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Non-linear Integrable Optics, Landau Damping

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IOTA Collaboration Meeting
12 March 2024

THE UNIVERSITY OF CHICAGO

Outline

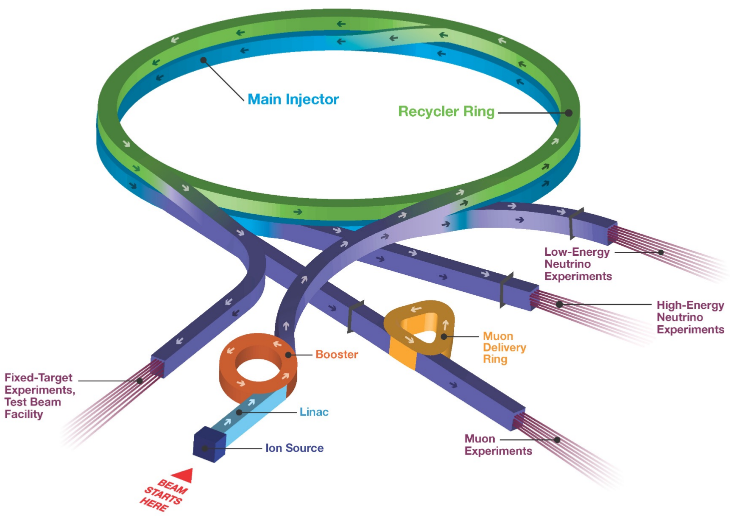
- Introduction
  - Motivation
  - Introduction to Landau Damping
  - Stability Diagram Theory
  - Method to Measure Stability Diagram
  - Measurement Predictions
- NIOLD
  - Experimental Setup
  - Data Collection methods
  - Analysis
- Conclusions
  - Successes
  - Next Steps

Introduction

Motivation

- In most Particle Accelerators, we want to:
    - Maximize beam intensity
- An accelerator's beam intensity is limited by collective instabilities
- If beam is unstable:
    - Produce losses, irradiate components, etc.
- We approach the grand challenge of beam intensity through studying beam stability

Fermilab Accelerator Complex



https://www.fnal.gov/pub/science/particle-accelerators/accelerator-complex.html

Background/Motivation – Landau Damping

- Landau Damping (LD) Historical Context:
  - Derived originally for plasmas with purely mathematical approach by Landau (1946)
  - First experimental evidence for LD observed in 1964 by Malmberg and Wharton:

COLLISIONLESS DAMPING OF ELECTROSTATIC PLASMA WAVES*

J. H. Malmberg and C. B. Wharton
John Jay Hopkins Laboratory for Pure and Applied Science,
General Atomic Division of General Dynamics Corporation, San Diego, California
(Received 6 July 1964)

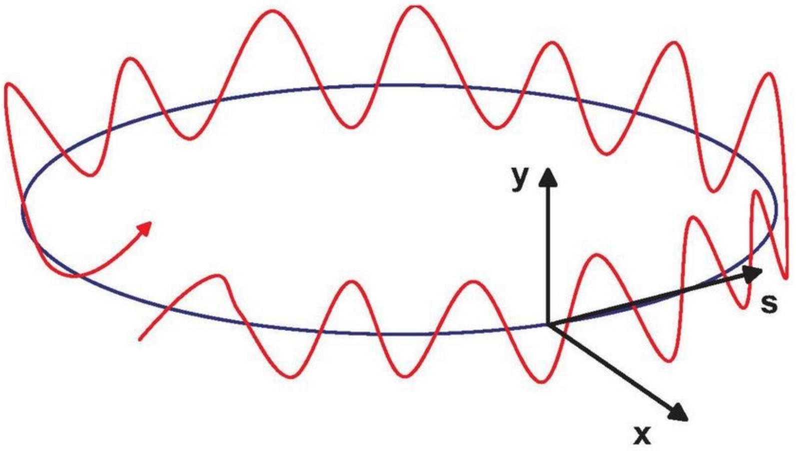
- In collisionless plasmas, Landau damping (LD) is the effect of damping of collective oscillation modes.

- Landau Damping acts a defense against collective instabilities

Background/Motivation – Landau Damping

Landau Damping in Accelerators:

- In our case, LD depends on spread of betatron frequencies
- Works through energy transfer between coherent & incoherent oscillation modes
- ‘damps’ collective oscillation modes in energy transfer, stabilizing intense beams



Detailed knowledge of LD strength is essential to predictions on beam stability

LD studies approached via Stability Diagram Theory

Stability Diagram Theory

- Given Collective mode tune shift (from external source in vert. plane), find resulting frequency in presence of LD using dispersion relation:

Collective mode tune shift

Action in y

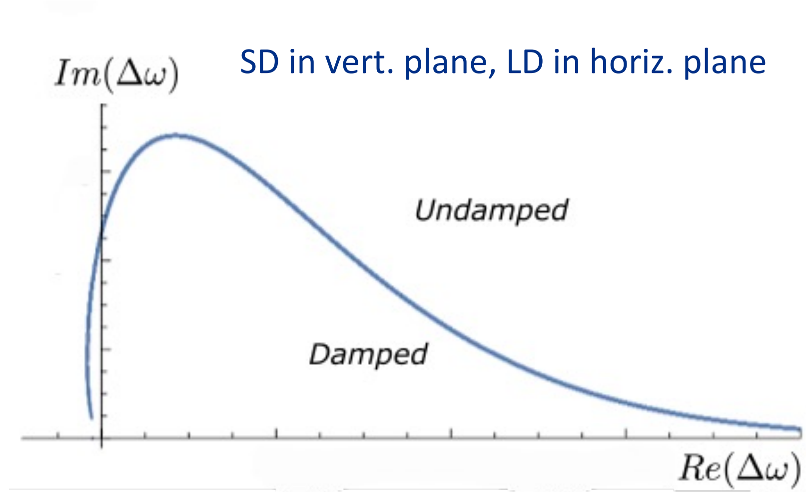
Bunch distribution function

$$\Delta\omega = -1/\int \frac{J_y \partial F/\partial J_y}{\Omega + \delta\omega(J_x, J_y) + io} dJ_x dJ_y$$

Freq. in presence of LD

Freq. shift of oscillating particles

Vanishingly small term (avoid singularities)



Alexey Burov. "Inverse stability problem in beam dynamics." In: *Phys. Rev. Accel. Beams* 26 (8 Aug. 2023),

- Often to find Ω: solve dispersion equation for all Δω.

- If map Im[Ω] = 0 onto the complex plane of Δω, obtain threshold separating stable and unstable states of bunch: **Stability Diagram**

SD Measurement Methods

- Current techniques measuring LD have limitations: Don't directly measure LD strength
- We investigate alternative method to measure LD strength:
  - Revert polarity of transverse feedback to excite collective mode: **antidamper**
  - Produces coupling impedance (G - gain, ϕ - phase):

$$Z(\omega) \propto G e^{i\phi} \delta(\omega)$$

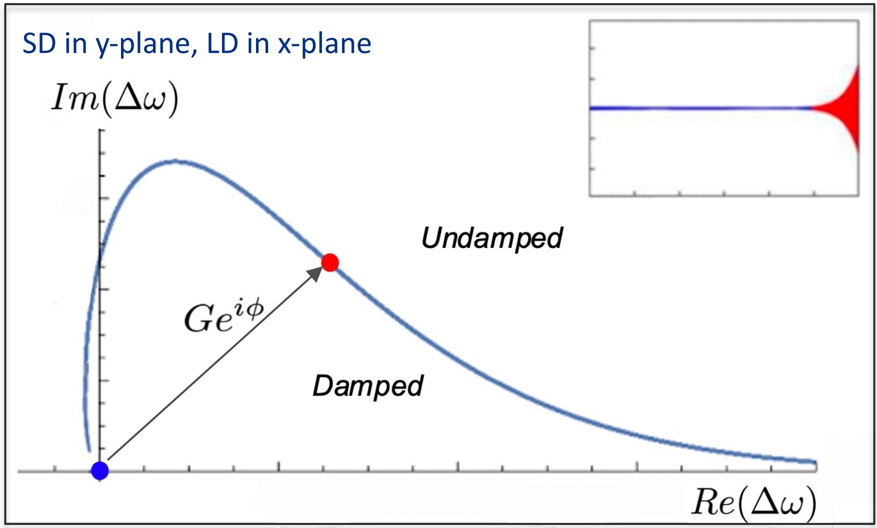
Delta function: antidamper kicks bunch as whole

- Shifts frequencies of collective modes by (g - growth rate):

$$\Delta\omega \propto g e^{i\phi}$$

- Change gain and phase: controlled impedance
- Observe gain where beam goes unstable: get SD

- **We measure SD in the vert. plane, LD provided in horiz. plane**



Alexey Burov. "Inverse stability problem in beam dynamics." In: *Phys. Rev. Accel. Beams* 26 (8 Aug. 2023),

I. Fadelli, "A procedure to directly measure the strength of landau damping," Phys. Org, 2021. https://phys.org/news/

SD Measurement Method

- Proof-of-principle study of this method has been performed at the LHC:

Proof-of-Principle Direct Measurement of Landau Damping Strength at the Large Hadron Collider with an Antidamper

S. A. Antipov,[1,2,*] D. Amorim,[1,3] N. Biancacci,[1] X. Buffat,[1] E. Métral,[1]
N. Mounet,[1] A. Oeftiger,[1,4] and D. Valuch[1]
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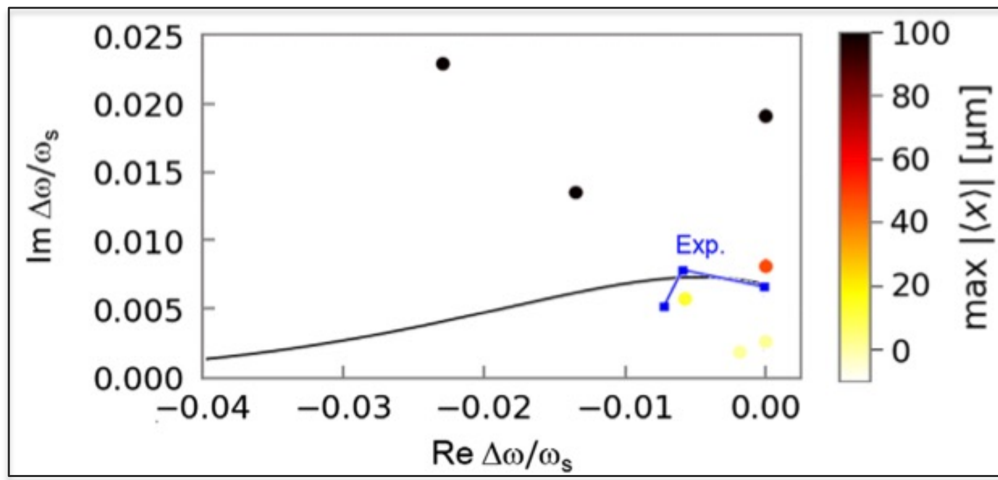
(Received 7 August 2020; revised 13 January 2021; accepted 12 March 2021; published 20 April 2021)

- Why expand on this research?
  - More phase measurements
  - investigate impact of machine's impedance
  - obtain beam distribution function



'The color of the dots depicts the maximum beam excursion. The blue squares and line show the measured limit of stability. The solid black line shows a SD prediction for a gaussian beam.'

S. Antipov et. al., Phys. Rev. Lett.126, 164801, 2021.

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SD Measurement Predictions

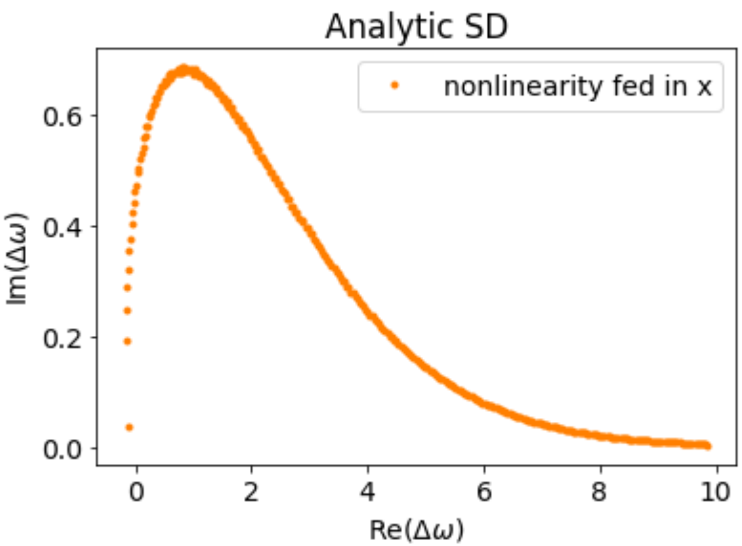
- Normalized analytical stability diagram:
  - Octupoles as LD source in horizontal plane (x)
  - Excitation fed through vertical plane (y)

Action in x

$$\Delta\omega = \left[\int dJ_x \frac{F_x(J_x)}{\Omega - J_x + io}\right]^{-1}$$

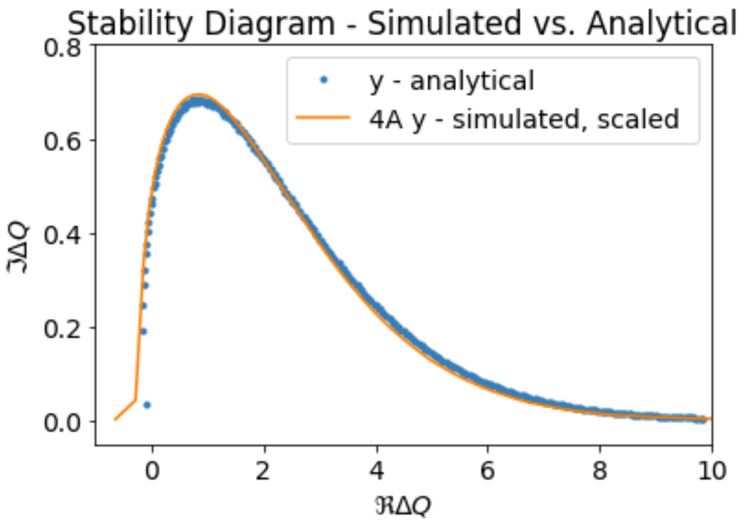
Collective mode tune shift

Frequency in presence of LD



Alexey Burov. "Inverse stability problem in beam dynamics." In: *Phys. Rev. Accel. Beams* 26 (8 Aug. 2023),

- Simulated SD in IOTA
  - IOTA madx lattice, Xsuite for simulation
  - Simulate at high LD: octupoles dominate
  - Left: scaled simulation with analytical



NIOLD Experiment

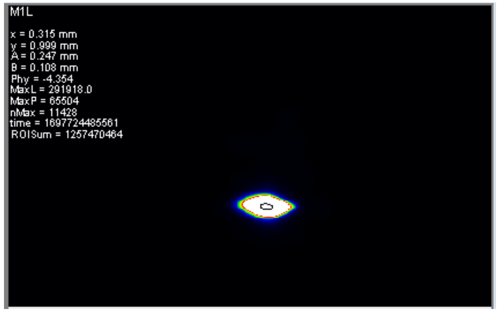
Current experiment does not involve Non-linear Integrable Optics

Experimental Shifts (IOTA Run 4)

- NIOLD Run 4 Experimental Shifts:
    - Difficulties collecting necessary data
        - did not know was necessary until post data-collection
    - Took many data sets with too small octupole strengths

Date	Notes
09/26/23	Commissioning
09/28/23	Commissioning
09/29/23	Data Collection – missing necessary data
10/03/23	Data Collection – missing necessary data
10/05/23	Data Collection – missing necessary data
10/14/23	Data Collection – low octupole currents
10/17/23	Data Collection – low octupole currents
10/19/23	**Data Collection – Have the right data!**

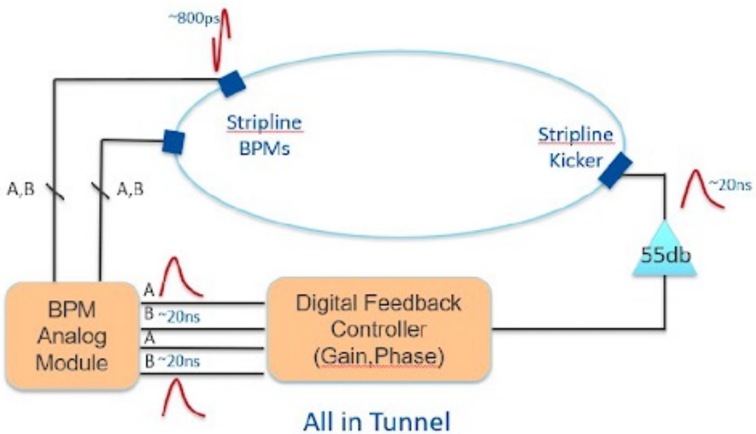
- Obtained beam size data from M1L camera:



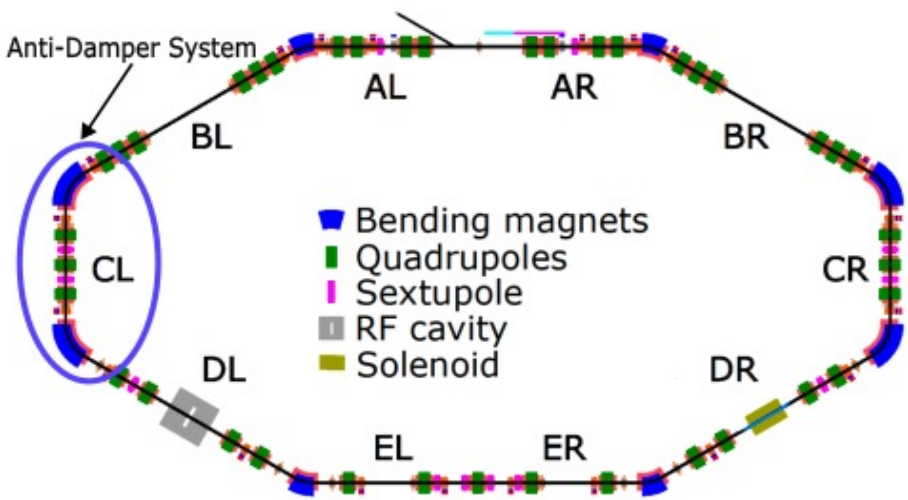
- Obtained bunch length data from wall current monitor

Experimental Setup

- Reverse polarity of transverse feedback to excite collective mode in the beam
- Main experimental elements:
    - Stripline Kicker
    - Two stripline BPMs: approx. 90° apart in phase
    - Octupoles



N. Eddy et al, 'IOTA Experiment Nonlinear Optics: Landau Damping (NIOLD)', Experiment Proposal, April 2022

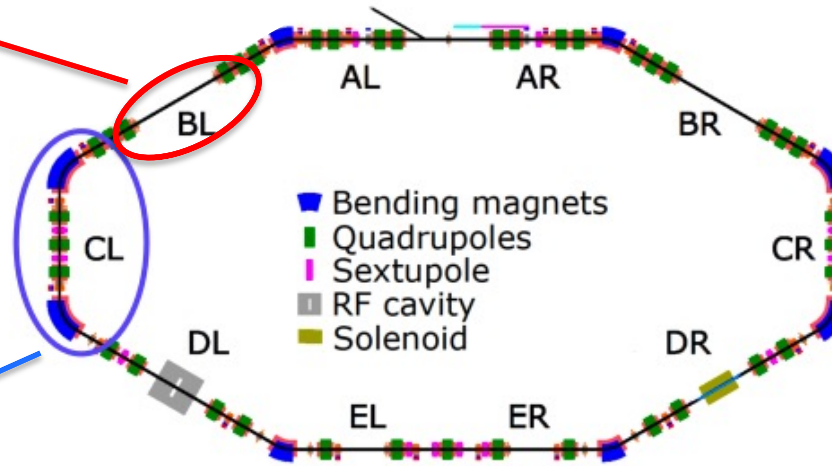


Experimental Setup

Octupole line (9 in total)

- Octupoles as strong source of nonlinear focusing
- Strength of Landau Damping changes depending on octupole strength

Stripline BPM Stripline kicker Stripline BPM



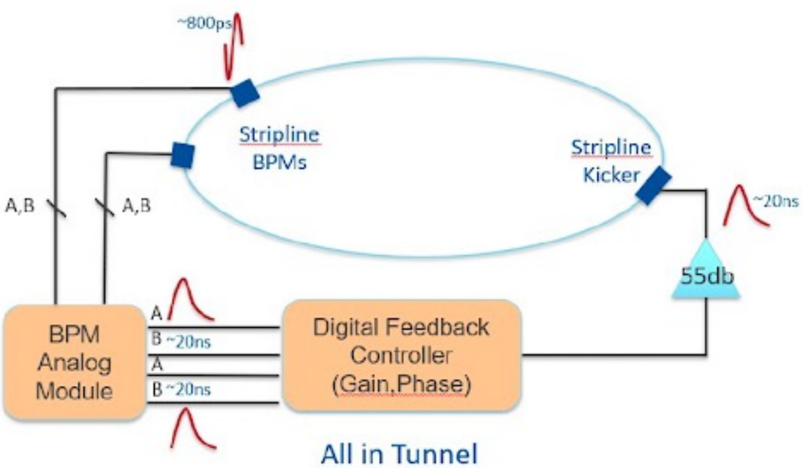
Note: striplines are located within the quadrupoles

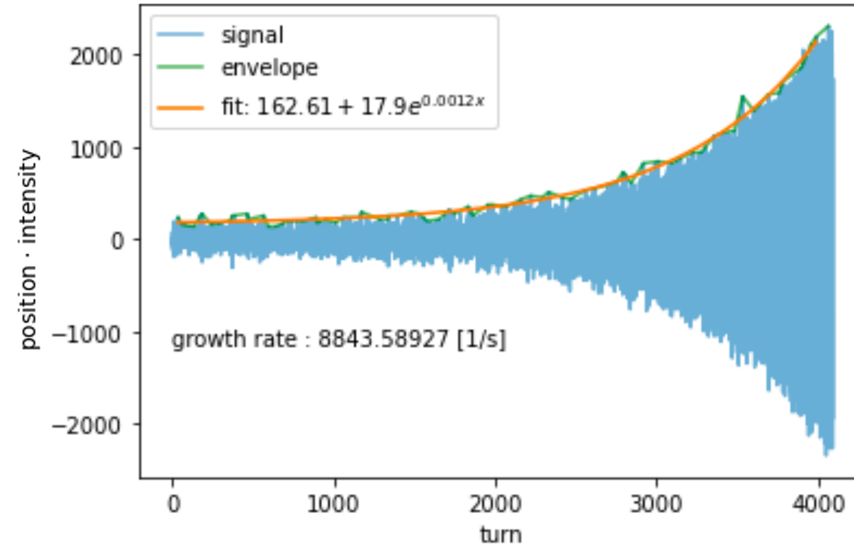
Data Collection

- Phase set by the BPM coefficients, gain set by the kicker

$$Z(\omega) \propto Ge^{i\phi}\delta(\omega)$$

- Stripline BPMs measure beam position, ~110° apart
- Experiment Process:
  - Sweep through ϕ of the antidamper
  - At each ϕ, observe what kicker gain beam becomes unstable
  - Obtain growth rate of this instability -> experimentally obtain g, ϕ



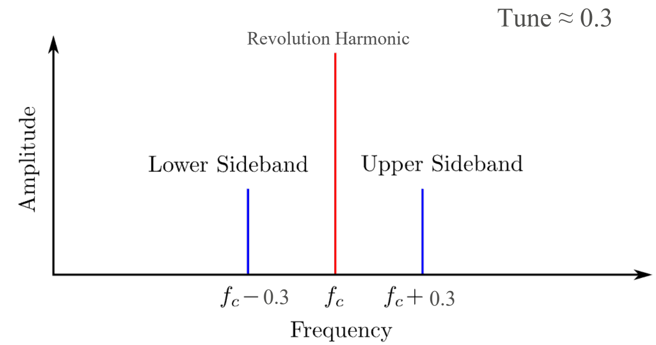


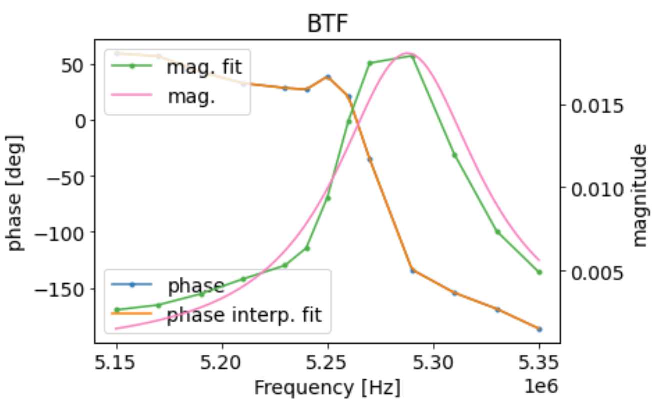
N. Eddy et al, 'IOTA Experiment Nonlinear Optics: Landau Damping (NIOLD)', Experiment Proposal, April 2022

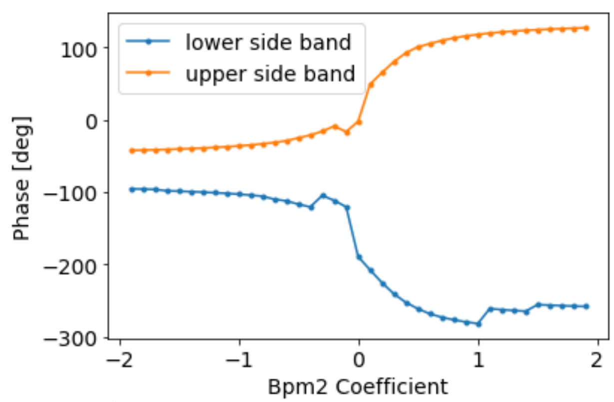
Analysis: BTFs

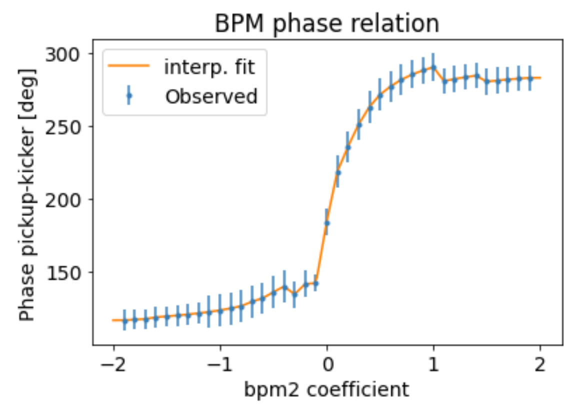
To obtain phase advance ϕ:

- Sweep through BPM coef.
- Perform a Beam Transfer Function (BTF): frequency dependence of the response to forced beam oscillations
  - Excite beam at frequencies, get upper and lower sidebands









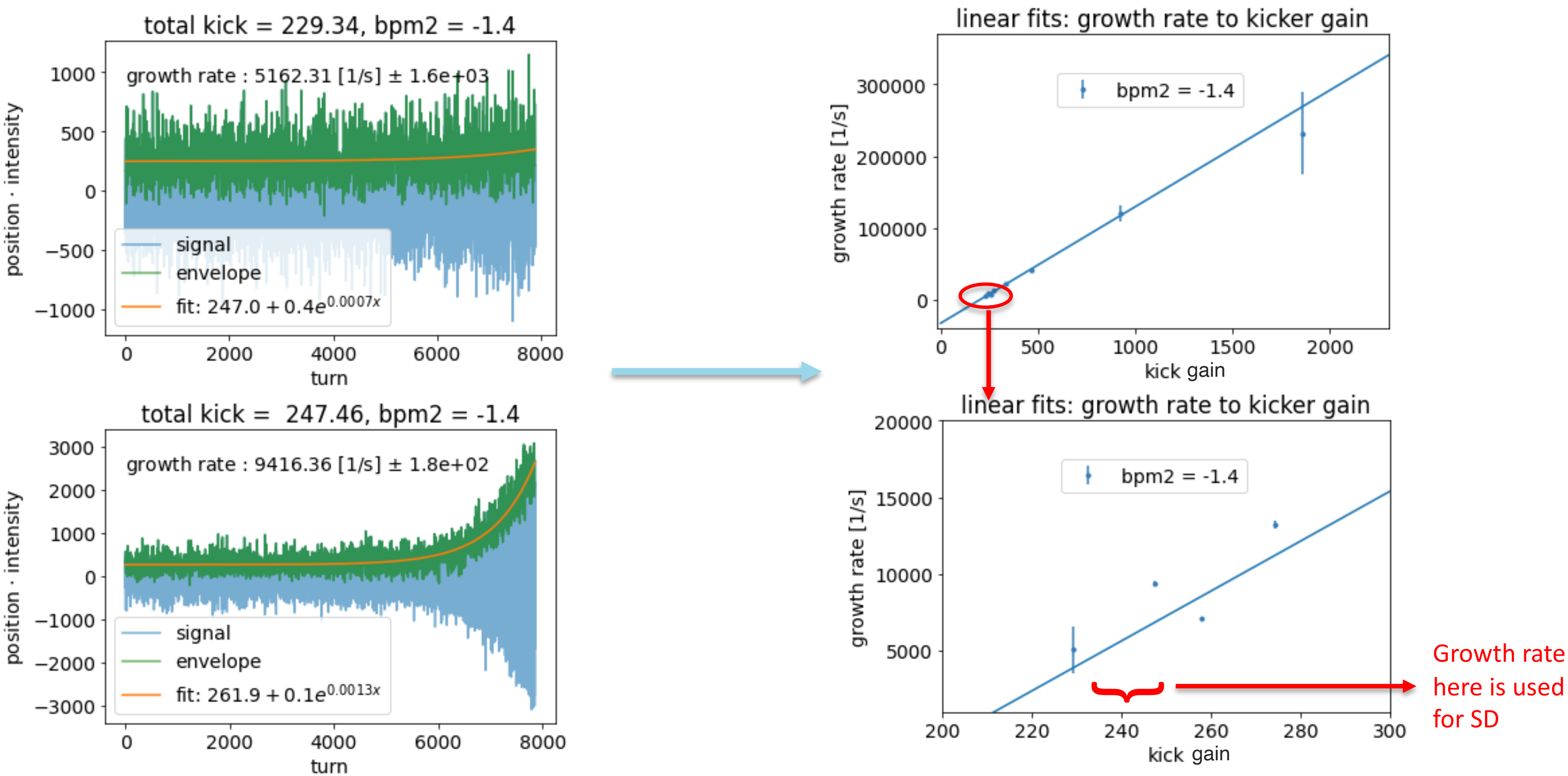
Perform BTFs: upper and lower sidebands

$$((\theta_{usb} - \theta_{lsb}) + 180)/2 = \phi$$

- BTF does not cover full phase map, took BTF data at different turn delays (turns before collected phase), each turn advanced phase by ∼60°. This allowed us to cover more phases.

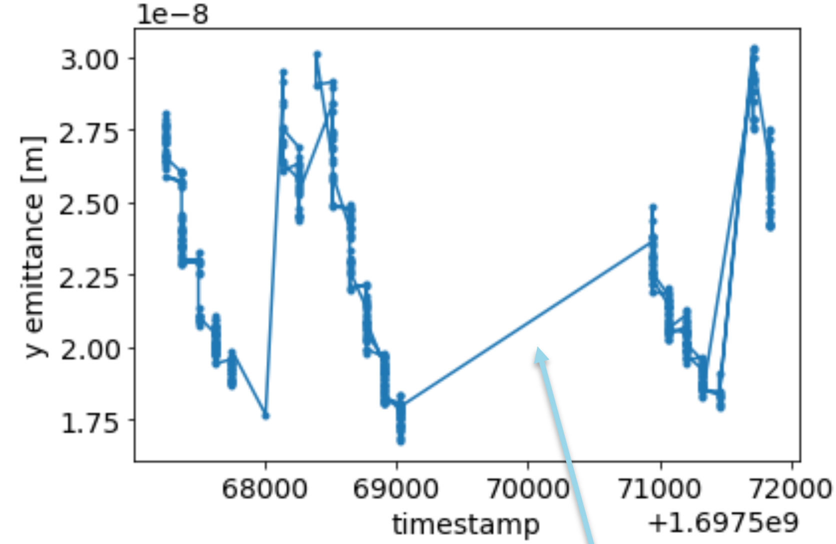
Analysis: Growth Rate

- Get growth rate for each phase: which kicker gain has first growth
- Linear fit between kicker gain and growth rate.
- Take linear fit value where see first growth
- Perform for each phase (bpm coefficient)



Analysis: Growth Rate

- During measurements: beam emittance and intensity changed over time
  - SD size relies on detuning from octupoles: octupole strength, emittance, as well as intensity
  - Normalize each growth by octupole detuning matrix and beam intensity



$$\Delta Q_y = k_{yx}\epsilon_x + k_{yy}\epsilon_y$$

Where:

$$k_{xy}, k_{yx} = -\frac{1}{8\pi}K_3 L \beta_x \beta_y$$

$$k_{yy} = \frac{1}{16\pi}K_3 L \beta_y^2$$

$$where: K_3 = \frac{1}{B\rho}3!\frac{B_y}{x^3}$$

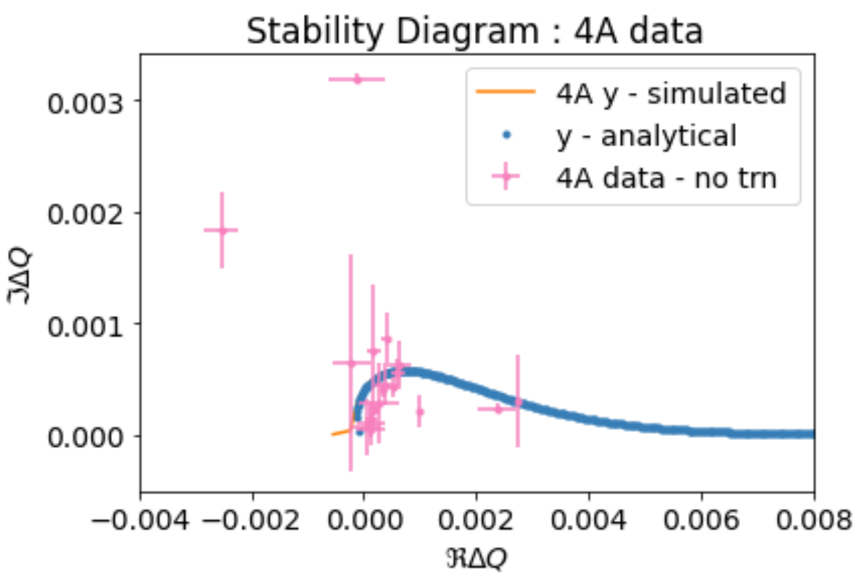
Normalize each Vert. GR by this to account for emittance variations. Normalize also by intensity.

* Note: $\epsilon_x >> \epsilon_y$ for 4A data, so $k_{yx}\ \epsilon_x$ term dominates

Analysis: Stability Diagram

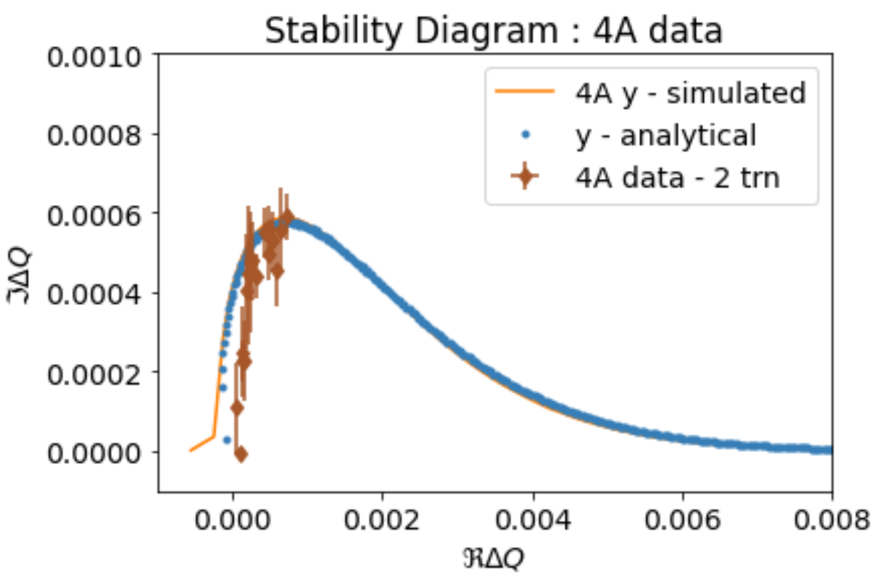
- Data taken with all octupoles at 4A
  - Two sub-sets of data: where the beam has no turn delays, where beam has two turns delays before data collection

No turn delay



Large error bars, large outliers, unexpected results with phases

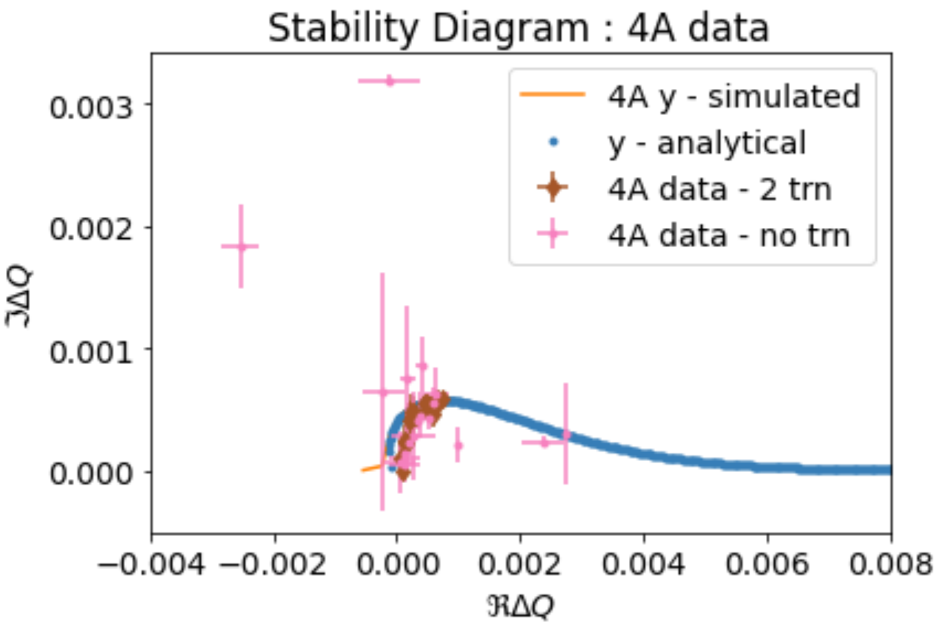
two turn delay

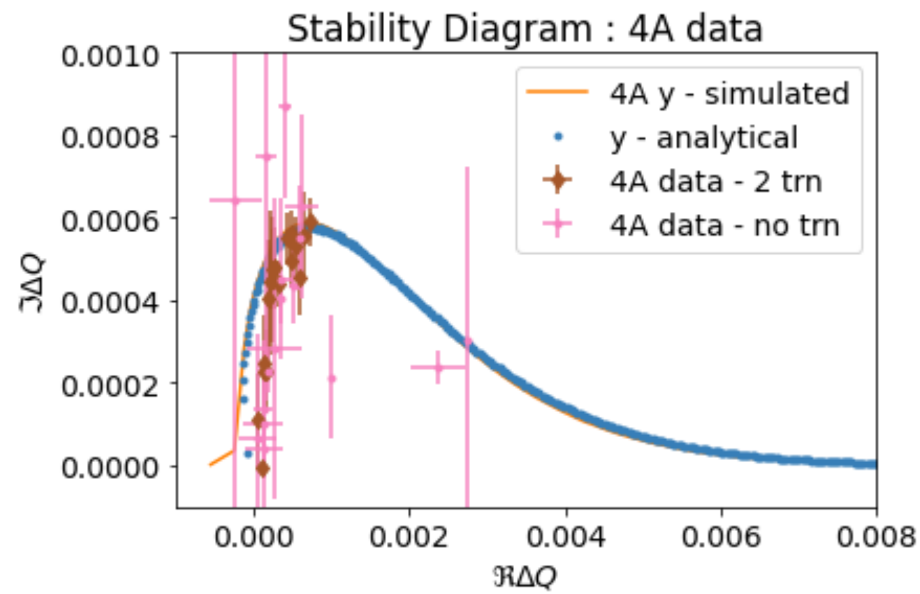


systematic shift rightward

Analysis: Stability Diagram

- All together: analytical, simulated, data





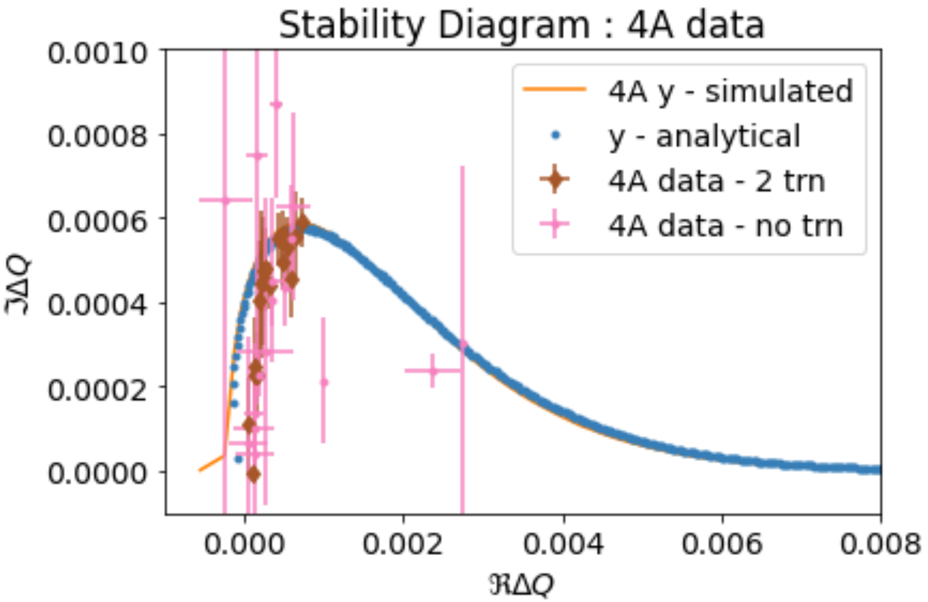
Exclude major outliers

- Major issues:
  - Large error bars:
    - Error bar sources mainly from BTF step size and kick gain step size
  - Systematic shift rightward in curve

Analysis: Stability Diagram – other factors

- Landau Damping is not only source of damping:
  - Synchrotron Radiation damping (SRD)
  - SRD would supply vertical shift to SD
- Stability Diagram Shift from SRD:
  - ΔQ (SRD) = 4.4E-07+3.4E-07j

○ <u>Impact of Synchrotron radiation damping is negligible compared to LD</u>



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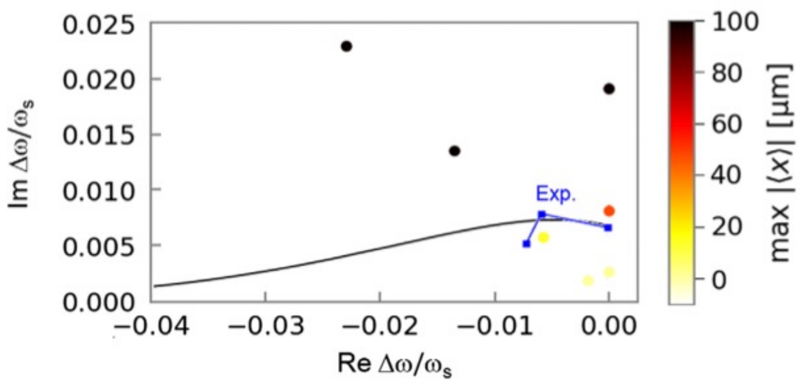
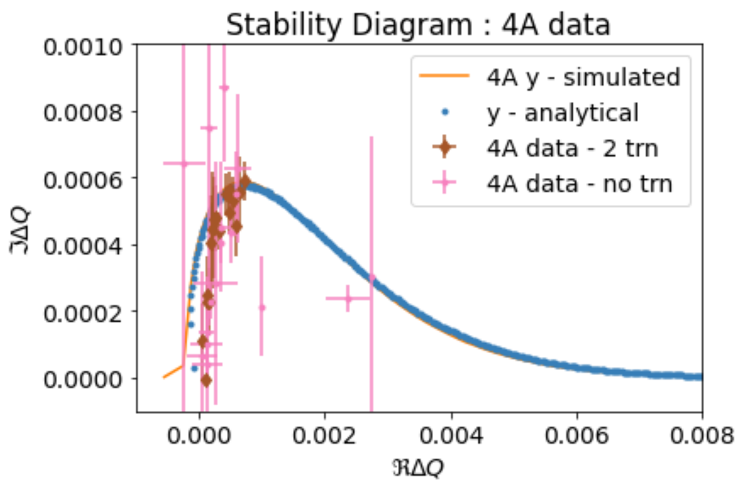
Successes

- Significantly increased quantity of phase measurements for a stability diagram:



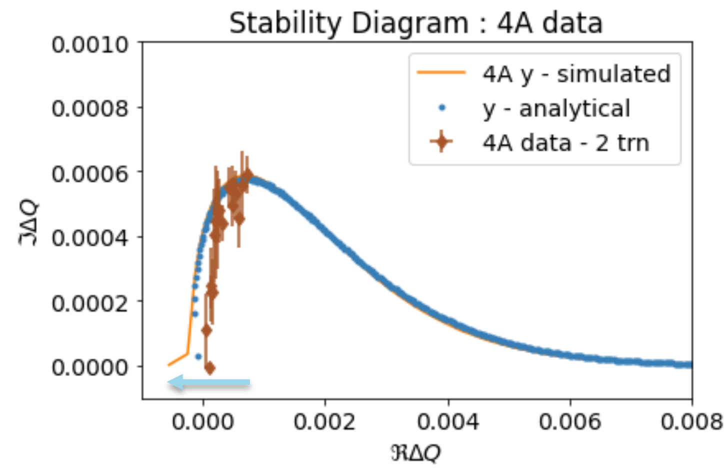


- Experimental data, simulation, and analytical predictions qualitatively agree.
- This first run was critical for understanding what we need to know and what we need in data collection

Next Steps – Current Data

Next Steps with current data:

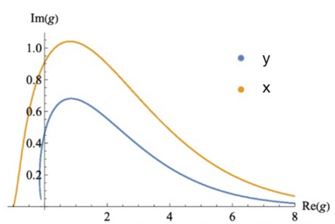
- Investigate the systematic rightward shift in data
- Further investigate issues in phase-wrapping
- Further analyze other sets of data - First data sets did not include beam size, we later understood the importance of it for analysis.
- Try to obtain beam distribution function from SD
- Investigate machine impedance impact on SD



use:

$$\Delta\omega \propto -ige^{i\phi}$$

To obtain:



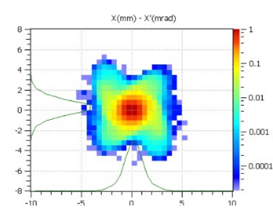
Alexey Burov. "Inverse stability problem in beam dynamics." In: *Phys. Rev. Accel. Beams* 26 (8 Aug. 2023),

use:

$$\Delta\omega = -1 / \int \frac{J_x \partial F / \partial J_x}{\Omega + \delta\omega(J_x, J_y) + io} dJ_x dJ_y$$

To solve for:

$$F(J_x, J_y)$$

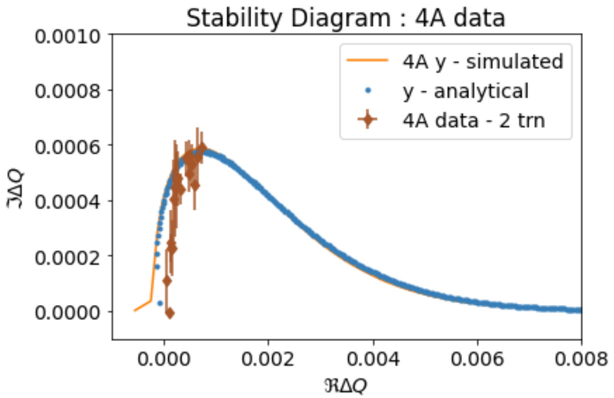


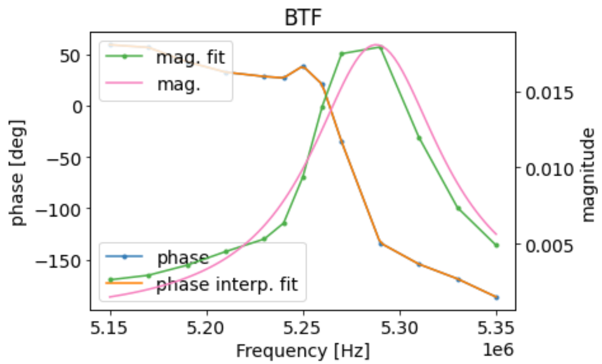
Next Steps – Future Runs

Future runs:

<u>Electrons:</u>

- Measure beam size for all the data collected - normalize by emittance
- Obtain more data for tails of the SDs: Tails are essential to obtain distribution function
  - More measurements at small phases
  - Better understand phase wrapping
- Take tighter measurements for the BTFs, so to minimize phase error
- Directly measure the amplitude detuning matrix
- Currently limited with the antidamper acting and measuring in one plane at a time: add capability to measure both planes at the same time





<u>Protons:</u>

- Analyze SDs with Impact of Electron Lens (protons)
- Investigate LD with bunched beams and space charge (protons)

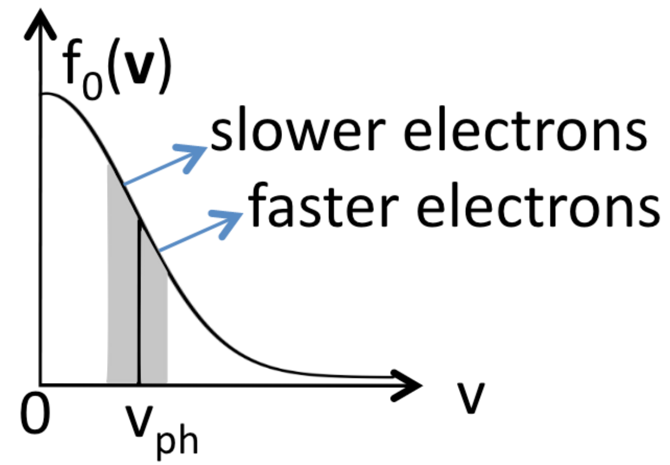
Thank you!

Photo Credit: Giulio Stancari

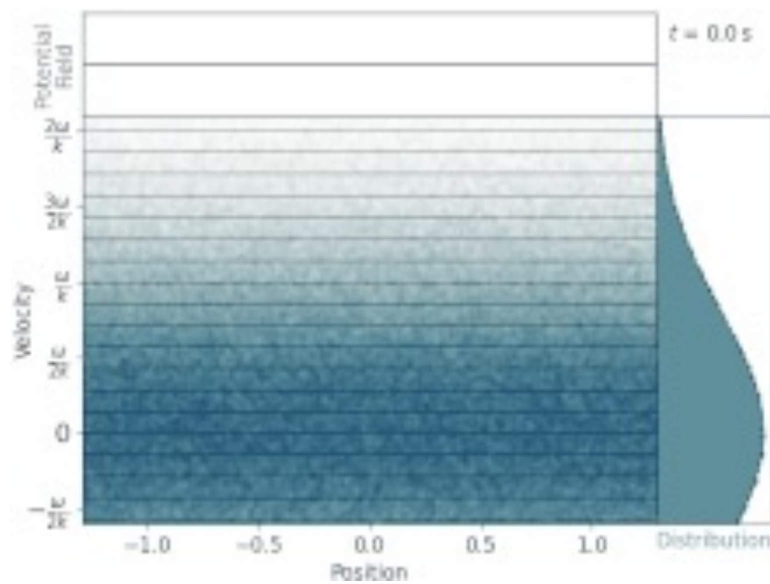
Appendix

Appendix: Background– Landau Damping

- Landau Damping (LD) Historical Context:
  - Derived originally for plasmas with purely mathematical approach (1946)
  - First experimental evidence for LD observed in 1964



- Physical Interpretation (plasmas)
  - Neutral plasma, Maxwellian vel. distribution
  - Perturbation in distribution: plasma wave propagates at Vph
  - Electrons near Vph interact strongly.
  - Greater energy e's: decelerate, lose energy
  - Lesser energy e's: accelerate, gain energy
  - There are more e's with less energy: <u>energy is transferred from perturbation to particles - damping the perturbation</u>

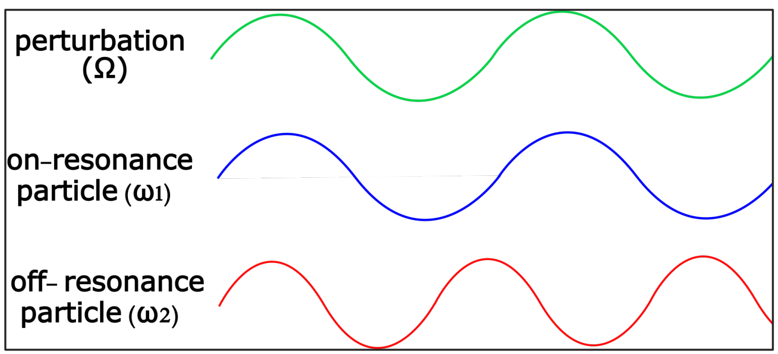


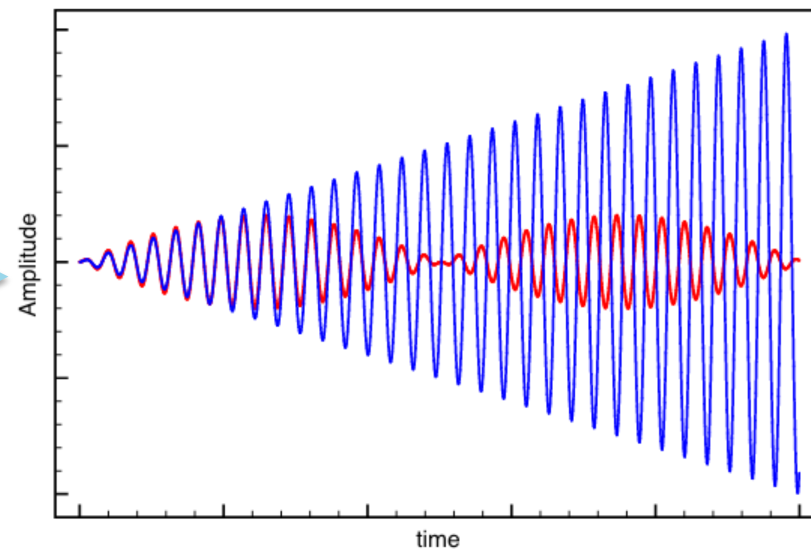
Background/Motivation – Landau Damping

Accelerators suffer from collective instabilities:

- Transverse EM force as kick (freq. Ω)
- Two particles: $\Omega = \omega 1$, $\Omega \neq \omega 2$
    - Amp. of $\Omega = \omega 1$ particle grows w/time
    - $\omega 2$ particle reaches max, later loses phase synchronism with Ω.
    - At time t, only oscillators $\Omega - \omega \approx 0$ maintain phase relation with Ω.
    - On-resonance particles absorb energy: bandwidth & number decrease w/time.

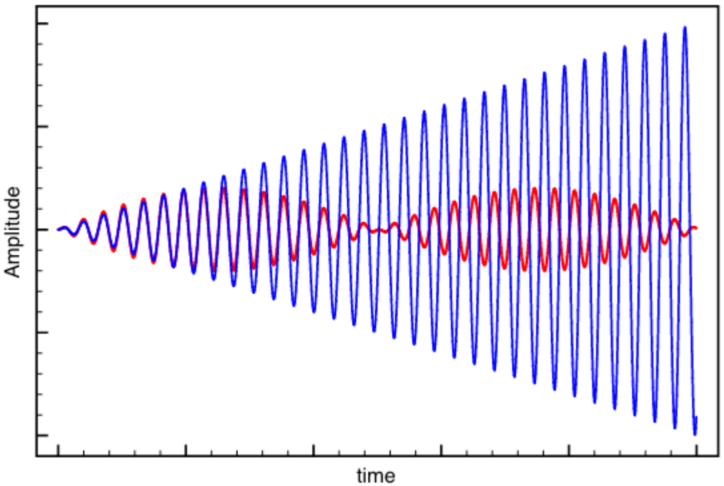
<u>Energy absorption by particles while total energy of oscillations (coherent and incoherent) remains constant</u>





Appendix: Landau Damping Mechanical model

- Physical Interpretation (mechanical model):
  - Model consisting of infinite set of harmonic oscillators: frequency distribution G(ω)
  - System driven by external sinusoidal force at frequency Ω.
  - All oscillator frequencies sufficiently close to one another and Ω lies within their spectrum.
  - Consider two oscillators: $\Omega = \omega$, $\Omega \neq \omega$.
    - Amplitude of on resonance oscillator grows linearly with time. Other reaches maximum and after time is out of resonance, loses phase synchronism with Ω.
    - At time t, only oscillators with frequency ω, where $\Omega - \omega$ is so small maintain phase relation with the external force. The later on, the narrower the frequency bandwidth $\Omega - \omega$ of synchronous oscillators.
    - The 'on resonance' oscillators are in phase with the external force and absorb energy from it, but their frequency bandwidth and number decreases with time.
    - Net effect is absorption of energy by the system while average amplitude of oscillation remains constant.



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NIOLD Experiment History at IOTA

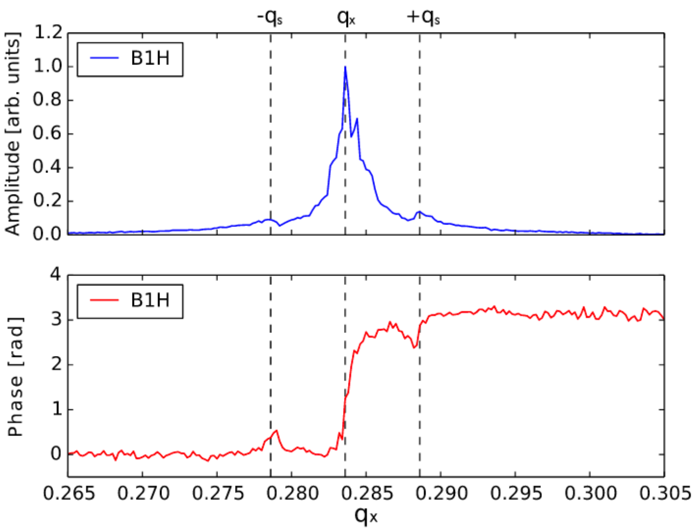
- Run 1:
  - simple analog system using a single button bpm and one of the horizontal kicker plates.
  - There was one experimental shift which showed improved stability threshold with octupoles powered.
- Run 2:
  - More extensive shifts were done
  - The same setup and more sophisticated data collection.
- Run 4:
  - Did major upgrades to install dedicated stripline pickups and kicker and implement the digital controller.
  - had major delays in stripline installation - final driving term was getting electricians to pull cables and install power to our crate.

Appendix: Stability Diagram Measurement Method

Measurement of Stability Diagrams

- Common technique to measure SDs: beam transfer function (BTF)
  - frequency dependence of response to forced beam oscillations
  - Stability diagram is inverse of BTF
- Technique has limitations:
  - Method does not test LD strength itself, but the BTF, relying on assumptions behind dispersion relation:
    - Synchrotron frequency is negligible
    - Betatron frequency spread is sufficiently small
    - Beam response to external excitation is linear
    - Coherent modes are uncoupled

Example of BTF measurement: amplitude and phase response for B1 at the LHC injection energy.



'Beam transfer function measurements used to probe the transverse Landau damping at the LHC' C. Tambasco et.al.

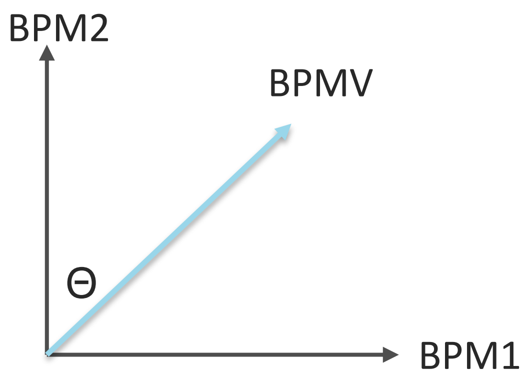
<u>Since other techniques have limitations, we investigate an alternative method to measure the strength of LD</u>

Appendix: Landau Damping in Accelerators

- Landau Damping in Accelerators:
  - Accelerators suffer from collective instabilities limiting the current intensity
  - beam perturbation from interaction with surrounding walls -> em fields interacting back on the beam -> certain conditions lead to resonance in the beam motion excited with growing amplitude.
  - Here we focus on transverse beam dynamics of bunched beam.
    - Have transverse wake field -> introduce transverse equations of motion to be used in the Vlasov equation to obtain dispersion relation -> Apply dispersion relation to distribution function.
    - Consider transverse electromagnetic force produced by the charge as a transverse deflecting kick divided by the machine length
    - there is a contribution to the transverse Landau damping also from a possible spread on the synchrotron frequencies.
    - in order to get more efficient betatron frequency spread, the so-called landau damping octupoles are sometimes used: introduce an amplitude frequency dependence which is thought to be more effective than the energy dependent betatron frequency spread produced by sextuples.

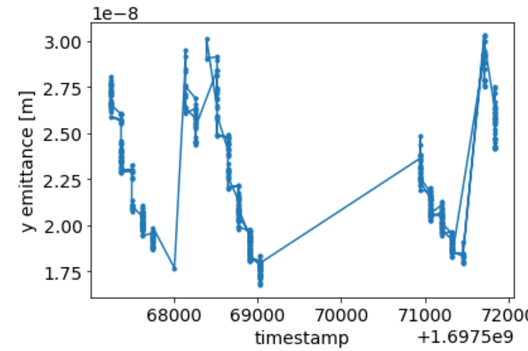
BPM Coefficients

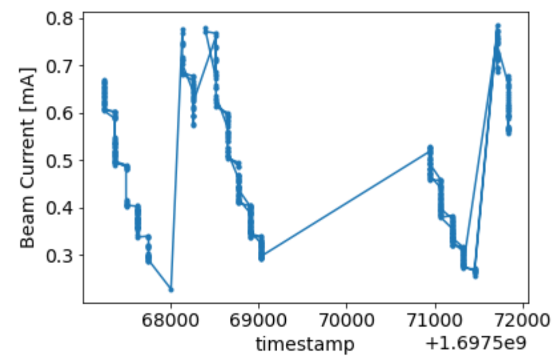
- BPMs are 90° apart in phase advance.
- Changing the BPM coefficients essentially changes the mapping of the virtual BPM's (BPMV) phase.
- C1, C2 represent the BPM coefficients, changing the phase advance according to their combination



$$\Theta = tan^{-1}\left({}^{C2 \, * \, BPM2}/_{C1 \, * \, BPM1}\right)$$

Analysis: Growth Rate





- During measurements: beam emittance and intensity changed over time
  - SD size relies on detuning from octupoles: octupole strength, emittance, as well as intensity
  - Normalize each growth by octupole detuning matrix and beam intensity

$$\Delta Q_y = k_{yx}\epsilon_x + k_{yy}\epsilon_y$$

$$\Delta Q_x = k_{xx}\epsilon_x + k_{xy}\epsilon_y$$

Where:

$$k_{xx} = \frac{1}{16\pi} K_3 L \beta_x^2$$

$$k_{xy}, k_{yx} = -\frac{1}{8\pi} K_3 L \beta_x \beta_y$$

$$k_{yy} = \frac{1}{16\pi} K_3 L \beta_y^2$$

$$where: K_3 = \frac{1}{B\rho} 3! \frac{B_y}{x^3}$$

Normalize each Vert. GR by this to account for emittance variations. Normalize also by intensity.

* Note: ϵ_x >> ϵ_y for 4A data, so k_{yx} ϵ_x term dominates

Appendix: IOTA Parameters

	Electrons	Protons
Circumference, C	39.96 m	39.96 m
Kinetic energy, K_b	100–150 MeV	2.5 MeV
Revolution period, τ_{rev}	133 ns	1.83 μs
Revolution frequency, f_{rev}	7.50 MHz	0.547 MHz
Rf harmonic number, h	4	4
Rf frequency, f_{rf}	30.0 MHz	2.19 MHz
Max. rf voltage, V_{rf}	1 kV	1 kV
Number of bunches	1	4 or coasting
Bunch population, N_b	$1\ e^- - 3.3 \times 10^9\ e^-$	$< 5.7 \times 10^9\ p$
Beam current, I_b	1.2 pA – 4 mA	< 2 mA
Transverse emittances (rms, geom.), $\epsilon_{x,y}$	20–90 nm	3–4 μm
Momentum spread, $\delta_p = \Delta p/p$	$1\text{–}4 \times 10^{-4}$	$1\text{–}2 \times 10^{-3}$
Radiation damping times, $\tau_{x,y,z}$	0.2–2 s	–
Max. space-charge tune shift, $\lvert\Delta\nu_{\mathrm{sc}}\rvert$	$< 10^{-3}$	0.5

Appendix: beam distribution function

- Beam Distribution Function:
  - Although SD important alone: measurement can be also used as data about beam distribution function
  - SD is map of the real axes of eigenvalue plane onto complex gain plane, beam distribution function is transformation kernel
  - This mathematical problem has never been treated in the past, so its solution requires new methods

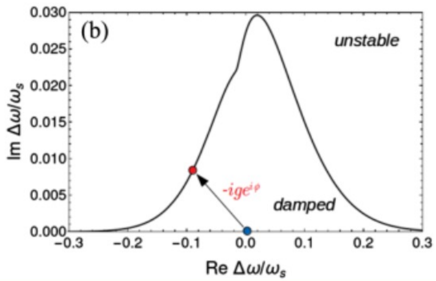
Experimentally obtain g, ϕ

→

use:

$$\Delta\omega \propto -ige^{i\phi}$$

To obtain:



→

use:

$$\Delta\omega = -1/\int \frac{J_x \partial F/\partial J_x}{\Omega + \delta\omega(J_x, J_y) + io} dJ_x dJ_y$$

To solve for: $F(J_x, J_y)$

For tails: take integral asymptotically to get simplified relations between $\Delta\omega$ and F

For core: assume distribution func. belongs to certain family of functions with few free parameters. Fit them to SD in core region