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The Waker Experiment: A wake-building feedback system to study beam instabilities in the presence of strong space charge

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24/10/22

Overview

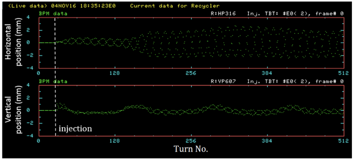
1. Introduction
   - Motivation
   - Transverse Mode Coupling Instability (TMCI)
   - Convective Instability
2. Experiment
   - The waker system
   - Fermilab Recycler
   - Results
3. Conclusion

Acknowledgment

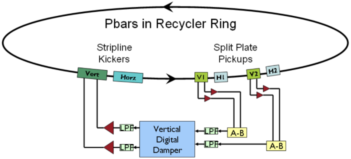
I would like to acknowledge the work and help from:
R. Ainsworth, N. Eddy, A. Burov and Eric Stern

Beam Instabilities

- Beam instabilities often stand in the way of the quest of beam intensity. As the intensity becomes high, machine suffer from beam losses and beam degradation.
- Several classes of instabilities exist in both Transverse (e.g. Head-Tail instability), and longitudinal (e.g. Robinson instability) plans.
- Typically, feedback systems (e.g. dampers) are used to stabilize the beam for some of these instabilities.



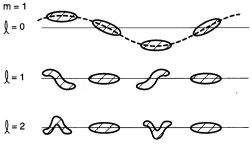
Electron cloud instabilities at the FermiLab Recylcer ((Antipov, 2018))



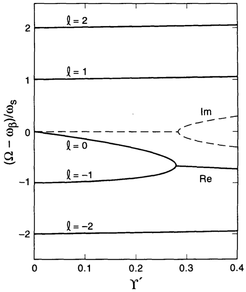
typical damper system at Fermilab(Eddy et al., 2008)

Transverse Mode Coupling Instability (TMCI)

- As the intensity increases, the frequency of the coherent modes of the beam shifts. Once 2 coherent modes become degenerate in frequency, the beam is unstable.
- The instability caused by the coupling of these coherent modes is known as Transverse Mode Coupling Instabilities (TMCI) and is known to be a limiting factor in beam intensity.



Coupling of modes.



frequency shift of coherent modes in the absence of SC (Chao, 1993)

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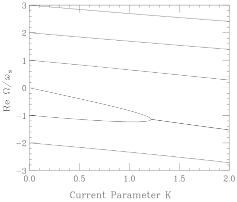
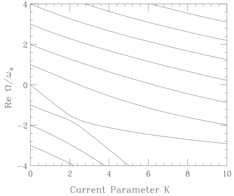
TMCI and space charge

- The threshold parameter of TMCI Γ and SC has been shown to be proportional (i.e. as SC increases, the threshold of TMCI increases).
- Recent theoretical models suggest the existence of convective instability that governs the lower portion of the SC-Wake Space.



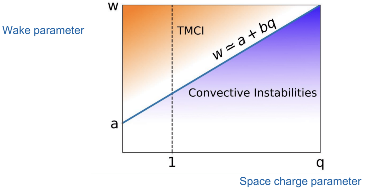
schematic of coherent Modes at low SC

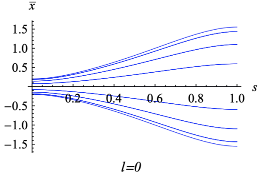


schematic of coherent Modes at High SC. The -1 mode shifted down such that it no longer couples with 0 mode (Ng, 2006)

Convective Instability

- As the space charge (intensity) increases, the threshold of TMCI is increased and TMCI becomes a vanishing instability. However, a new type of instability take place called Convective Instability.
- This instability is characterized by a large amplification of the head-tail oscillations. However, the beam remains meta-stable.
- Additional perturbation will cause the bunch become unstable and results in losses and intensity limits.

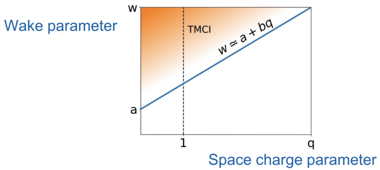




Large amplification of the head-to-tail oscillations associated with the convective instabilities (Burov, 2019)

The waker

- How do we explore the Wake-SC parameter space?
- Varying SC parameter can be achieved by increasing or decreasing the number of particle, but the wake is set by the machine.
- The solution is to have a system that artificially mimics and apply the wake.



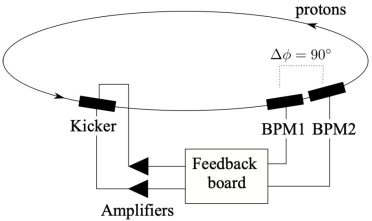
The waker

- A dedicated feedback system to induce instabilities in the beam.
- The system measures the position and intensity along a single bunch, then applies multiple kicks along the bunch:

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

- For such system to work, we need the bandwidth (BW) to be:

$$BW \gg \frac{1}{\sigma_t}$$



Schematic of the waker system in the Fermilab Recycler ring (Ainsworth, 2020)

- The recylcer rebunches the beam at 2.5 MHz (30 ns) for $g - 2$

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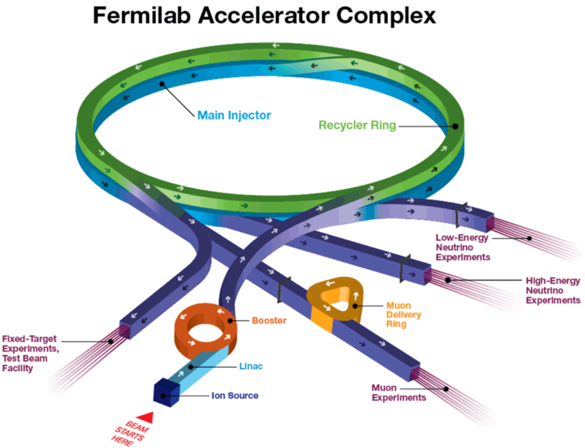
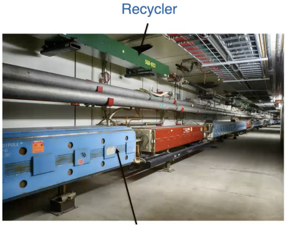


Fermilab Accelerator Complex
Main Injector
Recycler Ring
Low-Energy Neutrino Experiments
High-Energy Neutrino Experiments
Muon Delivery Ring
Booster
Fixed-Target Experiments, Test Beam Facility
Linac
Ion Source
Muon Experiments
BEAM STARTS HERE

Recycler Ring

- Permanent magnet ring that was designed to recycle anti-protons from the Tevatron.
- Currently, the Recycler is used for slip stacking and injection into Main Injector (MI).



Recycler (top) and Main Injector (bottom)

Machine parameters relevant to the waker experiment

Q_s	0.0005
$\zeta_{x,y}$	0.03,-0.15
$\delta p/p$	0.0005
N	1e11-5.5e11 pbb
σ_t	40-50 ns
$\varepsilon_{95\%}$	15 π mm mrad
β	0.9944
R	528 m

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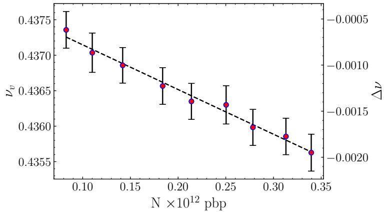
Recent results: Tune shift

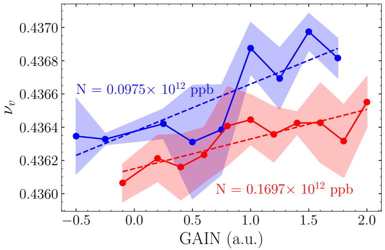
- For all of our measurements, we typically use strip-line pick-up to record the position along the bunch.
- By varying the intensity in the recycler and measuring the tune shift without the waker we can find the natural tune shift.



Measured vertical tune ν_V while varying the intensity.

Tune shift due to the waker

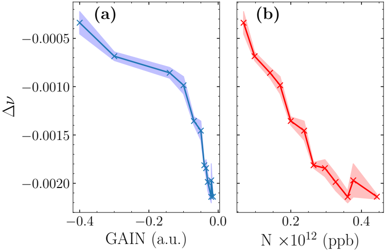
- The waker is turned on for 10,000 turns with a Heaviside step wake.
- Varying the gain in the system is equivalent to increasing or decreasing the wake kick.
- The gain effect on the tune is opposite to the natural tune shift observed (i.e. the tune increases as the gain increases).



Measured vertical tune ν_V at different gain for 2 different intensities.

Tune shift at instability threshold

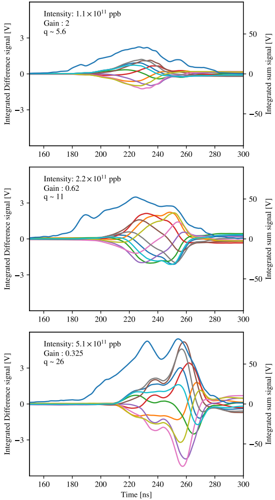
- We change the gain (decrease/increase) until we observe an instability, this is repeated at different intensities.
- At low intensities (small tune shifts) more negative gain is required to couple the transverse mode; i.e. where the instability threshold is found. Likewise, at high intensities, less negative gain is required to reach the instability threshold.



Measured vertical tune ν_V at different gain for 2 different intensities.

Head-Tail amplification

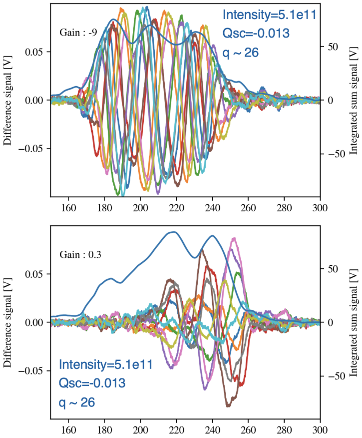
- From previous runs, we observed that, at different threshold , we observe different longitudinal profile of the beam.
- symmetrical (TMCI like) instabilities verses large head to tail amplification.



Different in long. profile of the bunch at different gain

Head-Tail amplification

- From previous runs, we also observe different long. profile for the same intensity at different gain.
- Due to time constrains, such measurement where not obtained this run.



Different in long. profile of the bunch at different gain.

Summary

- We have built and commissioned a waker system that is able to induce instabilities by applying a wake kick to the beam.
- Our initial results are very promising in terms what we expect from the tune shift and the long. profile of the bunch.
- Recent upgrades to the system will include a new board that allows us to go to a higher bandwidth.
- Our next step is to obtain quantitative data with respect to the instability threshold and benchmark with the existing theory.
- We are hoping to use different codes (e.g. Synergia) to benchmark our results.

Summary slide:

- I presented our waker experiments design and initial results at Fermi National Laboratory in the recycler ring
- More understanding in how TMCI is effected by space charge is required in order to attain higher intensities for future physics experiments and projects.
- More experimental investigation is required to pin down these issue. Moreover, impedance models in simulation codes need to be benchmarked and tested with different experiments and analytical models

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