by :

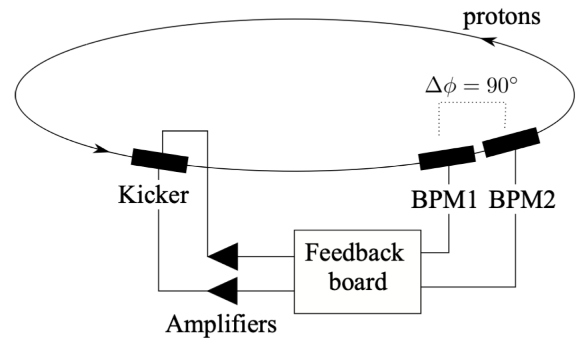

Figure 1: Schematic of the waker system.

$$\Delta\omega \gg \frac{1}{\sigma_t} \tag{1}$$

where σ_t is the bunch duration. Assuming a Gaussian bunch of length 4 σ_t, a 100 MHz system with a σ_t = 30 ns allows for 12 time slices across the bunch. At the Fermilab Recycler, we typically use 2.5 MHz bunches ($\sigma_t \approx 30$ ns) for the Muon program, making a system with 100 MHz bandwidth ideal for such bunches. For diagnostics, we use stripline pickups to observe intra-bunch motion as well as readily available diagnostics in the Recycler to observe beam losses and beam size; e.g. Wall Current Monitors and Ion Profile Monitors (IPM).

EXPERIMENTAL RESULTS

Tune shift in the Recycler can be found by measuring the tune while varying the intensity. To perform the measurement, the beam is kicked and its subsequent motion is recorded for several turns n. The motion is then analyzed using the Fourier transform to look at the frequency spectrum of the beam. Consecutively, the peak in the spectrum with the highest amplitude corresponds to the tune. Each tune

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measurement is performed 3 times where an average and a standard deviation σ of the tune are computed. The final error in the tune measurement is the quadratic sum of the standard deviation σ and the error in the Fourier transform $\delta\nu \equiv \frac{1}{2n}$; see Fig. 2.

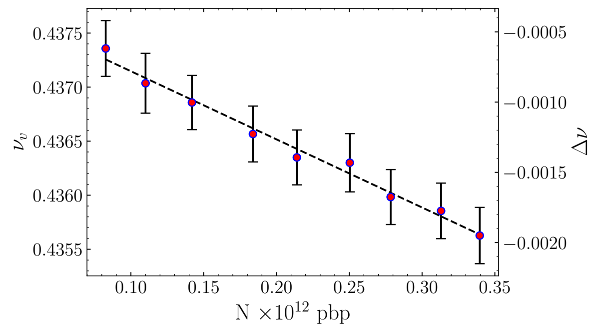

Figure 2: Measured vertical tune ν_V while varying the intensity. The same data is shown in units of relative tune shift $\Delta\nu$ on the right y-axis. The vertical lines represent the standard deviation σ in the measurement and the dashed line represents the best fit for the data.

The effect of the waker on the natural tune of the machine was examined by varying the gain of the waker at fixed intensities. For these measurements, the waker was active for $n = 10000$ turns. The data acquisition was timed when the waker was active and lasted for $n = 20000$ turns. The gain parameter was varied from negative to positive values until beam fallout was observed. Finally, the intensity was recorded using DC Current Transformers (DCCT) in the Recycler. The measurement was performed at 2 different intensities; see Fig. 3.

The tune shift at instability threshold can be found by varying the gain of the waker at a certain intensity just before beam fallout is observed. Consequently, this can be repeated at different intensities to find the corresponding instability threshold at various intensities. An example of such measurement is shown in Fig. 4. The machine parameters used in the earlier experiments are summarized in Table 1.

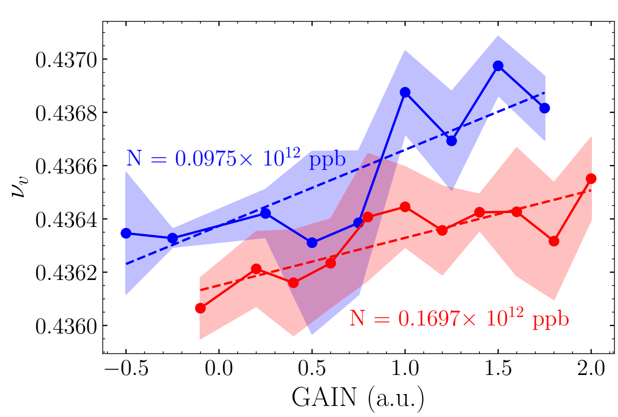

Figure 3: Vertical tune ν_v versus the waker gain at 2 different $N = 0.0975 \times 10^{12}$ ppb (blue) and $N = 0.1697 \times 10^{12}$ ppb (red). The shaded area represents the standard deviation in the tune measurement. The dashed lines represent the best fit of the data.

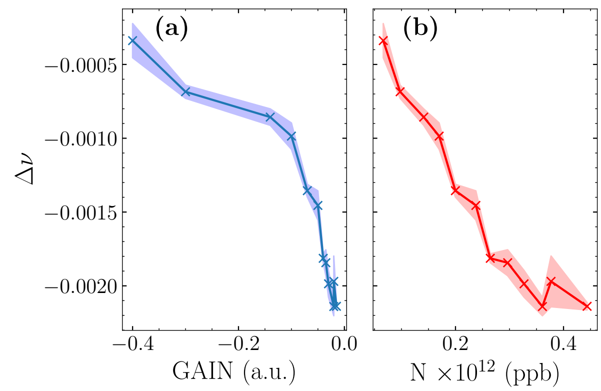

Figure 4: Waker gain versus the tune at instability threshold (a). The same tune is plotted against the intensity N in (b). The shaded area represents the standard deviation σ in the tune measurement.

Table 1: Parameters Used in the Experiments in the Recycler

Parameter		Value
Synchrotron tune	ν_s	0.0005
Chromaticity	ξ_x,ξ_y	-0.75,-0.16
Betatrone tune	ν_x,ν_y	25.42,20.44
Emittance	$\epsilon_{N,rms}$	2.5 π mm mrad
Energy	E	8 GeV
Radius	R	528 m

DISCUSSION

Tune shifts in the Recycler can be used to estimate the effective impedance of the machine. For instance, the imaginary part of the effective impedance $Im\left(Z_{eff}\right)$ is related to the tune shift with intensity by:

$$Im\left(Z_{eff}\right) = \frac{2}{3}\frac{\Delta\nu}{N_b}\frac{8\pi^{3/2}\nu\beta^2 E\sigma_t}{q^2 R} \tag{2}$$

where $\frac{\Delta\nu}{N_b}$ is the slope from Fig. 2, ν is the unperturbed tune, $\beta \equiv \frac{v}{c}$, σ_t is the bunch duration, E is the energy, q is the proton charge and R is the radius of the machine. This yield an effective Impedance of 10 MΩ m^{-1} which agrees with previously published results [7].

The result in Fig. 3 shows that as the gain increases, the tune increases. This means that the waker gain has an opposite effect on the tune compared to the tune shift without the waker.

The tune shift at instability threshold is shown in Fig. 4. For TMCI, the threshold occurs when 2 transverse modes become degenerate; i.e. when the 2 modes have the same frequency. Without the waker, as the intensity increase a negative tune shift is observed; see Fig. 2. Once the waker

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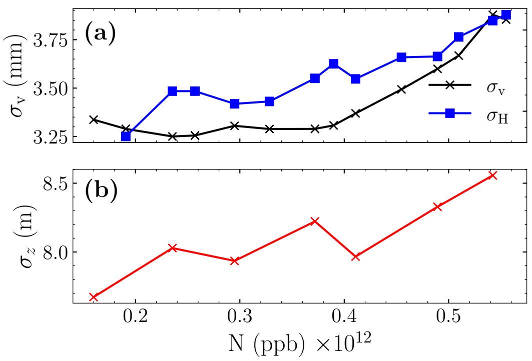

Figure 5: Measured vertical σ_V (left - a), horizontal σ_H beam sizes (right -a) and bunch length σ_z (b).

is active, a negative gain will result in a negative tune shift while a positive gain will shift the tune positively. Thus, at low intensities (small tune shifts) more negative gain is required to couple the transverse mode; i.e. where the instability threshold is found. Likewise, at high intensities, less negative gain is required to reach the instability threshold. This agrees very well with Fig. 4. For instance, at intensity N ~ 0.1 $\times 10^{12}$, a gain of -0.3 was required to reach the threshold while at N ~ 0.2 $\times 10^{12}$ only a gain of -0.07 was required to reach the threshold.

The result in Fig. 4 also shows a non-linear dependence as the intensity increase. To investigate this, a separate measurement was performed to estimate the incoherent tune shift due to SC. By measuring the beam size σ and the bunch duration σ_t at different intensities, we can estimate the tune shift due to SC as:

$$\Delta\nu = \frac{-N r_o R S}{8\sigma_z M \beta \gamma^2 \epsilon_{N,rms}} F \tag{3}$$

where N is the number of protons (i.e. intensity) r_o is the classical radius of the proton $r_o = 1.535\times10^{-18}$ m, σ_z is the bunch length, γ is the Lorentz factor, $S \equiv 1.596$ is related the bunch geometry, M is the number of bunches, $\epsilon_{N,rms}$ is the normalized root mean square emittance and F is a factor to account for the unequal beam sizes in both planes [8]. To measure the beam size, we use the readily available Ion Profile Monitor (IPM) in the Recycler. Furthermore, we use the Wall Current Monitor data to estimate the bunch length; see Fig. 5.

The estimated tune shift due to SC is shown in Fig. 6 and it shows that as the intensity increases, the magnitude of the tune shift increases linearly with intensity. However, a further increase in the intensity ($N > 0.4\times10^{12}$ ppb) results in a slope change of the tune shift and the magnitude of the tune shift becomes smaller. This behavior is not well understood here and could be the result of an emittance blow-up in the machine. For instance, a similar intensity effect is observed in the Fermilab booster [9].

Figure 7 shows the tune shift without the waker (at gain = 0) plotted next to the tune at the intensity threshold. When comparing both, it confirms that, despite invoking instabilities in the beam, the waker does not shift the tune as

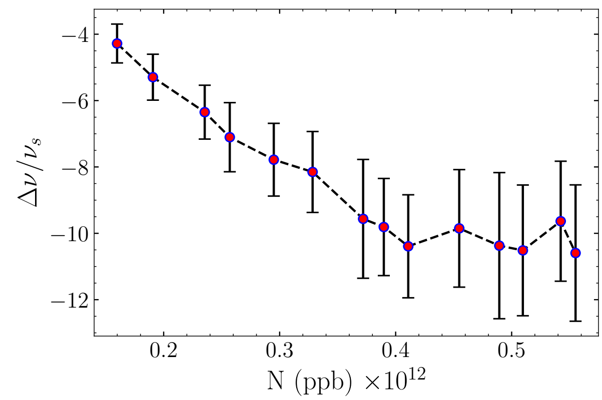

Figure 6: Direct SC contribution to the tune shift. The vertical bars indicate the standard deviation in the tune.

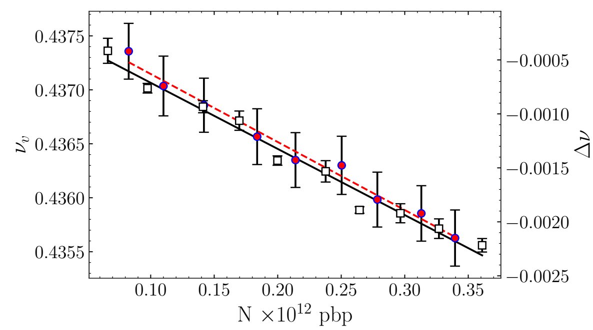

Figure 7: Tune shift at intensity threshold (white squares) and natural tune shift (red circles). The same data is shown in units of relative tune shift $\Delta\nu$ on the right y-axis.

expected; i.e. the tune shift measurement while the waker is active is within the uncertainty limit when it is not.

One of the main differences between TMCI and the newly predicted instabilities is the amplification in the longitudinal profile of the beam from the head to the tail. Such behavior is only present in convective instabilities while TMCI shows a semi-symmetrical longitudinal profile. In future runs, observing these differences will be one of the goals. Moreover, the focus will be on a quantitative description of these instabilities as well as measuring the stability diagram of the machine.

CONCLUSION

A New Waker system dedicated to studying beam instabilities has been successfully installed and commissioned at the Fermilab Recycler. Such a system will help in understanding and mitigating beam instabilities at higher intensities. Furthermore, a new upgrade to the digital board is currently ongoing and will increase the system bandwidth to 200 MHz.

ACKNOWLEDGEMENTS

Fermi Research Alliance, LLC manages and operates the Fermi National Accelerator Laboratory pursuant to Contract number DE-AC02-07CH11359 with the US DOE.

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REFERENCES

[1] A. W. Chao, "Physics of collective beam instabilities in high energy accelerators," *Wiley Series in Beam Physics and Accelerator Technology*, 1993.

[2] M. Blaskiewicz, "Fast head-tail instability with space charge," *Phys. Rev. ST Accel. Beams*, vol. 1, no. 4, p. 044 201, 1998. doi:10.1103/PhysRevSTAB.1.044201

[3] A. Burov, "Head-tail modes for strong space charge," *Phys. Rev. ST Accel. Beams*, vol. 12, no. 4, p. 044 202, 2009. doi:10.1103/PhysRevSTAB.12.044202

[4] V. Balbekov, "Transverse mode coupling instability threshold with space charge and different wakefields," *Phys. Rev. Accel. Beams*, vol. 20, no. 3, p. 034 401, 2017. doi:10.1103/PhysRevAccelBeams.20.034401

[5] A. Burov, "Convective instabilities of bunched beams with space charge," *Phys. Rev. Accel. Beams*, vol. 22, no. 3, p. 034 202, 2019. doi:10.1103/PhysRevAccelBeams.22.034202

[6] R. Ainsworth, A. Burov, N. Eddy, and A. Semenov, "A dedicated wake-building feedback system to study single bunch instabilities in the presence of strong space charge," in *Proc. HB'21*, Batavia, IL, USA, Oct. 2021, pp. 135–139. doi:10.18429/JACoW-HB2021-MOP22

[7] R. Ainsworth, P. Adamson, A. V. Burov, I. Kourbanis, and M.-J. Yang, "Estimating the Transverse Impedance in the Fermilab Recycler," in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 867–869. doi:10.18429/JACoW-IPAC2016-MOPOY011

[8] T. Roser and W. Weng, "Calculation of lncoherent space charge tune spread," Brookhaven National Lab., Upton, NY, USA, Tech. Rep. 449, 1996.

[9] J. Eldred, V. Lebedev, K. Seiya, and V. Shiltsev, "Beam intensity effects in fermilab booster synchrotron," *Phys. Rev. Accel. Beams*, vol. 24, p. 044 001, 4 2021. doi:10.1103/PhysRevAccelBeams.24.044001