ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THAFP04

INVESTIGATION OF TAIL-DOMINATED INSTABILITY IN THE FERMILAB RECYCLER RING

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Abstract

In the latest operational run at the Fermilab accelerator complex (22-23), a single bunch, tail-dominated instability was observed in the Recycler Ring (RR). This instability exclusively occurs in the vertical plane when the chromaticity is close to zero. In this work, we conduct a detailed analysis of this instability under different operational parameters. We investigate the impact of space-charge on the head-tail motion and propose potential interpretations of the underlying mechanism of the instability. Moreover, we explore methods to mitigate this instability in the future.

INTRODUCTION

Accelerators are vital instruments in the realm of particle physics, playing an indispensable role in our quest to unravel the fundamental constituents of matter and their interactions. As the need to increase beam power and intensity becomes more pressing, accelerators are often faced with operational challenges, most importantly beam instabilities, which often stand as a limitation to increasing beam intensity. These instabilities manifest as deviations from the desired beam trajectories in planes of motion, leading to beam loss, diminished beam quality, and increased beam emittance [1, 2].

The Transverse Mode Coupling Instability (TMCI) poses a significant obstacle to both current and future accelerator designs due to its stringent intensity threshold. Consequently, surmounting this instability is essential in attaining the desired energies and intensities required for future physics experiments. The effect of space-charge on TMCI threshold has been explored before [3–5]. It is shown that space-charge increases the TMCI threshold. However, recent theoretical and analytical frameworks suggest a different type of instabilities that take over at higher space-charge tune shifts, namely convective instabilities [6]. Such instabilities can occur at high space-charge tune shifts in the presence of a strong wake and differ from TMCI by having an asymmetrical transverse motion with a large head-to-tail amplification.

In this work, we describe our recent observation of transverse instabilities in the vertical plane that was recently found in the Fermilab Recycler Ring (RR). During our observation, we gathered evidence that this instability is not TMCI but rather convective. Nevertheless, the instability shows a tune dependence that is not yet well understood.

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INSTABILITIES STUDY

In the RR, we can study beam instabilities under several operational conditions. For this work, we use a single bunch for our studies with different beam intensities (N) at energy $E = 8$ GeV. Typically, we use a dedicated event that can be placed within our supercycle parasitically. This allows us to perform studies while having normal beam operation. Some of the RR parameters used in our studies are summarized in Table 1.

Table 1: Typical RR Parameters Used for the Instability Studies

Parameter	Symbol	Value
Energy	E	8 GeV
Radius	R	528 m
Betatrone tune	ν_x, ν_y	25.40, 20.44
Synchrotron tune	ν_s	0.0005
Chromaticity	ξ_x, ξ_y	−0.75, −0.16
Emittance	$\varepsilon_{N,\text{rms}}$	2.5 π mm mrad

Our typical study event lasts for 2 seconds. During the event and following the injection of the beam from the upstream machine, we employ the RR gap-clearing kickers to partially batch the beam thus aborting 70-72 of the 84 bunches. Subsequently, a rebunching process is utilized to reconfigure the remaining 12-14 bunches from 53 MHz into a single 2.5 MHz bunch while allowing sufficient time for the beam to undergo this process adiabatically. Afterwards, we turn off the bunch-by-bunch dampers and tune the chromaticity to values close to zero; see Fig. 1. Following these processes, we initiate instabilities using a diverse range of techniques. To facilitate diagnostics, we employ Ion Profile Monitors (IPMs) and a wall current monitor to gauge transverse and longitudinal beam sizes, respectively. For the IPMs, we avoid changing the Micro Channel Plate (MCP) to avoid any uncertainties caused by the IPMs. Subsequently, our diagnostic includes a stripline Beam Position Monitor (BPM) to capture intra-bunch motion. The signal from the stripline BPM plates (A, B) is passed through a hybrid filter where the sum ($A + B$) and the difference ($A - B$) are outputted. The signal from the hybrid filter is then processed via an oscilloscope. The resulting signal must be integrated since the bunch length is much longer than the stripline. The processed $A + B$ signal is then related to the beam intensity $I(\zeta)$ along the bunch, where ζ is particle coordinates inside the bunch. Subsequently, the signal from $A - B$ is related to the dipole moment of the beam $I(\zeta) \times y(\zeta)$, where $y(\zeta)$ is the vertical displacement of particles along the bunch. The

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ratio between both signals is directly proportional to the vertical displacement of the beam $y(\zeta)$. Typically, we offset the $A+B$ signal by a small voltage to avoid any singularities when computing $(A-B)/(A+B)$.

In addition to the diagnostics tools mentioned earlier, we employ DC Current Transformers (DCCTs), conventional BPMs, and beam loss monitors to comprehensively monitor the behavior of the beam. However, conventional diagnostics are often not recorded during our event.

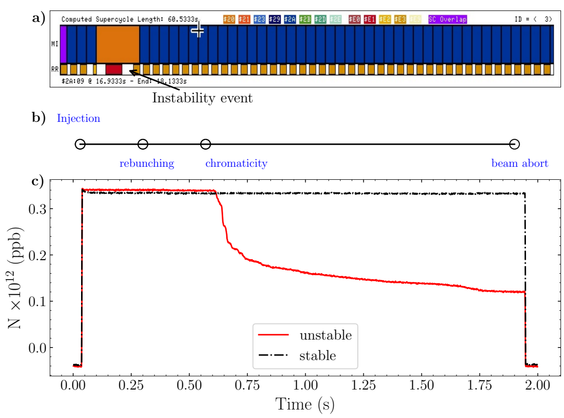

Figure 1: Operational supercycle with the instability event shown (a), the processes that occur during our study event (b) and beam intensity (N) during two separate events (c). In (c) the red solid trace represents the intensity when the instability occurred, while the red dashed trace shows the beam intensity after the instability was mitigated by the tune change.

OBSERVED INSTABILITY

In our prior experimental run and during our typical study event, we encountered an instability when approaching near-zero values in our chromaticity, as depicted in Fig. 1. Despite not being present in earlier runs, the instability manifested predominantly in the vertical plane, resulting in significant head-to-tail amplification within the intra-bunch monitor; see Fig. 2. While the extent of this instability was subject to daily variations in the upstream beam, it exhibited a distinct threshold, approximately at $\sim 0.35 \times 10^{12}$ proton per bunch (ppb). Remarkably, this instability was mitigated when we adjusted the horizontal and vertical tunes from 0.40 to 0.39 and from 0.44 to 0.46, respectively, as shown in Fig. 1. Interestingly, maintaining the same separation in tune space for both horizontal and vertical tunes, albeit at different values, did not resolve the instability. This outcome allowed us to rule out tune coupling as a contributing factor. Notably, we did not detect any signs of instability, such as beam growth, in the horizontal plane, yet modifying the horizontal tune remained essential to eliminate the instability.

To delve deeper into understanding this instability, we conducted a series of investigations. These inquiries aimed to explore the potential influence of space-charge on the instability and monitor any alterations in the longitudinal or transverse profile resulting from the tune adjustments.

For the longitudinal profile, no significant changes were observed on the average profile of the beam; see Fig. 3, The average bunch length over 5000 turns was 31.0 ± 3.0 ns and 32.0 ± 3.0 ns before and after the tune change, respectively.

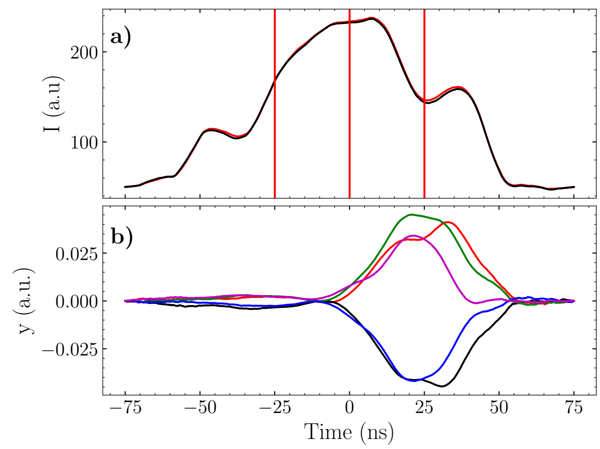

Figure 2: Transverse distribution along the bunch (a) and the beam vertical displacement (b) for 5 consecutive turns during an instability. The vertical lines in (a) represent $\sim -\sigma_t$, 0, and σ_t and are hereafter referred to as the head, center, and tail of the bunch, respectively.

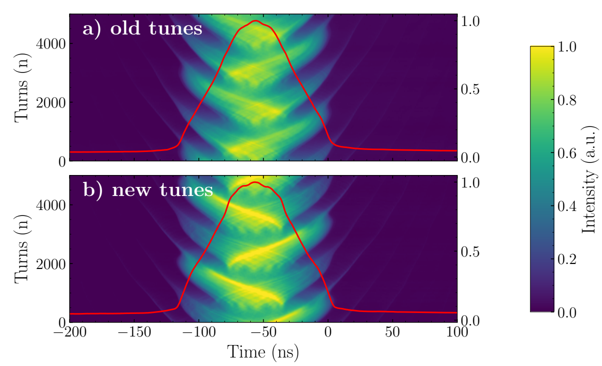

Figure 3: longitudinal profile of the beam over 5000 turns before the tune change (a) and after the tune change (b). The red trace in both (a) and (b) shows the average longitudinal profile over the same number of turns.

To investigate the influence of space charge on instability, we carried out an experiment in which we tried to increase the beam size while maintaining the same intensity. To achieve this, we deliberately drove the beam into resonance immediately after the injector for a small amount of time, ensuring minimal beam loss within the machine. Subsequently, we transitioned the beam into its nominal tune configuration; i. e., where the instability was typically observed. This resulted in increasing the beam size by ~ 1 mm in both planes while causing very minimal beam loss; see Fig. 4. Noticeably, when the beam size increased as a result of this, the instability no longer presented.

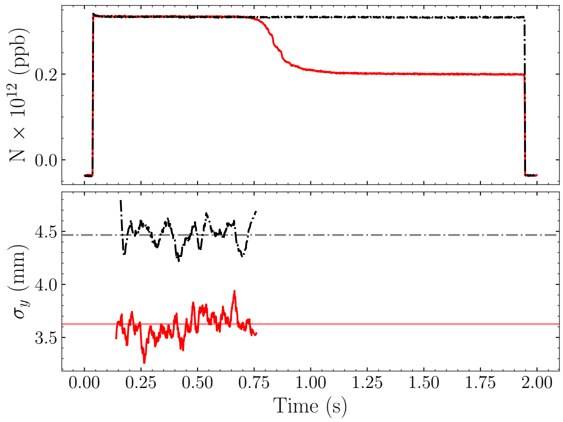

Figure 4: Beam intensity (a) and IPM data (b) when the beam size increased (dotted black) and without the beam size blowup (solid red).

DISCUSSION

The change in the tune to eliminate the instability resulted in a small difference in the bunch length that is within the measurement uncertainty, thus eliminating any longitudinal emittance growth that could contribute to the effect. Moreover, the shape of the longitudinal profile remained almost identical despite the tune change. In terms of the transverse profile of the beam, the IPM data showed no significant beam size increase ($\sigma_V \sim 3$ mm and $\sigma_H \sim 2.5$ mm) before and after the tune change. Subsequently, the bunch distribution in the vertical plane did not significantly change; i. e., no significant changes were observed in the $A + B$ signal from split-plate BPM.

Space charge forces generate an incoherent tune shift that can be computed, for a Gaussian beam as:

$$\Delta\nu = \frac{-N r_0 R S}{8\sigma_z M \beta\gamma^2 \varepsilon_{N,\text{rms}}} F, \quad (1)$$

where N is the number of protons (i. e., intensity) $r_0 = 1.535 \times 10^{-18}$ m is the classical radius of the proton, 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, $\varepsilon_{N,\text{rms}}$ is the normalized root mean square emittance and F is a factor to account for the unequal beam sizes in both planes [7]. It is convenient to express the space-charge tune shift in units of synchrotron tune where:

$$q = \frac{\Delta\nu}{\nu_s}, \quad (2)$$

where $\nu_s = 0.0005$ is the synchrotron tune. During our experiment, the normalized space-charge tune shift q decreases from 16 to 10, for 3.6 and 4.5 mm size beam, respectively. Since the instability vanishes at this tune shift, it could be an indication that it may not be a TMCI, since a lower space-charge tune shift should decrease the TMCI threshold. This can also be further confirmed by observing the intra-bunch motion of the beam while the instability is growing; see Fig. 5. The motion is dominated by the tail of the beam rather than having a symmetrical shape between the head and the tail. This shape is not commonly observed in TMCI instabilities, but rather a symmetrical standing wave [8] or a head dominated structure. It should be noted that, despite only being observed in the tail region of the beam, the vertical displacement of the beam shows a node-like structure, which indicates that different modes are excited by the instability.

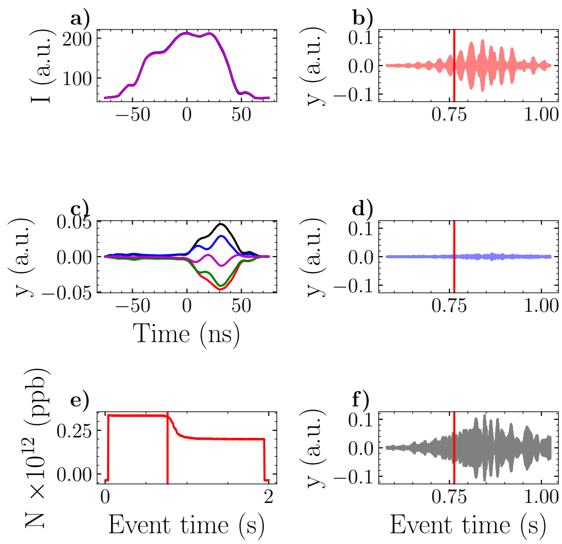

Figure 5: Transverse distribution (a) and vertical motion of the bunch when the instability was present (c). In (e), the plot shows the beam intensity, and the vertical line represents when the snapshot was taken in the event timeline. In (b), (d), and (f) the average motion of the beam was sampled at the center, head, and tail of the bunch, respectively.

SUMMARY

In RR, a single-bunch instability was addressed by adjusting the horizontal and vertical tunes from 0.4/0.44 to 0.39/0.46, respectively, effectively eliminating the instability without causing notable changes in beam distribution or size.

To explore the role of space-charge in this instability, we increased beam size at constant intensity, leading to the instability's disappearance, indicating it might not be TMCI. Furthermore, vertical intra-bunch motion exhibited significant tail amplification, linearly increasing with higher intensities, along with the instability's growth rate.

Despite these insights, the instability's origin remains unclear. The interplay between vertical motion and space charge suggests a potential new convective instability, as theorized by Ref. [6]. However, the unexpected tune dependence prompts further investigation. The introduced tune change may have induced subtle changes in the particle distribution at the tail of the beam, where these particles exert a substantial influence on Landau damping. This change may have been too small to register on our diagnostic instruments. Nevertheless, more simulation tools with realistic impedance models will be employed to investigate this further.

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ACKNOWLEDGEMENTS

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

REFERENCES

[1] A. W. Chao, "Physics of collective beam instabilities in highenergy accelerators," *Wiley Series in Beam Physics and Accelerator Technology*, New York, USA, Wiley-VCH, 1993.

[2] K.-Y. Ng, *Physics of intensity dependent beam instabilities*, Singapore, World Scientific, 2006. doi:10.1142/5835,

[3] M. Blaskiewicz, "Fast head-tail instability with space charge," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 1, no. 4, p. 044201, 1998. doi:10.1103/PhysRevSTAB.1.044201

[4] V. Balbekov, "Transverse mode coupling instability threshold with space charge and different wakefields," *Phys. Rev. Accel. Beams*, vol. 20, no. 3, p. 034401, 2017. doi:10.1103/PhysRevAccelBeams.20.034401

[5] T. Zolkin, A. Burov, and B. Pandey, "Transverse mode-coupling instability and space charge," *Phys. Rev. Accel. Beams*, vol. 21, no. 10, p. 104201, 2018. doi:10.1103/PhysRevAccelBeams.21.104201

[6] A. Burov, "Convective instabilities of bunched beams with space charge," *Phys. Rev. Accel. Beams*, vol. 22, no. 3, p. 034202, 2019. doi:10.1103/PhysRevAccelBeams.22.034202

[7] Z. Y. Zhang, T. Roser, and W. Weng, "Calculation of incoherent space charge tune spread," Brookhaven National Lab., Upton, NY, USA, Rep. 449, 1996.

[8] E. Métral *et al.*, "Space charge and transverse instabilities at the CERN SPS and LHC", in *Proc. ICAP'18*, Key West, Florida, USA, Oct. 2018, pp. 80–86. doi:10.18429/JACoW-ICAP2018-SUPAG01