

September 30, 2026

Experimental Studies of Space Charge and Collective Beam Instabilities with the Fermilab Recycler Waker System

Cristhian Gonzalez-Ortiz

Space Charge 2026



U.S. DEPARTMENT
of **ENERGY**

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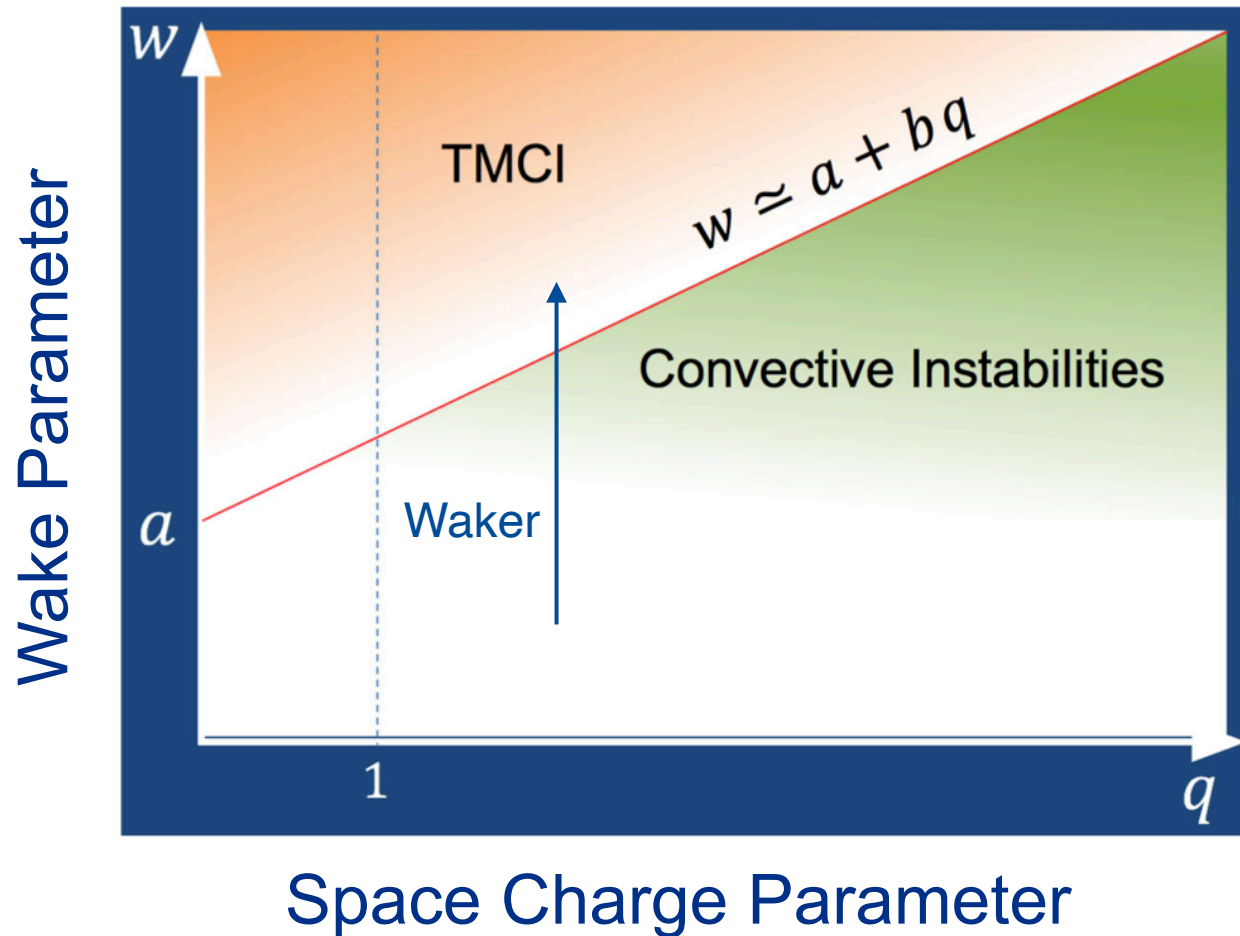
Waker Motivation



The Waker and Convective Instabilities

This talk is about dipole head-tail modes in a single bunch.

A. Burov proposes the ABS (Air Bag in a Square well) model to study this phenomenon.



$$w = \frac{N_p W_0 r_0 R_0}{4\pi\gamma\beta^2 Q_\beta Q_s} \sim \frac{\Delta Q_\beta^{(\text{coh})}}{Q_s}$$

$$q_{SC} = \frac{\Delta Q_\beta^{(\text{inc})}}{Q_s}$$

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 034202 (2019)

Convective instabilities of bunched beams with space charge

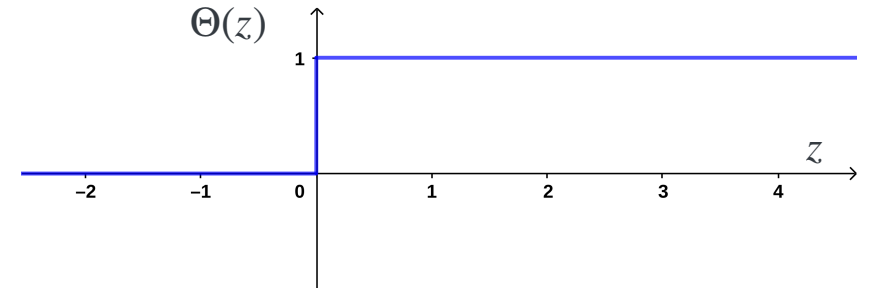
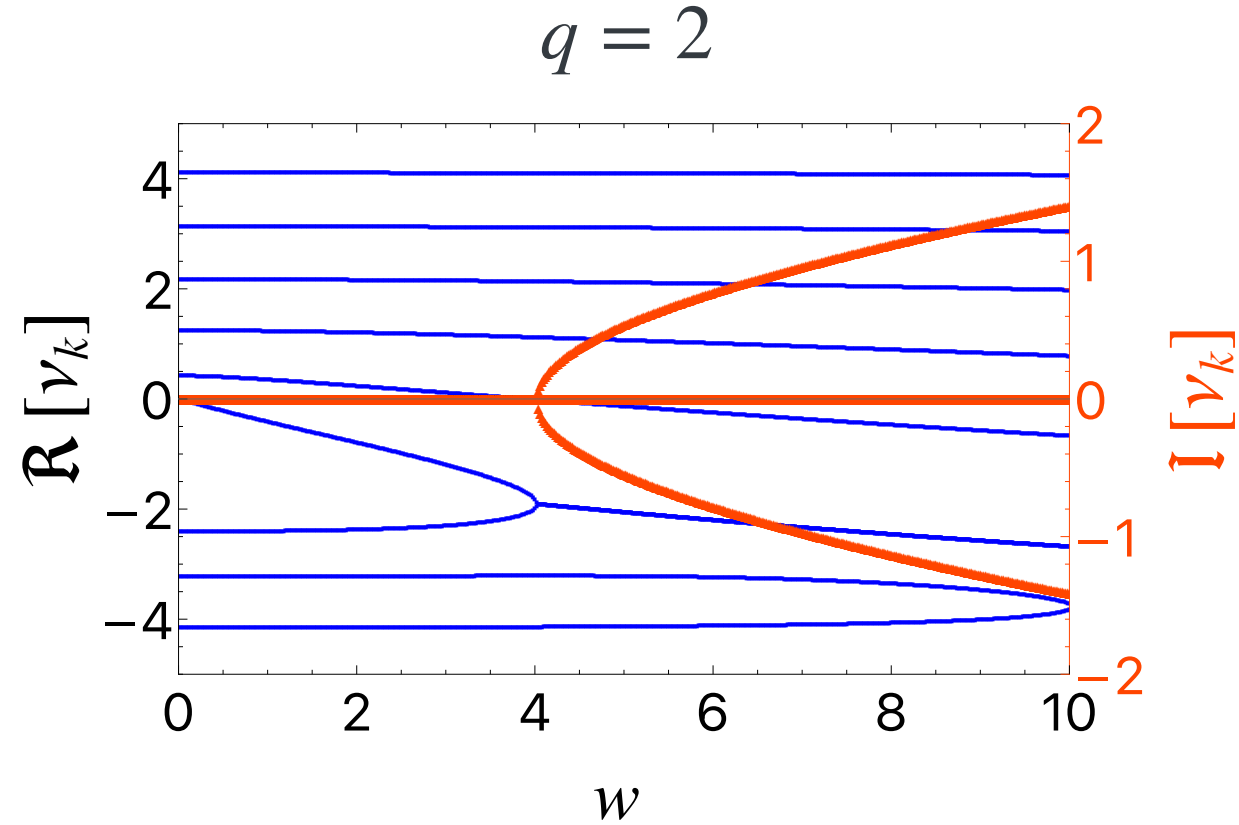
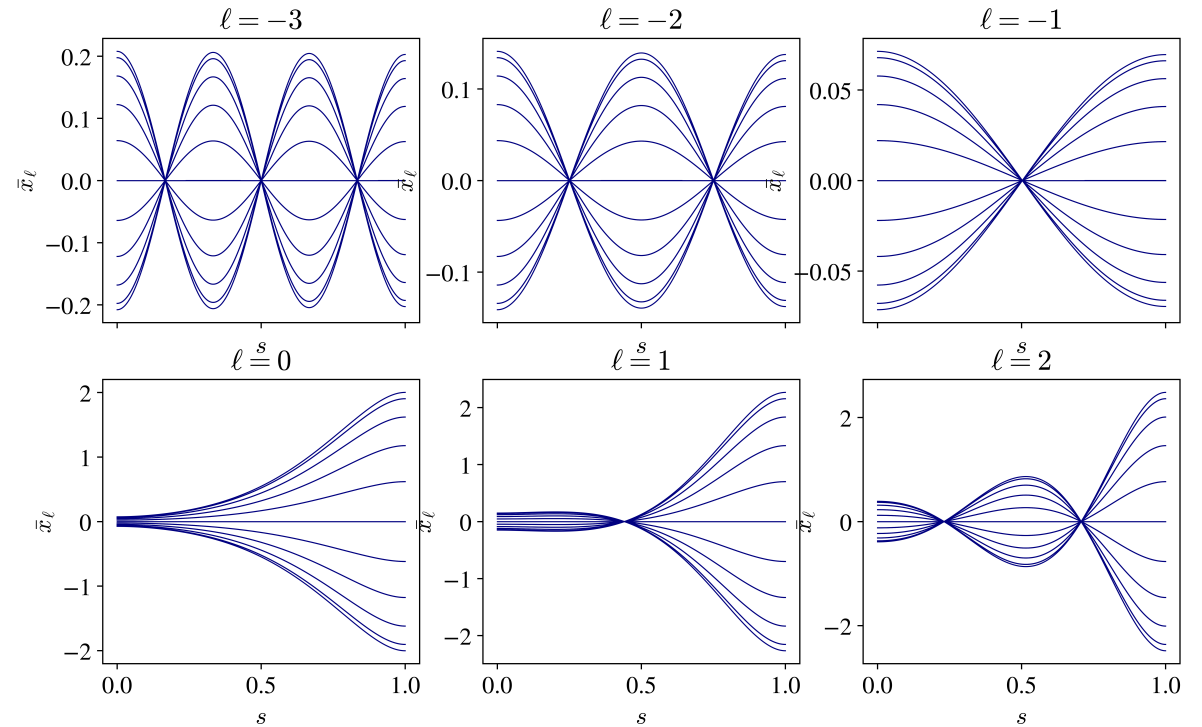
A. Burov*

Fermilab, P.O. Box 500, Batavia, Illinois 60510-5011, USA



Convective Instabilities

Solution to the ABS equations for a step (theta) single-turn wake



TMCI

vs.

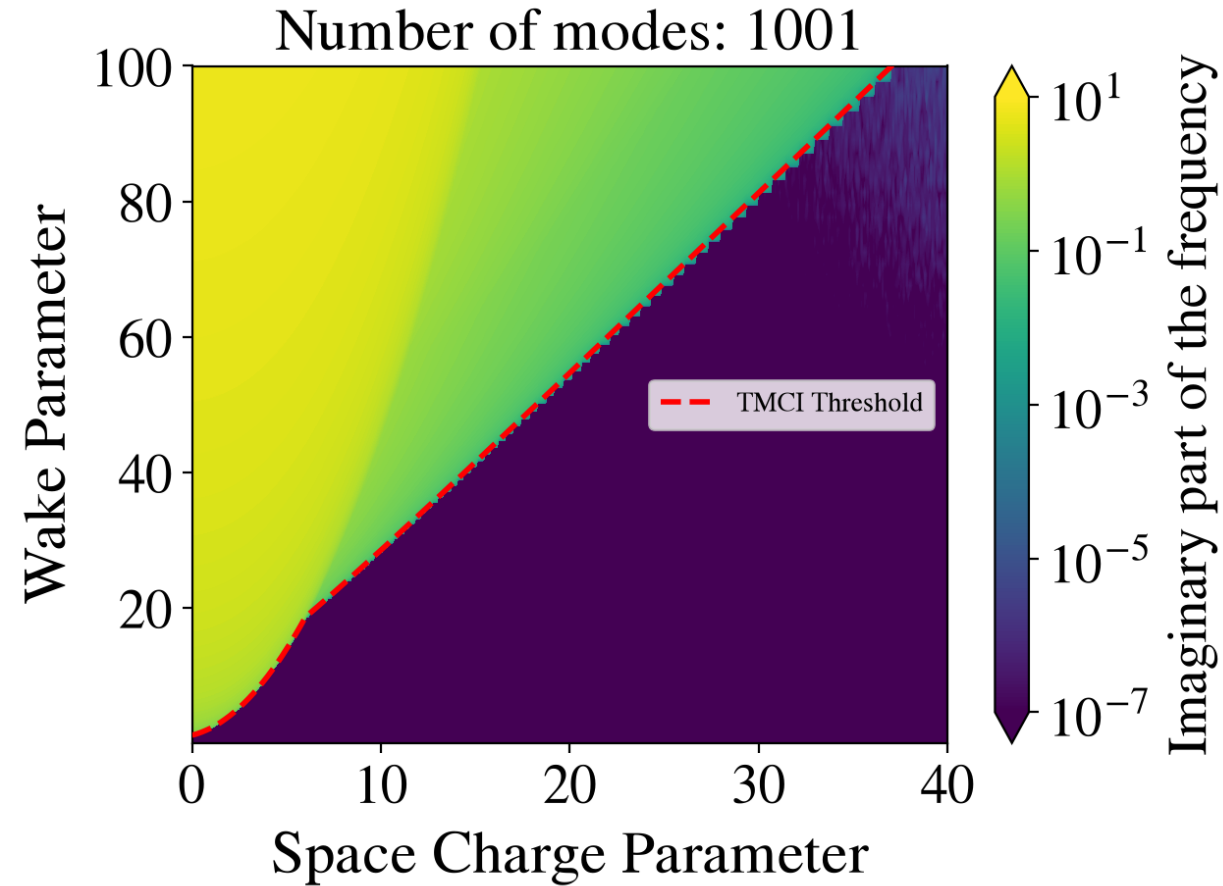
Convective Instabilities



Convective Instabilities

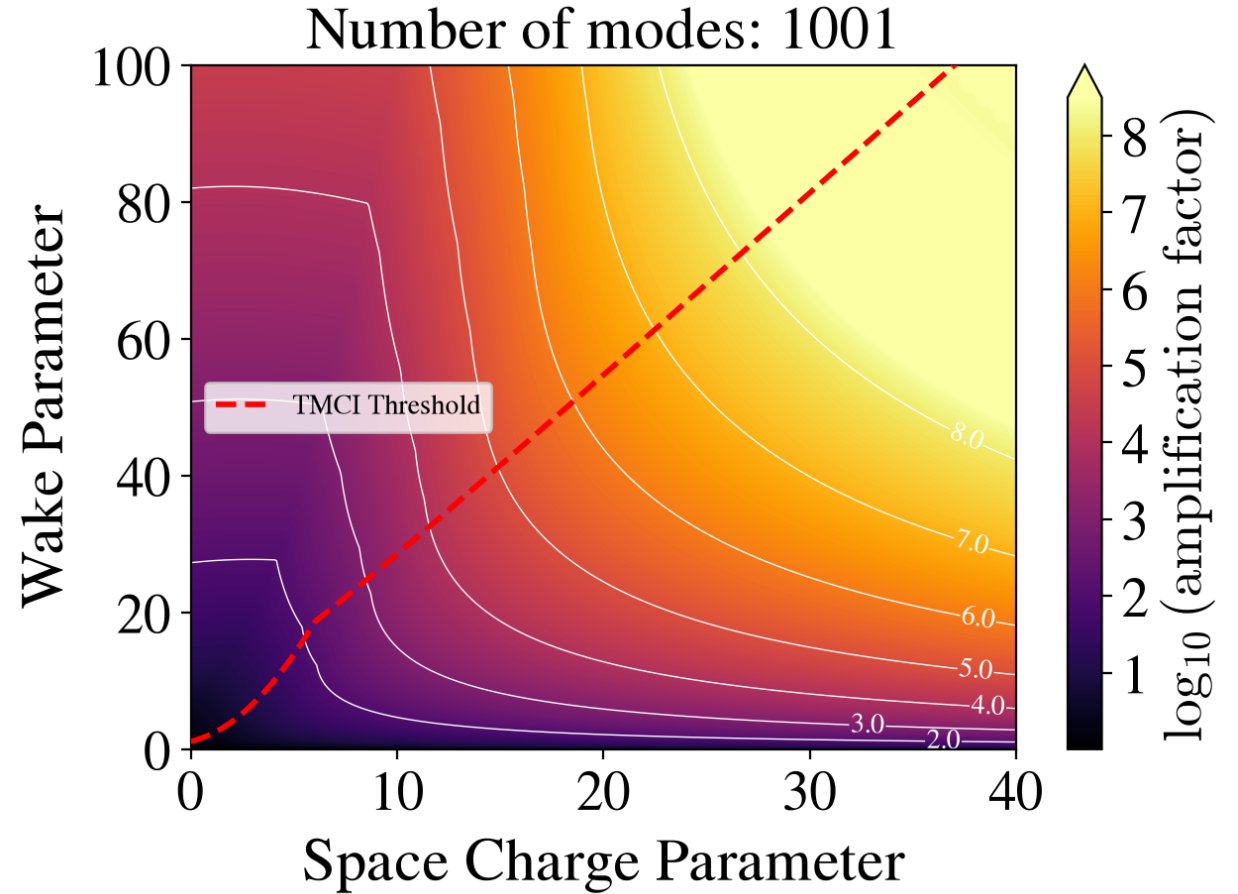
TMCI threshold changes with space charge parameter.

TMCI and convective instabilities landscape for a step (theta) single-turn wake.



TMCI

vs.



Convective Instabilities

01

Waker Experimental Setup

5th North American Particle Accel. Conf.
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ISSN: 2673-7000

FERMILAB CONF-22-011-AD
JACoW Publishing
doi:10.18429/JACoW-NAPAC2022-MOPA33

WAKER EXPERIMENTS AT FERMILAB RECYCLER RING

O. Mohsen*, R. Ainsworth, N. Eddy
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

64th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams
ISBN: 978-3-95450-225-7

HB2021, Batavia, IL, USA
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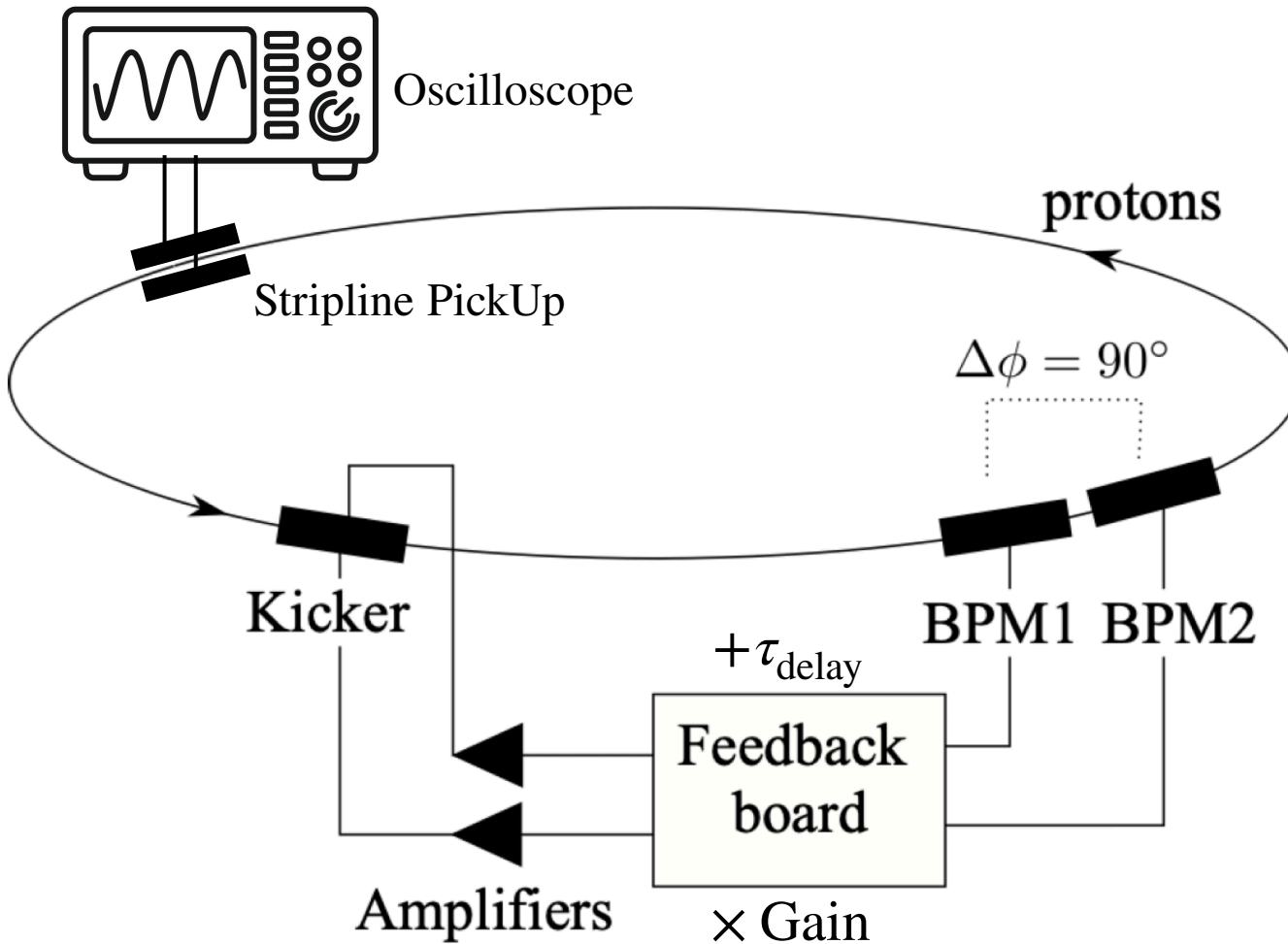
A DEDICATED WAKE-BUILDING FEEDBACK SYSTEM TO STUDY SINGLE BUNCH INSTABILITIES IN THE PRESENCE OF STRONG SPACE CHARGE

R. Ainsworth*, A. Burov, N. Eddy, A. Semenov, Fermilab[†], Batavia, USA



Waker Experimental Setup

We can control the gain of the Waker after the signal is convoluted with combined BPM signal



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

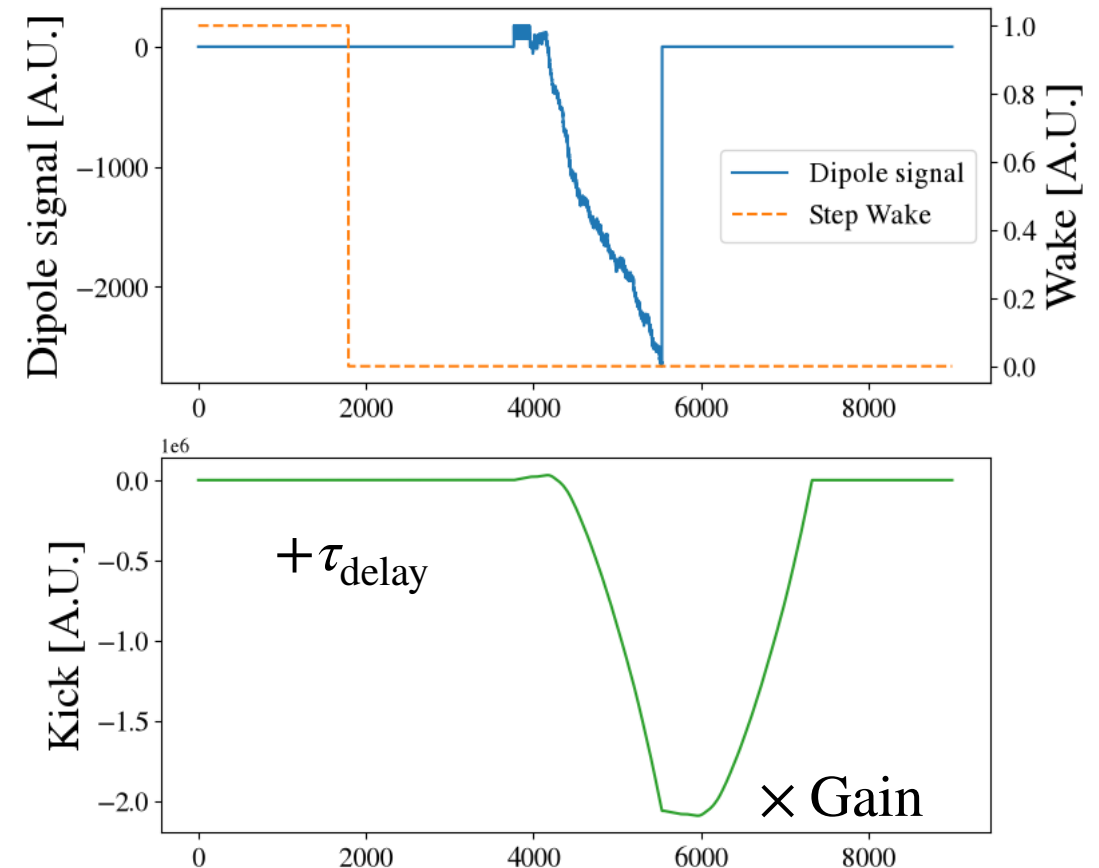
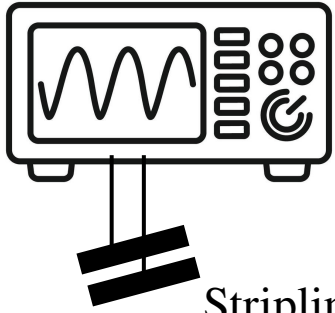


Figure 1: Schematic of the waker system.



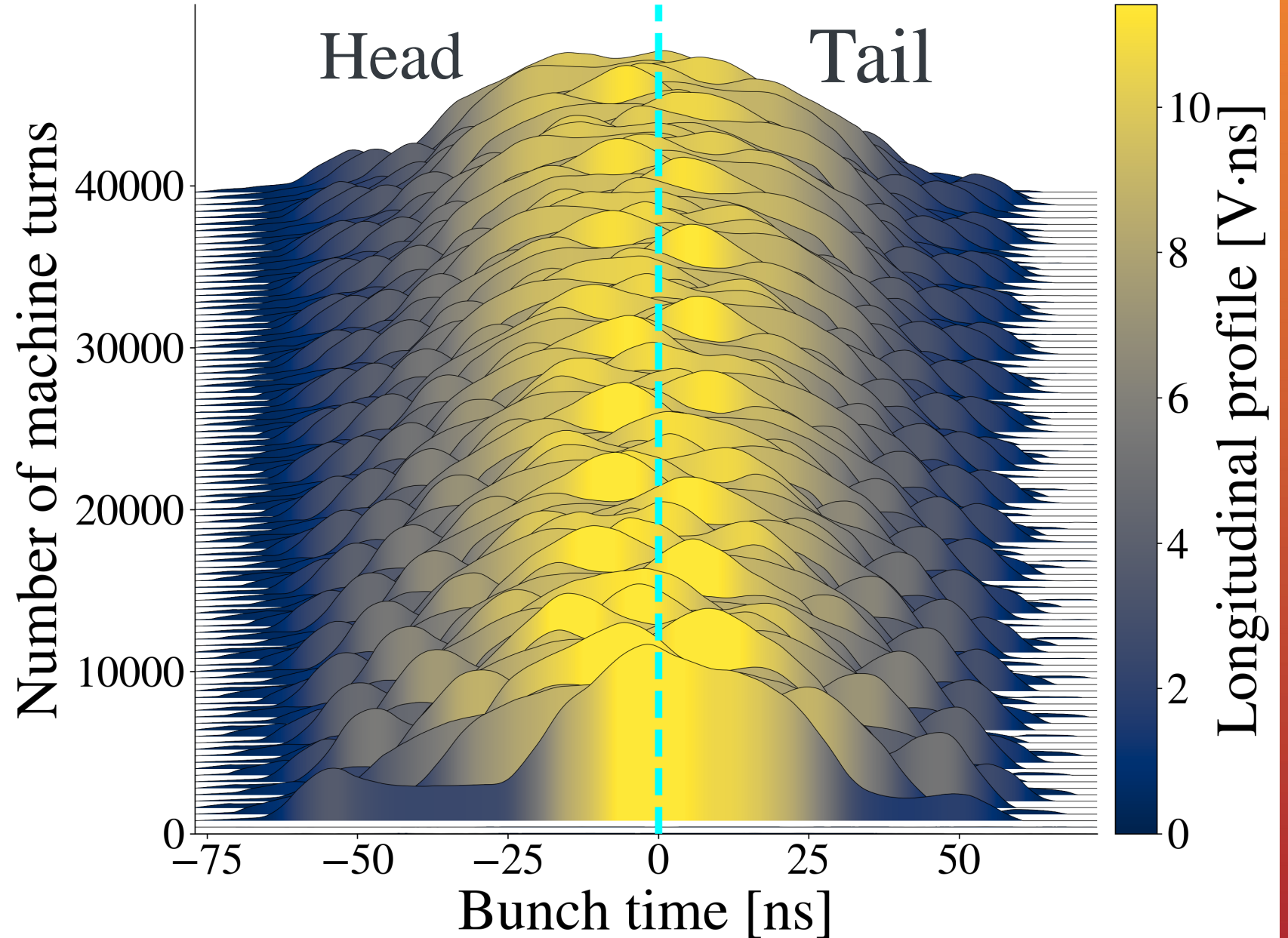
Waker Experimental Setup: Longitudinal Profile



Stripline PickUp

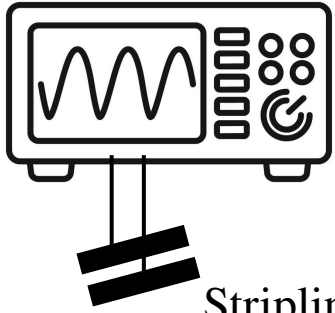
$$A + B \sim \lambda(z)$$

Longitudinal Profile





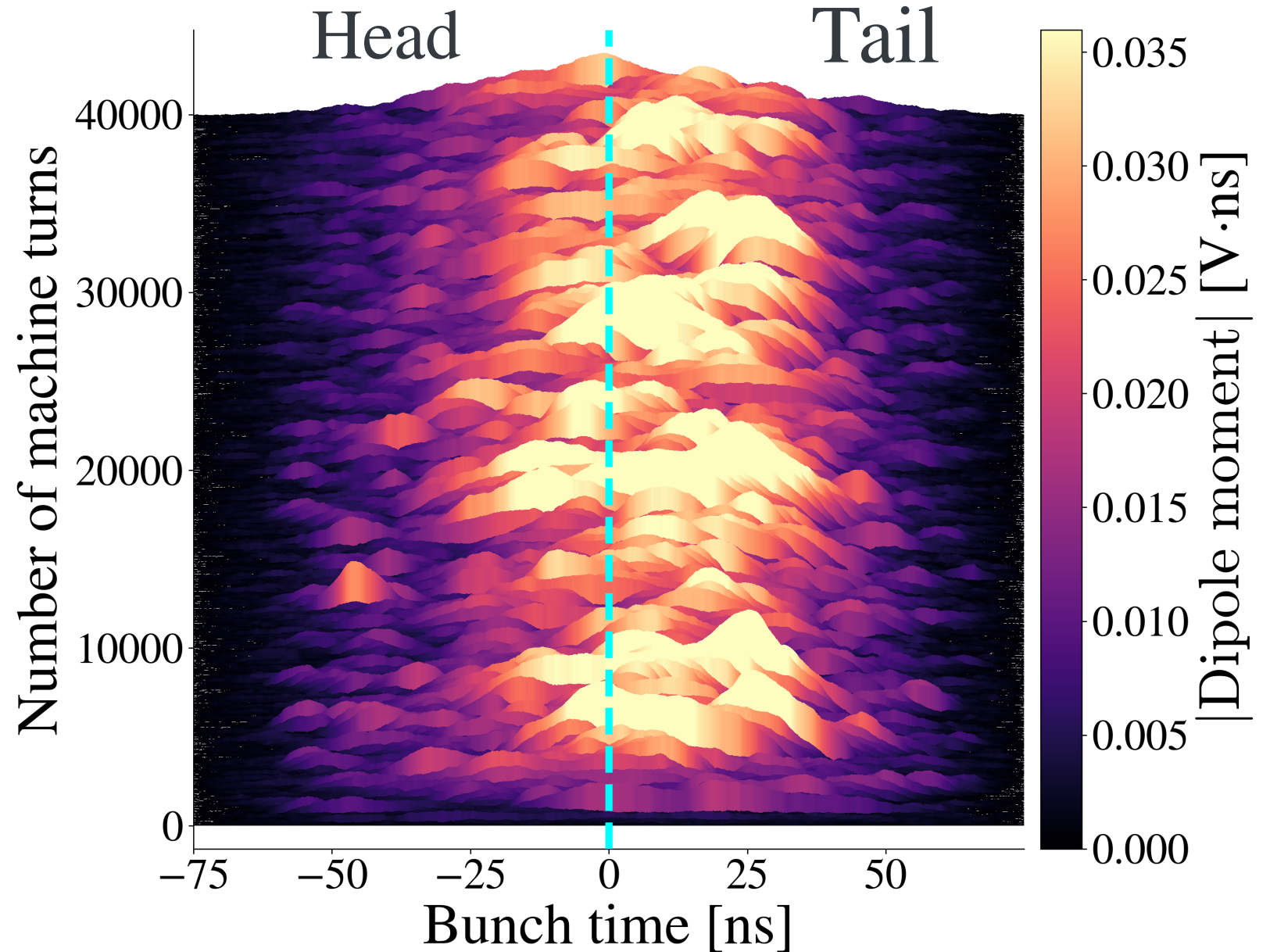
Waker Experimental Setup: Vertical Dipole Moment



Stripline PickUp

$$A - B \sim \bar{y}(z) \lambda(z)$$

Vertical Dipole Profile





02

Intensity and Gain Scan



Experiment: Intensity and Gain Scan

Nominal parameters for Waker experiments

Parameter	Value	Unit
Horizontal Tune Q_x	25.4601	
Vertical Tune Q_y	24.412	
Horizontal Chromaticity ξ_x	0	
Vertical Chromaticity ξ_y	0	
95% Normalized Emittance	15	π mm mrad
Bunch Length σ_z	9	m
95% Longitudinal Emittance	3.64	eV s



Intensity [protons per bunch]



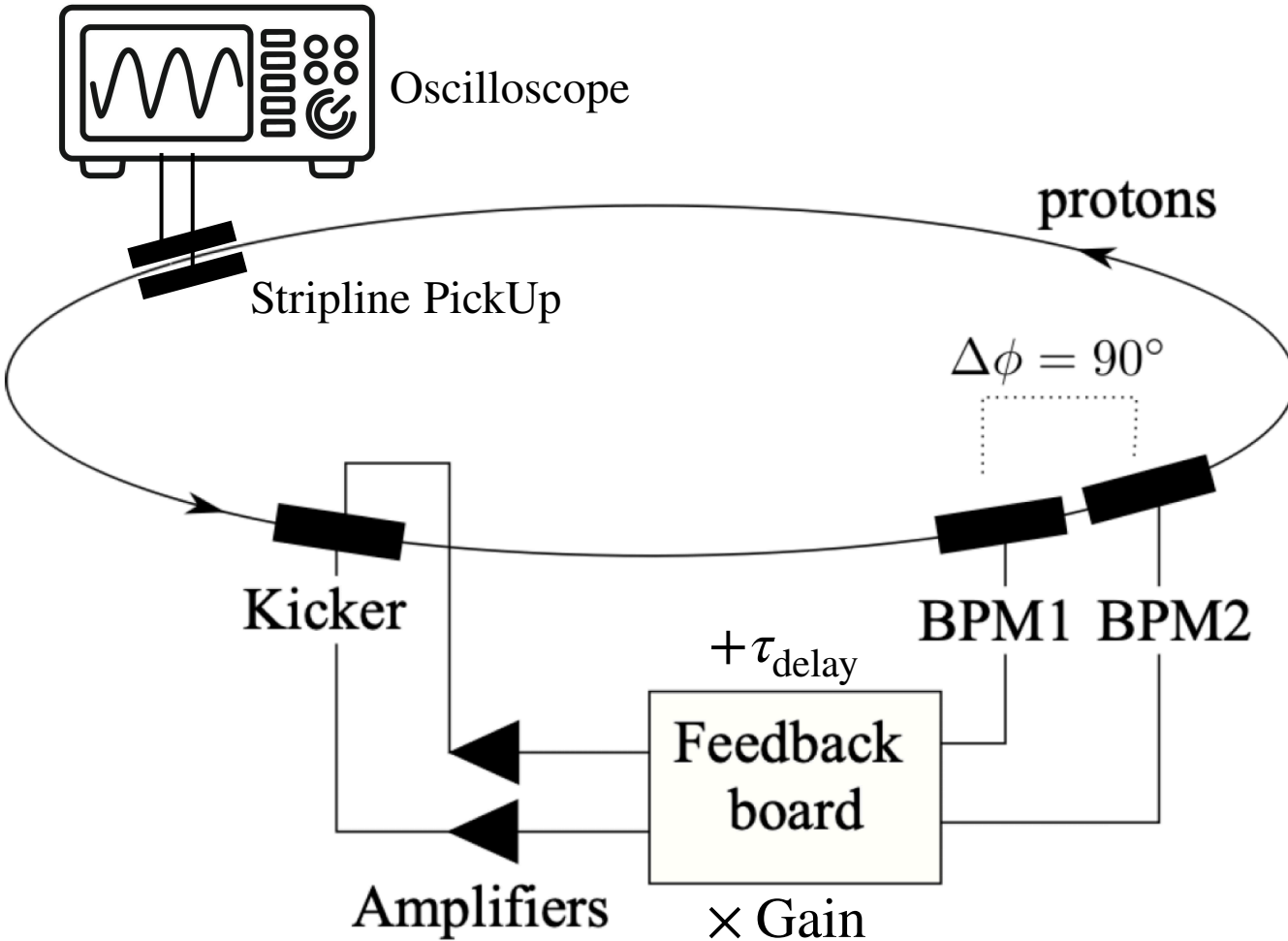
Waker Gain

Parameter	Value	Unit
Circumference C	3319.4	m
Machine Mean Radius R_0	528.30	m
Momentum	8.835	GeV/c
Relativistic Factor γ	9.47	
Revolution Period T_0	11.1	μ s
Revolution Frequency f_0	89.8	kHz
RF Frequency	2.5	MHz
RF Voltage	80	kV
Synchrotron Tune Q_s	0.000595	
Slip Factor η	-8.6×10^{-3}	



Experiment: Intensity and Gain Scan

We can control the gain of the Waker after the step wake is convoluted with combined BPM signal



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

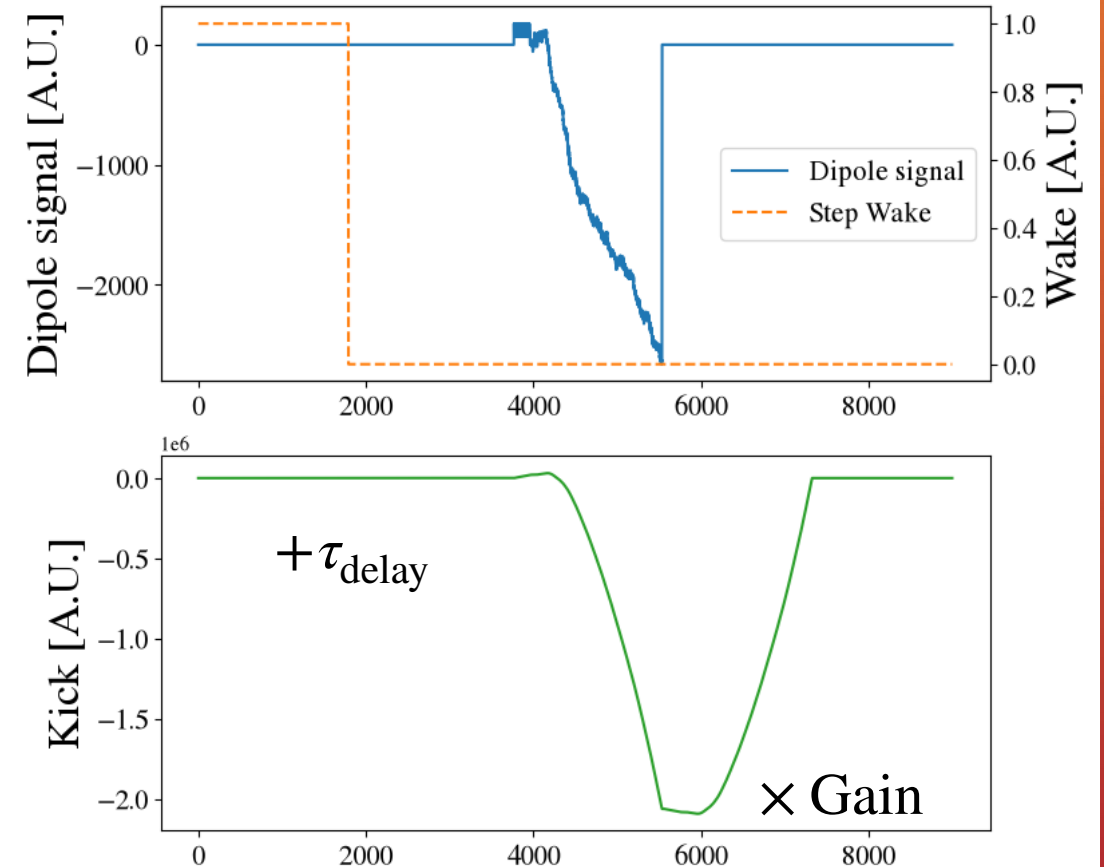
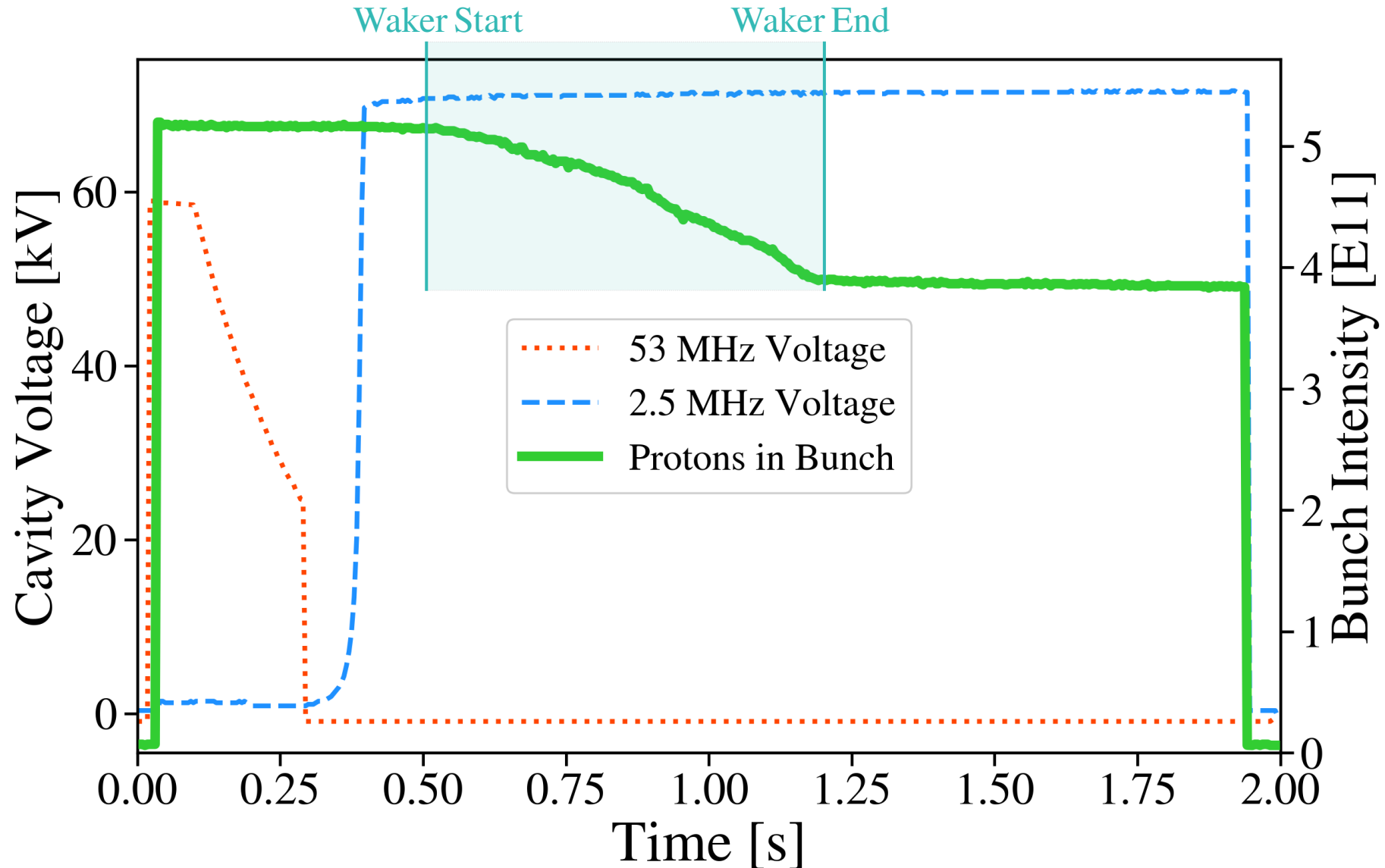


Figure 1: Schematic of the waker system.



Experiment: Intensity and Gain Scan

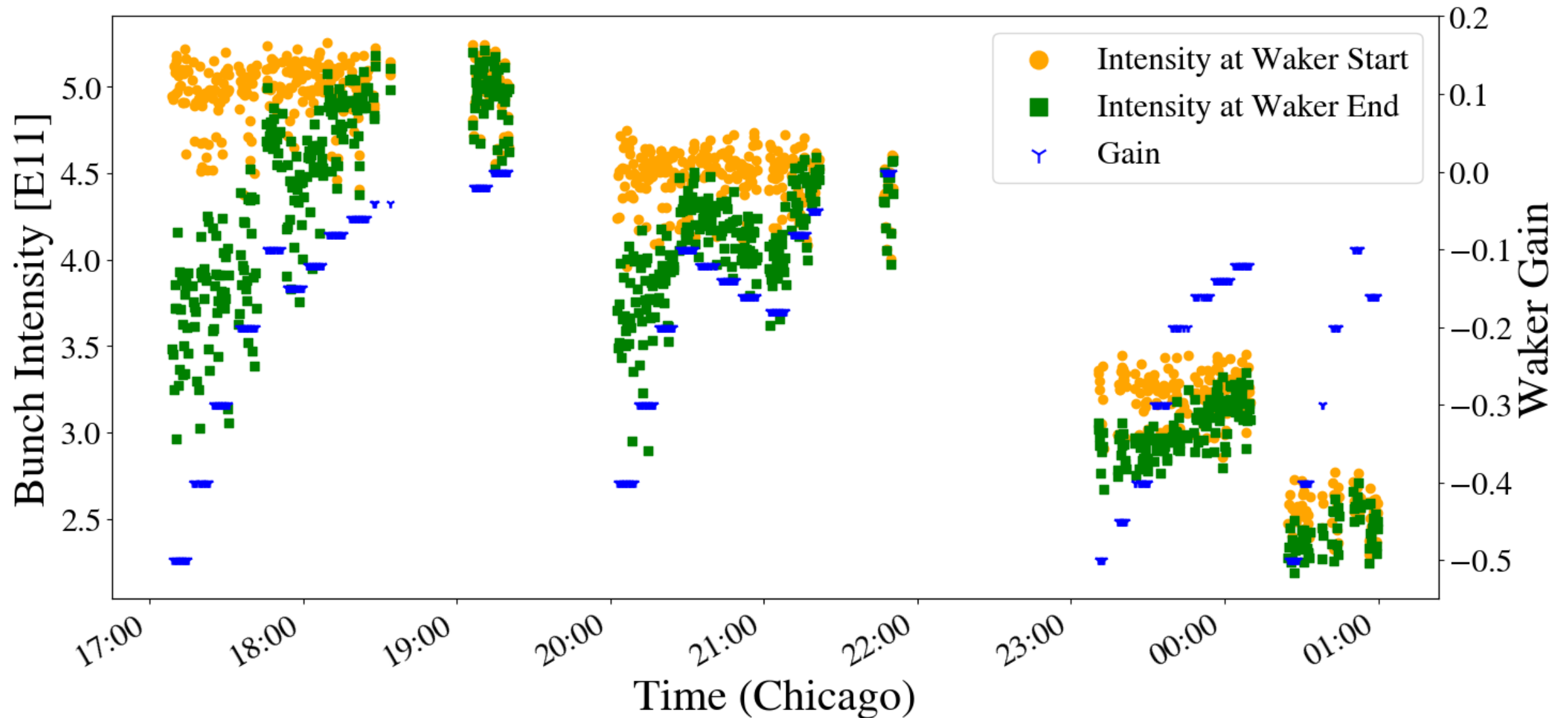
We can control the gain of the Waker after the signal is convoluted with combined BPM signal





Experiment: Intensity and Gain Scan

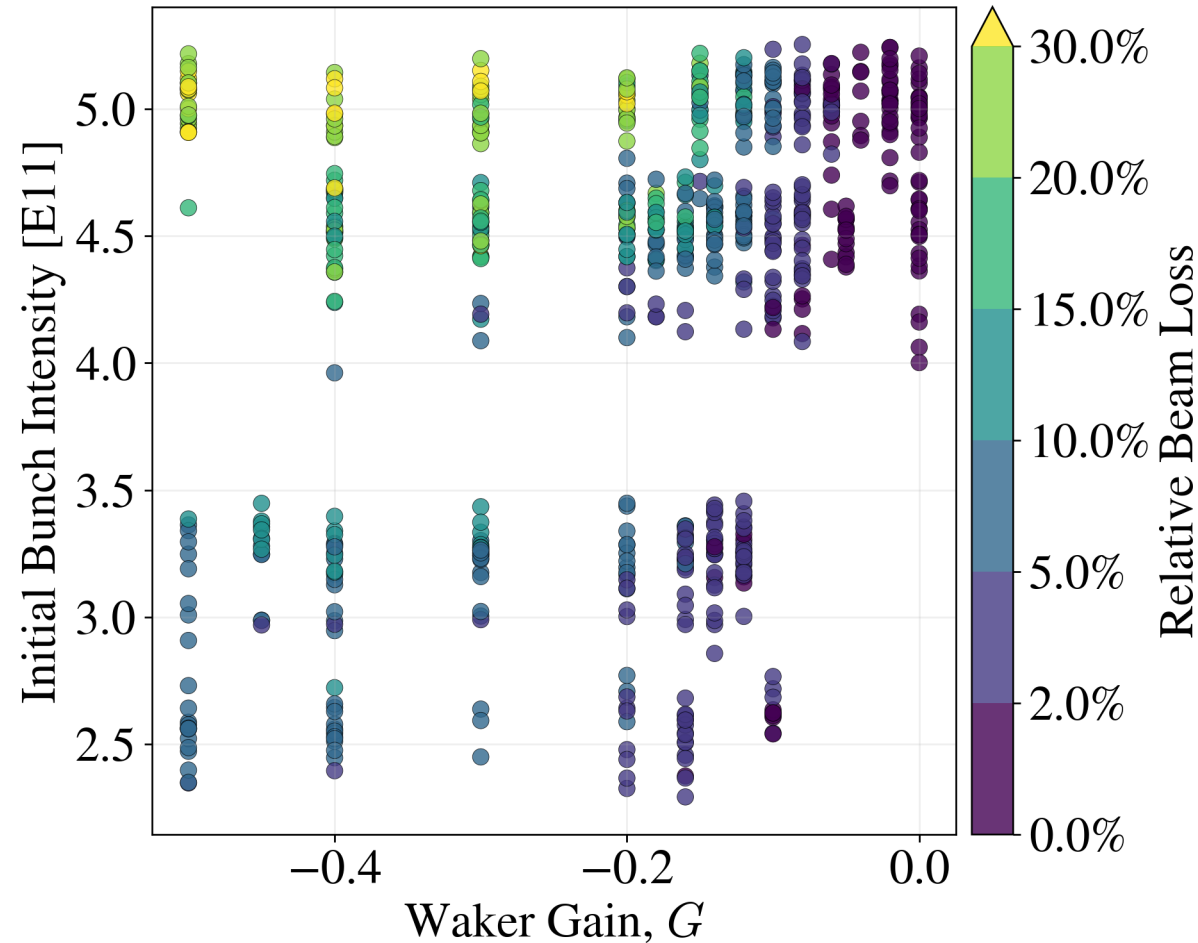
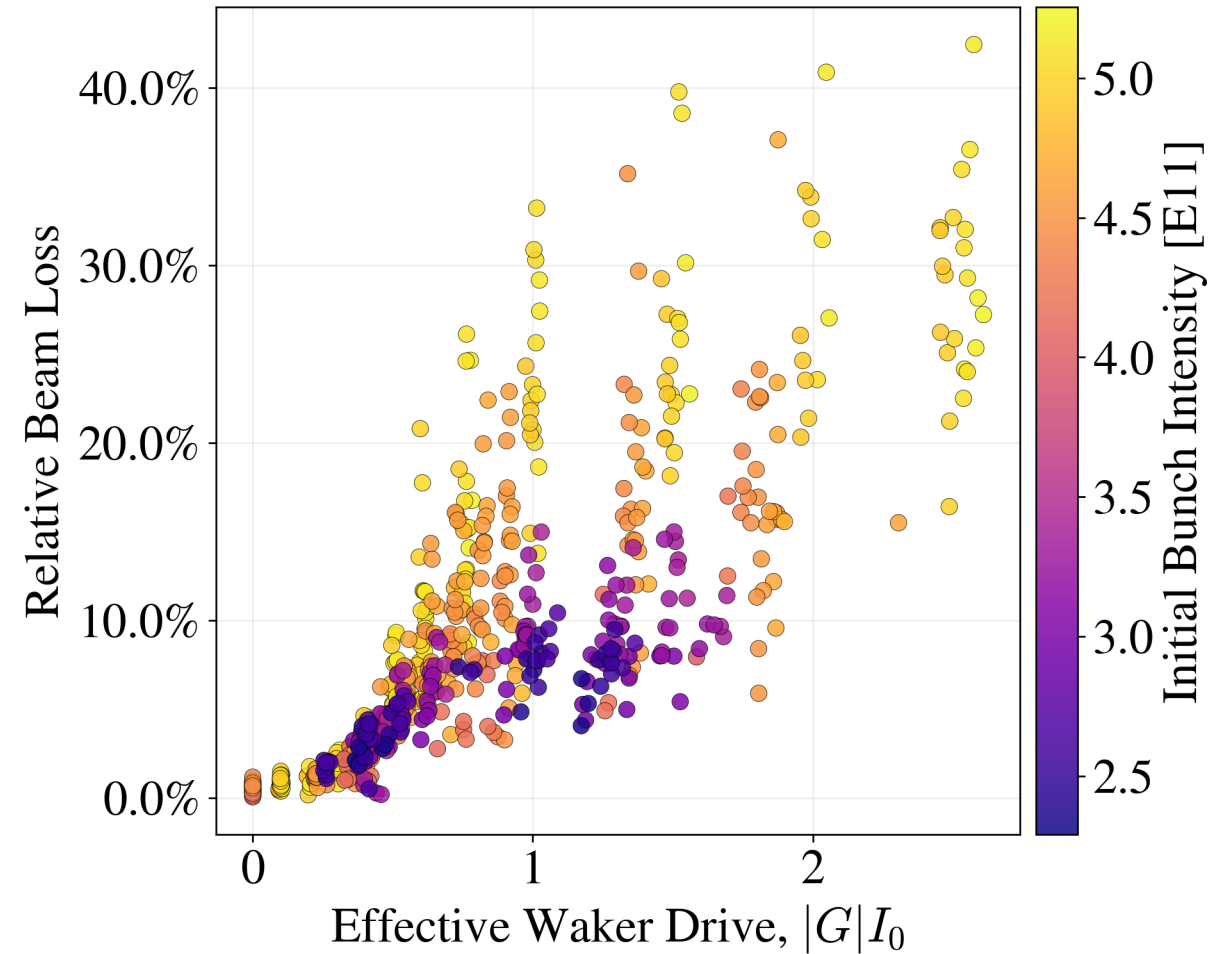
Scanned Waker gain to find threshold at 4 different nominal intensities





Experiment: Intensity and Gain Scan

Relative beam loss against waker gain and initial beam intensity





Experiment: Intensity and Gain Scan

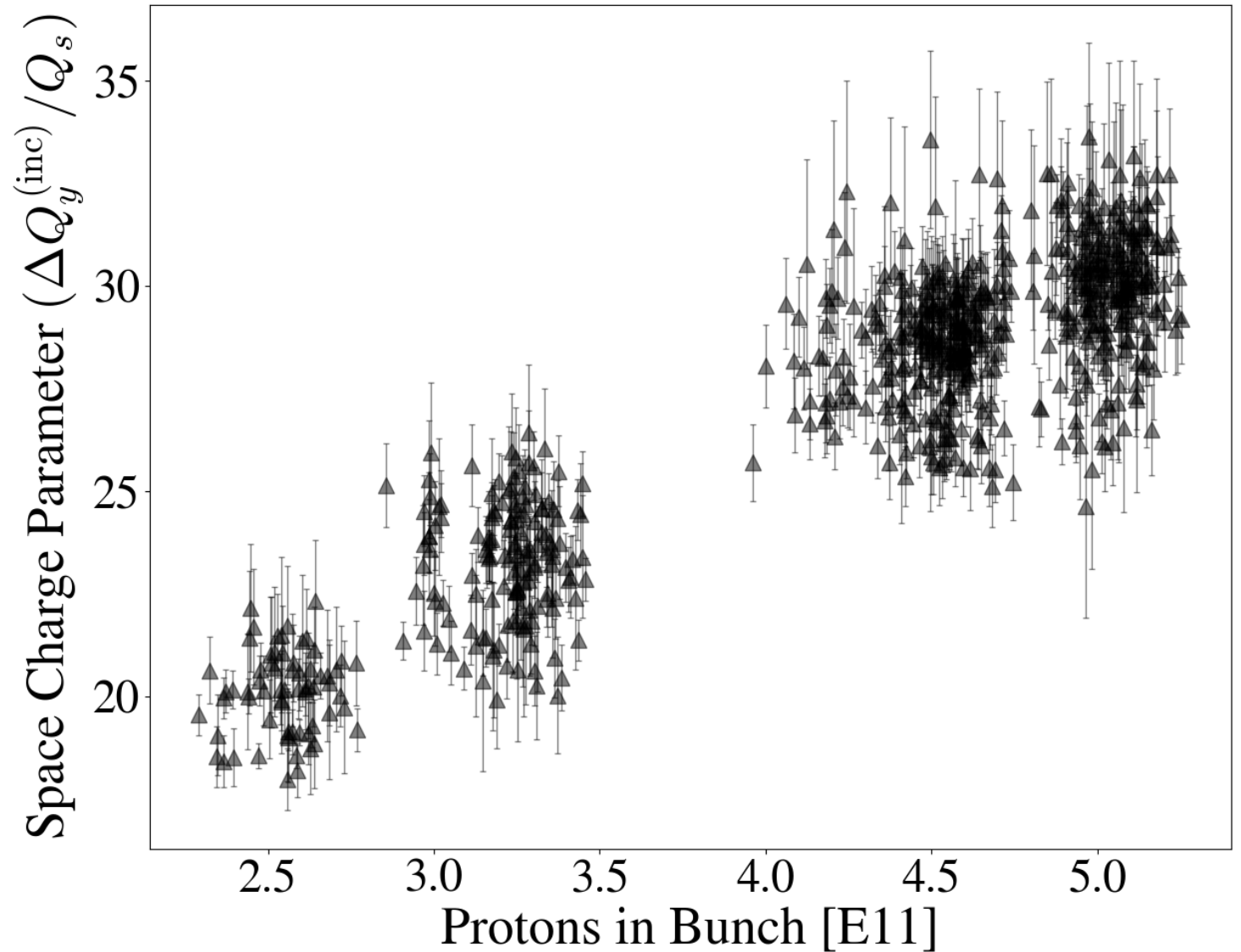
Estimate maximum incoherent tune shift from longitudinal beam size and vertical emittance

$$Q_s = \sqrt{\frac{heV_{RF}|\eta|}{2\pi\beta^2E}}$$

$$Q_s = 0.00043$$

$$\Delta Q_y^{(\text{inc})} = \frac{3Nr_0RS}{4\sigma_z\beta\gamma^2\epsilon_{N,95\%}}$$

S. Y. Zhang, Calculation of Incoherent Space Charge Tune Spread, Technical Report AGS/AD/Tech. Note No. 449 (Brookhaven National Laboratory, 1996).





Experiment: Intensity and Gain Scan

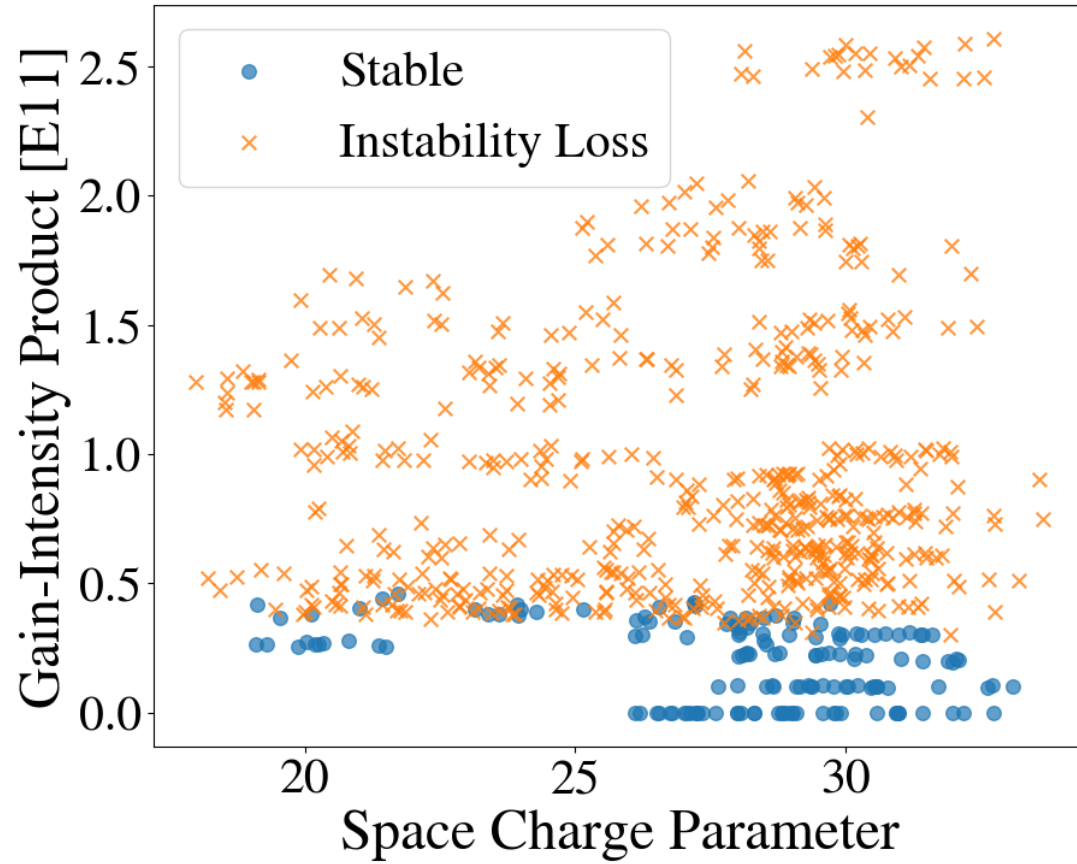
Wake parameter should be proportional to gain-intensity product.

Instability threshold saturates with space charge parameter.

$$w = \frac{N_p W_0 r_0 R_0}{4\pi\gamma\beta^2 Q_\beta Q_s}$$

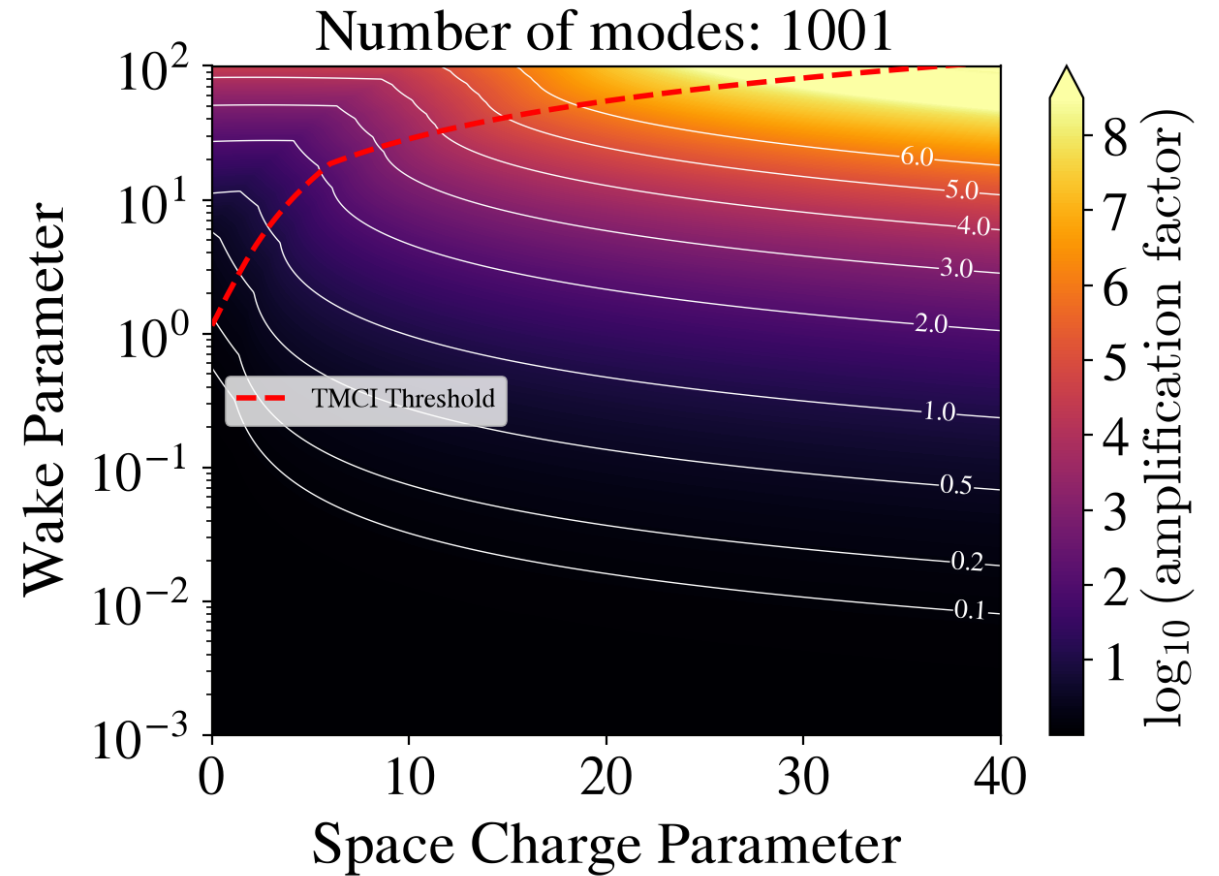
$$W_0 \sim G_{\text{waker}}$$

$$w \sim G N_p$$



Experiment

vs.



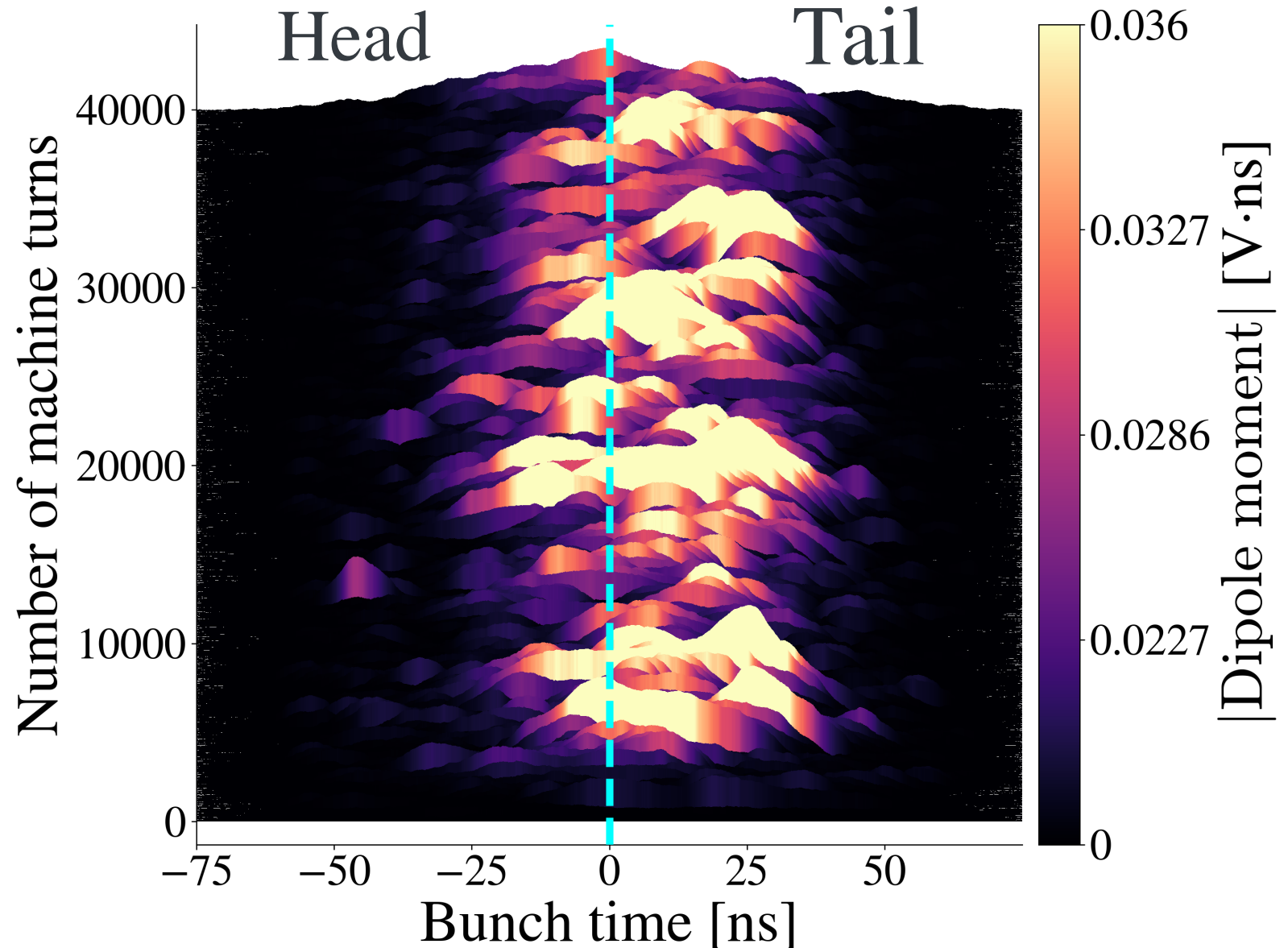
Theory



Experiment: Intensity and Gain Scan

Vertical dipole moment for stable beam. Space charge parameter ~ 30 , **tail-dominated**

OBSERVATION:
Asymmetry
towards tail
for stable beam





Future Work and Outlook

- Instability threshold does not change with space charge parameter (incoherent tune shift).
- Are we looking at convective instabilities?
- Analyze full dataset (1 TB) of scope data
 - Any ideas on how to clean data?
 - Dynamic Mode Decomposition for dipole?
- Waker Run in Recycler Ring for 2026-2027
 - Get more data at lower space charge parameters
 - Try different types of wakes





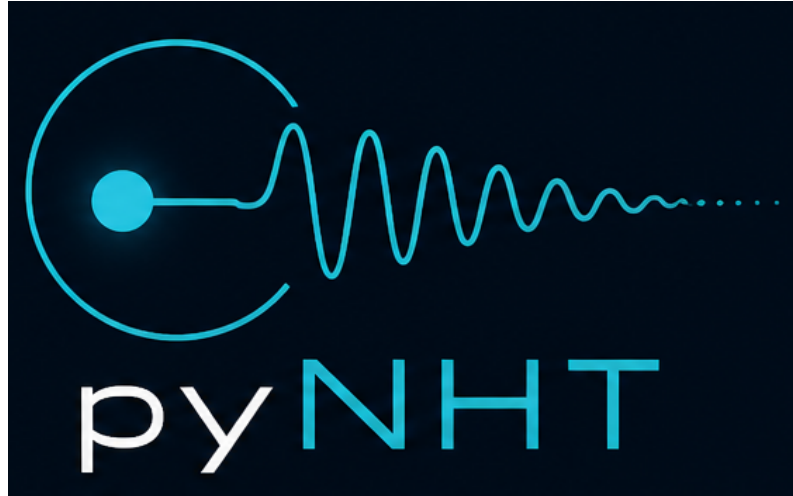
04

Backup Slides

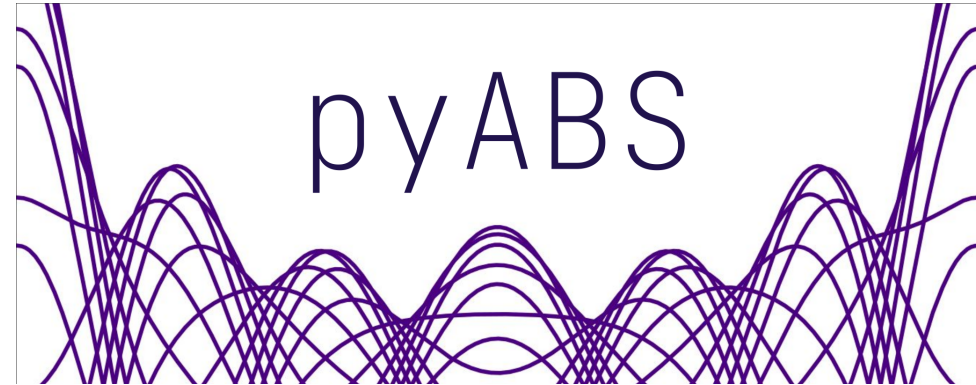


Actively developing code libraries

We have built python libraries for TMCI and Convective instability calculations for the community



<https://github.com/gonza94/pyNHT>



Jake Dulya (Grad Student from IIT)

<https://github.com/gonza94/pyABS>

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17**, 021007 (2014)

Nested head-tail Vlasov solver

A. Burov

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

(Received 4 September 2013; published 25 February 2014)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 034202 (2019)

Convective instabilities of bunched beams with space charge

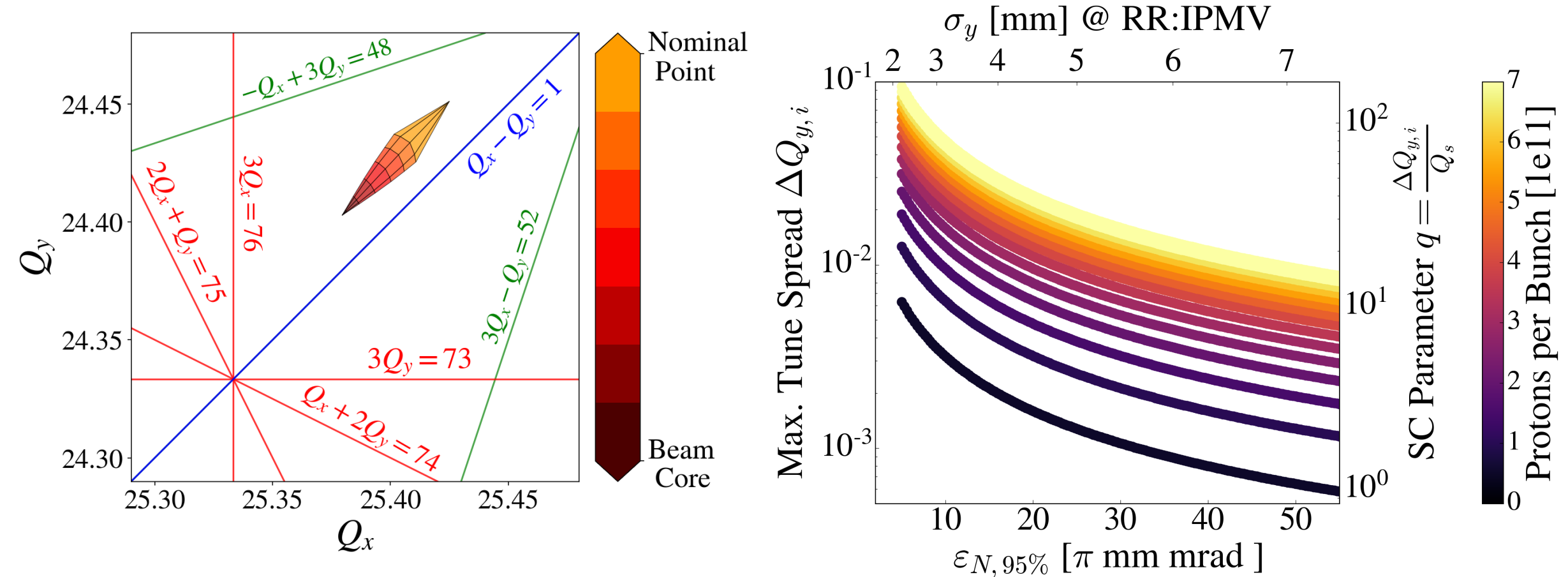
A. Burov*

Fermilab, P.O. Box 500, Batavia, Illinois 60510-5011, USA

(Received 12 July 2018; revised manuscript received 6 December 2018; published 28 March 2019)

Space Charge Parameters in the Recycler Ring

One can calculate the space charge tune shifts for uncoupled modes $\Delta Q_{sc,x}$ and $\Delta Q_{sc,y}$ for a given intensity and a given normalized emittance.

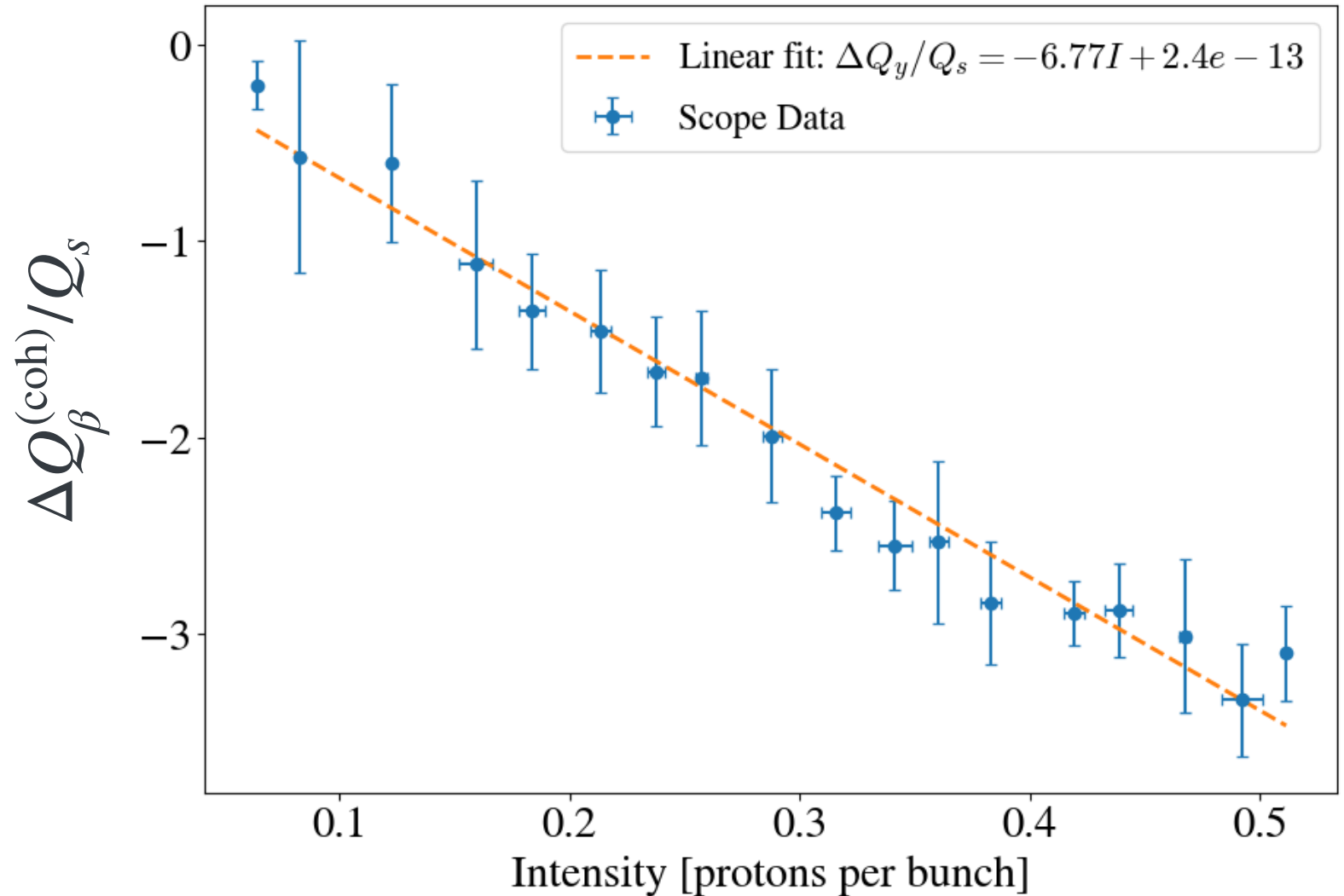




Experiment #1: Measuring Natural Coherent Tune Shift

Normalize by synchrotron frequency using R:MURSUM (RF Voltage)

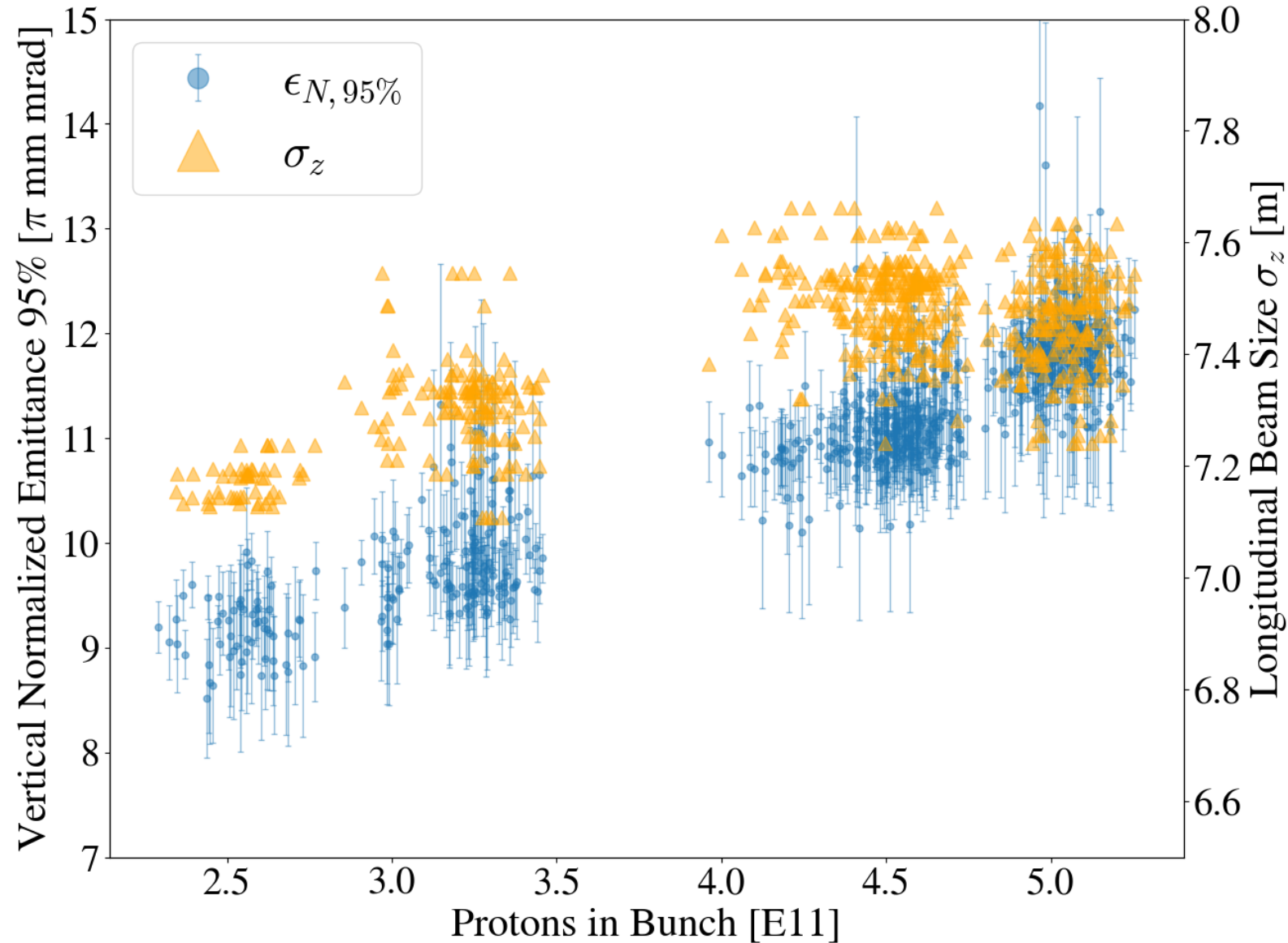
$$Q_s = \sqrt{\frac{heV_{RF}|\eta|}{2\pi\beta^2E}}$$
$$Q_s = 0.00043$$





Experiment: Intensity and Gain Scan

Extracted multiwire data and used lattice to reconstruct vertical emittance.

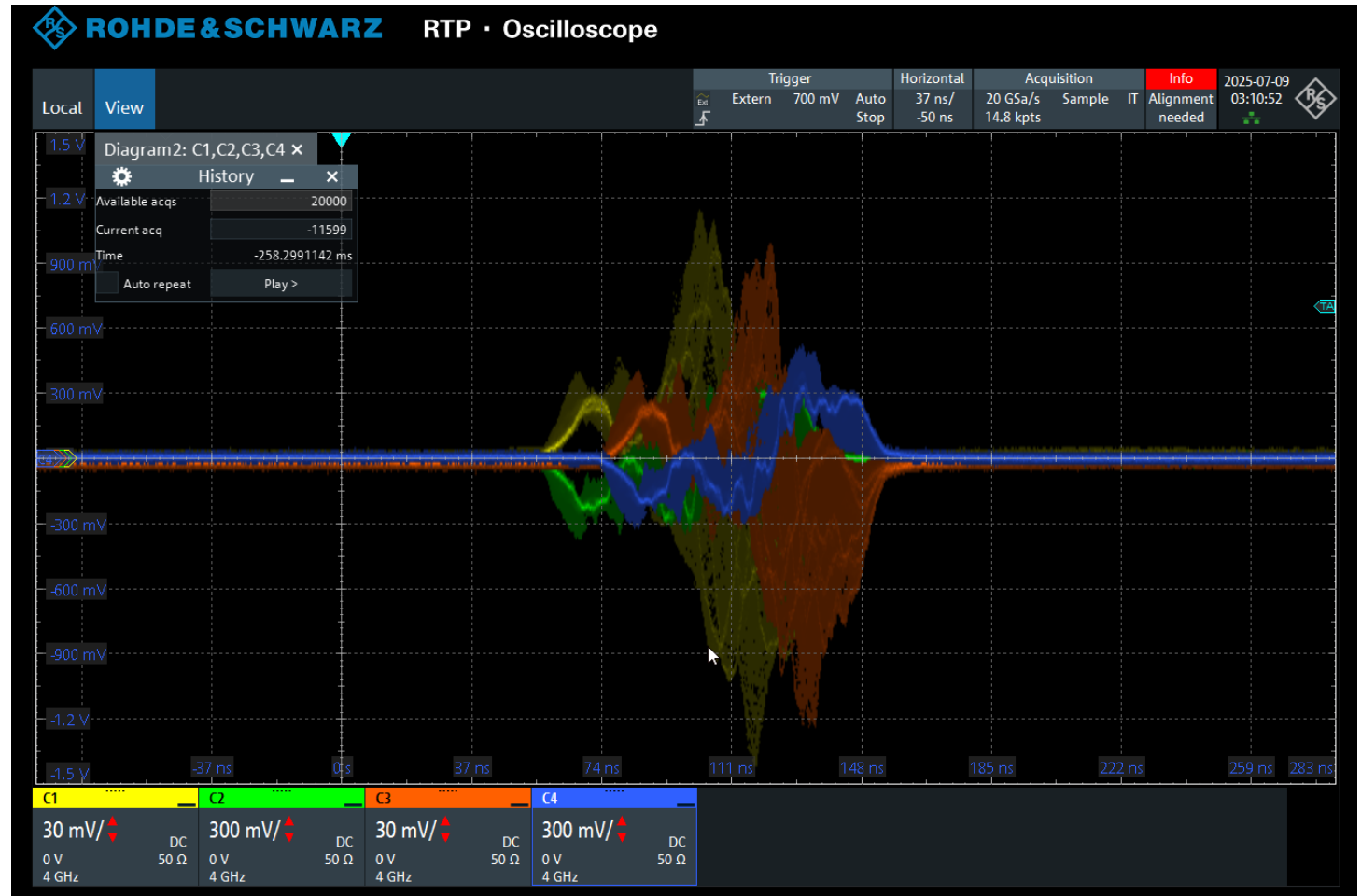




Experimental Setup

Used **stripline pick-up** to reconstruct **dipole oscillations** and longitudinal beam profile. Saved data to oscilloscope and accessed it for offline analysis.

- Long stripline pickup to capture dipole motion in both planes
 - A+B (Sum: Longitudinal Profile)
 - A-B (Difference: Centroid Position)
- Transverse dampers and WAKER system are turned off.
- Got data every other turn with our trigger system.
- 2.5 MHz RF station is used (as opposed to 53 MHz used in high-intensity neutrino operation).
 - Relatively long bunches allowing to capture intrabunch motion



Vertical
A-B

Vertical
A+B

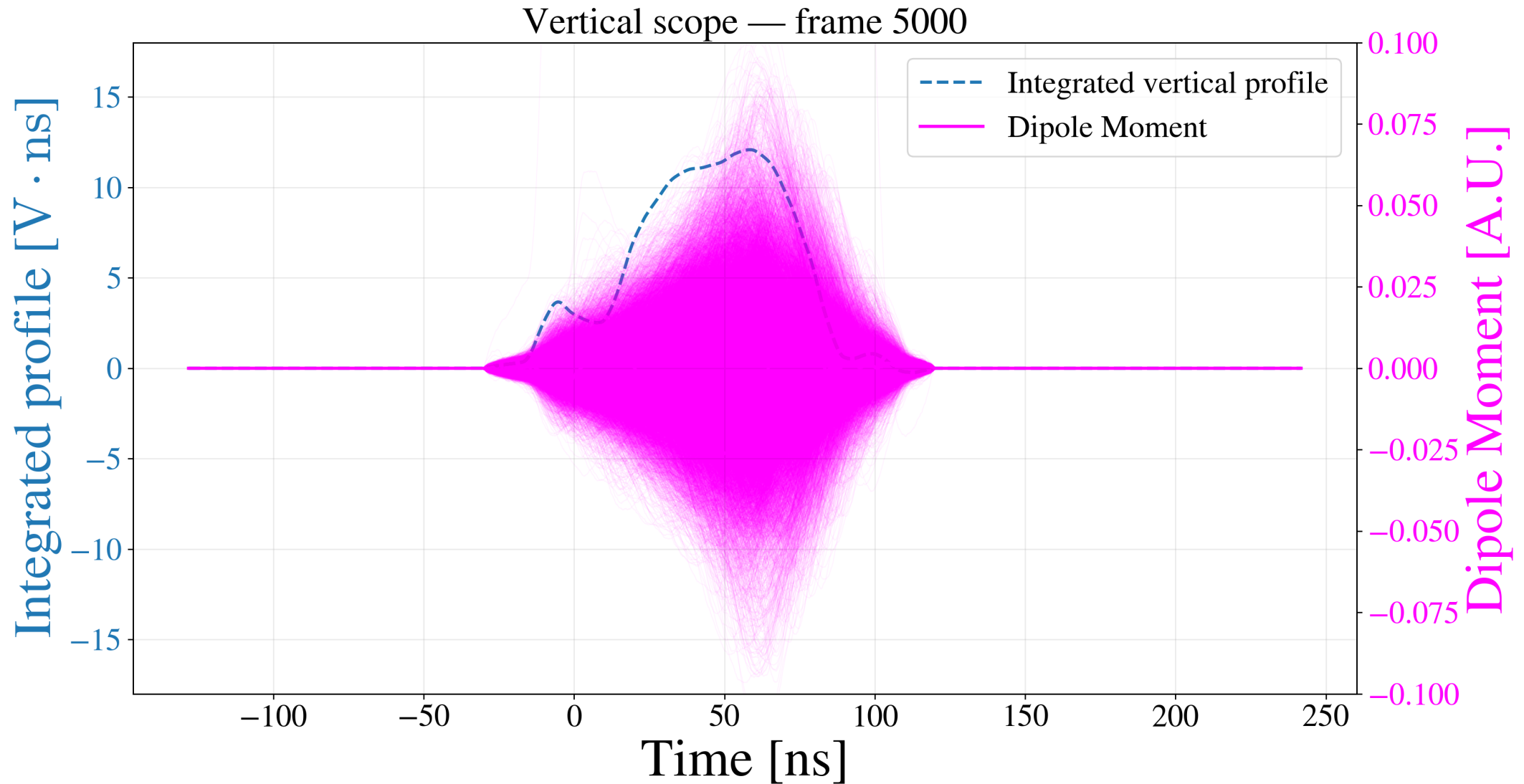
Horizontal
A-B

Horizontal
A+B



Experiment:

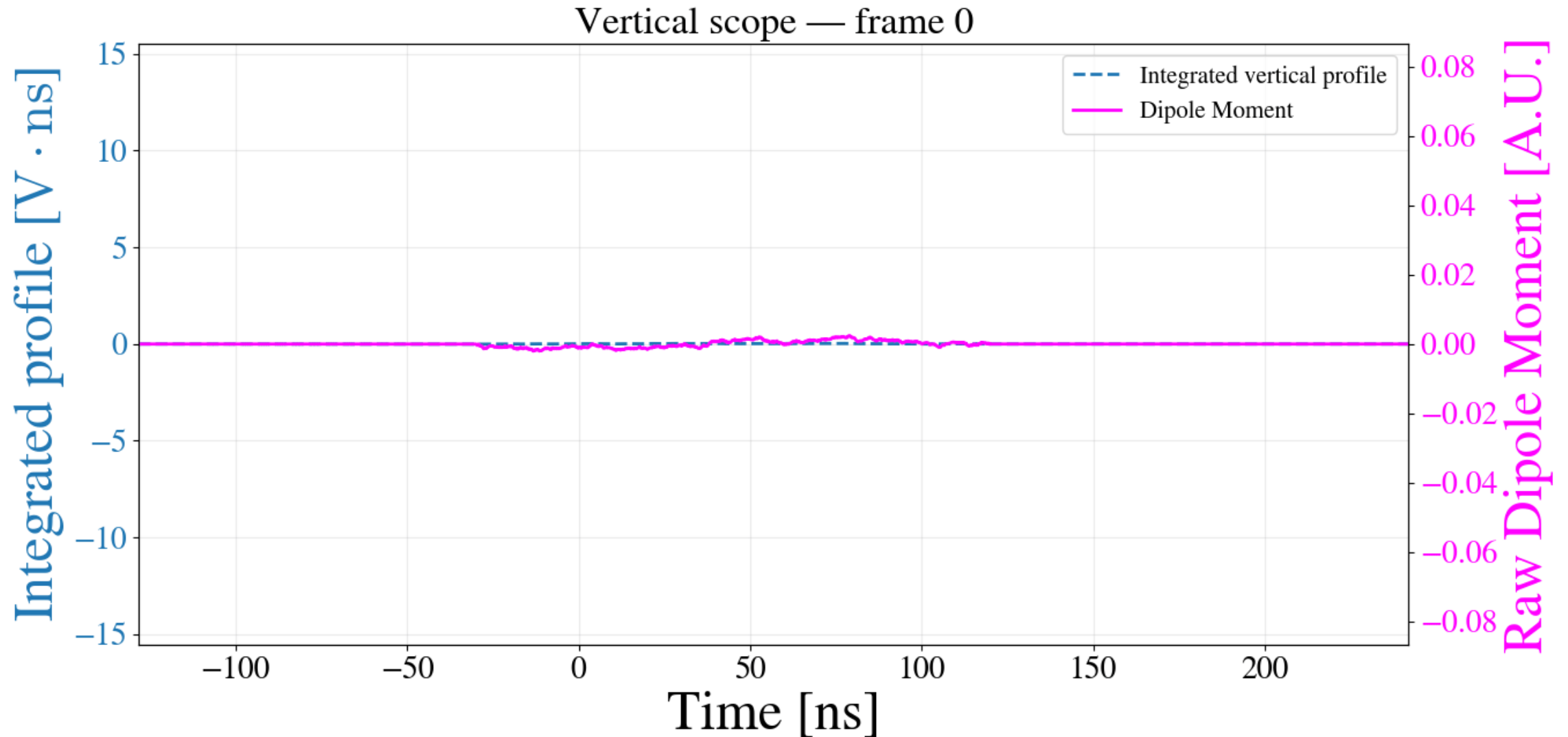
Profile data and dipole moment for stable beam. Space charge parameter ~ 30 , **tail-dominated**





Waker Experimental Setup

Profile data and raw dipole moment from scope data. Space charge parameter ~ 30



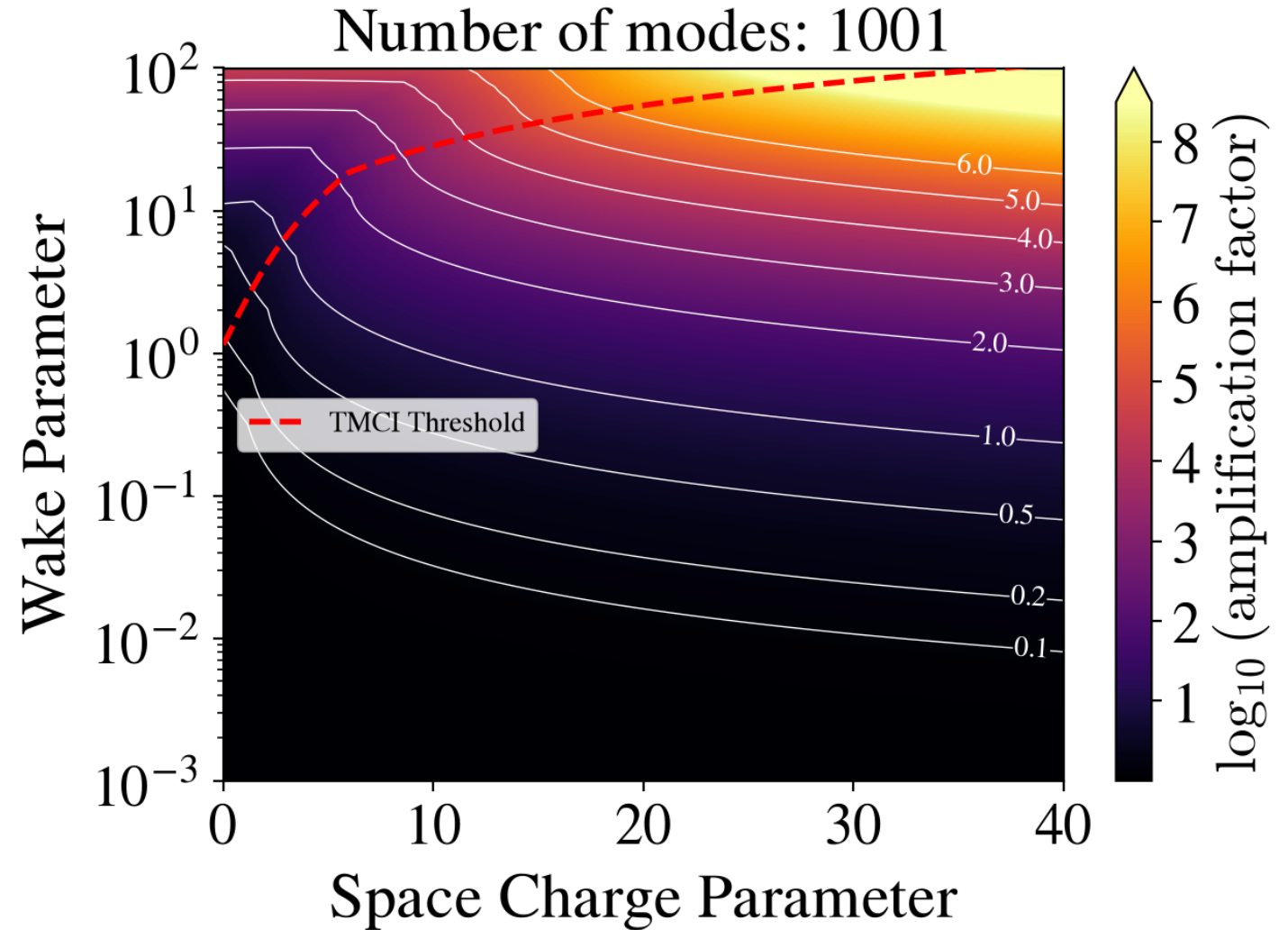


Experiment: Intensity and Gain Scan

Qualitative conclusions from experiments

- **Instability threshold does not increase with space charge parameter**
- **Instability threshold saturates with space charge parameter**

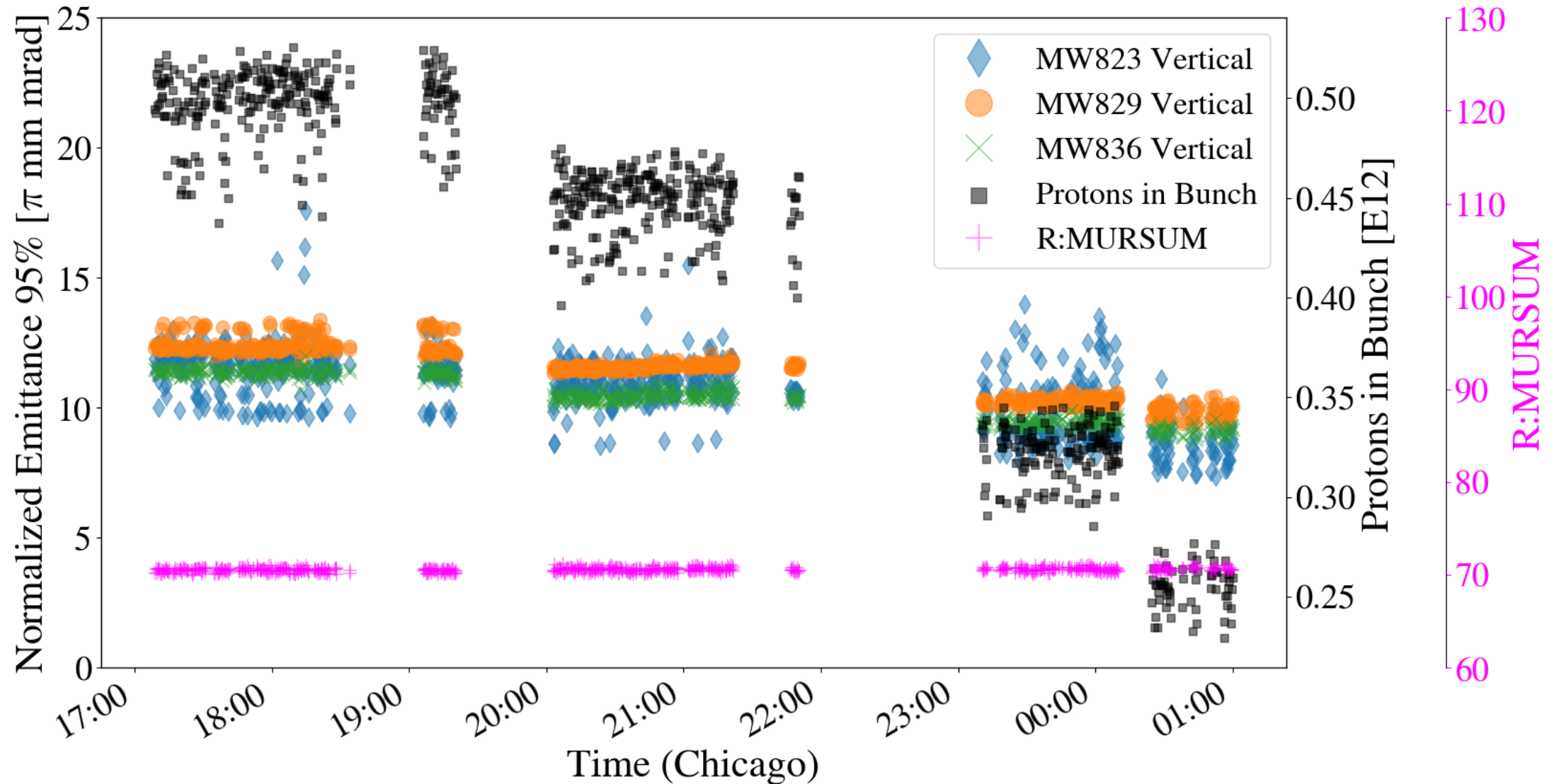
✓ **Agrees qualitatively with Burov's convective theory**





Experiment: Intensity and Gain Scan

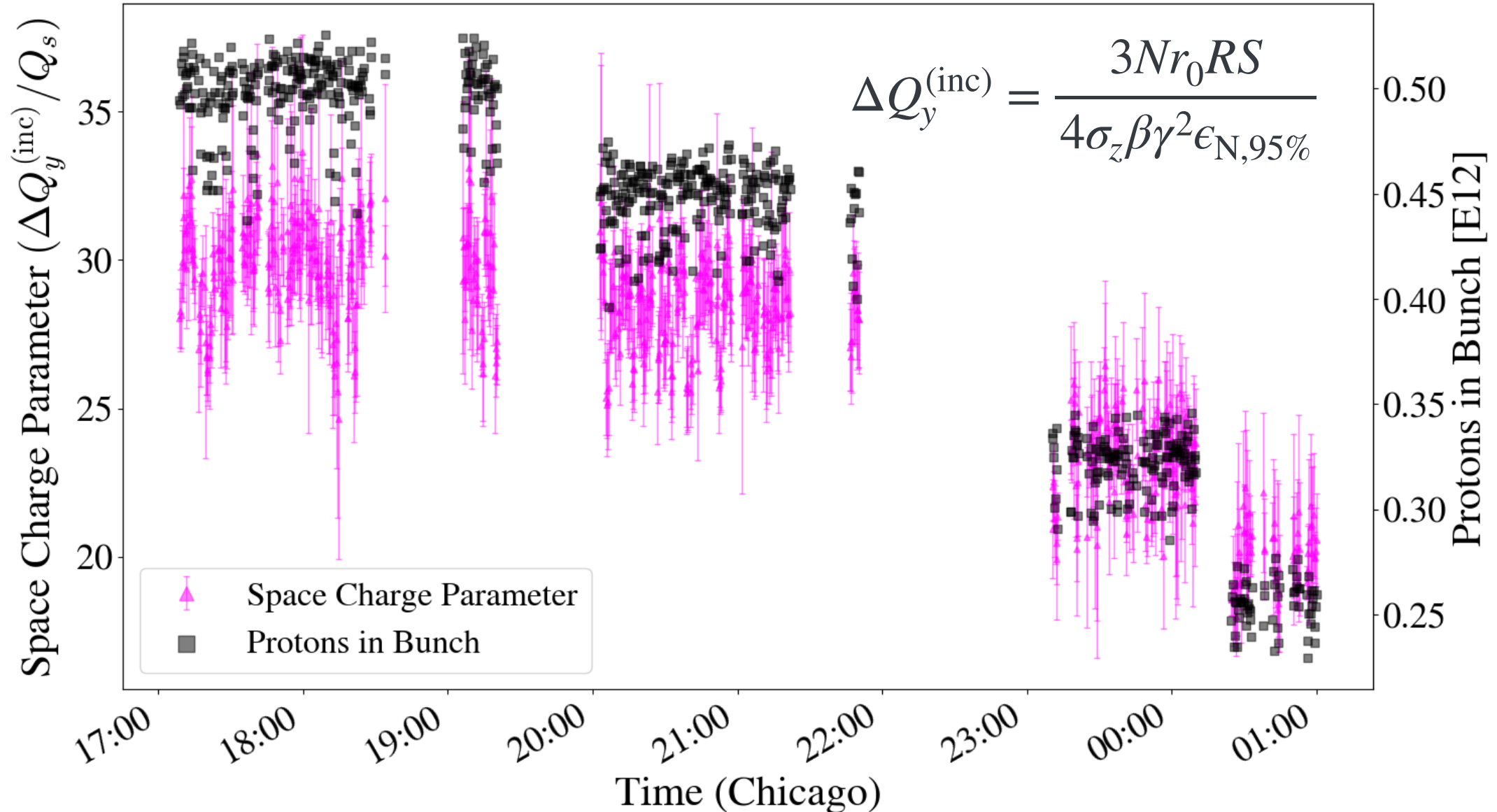
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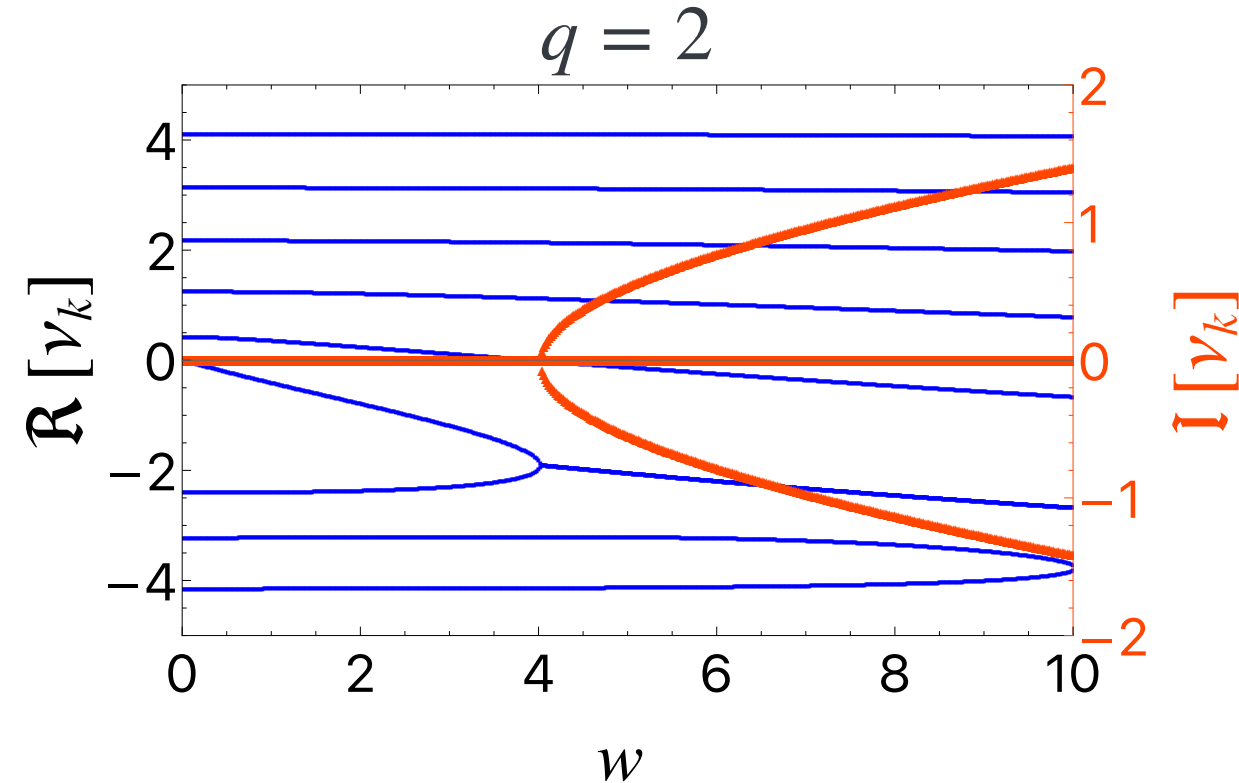
Estimate maximum incoherent tune shift from longitudinal beam size and vertical emittance





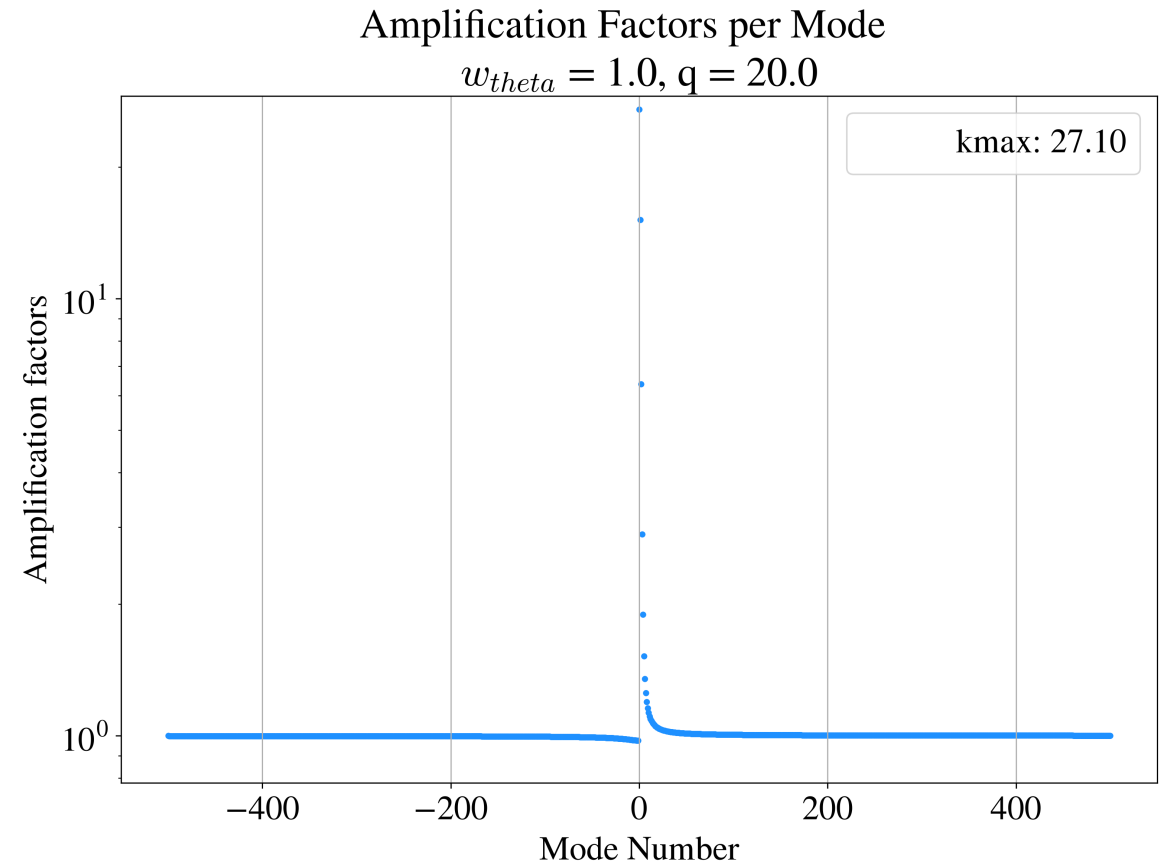
Convective Instabilities for a single-turn step wake

TMCI threshold changes with space charge parameter. Nevertheless, at high space charge we have to deal with convective instabilities. Solving Airbag in Square-Well Model (ABS model).



TMCI

vs.

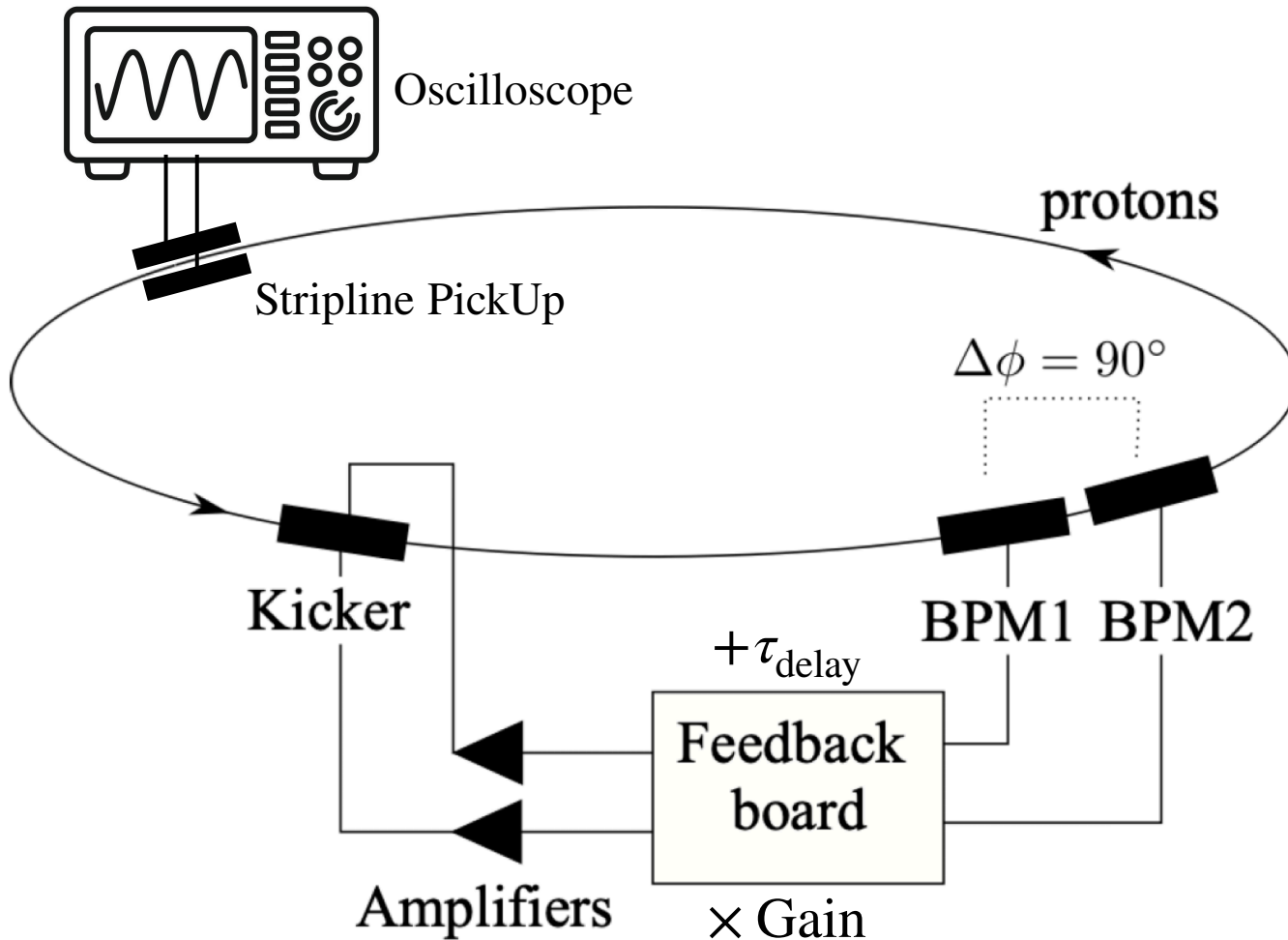


Convective Instabilities



The Waker Experiment

Commissioned new 1 GHz feedback board this run and was able to time and synchronize the system



64th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams HB2021, Batavia, IL, USA JACoW Publishing
ISBN: 978-3-95450-225-7 ISSN: 2673-5571 doi:10.18429/JACoW-HB2021-MOP22

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STRONG SPACE CHARGE**

R. Ainsworth*, A. Burov, N. Eddy, A. Semenov, Fermilab[†], Batavia, USA

Figure 1: Schematic of the waker system.



Experimental Results from Waker Run 2025-2026

Outline

- ✓ Waker Motivation
- ✓ Waker Setup and Commissioning
- ✓ Experiment #1
 - * Natural Coherent Tune Shift
- ✓ Experiment #2
 - * Intensity and Gain Scan
- ✓ Conclusions and Future Work

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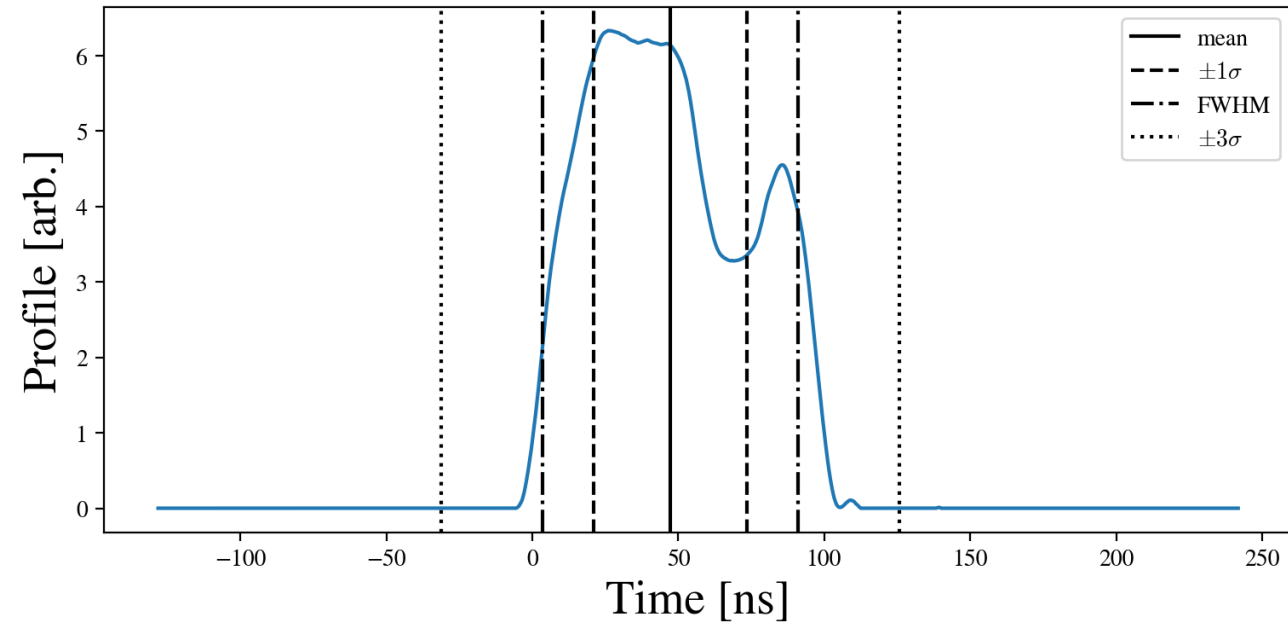
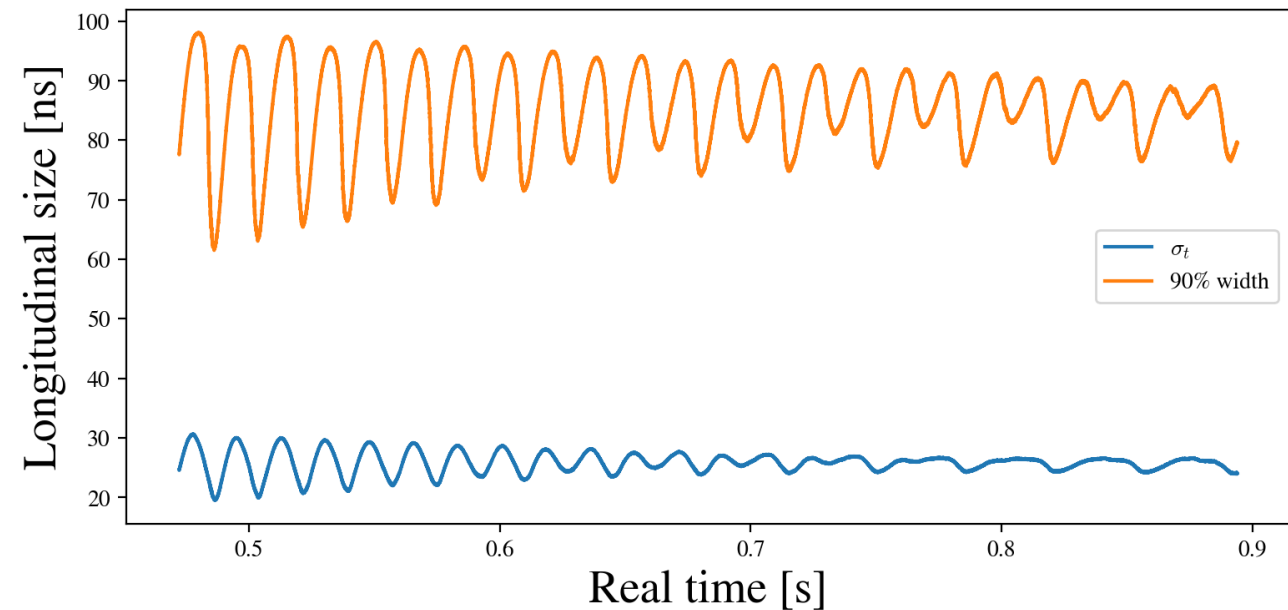
R. Ainsworth*, A. Burov, N. Eddy, A. Semenov, Fermilab[†], Batavia, USA



Experiment #2: Intensity and Gain Scan

Retrieving longitudinal beam size

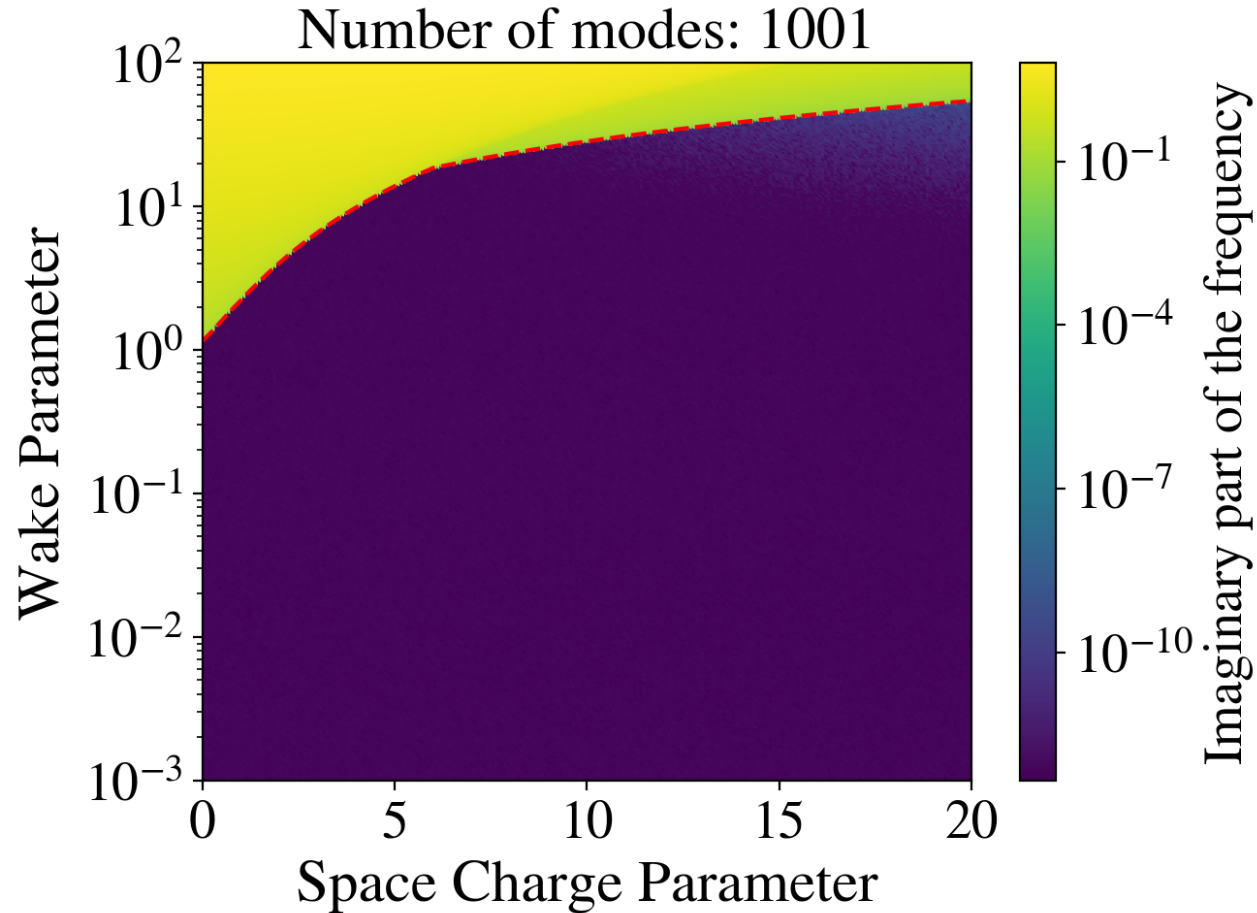
$$\Delta Q_y^{(\text{inc})} = \frac{3Nr_0RS}{4\sigma_z\beta\gamma^2\epsilon_{N,95\%}}$$





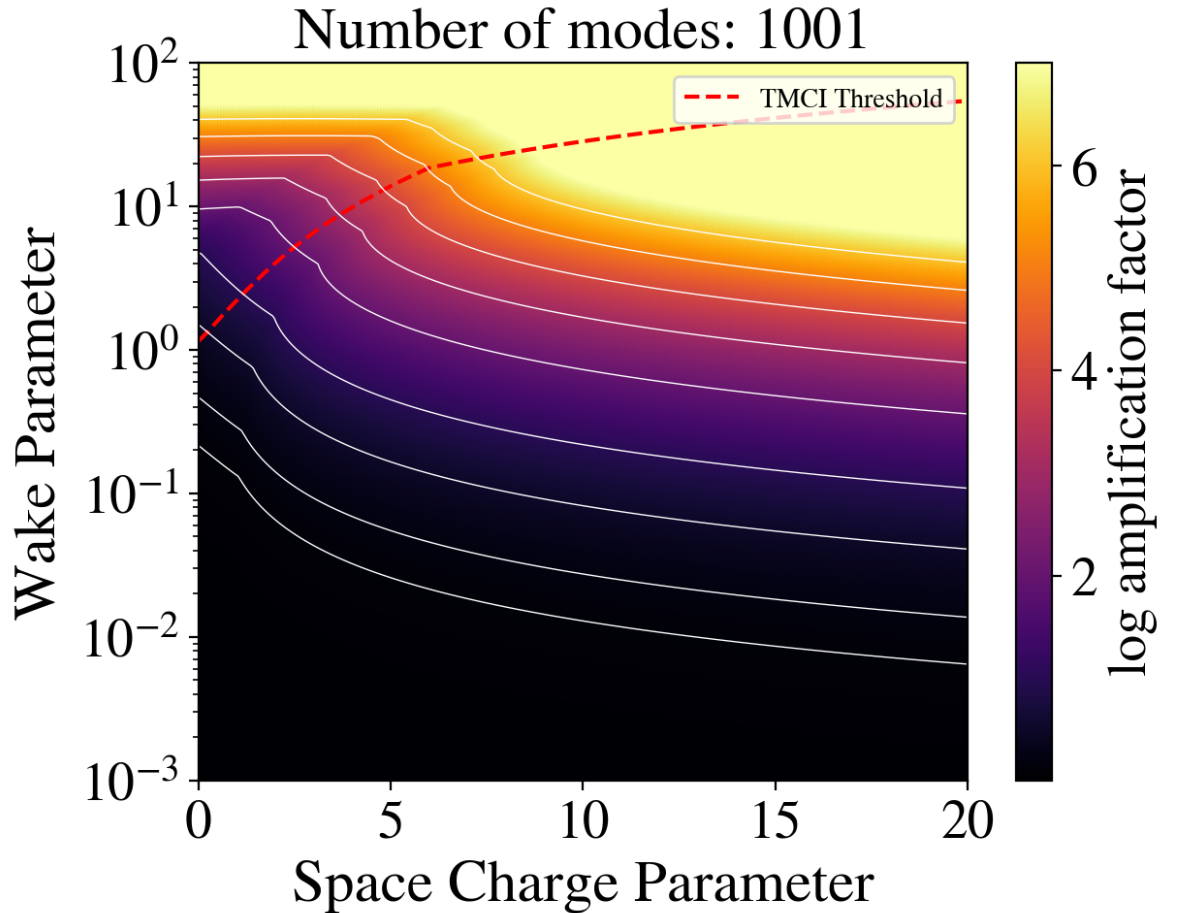
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TMCI threshold changes with space charge parameter. Nevertheless, at high space charge we have to deal with convective instabilities. Solving Airbag in Square-Well Model (ABS model).



TMCI

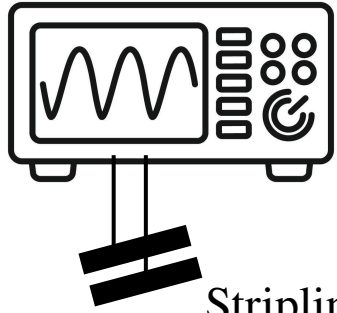
vs.



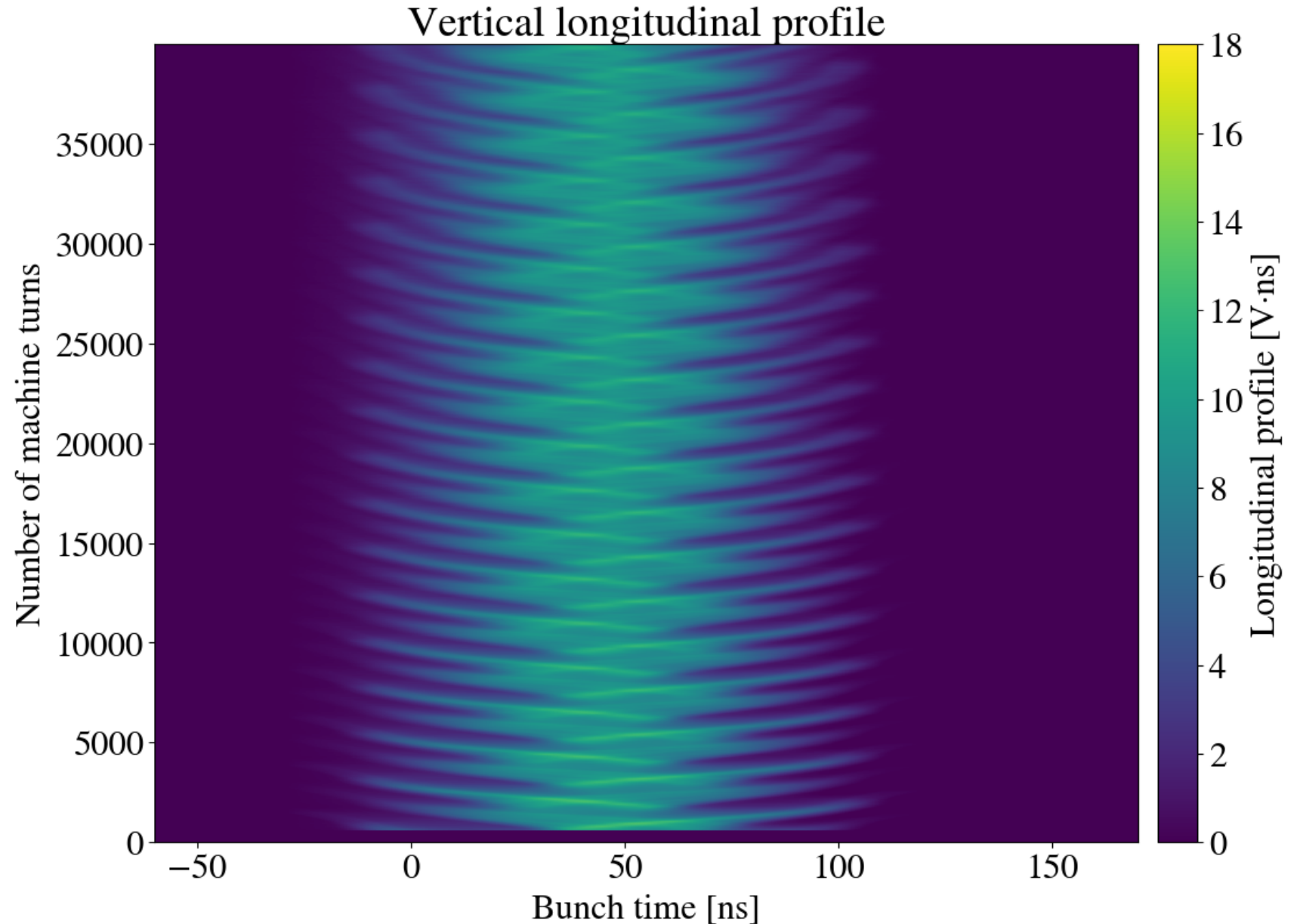
Convective Instabilities



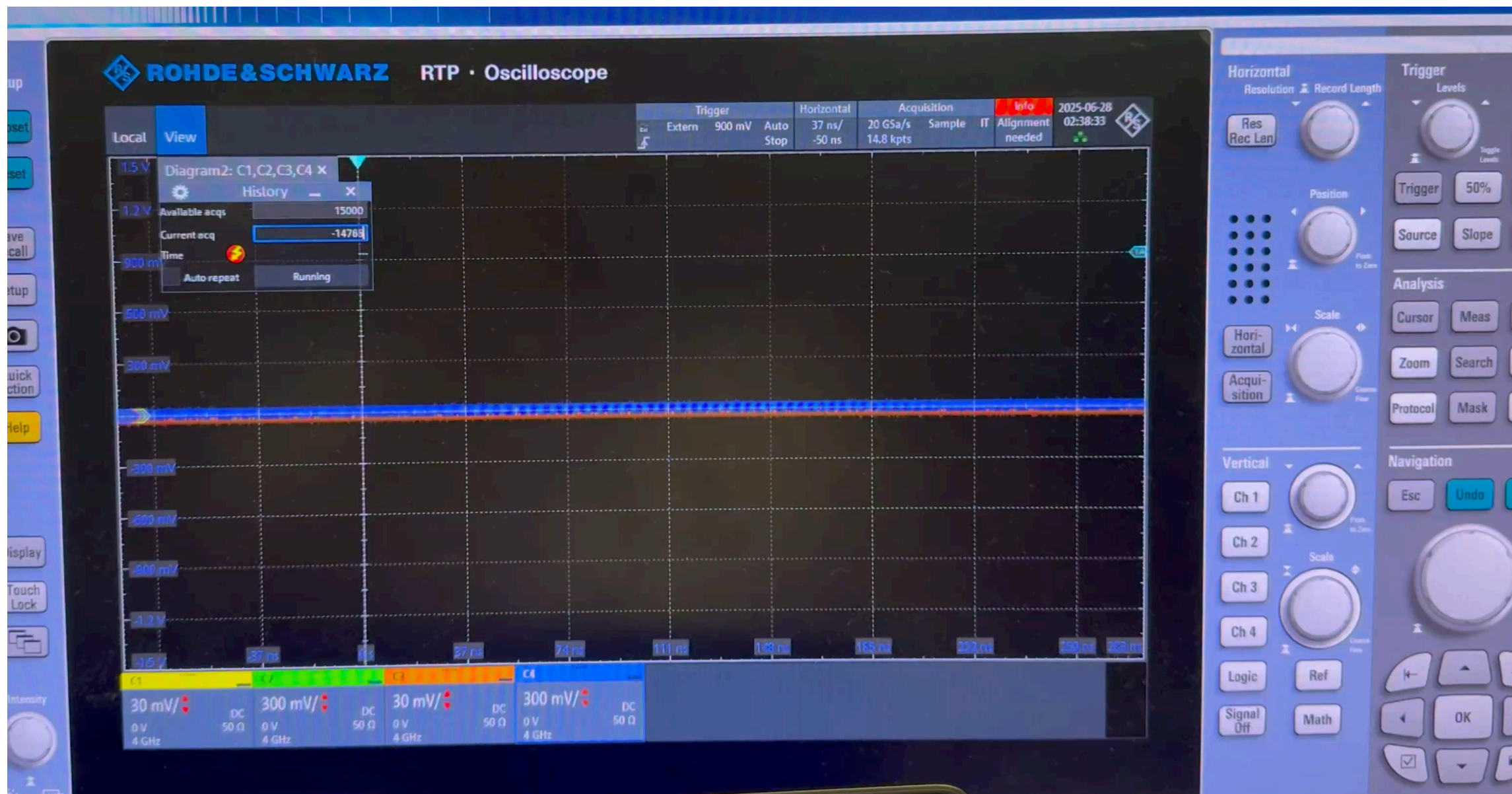
Waker Experimental Setup: Longitudinal Profile



Stripline PickUp

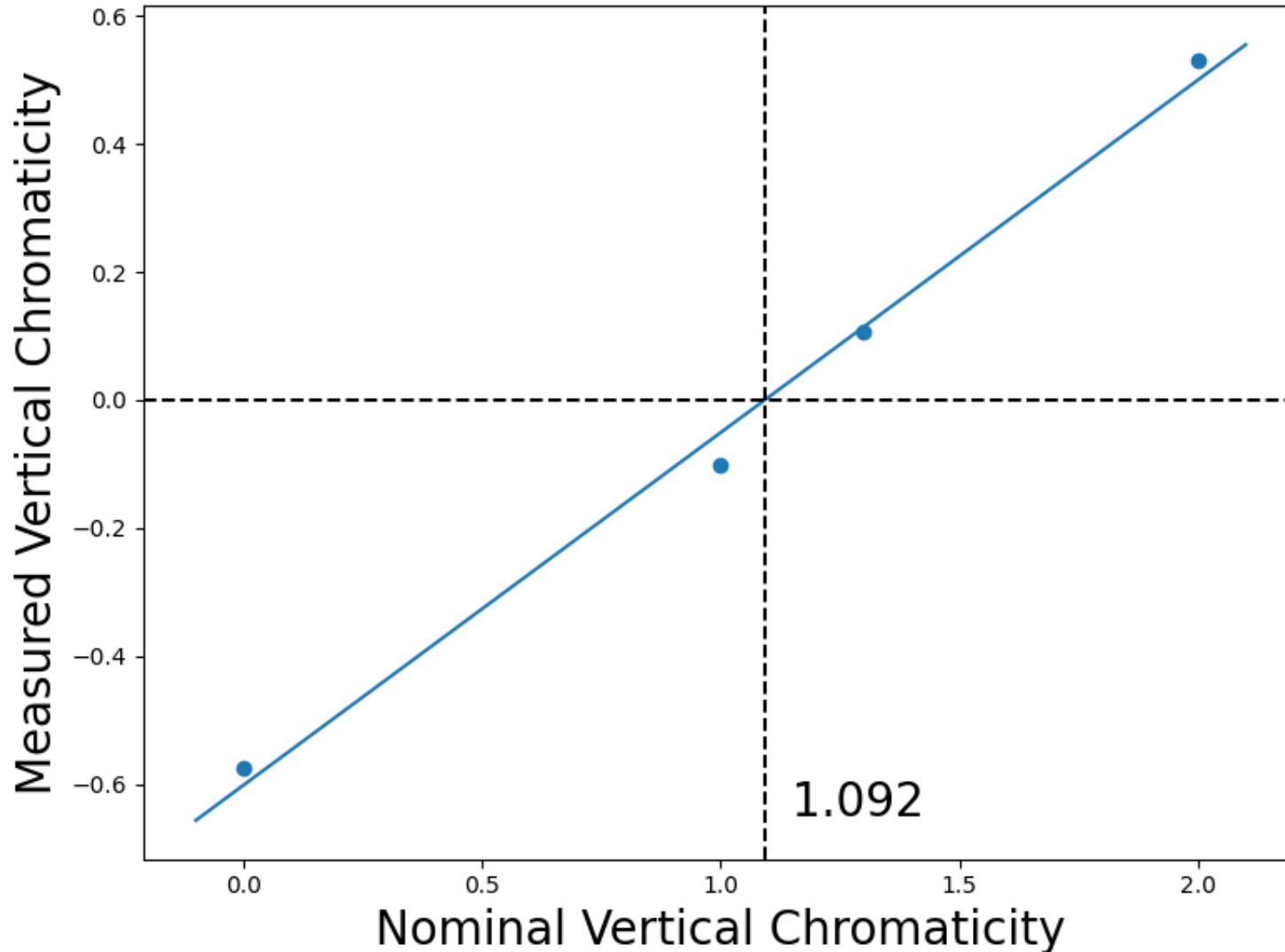


Experimental Setup: Instability Example



Experiment #1: Zero Chromaticity Calibration

Find zero chromaticity (first order) and reduce head-tail phase as close to zero



Head-Tail Phase

$$\chi = \frac{\xi \omega_{\beta} \sigma_z}{c\eta}$$

$$\xi = 0.00 \pm 0.05$$

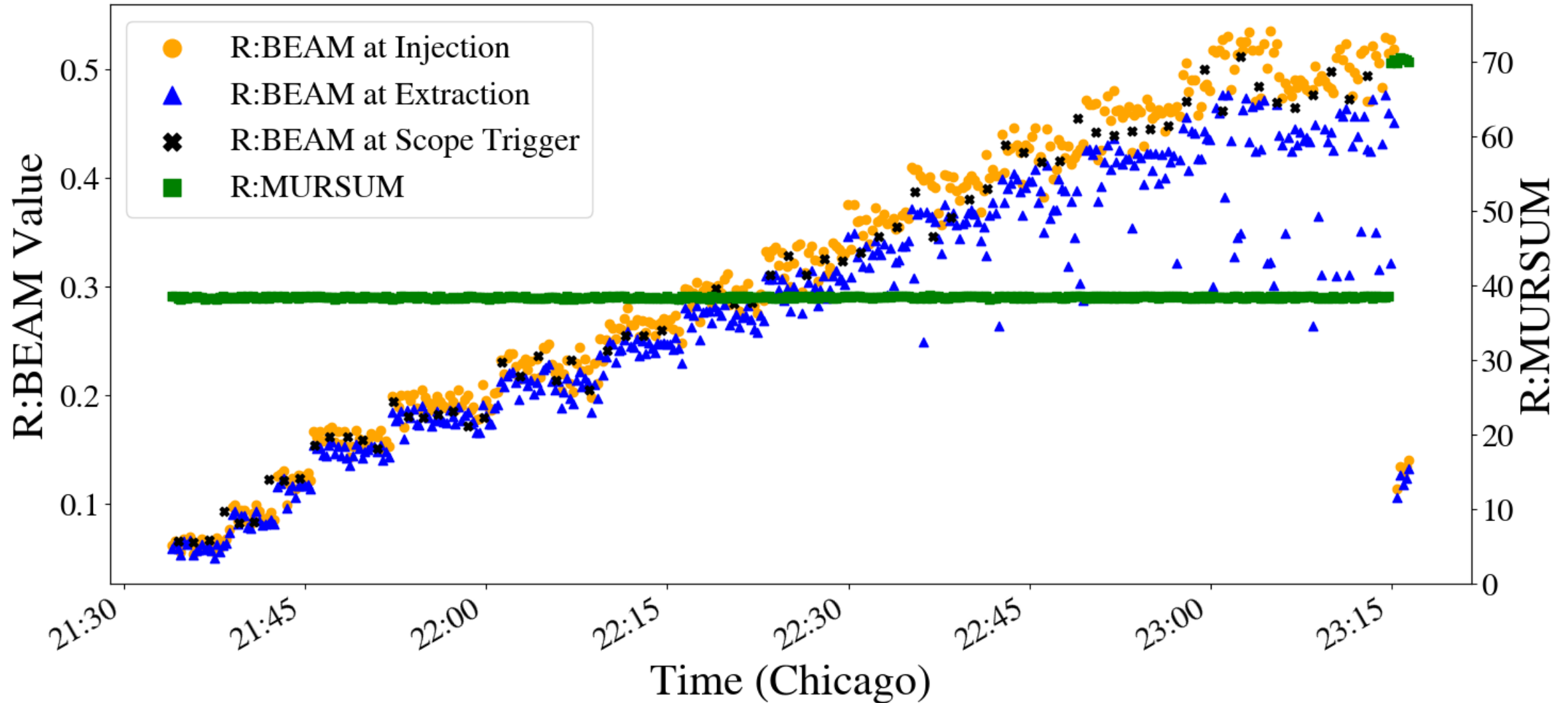
$$\chi = 0.0 \pm 0.1 \text{ rad}$$

$$\chi = 0.0^\circ \pm 5.7^\circ$$



Experiment #1: Measuring Natural Coherent Tune Shift

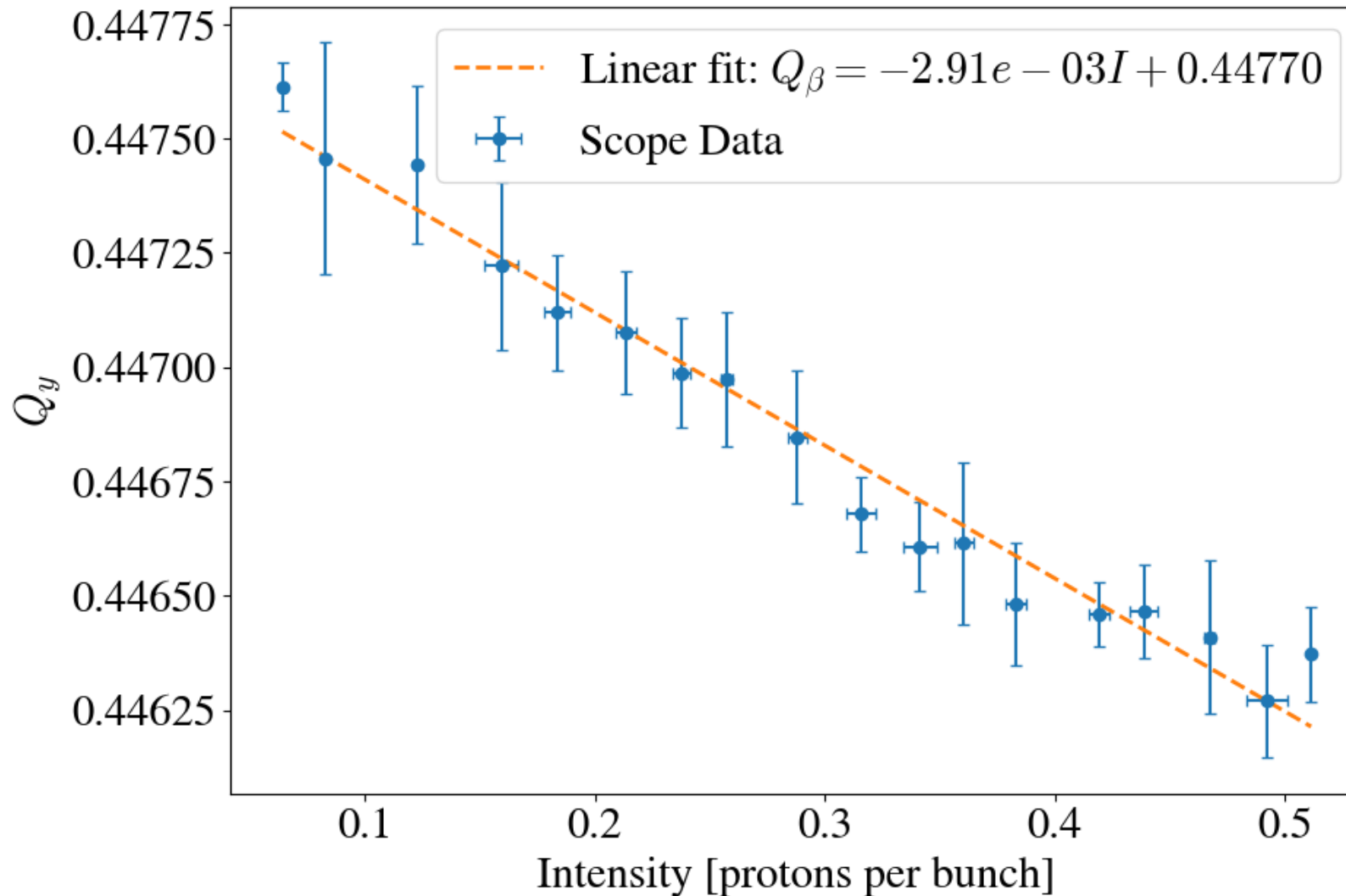
Increase beam intensity in a single bunch and measure tune. R:MURSUM is RF Voltage.





Experiment #1: Measuring Natural Coherent Tune Shift

Extract main harmonic from NAFF (Numerical Analysis of Fundamental Frequencies)



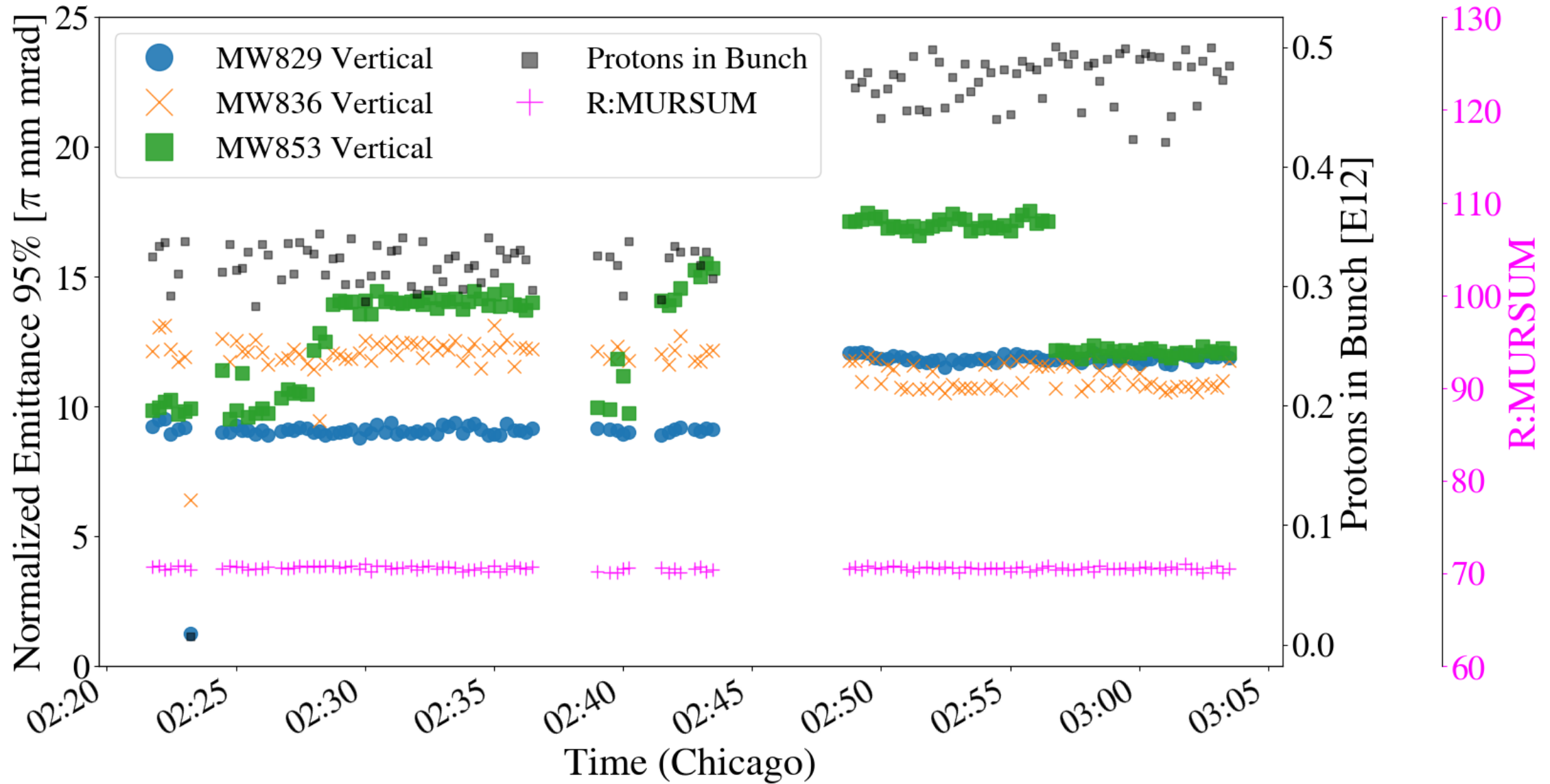


04

Emittance Blowup Experiment

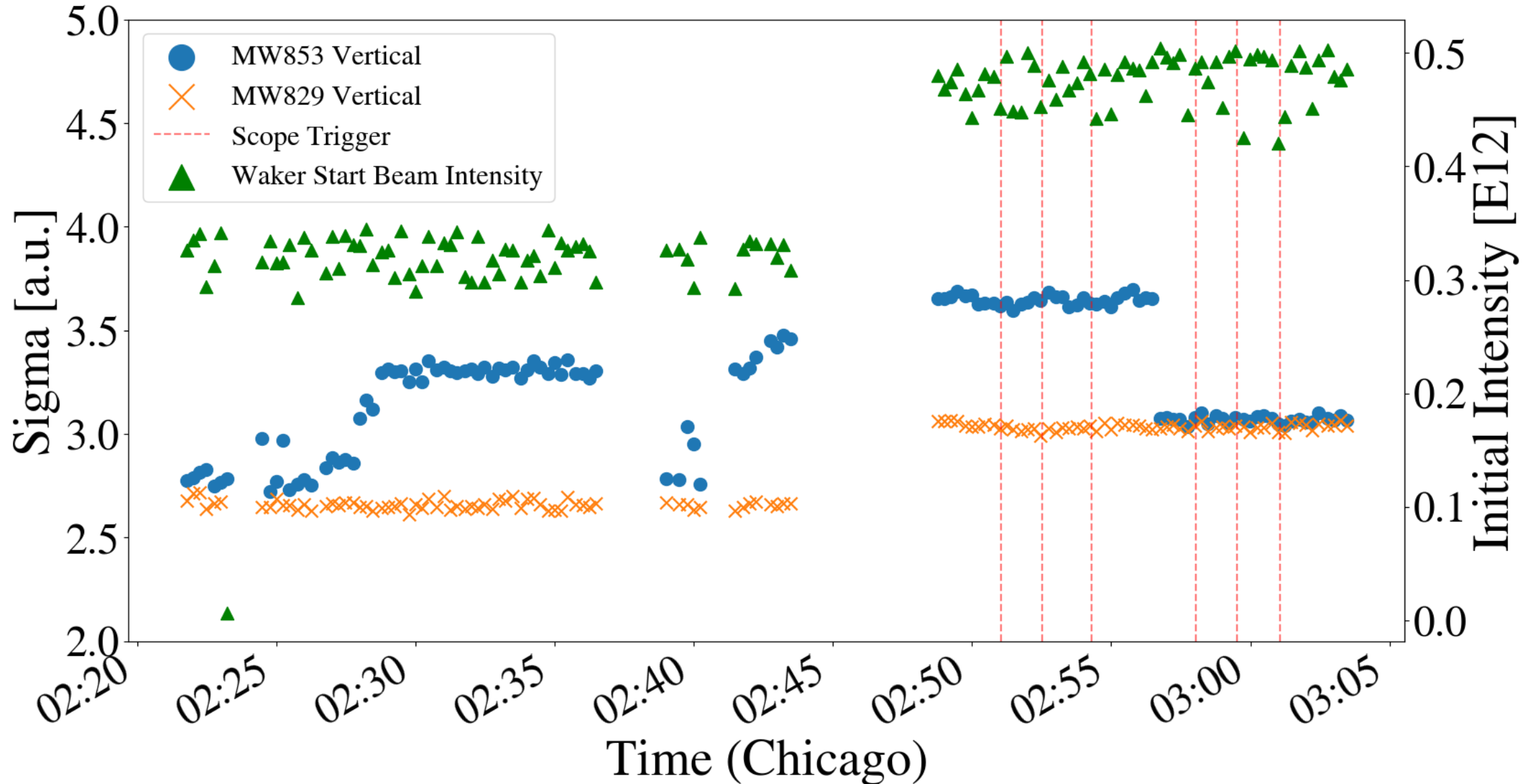
Experiment #4: Emittance Blowup Experiment

Placeholder subheading (optional)



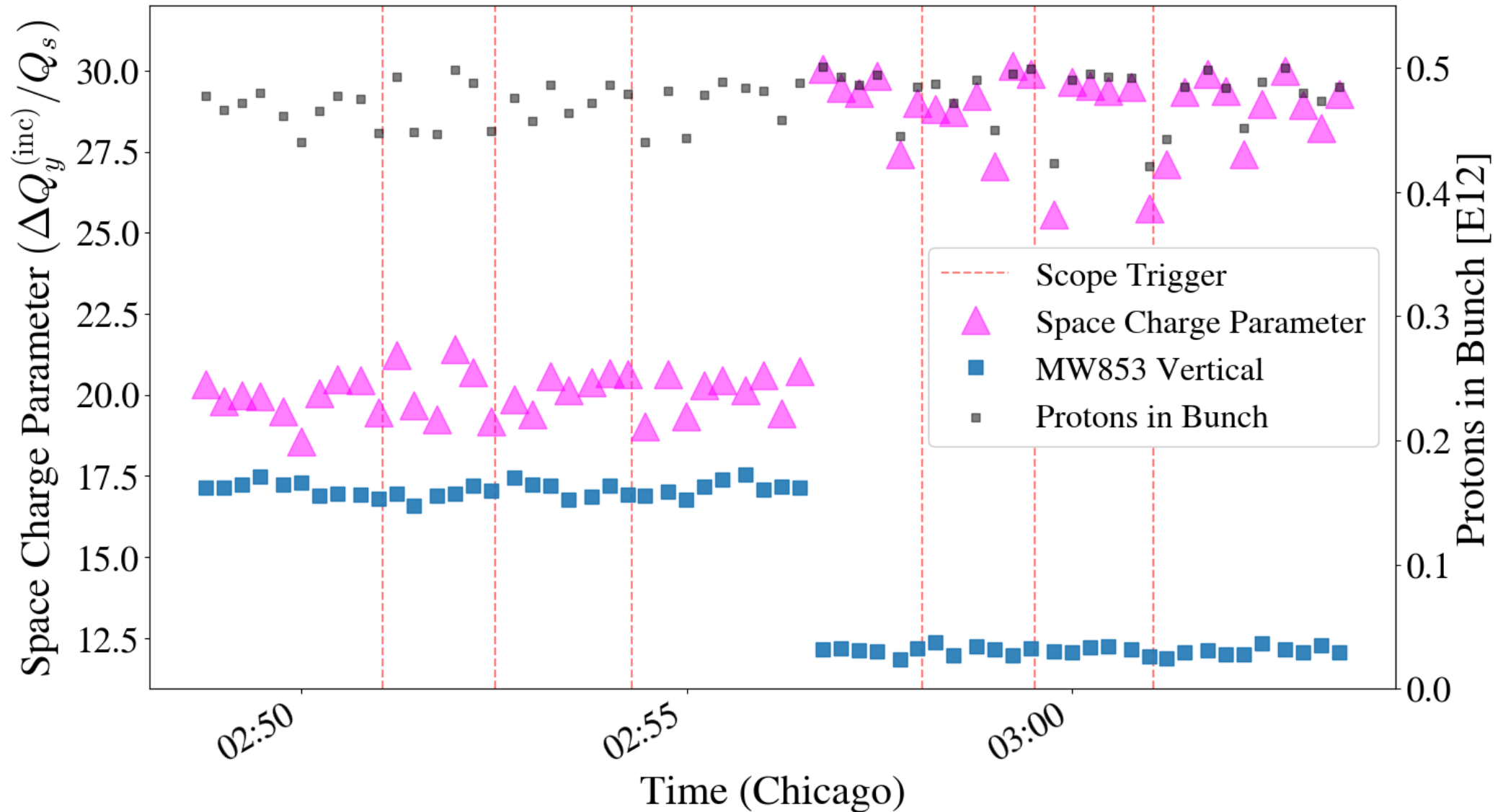
Experiment #4: Emittance Blowup Experiment

We found a knob in the MI-8 line that increased the beam size injected into Recycler



Experiment #4: Emittance Blowup Experiment

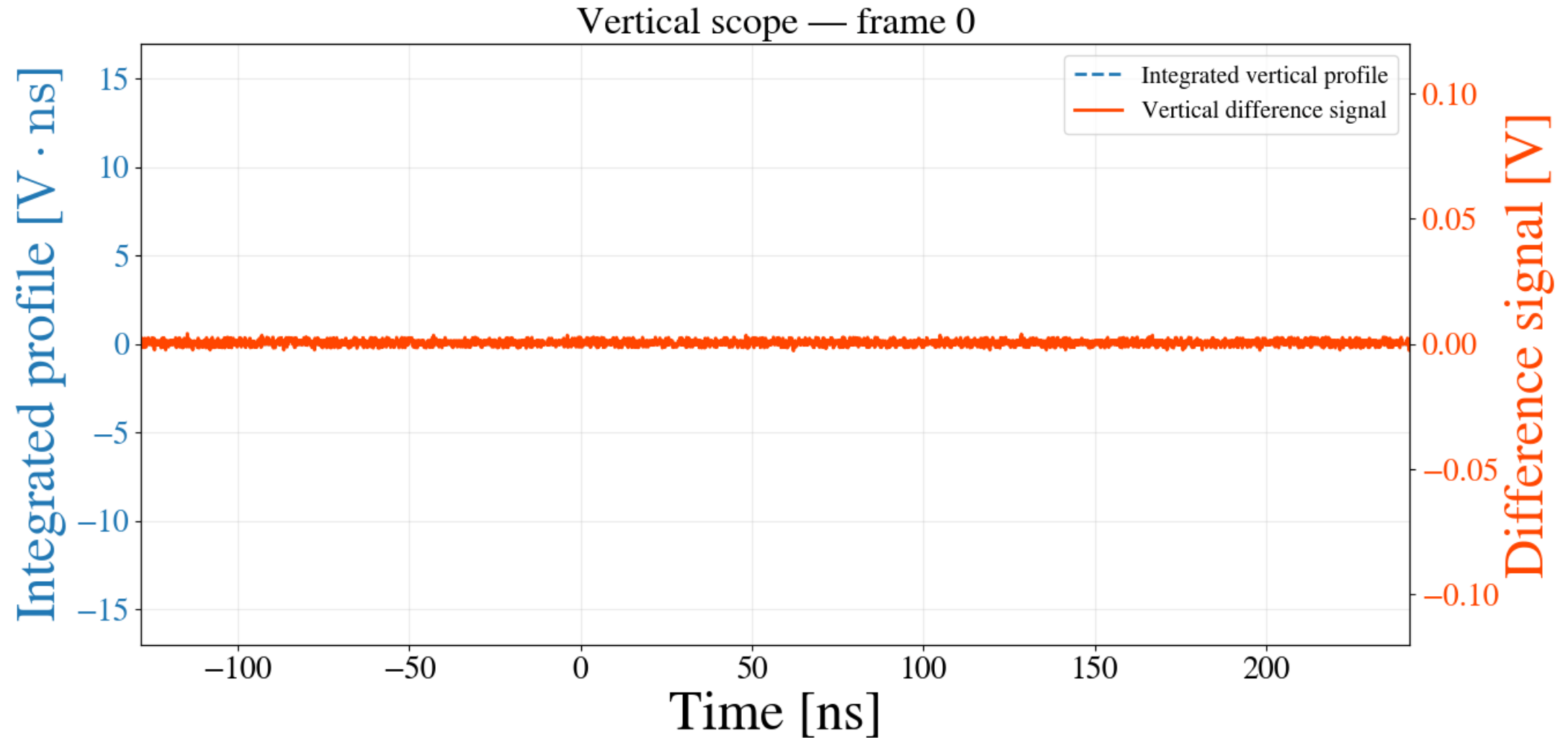
Changed space charge parameter





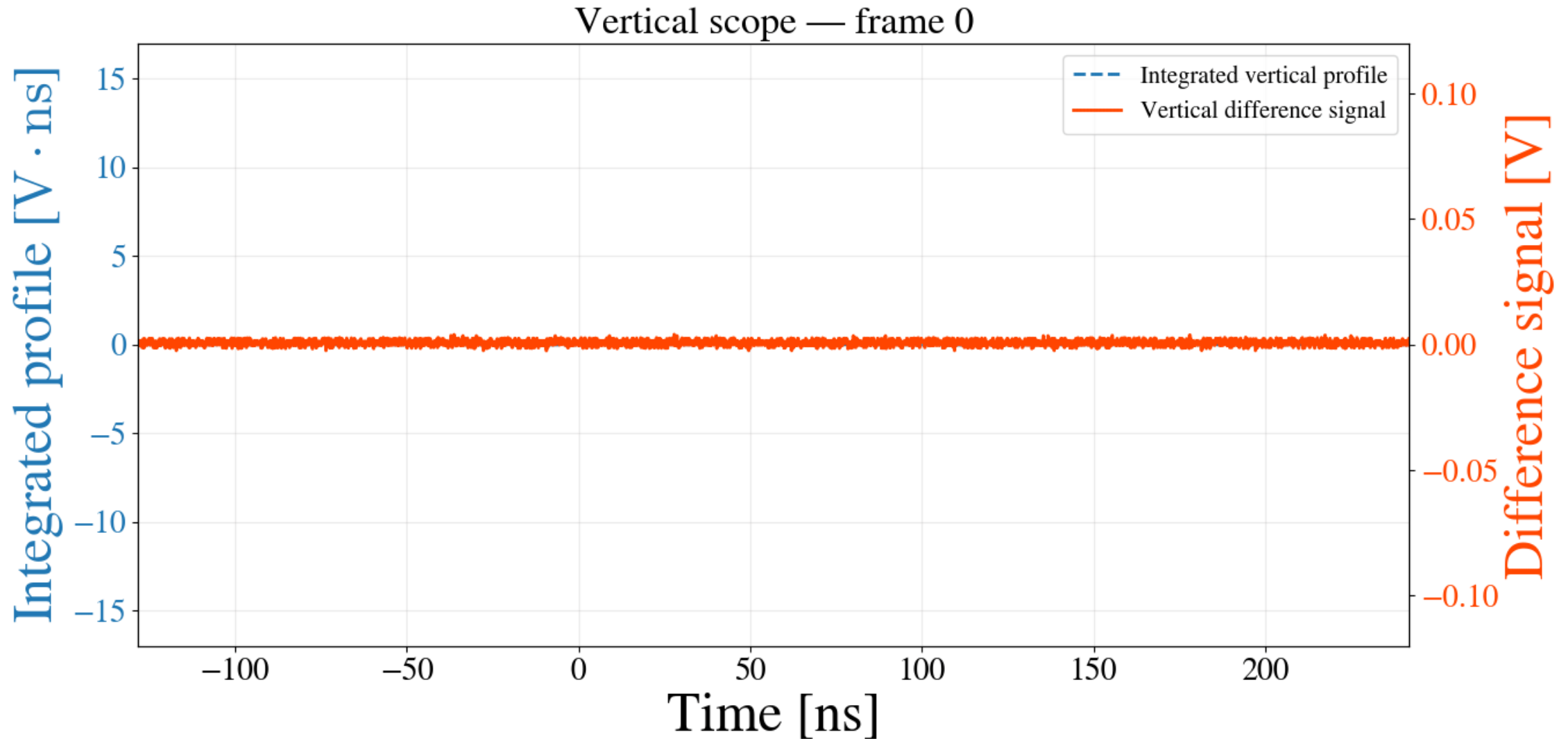
Experiment #4: Emittance Blowup Experiment

Profile data and raw difference signal (A-B). Space charge parameter ~ 30



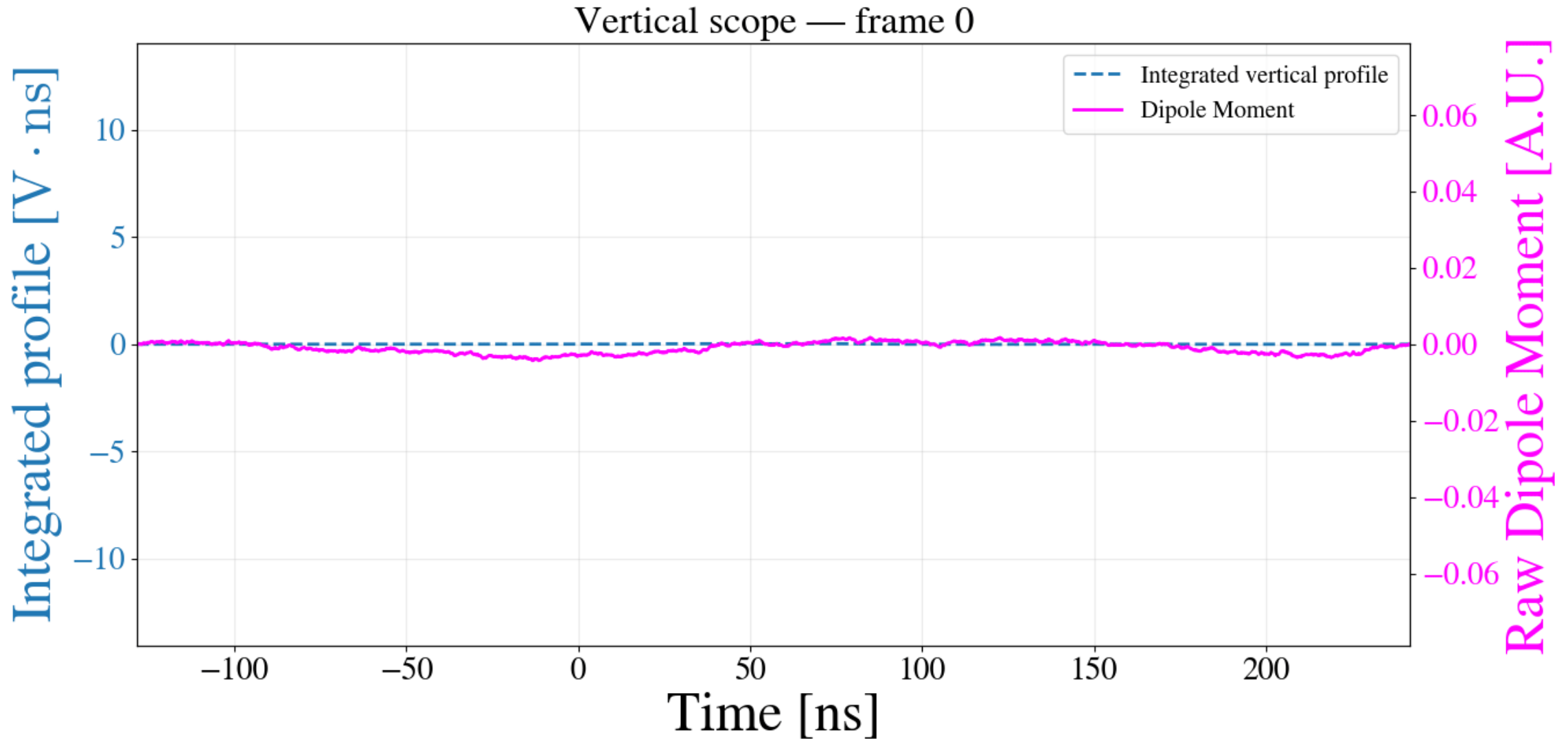
Experiment #4: Emittance Blowup Experiment

Profile data and raw difference signal (A-B). Space charge parameter ~ 20



Experiment #4: Emittance Blowup Experiment

Profile data and raw dipole moment. Space charge parameter ~ 20





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