

Lowpass Differentiator Controllers for the Longitudinal Bunch-by-bunch Feedback

D. Teytelman

Dimtel, Inc., San Jose, CA, USA

LLRF Topical Workshop on Advanced Feedback Control



Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Outline

Motivation

Concept

Surprise Discovery

Some Observations

Design Procedure

Recent Results

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Summary

- ◀ ◻ ▶ ◀ ◻ ▶ ◀ ≡ ▶ ◀ ≡ ▶ ≡ ↺ 🔍 ↻ 3/16

Longitudinal Stabilization and Tune Variation

- ▶ Traditionally, longitudinal feedback controllers are designed to satisfy three requirements:
 - ▶ 90° phase shift at the synchrotron frequency;
 - ▶ DC rejection;
 - ▶ Bandpass response.
- ▶ This approach is limited in its tune acceptance range;
- ▶ Many modern light sources use harmonic cavities to lengthen the bunches for the improved lifetime;
- ▶ This leads to wide range of synchrotron frequency variation versus beam current, as well as wide spread of frequencies at nominal operating current.

Motivation

Concept

Surprise Discovery

Some Observations

Design Procedure

Recent Results

Summary

Longitudinal Stabilization and Tune Variation

- ▶ Traditionally, longitudinal feedback controllers are designed to satisfy three requirements:
 - ▶ 90° phase shift at the synchrotron frequency;
 - ▶ DC rejection;
 - ▶ Bandpass response.
- ▶ This approach is limited in its tune acceptance range;
- ▶ Many modern light sources use harmonic cavities to lengthen the bunches for the improved lifetime;
- ▶ This leads to wide range of synchrotron frequency variation versus beam current, as well as wide spread of frequencies at nominal operating current.

Motivation

Concept

Surprise Discovery

Some Observations

Design Procedure

Recent Results

Summary

Longitudinal Stabilization and Tune Variation

- ▶ Traditionally, longitudinal feedback controllers are designed to satisfy three requirements:
 - ▶ 90° phase shift at the synchrotron frequency;
 - ▶ DC rejection;
 - ▶ Bandpass response.
- ▶ This approach is limited in its tune acceptance range;
- ▶ Many modern light sources use harmonic cavities to lengthen the bunches for the improved lifetime;
- ▶ This leads to wide range of synchrotron frequency variation versus beam current, as well as wide spread of frequencies at nominal operating current.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Longitudinal Stabilization and Tune Variation

- ▶ Traditionally, longitudinal feedback controllers are designed to satisfy three requirements:
 - ▶ 90° phase shift at the synchrotron frequency;
 - ▶ DC rejection;
 - ▶ Bandpass response.
- ▶ This approach is limited in its tune acceptance range;
- ▶ Many modern light sources use harmonic cavities to lengthen the bunches for the improved lifetime;
- ▶ This leads to wide range of synchrotron frequency variation versus beam current, as well as wide spread of frequencies at nominal operating current.

Concept

Some Observations

Recent Results

Summary

Longitudinal Stabilization and Tune Variation

- ▶ Traditionally, longitudinal feedback controllers are designed to satisfy three requirements:
 - ▶ 90° phase shift at the synchrotron frequency;
 - ▶ DC rejection;
 - ▶ Bandpass response.
- ▶ This approach is limited in its tune acceptance range;
- ▶ Many modern light sources use harmonic cavities to lengthen the bunches for the improved lifetime;
- ▶ This leads to wide range of synchrotron frequency variation versus beam current, as well as wide spread of frequencies at nominal operating current.

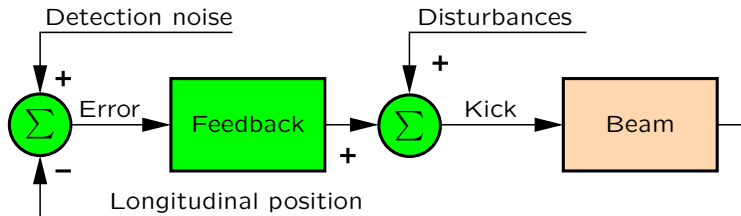
Concept

Some Observations

Recent Results

◀ ◻ ▶ ◀ ◻ ▶ ◀ ≡ ▶ ◀ ≡ ▶ ≡ ↺ 🔍 ↻ 3/16

Differentiator Feedback in the Longitudinal Plane



- ▶ Beam response $B(s) = \frac{C}{s^2 - 2\lambda s + \omega^2}$;
- ▶ C absorbs front-end and back-end gains, as well as optics parameters;
- ▶ Differentiator $F(s) = Ks$ is mathematically ideal to stabilize $B(s)$:
- ▶ Closed loop response $H_{cl}(s) = \frac{B(s)}{1 + F(s)B(s)} = \frac{C}{s^2 - (2\lambda - KC)s + \omega^2}$;
- ▶ Differentiator only affects the growth rate and provides constant damping independent of the synchrotron frequency.

Motivation

Concept

Surprise Discovery

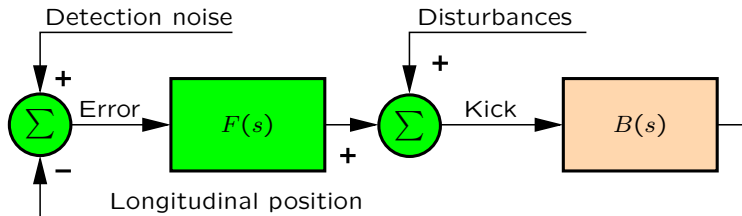
Some
Observations

Design Procedure

Recent Results

Summary

Differentiator Feedback in the Longitudinal Plane



- ▶ Beam response $B(s) = \frac{C}{s^2 - 2\lambda s + \omega^2}$;
- ▶ C absorbs front-end and back-end gains, as well as optics parameters;
- ▶ Differentiator $F(s) = Ks$ is mathematically ideal to stabilize $B(s)$;
- ▶ Closed loop response $H_{cl}(s) = \frac{B(s)}{1 + F(s)B(s)} = \frac{C}{s^2 - (2\lambda - KC)s + \omega^2}$;
- ▶ Differentiator only affects the growth rate and provides constant damping independent of the synchrotron frequency.

Motivation

Concept

Surprise Discovery

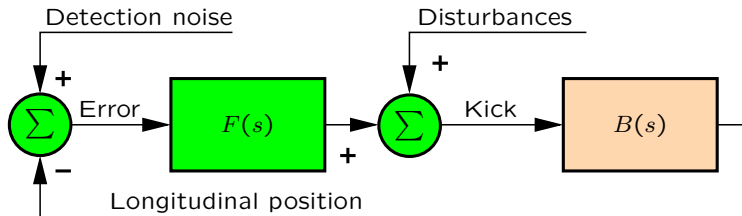
Some
Observations

Design Procedure

Recent Results

Summary

Differentiator Feedback in the Longitudinal Plane



- ▶ Beam response $B(s) = \frac{C}{s^2 - 2\lambda s + \omega^2}$;
- ▶ C absorbs front-end and back-end gains, as well as optics parameters;
- ▶ Differentiator $F(s) = Ks$ is mathematically ideal to stabilize $B(s)$:
- ▶ Closed loop response $H_{cl}(s) = \frac{B(s)}{1 + F(s)B(s)} = \frac{C}{s^2 - (2\lambda - KC)s + \omega^2}$;
- ▶ Differentiator only affects the growth rate and provides constant damping independent of the synchrotron frequency.

Motivation

Concept

Surprise Discovery

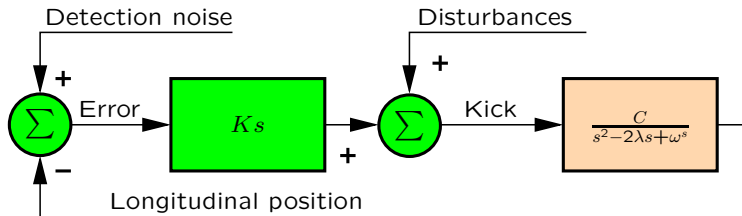
Some
Observations

Design Procedure

Recent Results

Summary

Differentiator Feedback in the Longitudinal Plane



- ▶ Beam response $B(s) = \frac{C}{s^2 - 2\lambda s + \omega^2}$;
- ▶ C absorbs front-end and back-end gains, as well as optics parameters;
- ▶ Differentiator $F(s) = Ks$ is mathematically ideal to stabilize $B(s)$:
- ▶ Closed loop response $H_{cl}(s) = \frac{B(s)}{1 + F(s)B(s)} = \frac{C}{s^2 - (2\lambda - KC)s + \omega^2}$;
- ▶ Differentiator only affects the growth rate and provides constant damping independent of the synchrotron frequency.

Motivation

Concept

Surprise Discovery

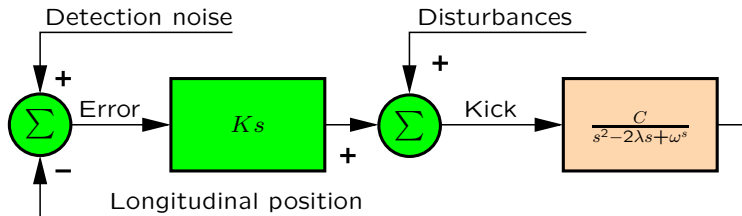
Some
Observations

Design Procedure

Recent Results

Summary

Differentiator Feedback in the Longitudinal Plane



- ▶ Beam response $B(s) = \frac{C}{s^2 - 2\lambda s + \omega^2}$;
- ▶ C absorbs front-end and back-end gains, as well as optics parameters;
- ▶ Differentiator $F(s) = Ks$ is mathematically ideal to stabilize $B(s)$:
- ▶ Closed loop response $H_{cl}(s) = \frac{B(s)}{1 + F(s)B(s)} = \frac{C}{s^2 - (2\lambda - KC)s + \omega^2}$;
- ▶ Differentiator only affects the growth rate and provides constant damping independent of the synchrotron frequency.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
- ▶ Seemed to work on the bench — next step would be testing it in a machine.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
- ▶ Seemed to work on the bench — next step would be testing it in a machine.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
- ▶ Seemed to work on the bench — next step would be testing it in a machine.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
- ▶ Seemed to work on the bench — next step would be testing it in a machine.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
- ▶ Seemed to work on the bench — next step would be testing it in a machine.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

It Could Never Work...

- ▶ When I started working on longitudinal bunch-by-bunch feedback as a first year graduate student I almost immediately learned that “differentiator could never work”.
- ▶ Approximate differentiator by one turn difference $u_n = z_n - z_{n-1}$
- ▶ Problems:
 - ▶ Very little gain at synchrotron frequencies — small phase advance per turn;
 - ▶ Controller gain increases linearly with frequency — output will be swamped with the amplified wideband detection and quantization noise.
- ▶ For me the matter rested there until summer 2022 (NAPAC 2022), when I learned that Ryan Lindberg of APS-U arrived at the differentiator idea;
- ▶ I set out to demonstrate why this was a bad idea and was surprised to discover that, at least in the Simulink model, it worked as well as the conventional approach;
- ▶ Seemed to work on the bench — next step would be testing it in a machine.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Test in an Accelerator

- ▶ A month later I got a call from the ALS — they had trouble reaching 500 mA operating current;
- ▶ What is ALS:
 - ▶ 1.5 GeV storage ring with normal conducting main and harmonic RF cavities;
 - ▶ Multiple unstable modes in the longitudinal plane;
 - ▶ Zero current synchrotron frequency of 8.5 kHz decreases to 5.5 kHz at full current due to the action of the harmonic cavities;
 - ▶ Mode 0 is shifted to 4 kHz by the interaction with the main RF impedance, normally stable.
- ▶ Feedback filter for the ALS is designed to damp instabilities from 5 to 9 kHz, rolls off gently below 5 kHz to avoid destabilizing mode 0.
- ▶ In September 2022, mode 0 was going unstable at the ALS and the existing feedback filter could not damp the instability;
- ▶ Tried a low-pass differentiator — worked like a charm.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Test in an Accelerator

- ▶ A month later I got a call from the ALS — they had trouble reaching 500 mA operating current;
- ▶ What is ALS:
 - ▶ 1.5 GeV storage ring with normal conducting main and harmonic RF cavities;
 - ▶ Multiple unstable modes in the longitudinal plane;
 - ▶ Zero current synchrotron frequency of 8.5 kHz decreases to 5.5 kHz at full current due to the action of the harmonic cavities;
 - ▶ Mode 0 is shifted to 4 kHz by the interaction with the main RF impedance, normally stable.
- ▶ Feedback filter for the ALS is designed to damp instabilities from 5 to 9 kHz, rolls off gently below 5 kHz to avoid destabilizing mode 0.
- ▶ In September 2022, mode 0 was going unstable at the ALS and the existing feedback filter could not damp the instability;
- ▶ Tried a low-pass differentiator — worked like a charm.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Test in an Accelerator

- ▶ A month later I got a call from the ALS — they had trouble reaching 500 mA operating current;
- ▶ What is ALS:
 - ▶ 1.5 GeV storage ring with normal conducting main and harmonic RF cavities;
 - ▶ Multiple unstable modes in the longitudinal plane;
 - ▶ Zero current synchrotron frequency of 8.5 kHz decreases to 5.5 kHz at full current due to the action of the harmonic cavities;
 - ▶ Mode 0 is shifted to 4 kHz by the interaction with the main RF impedance, normally stable.
- ▶ Feedback filter for the ALS is designed to damp instabilities from 5 to 9 kHz, rolls off gently below 5 kHz to avoid destabilizing mode 0.
- ▶ In September 2022, mode 0 was going unstable at the ALS and the existing feedback filter could not damp the instability;
- ▶ Tried a low-pass differentiator — worked like a charm.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Test in an Accelerator

- ▶ A month later I got a call from the ALS — they had trouble reaching 500 mA operating current;
- ▶ What is ALS:
 - ▶ 1.5 GeV storage ring with normal conducting main and harmonic RF cavities;
 - ▶ Multiple unstable modes in the longitudinal plane;
 - ▶ Zero current synchrotron frequency of 8.5 kHz decreases to 5.5 kHz at full current due to the action of the harmonic cavities;
 - ▶ Mode 0 is shifted to 4 kHz by the interaction with the main RF impedance, normally stable.
- ▶ Feedback filter for the ALS is designed to damp instabilities from 5 to 9 kHz, rolls off gently below 5 kHz to avoid destabilizing mode 0.
- ▶ In September 2022, mode 0 was going unstable at the ALS and the existing feedback filter could not damp the instability;
- ▶ Tried a low-pass differentiator — worked like a charm.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Test in an Accelerator

- ▶ A month later I got a call from the ALS — they had trouble reaching 500 mA operating current;
- ▶ What is ALS:
 - ▶ 1.5 GeV storage ring with normal conducting main and harmonic RF cavities;
 - ▶ Multiple unstable modes in the longitudinal plane;
 - ▶ Zero current synchrotron frequency of 8.5 kHz decreases to 5.5 kHz at full current due to the action of the harmonic cavities;
 - ▶ Mode 0 is shifted to 4 kHz by the interaction with the main RF impedance, normally stable.
- ▶ Feedback filter for the ALS is designed to damp instabilities from 5 to 9 kHz, rolls off gently below 5 kHz to avoid destabilizing mode 0.
- ▶ In September 2022, mode 0 was going unstable at the ALS and the existing feedback filter could not damp the instability;
- ▶ Tried a low-pass differentiator — worked like a charm.

Motivation

Concept

Surprise Discovery

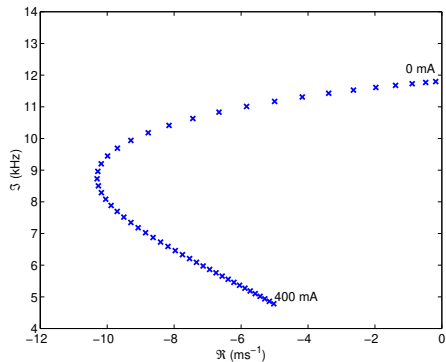
Some
Observations

Design Procedure

Recent Results

Summary

Mode 0 vs. Beam Current



- ▶ Root locus of the modal eigenvalue versus beam current;
- ▶ Damping on the real axis, frequency on the imaginary;
- ▶ Old ALS configuration (higher RF voltage).

Motivation

Concept

Surprise Discovery

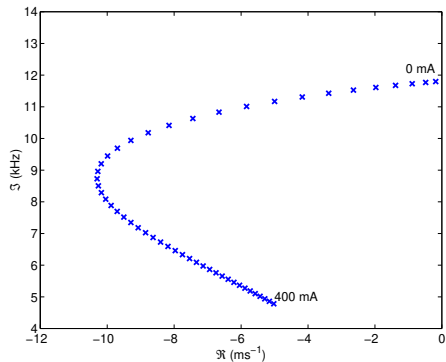
Some
Observations

Design Procedure

Recent Results

Summary

Mode 0 vs. Beam Current



- ▶ Root locus of the modal eigenvalue versus beam current;
- ▶ Damping on the real axis, frequency on the imaginary;
- ▶ Old ALS configuration (higher RF voltage).

Motivation

Concept

Surprise Discovery

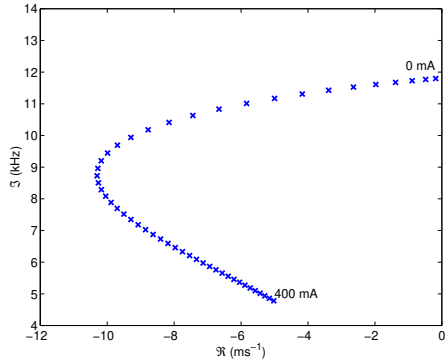
Some
Observations

Design Procedure

Recent Results

Summary

Mode 0 vs. Beam Current



- ▶ Root locus of the modal eigenvalue versus beam current;
- ▶ Damping on the real axis, frequency on the imaginary;
- ▶ Old ALS configuration (higher RF voltage).

Motivation

Concept

Surprise Discovery

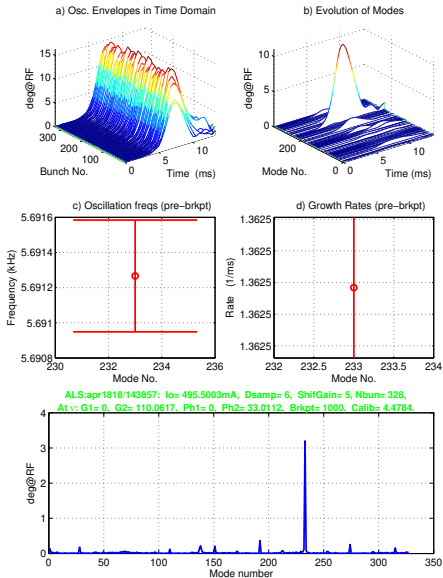
Some
Observations

Design Procedure

Recent Results

Summary

Modal Behavior



► A grow/damp measurement from 2018;

- 12 ms open loop time;
- Well-known HOMs in main RF cavities drive mode 233;
- A measurement on September 8, 2022;
- 3 ms open loop time;
- Modes 0, 1, and -1 grow.

Motivation

Concept

Surprise Discovery

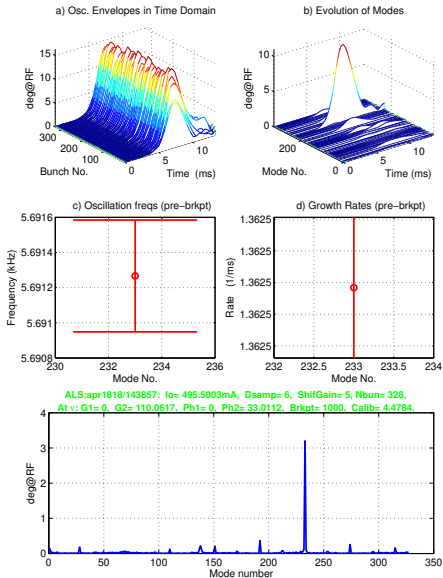
Some
Observations

Design Procedure

Recent Results

Summary

Modal Behavior



- ▶ A grow/damp measurement from 2018;
- ▶ 12 ms open loop time;
- ▶ Well-known HOMs in main RF cavities drive mode 233;
- ▶ A measurement on September 8, 2022;
- ▶ 3 ms open loop time;
- ▶ Modes 0, 1, and -1 grow.

Motivation

Concept

Surprise Discovery

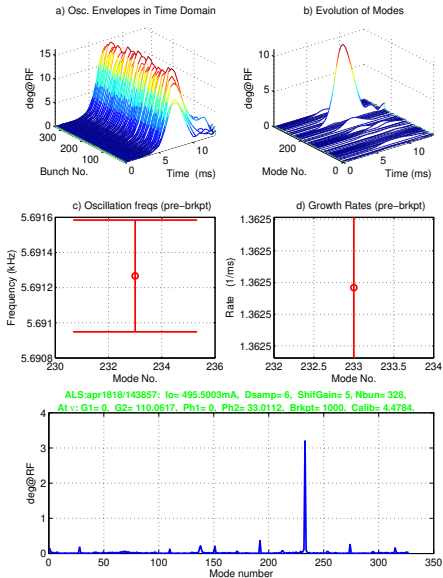
Some
Observations

Design Procedure

Recent Results

Summary

Modal Behavior



- ▶ A grow/damp measurement from 2018;
- ▶ 12 ms open loop time;
- ▶ Well-known HOMs in main RF cavities drive mode 233;
- ▶ A measurement on September 8, 2022;
- ▶ 3 ms open loop time;
- ▶ Modes 0, 1, and -1 grow.

Motivation

Concept

Surprise Discovery

Some
Observations

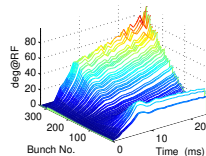
Design Procedure

Recent Results

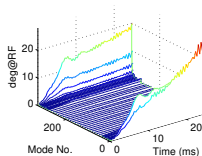
Summary

Modal Behavior

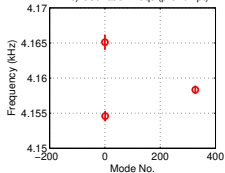
a) Osc. Envelopes in Time Domain



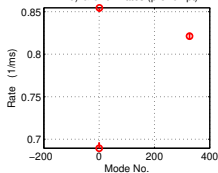
b) Evolution of Modes



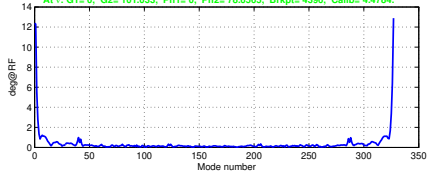
c) Oscillation freqs (pre-brkpt)



d) Growth Rates (pre-brkpt)



ALS:sep0822/095711: Io= 496.8892mA, Dsamp= 1, ShifGain= 6, Nbnun= 328,
At v: G1= 0, G2= 101.033, Ph1= 0, Ph2= 78.6565, Brkpt= 4396, Calib= 4.4784.



- ▶ A grow/damp measurement from 2018;
- ▶ 12 ms open loop time;
- ▶ Well-known HOMs in main RF cavities drive mode 233;
- ▶ A measurement on September 8, 2022;
- ▶ 3 ms open loop time;
- ▶ Modes 0, 1, and -1 grow.

Motivation

Concept

Surprise Discovery

Some
Observations

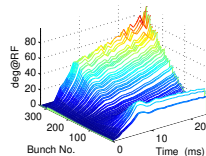
Design Procedure

Recent Results

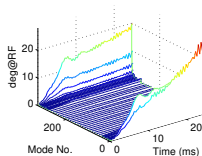
Summary

Modal Behavior

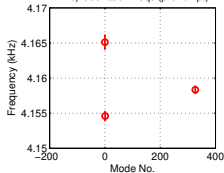
a) Osc. Envelopes in Time Domain



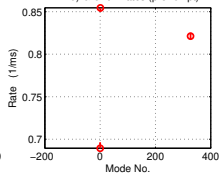
b) Evolution of Modes



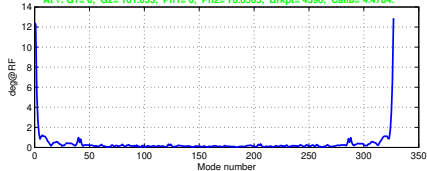
c) Oscillation freqs (pre-brkpt)



d) Growth Rates (pre-brkpt)



ALS:sep0822/095711: Io= 496.8892mA, Dsamp= 1, ShifGain= 6, Nbnun= 328,
At v: G1= 0, G2= 101.033, Ph1= 0, Ph2= 78.6565, Brkpt= 4396, Calib= 4.4784.



- ▶ A grow/damp measurement from 2018;
- ▶ 12 ms open loop time;
- ▶ Well-known HOMs in main RF cavities drive mode 233;
- ▶ A measurement on September 8, 2022;
- ▶ 3 ms open loop time;
- ▶ Modes 0, 1, and -1 grow.

Motivation

Concept

Surprise Discovery

Some
Observations

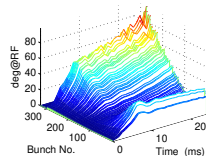
Design Procedure

Recent Results

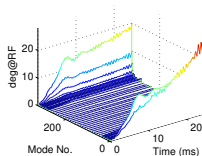
Summary

Modal Behavior

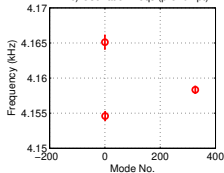
a) Osc. Envelopes in Time Domain



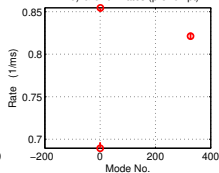
b) Evolution of Modes



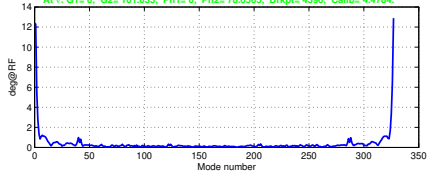
c) Oscillation freqs (pre-brkpt)



d) Growth Rates (pre-brkpt)



ALS:sep0822/095711: Io= 496.8892mA, Dsamp= 1, ShifGain= 6, Nbnun= 328,
At v: G1= 0, G2= 101.033, Ph1= 0, Ph2= 78.6565, Brkpt= 4396, Calib= 4.4784.



- ▶ A grow/damp measurement from 2018;
- ▶ 12 ms open loop time;
- ▶ Well-known HOMs in main RF cavities drive mode 233;
- ▶ A measurement on September 8, 2022;
- ▶ 3 ms open loop time;
- ▶ Modes 0, 1, and -1 grow.

Motivation

Concept

Surprise Discovery

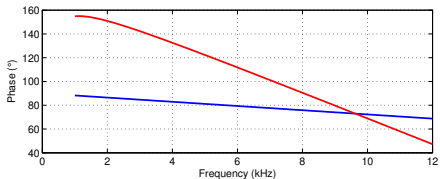
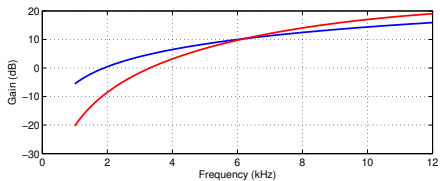
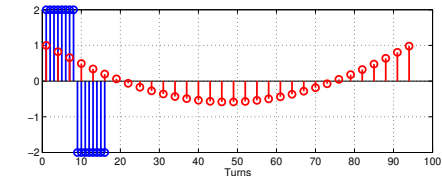
Some
Observations

Design Procedure

Recent Results

Summary

ALS Filter Comparison



- ▶ Comparison of the normal ALS filter and a 16-tap low-pass differentiator;
- ▶ Similar gains in the working range;
- ▶ Much steeper slope for the normal filter (32 taps, downsampling of 3);
- ▶ Log scale plot over a wider frequency range.

Motivation

Concept

Surprise Discovery

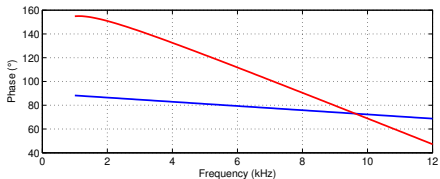
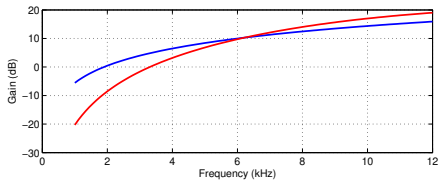
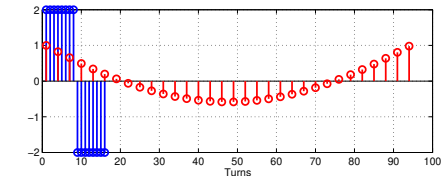
Some
Observations

Design Procedure

Recent Results

Summary

ALS Filter Comparison



- ▶ Comparison of the normal ALS filter and a 16-tap low-pass differentiator;
- ▶ Similar gains in the working range;
- ▶ Much steeper slope for the normal filter (32 taps, downsampling of 3);
- ▶ Log scale plot over a wider frequency range.

Motivation

Concept

Surprise Discovery

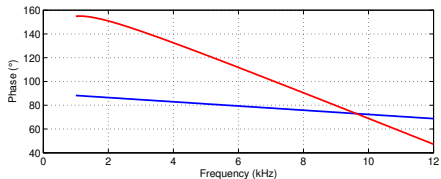
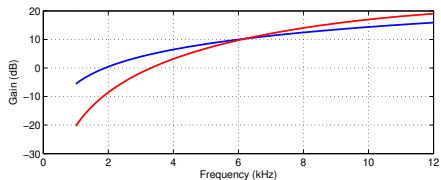
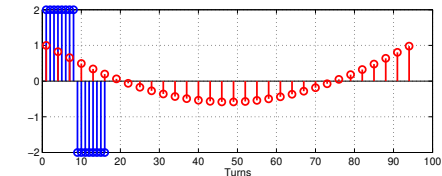
Some
Observations

Design Procedure

Recent Results

Summary

ALS Filter Comparison



- ▶ Comparison of the normal ALS filter and a 16-tap low-pass differentiator;
- ▶ Similar gains in the working range;
- ▶ Much steeper slope for the normal filter (32 taps, downsampling of 3);
- ▶ Log scale plot over a wider frequency range.

Motivation

Concept

Surprise Discovery

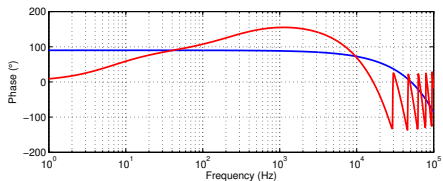
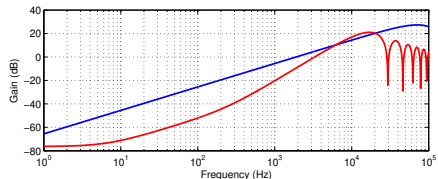
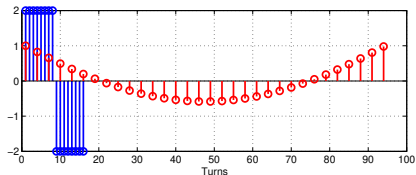
Some
Observations

Design Procedure

Recent Results

Summary

ALS Filter Comparison



- ▶ Comparison of the normal ALS filter and a 16-tap low-pass differentiator;
- ▶ Similar gains in the working range;
- ▶ Much steeper slope for the normal filter (32 taps, downsampling of 3);
- ▶ Log scale plot over a wider frequency range.

Motivation

Concept

Surprise Discovery

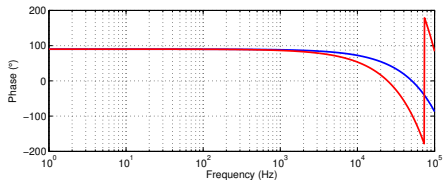
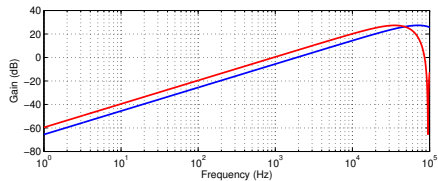
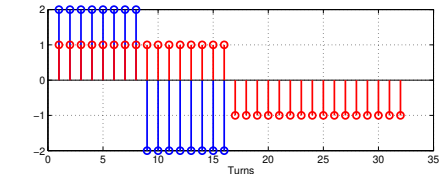
Some
Observations

Design Procedure

Recent Results

Summary

Simple Low-pass Differentiators



- ▶ Since the original “emergency intervention” we have updated the ALS differentiator from 16 to 32 taps;
- ▶ Factor of 2 in the shorter filter’s coefficients reflects higher shift gain;
- ▶ 6 dB gain difference in the linear range;
- ▶ As expected, a longer filter has faster phase roll due to higher group delay;
- ▶ Identical peak gains.

Motivation

Concept

Surprise Discovery

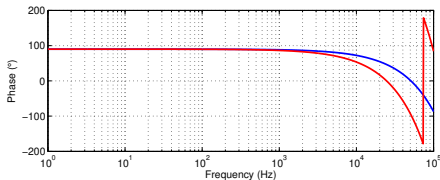
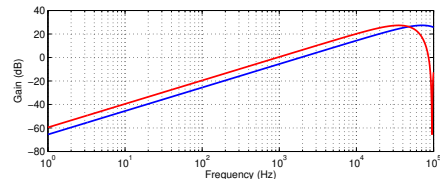
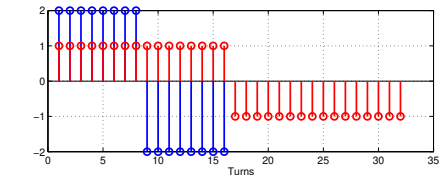
Some
Observations

Design Procedure

Recent Results

Summary

Simple Low-pass Differentiators



- ▶ Since the original “emergency intervention” we have updated the ALS differentiator from 16 to 32 taps;
- ▶ Factor of 2 in the shorter filter’s coefficients reflects higher shift gain;
- ▶ 6 dB gain difference in the linear range;
- ▶ As expected, a longer filter has faster phase roll due to higher group delay;
- ▶ Identical peak gains.

Motivation

Concept

Surprise Discovery

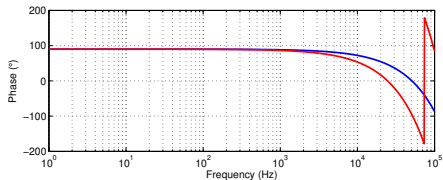
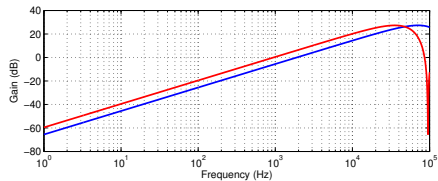
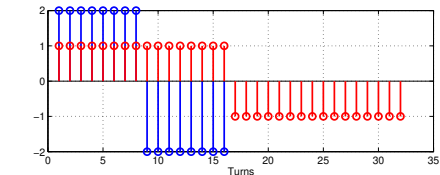
Some
Observations

Design Procedure

Recent Results

Summary

Simple Low-pass Differentiators



- ▶ Since the original “emergency intervention” we have updated the ALS differentiator from 16 to 32 taps;
- ▶ Factor of 2 in the shorter filter’s coefficients reflects higher shift gain;
- ▶ 6 dB gain difference in the linear range;
- ▶ As expected, a longer filter has faster phase roll due to higher group delay;
- ▶ Identical peak gains.

Motivation

Concept

Surprise Discovery

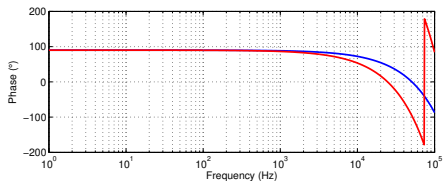
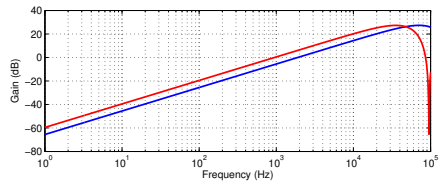
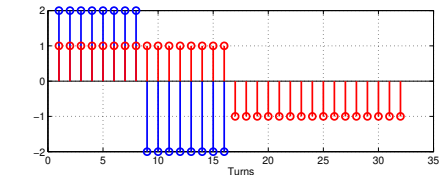
Some
Observations

Design Procedure

Recent Results

Summary

Simple Low-pass Differentiators



- ▶ Since the original “emergency intervention” we have updated the ALS differentiator from 16 to 32 taps;
- ▶ Factor of 2 in the shorter filter’s coefficients reflects higher shift gain;
- ▶ 6 dB gain difference in the linear range;
- ▶ As expected, a longer filter has faster phase roll due to higher group delay;
- ▶ Identical peak gains.

Motivation

Concept

Surprise Discovery

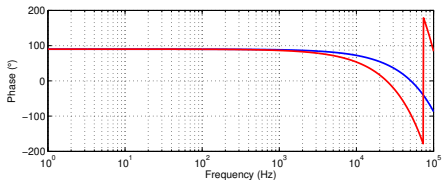
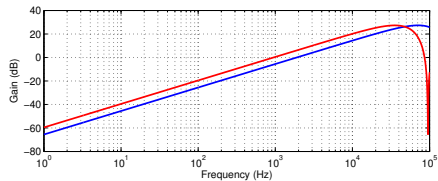
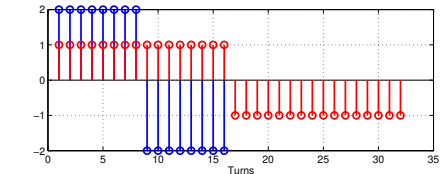
Some
Observations

Design Procedure

Recent Results

Summary

Simple Low-pass Differentiators



- ▶ Since the original “emergency intervention” we have updated the ALS differentiator from 16 to 32 taps;
- ▶ Factor of 2 in the shorter filter’s coefficients reflects higher shift gain;
- ▶ 6 dB gain difference in the linear range;
- ▶ As expected, a longer filter has faster phase roll due to higher group delay;
- ▶ Identical peak gains.

Motivation

Concept

Surprise Discovery

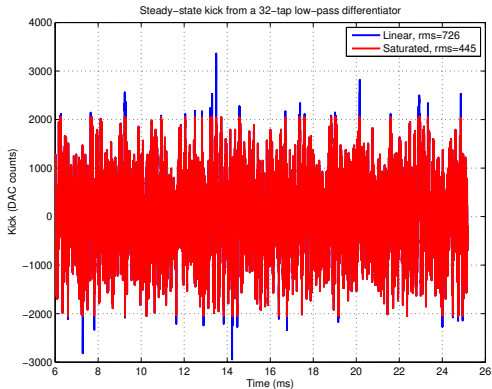
Some
Observations

Design Procedure

Recent Results

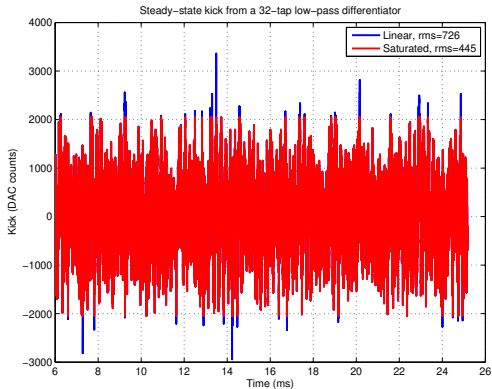
Summary

Kick Signals



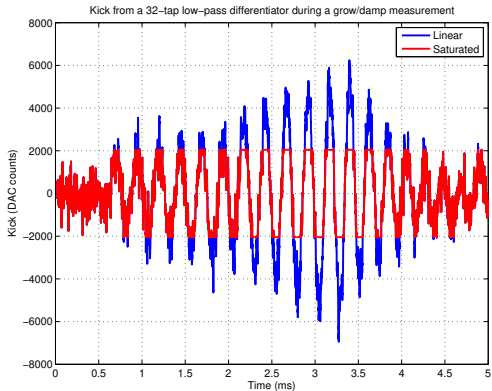
- ▶ Standard worry — differentiator will saturate the output with amplified noise, leaving no power for feedback correction;
- ▶ Steady-state kick at 500 mA with a 32-tap low-pass differentiator;
- ▶ Consistently hits full scale, reflected in the difference in the RMS kick;
- ▶ When the longitudinal motion develops, power is directed exactly where it's needed.

Kick Signals



- ▶ Standard worry — differentiator will saturate the output with amplified noise, leaving no power for feedback correction;
- ▶ Steady-state kick at 500 mA with a 32-tap low-pass differentiator;
- ▶ Consistently hits full scale, reflected in the difference in the RMS kick;
- ▶ When the longitudinal motion develops, power is directed exactly where it's needed.

Kick Signals



- ▶ Standard worry — differentiator will saturate the output with amplified noise, leaving no power for feedback correction;
- ▶ Steady-state kick at 500 mA with a 32-tap low-pass differentiator;
- ▶ Consistently hits full scale, reflected in the difference in the RMS kick;
- ▶ When the longitudinal motion develops, power is directed exactly where it's needed.

Motivation

Concept

Surprise Discovery

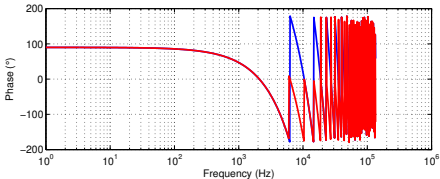
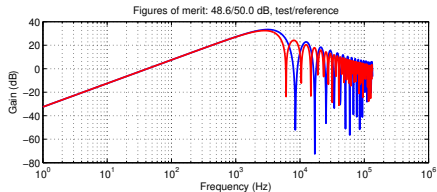
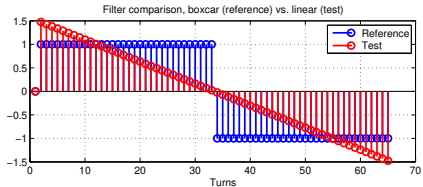
Some
Observations

Design Procedure

Recent Results

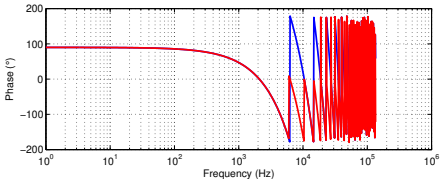
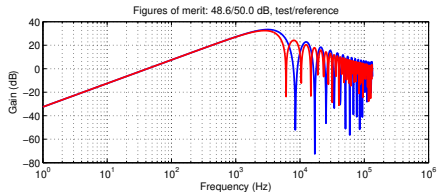
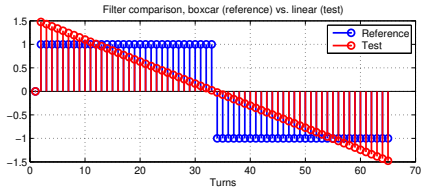
Summary

Low-pass Differentiator Figure of Merit



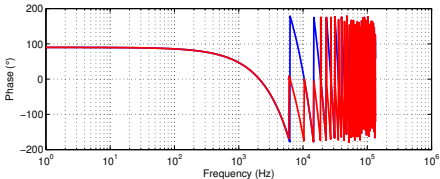
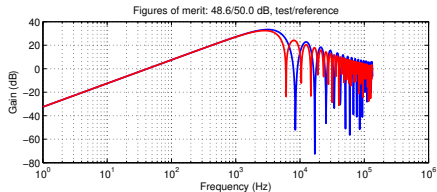
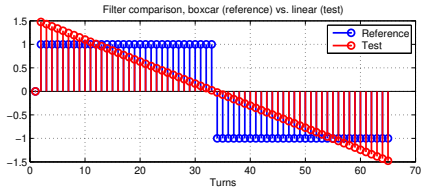
- ▶ A very simple-minded Figure of Merit:
 - ▶ Define a high-frequency cutoff f_c , quadratically average the gain between f_c and $f_{\text{rev}}/2$;
 - ▶ Normalize by the gain at 1 Hz;
 - ▶ FOM in dB, lower is better.
- ▶ Rationale: maximize in-band gain, while minimizing high-frequency noise amplification;
- ▶ Linear filter seems optimal;
- ▶ Cosine filter is not far off.

Low-pass Differentiator Figure of Merit



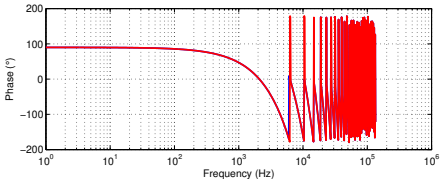
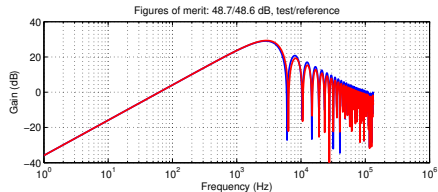
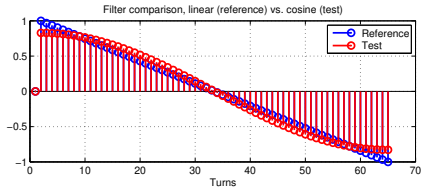
- ▶ A very simple-minded Figure of Merit:
 - ▶ Define a high-frequency cutoff f_c , quadratically average the gain between f_c and $f_{\text{rev}}/2$;
 - ▶ Normalize by the gain at 1 Hz;
 - ▶ FOM in dB, lower is better.
- ▶ Rationale: maximize in-band gain, while minimizing high-frequency noise amplification;
- ▶ Linear filter seems optimal;
- ▶ Cosine filter is not far off.

Low-pass Differentiator Figure of Merit



- ▶ A very simple-minded Figure of Merit:
 - ▶ Define a high-frequency cutoff f_c , quadratically average the gain between f_c and $f_{\text{rev}}/2$;
 - ▶ Normalize by the gain at 1 Hz;
 - ▶ FOM in dB, lower is better.
- ▶ Rationale: maximize in-band gain, while minimizing high-frequency noise amplification;
- ▶ Linear filter seems optimal;
- ▶ Cosine filter is not far off.

Low-pass Differentiator Figure of Merit



- ▶ A very simple-minded Figure of Merit:
 - ▶ Define a high-frequency cutoff f_c , quadratically average the gain between f_c and $f_{\text{rev}}/2$;
 - ▶ Normalize by the gain at 1 Hz;
 - ▶ FOM in dB, lower is better.
- ▶ Rationale: maximize in-band gain, while minimizing high-frequency noise amplification;
- ▶ Linear filter seems optimal;
- ▶ Cosine filter is not far off.

Picking Filter Parameters

- ▶ Start from defining two parameters:
 - ▶ f_s — the highest synchrotron frequency the controller will need to damp;
 - ▶ Typically this is the nominal synchrotron frequency with harmonic cavities inactive;
 - ▶ $\phi_{\max}$ (degrees) — the maximum allowable deviation from the ideal 90° phase shift at f_s ;
 - ▶ Typically $20\text{-}30^\circ$ is a reasonable value;
- ▶ Calculate the filter length $N = \frac{\phi_{\max}}{180 f_s T_0} - 1$, where T_0 is the revolution period;
- ▶ Figure out the sign: positive to negative or negative to positive;
- ▶ That is it!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Picking Filter Parameters

- ▶ Start from defining two parameters:
 - ▶ f_s — the highest synchrotron frequency the controller will need to damp;
 - ▶ Typically this is the nominal synchrotron frequency with harmonic cavities inactive;
 - ▶ $\phi_{\max}$ (degrees) — the maximum allowable deviation from the ideal 90° phase shift at f_s ;
 - ▶ Typically $20\text{-}30^\circ$ is a reasonable value;
- ▶ Calculate the filter length $N = \frac{\phi_{\max}}{180f_s T_0} - 1$, where T_0 is the revolution period;
- ▶ Figure out the sign: positive to negative or negative to positive;
- ▶ That is it!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Picking Filter Parameters

- ▶ Start from defining two parameters:
 - ▶ f_s — the highest synchrotron frequency the controller will need to damp;
 - ▶ Typically this is the nominal synchrotron frequency with harmonic cavities inactive;
 - ▶ $\phi_{\max}$ (degrees) — the maximum allowable deviation from the ideal 90° phase shift at f_s ;
 - ▶ Typically $20\text{-}30^\circ$ is a reasonable value;
- ▶ Calculate the filter length $N = \frac{\phi_{\max}}{180f_s T_0} - 1$, where T_0 is the revolution period;
- ▶ Figure out the sign: positive to negative or negative to positive;
- ▶ That is it!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Picking Filter Parameters

- ▶ Start from defining two parameters:
 - ▶ f_s — the highest synchrotron frequency the controller will need to damp;
 - ▶ Typically this is the nominal synchrotron frequency with harmonic cavities inactive;
 - ▶ $\phi_{\max}$ (degrees) — the maximum allowable deviation from the ideal 90° phase shift at f_s ;
 - ▶ Typically $20\text{-}30^\circ$ is a reasonable value;
- ▶ Calculate the filter length $N = \frac{\phi_{\max}}{180f_s T_0} - 1$, where T_0 is the revolution period;
- ▶ Figure out the sign: positive to negative or negative to positive;
- ▶ That is it!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Motivation

Concept

Surprise Discovery

Some Observations

Design Procedure

Recent Results

Summary

- ◀ ◻ ▶ ◀ ◻ ▶ ◀ ≡ ▶ ◀ ≡ ▶ ≡ ↺ 🔍 ↻ 13/16

Motivation

Concept

Surprise Discovery

Some Observations

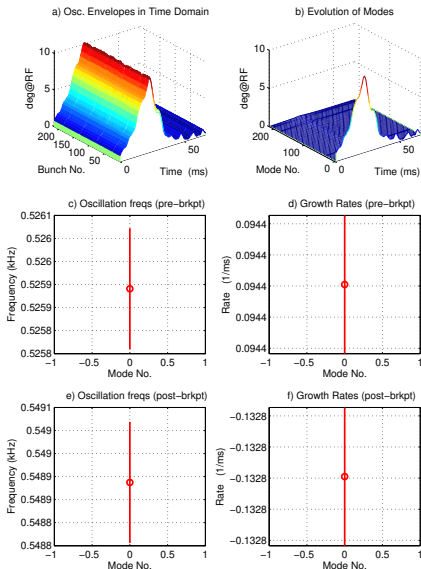
Design Procedure

Recent Results

Summary

- ◀ ◻ ▶ ◀ ◻ ▶ ◀ ≡ ▶ ◀ ≡ ▶ ≡ ↺ 🔍 ↻ 13/16

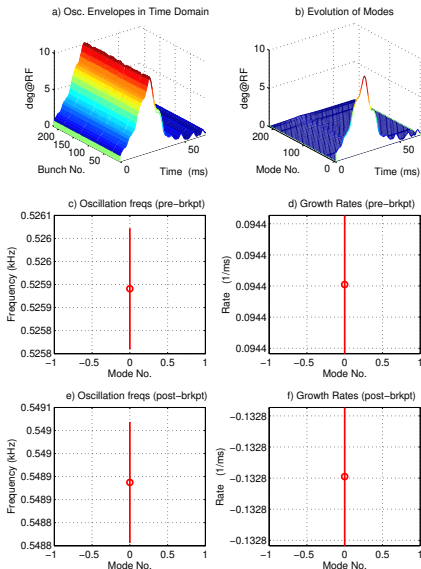
APS-U



- ▶ 216 bunch pattern (every 6th bucket), 117 mA;
- ▶ APS-U zero-current synchrotron frequency is 610 Hz;
- ▶ With the superconducting harmonic cavity tuned in the frequencies are:
 - ▶ HOMs are around 250 Hz;
 - ▶ Mode 0 is at 520 Hz.
- ▶ Mode 0 is unstable due to the fundamental impedance of the harmonic cavity;
- ▶ Adjusted cavity temperatures to excite an HOM (mode 133);
- ▶ Easily handled by the differentiator.

APS:Studies_20251208215746: Io= 116.9708mA, Dsamp= 2, ShiftGain= 3, Nbnun= 216,
At v: G1= 39.6556, G2= 0, Ph1= 67.0159, Ph2= 0, Brkpt= 3107, Calib= 46.7,

APS-U



- ▶ 216 bunch pattern (every 6th bucket), 117 mA;

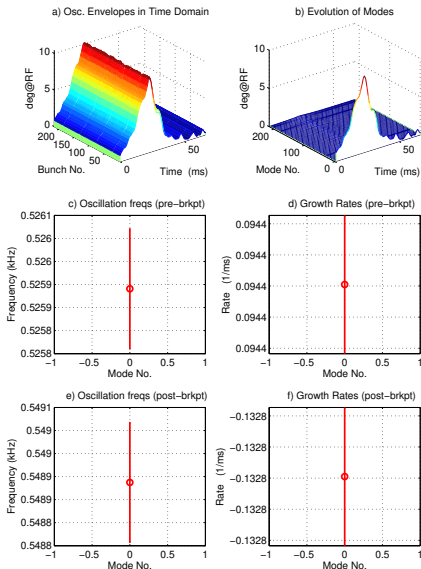
- ▶ APS-U zero-current synchrotron frequency is 610 Hz;

► With the superconducting harmonic cavity tuned in the frequencies are:

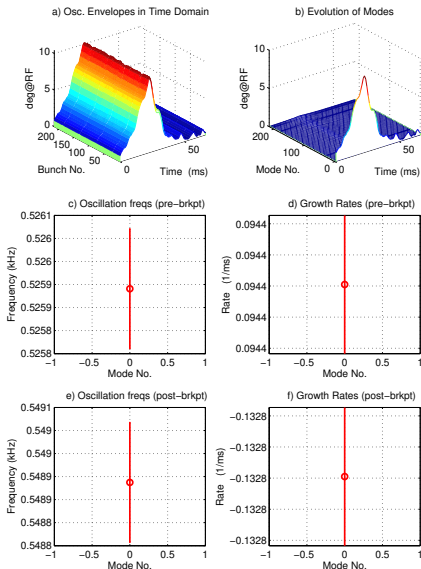
- ▶ HOMs are around 250 Hz;
- ▶ Mode 0 is at 520 Hz.

- ▶ Mode 0 is unstable due to the fundamental impedance of the harmonic cavity;

- ▶ Easily handled by the differentiator.



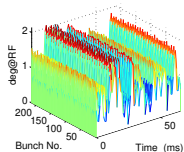
- ▶ 216 bunch pattern (every 6th bucket), 117 mA;
- ▶ APS-U zero-current synchrotron frequency is 610 Hz;
- ▶ With the superconducting harmonic cavity tuned in the frequencies are:
 - ▶ HOMs are around 250 Hz;
 - ▶ Mode 0 is at 520 Hz.
- ▶ Mode 0 is unstable due to the fundamental impedance of the harmonic cavity;
- ▶ Adjusted cavity temperatures to excite an HOM (mode 133);
- ▶ Easily handled by the differentiator.



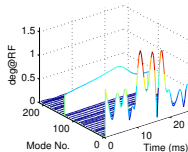
- ▶ 216 bunch pattern (every 6th bucket), 117 mA;
- ▶ APS-U zero-current synchrotron frequency is 610 Hz;
- ▶ With the superconducting harmonic cavity tuned in the frequencies are:
 - ▶ HOMs are around 250 Hz;
 - ▶ Mode 0 is at 520 Hz.
- ▶ Mode 0 is unstable due to the fundamental impedance of the harmonic cavity;
- ▶ Adjusted cavity temperatures to excite an HOM (mode 133);
- ▶ Easily handled by the differentiator.

APS-U

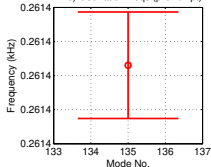
a) Osc. Envelopes in Time Domain



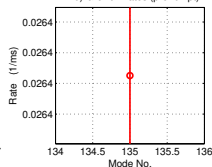
b) Evolution of Modes



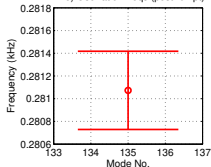
c) Oscillation freqs (pre-brkpt)



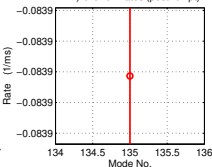
d) Growth Rates (pre-brkpt)



e) Oscillation freqs (post-brkpt)



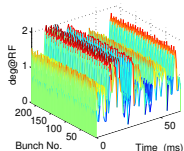
f) Growth Rates (post-brkpt)



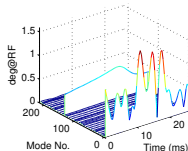
- ▶ 216 bunch pattern (every 6th bucket), 117 mA;
- ▶ APS-U zero-current synchrotron frequency is 610 Hz;
- ▶ With the superconducting harmonic cavity tuned in the frequencies are:
 - ▶ HOMs are around 250 Hz;
 - ▶ Mode 0 is at 520 Hz.
- ▶ Mode 0 is unstable due to the fundamental impedance of the harmonic cavity;
- ▶ Adjusted cavity temperatures to excite an HOM (mode 133);
- ▶ Easily handled by the differentiator.

APS:Studies_20251208/230132: Io= 117.1044mA, Dsamp= 2, ShiftGain= 3, Nbun= 216,
At v: G1= 0. G2= 19.3519. Ph1= 0. Ph2= 78.9143. Brkpt= 2100. Calib= 46.7.

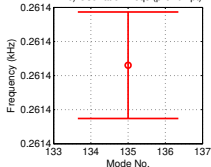
a) Osc. Envelopes in Time Domain



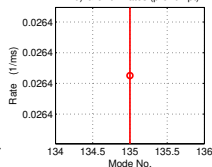
b) Evolution of Modes



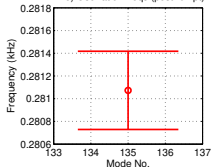
c) Oscillation freqs (pre-brkpt)



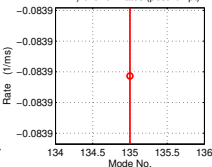
d) Growth Rates (pre-brkpt)



e) Oscillation freqs (post-brkpt)

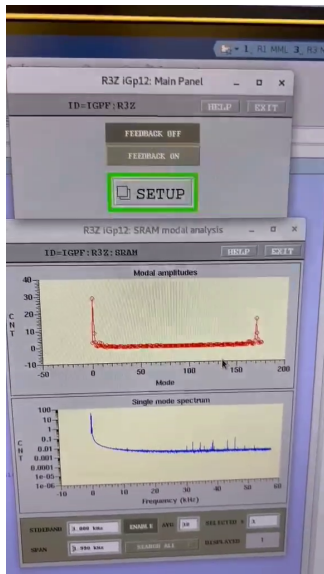


f) Growth Rates (post-brkpt)



- ▶ 216 bunch pattern (every 6th bucket), 117 mA;
- ▶ APS-U zero-current synchrotron frequency is 610 Hz;
- ▶ With the superconducting harmonic cavity tuned in the frequencies are:
 - ▶ HOMs are around 250 Hz;
 - ▶ Mode 0 is at 520 Hz.
- ▶ Mode 0 is unstable due to the fundamental impedance of the harmonic cavity;
- ▶ Adjusted cavity temperatures to excite an HOM (mode 133);
- ▶ Easily handled by the differentiator.

MAX IV 3 GeV Video



- ▶ MAX IV at 400 mA;
- ▶ Fifth harmonic cavity providing full lengthening in passive mode;
- ▶ Synchrotron mode amplitudes on the top plot, spectrum of the largest mode on the bottom;
- ▶ Modes 1 and 2 are excited by the fundamental impedance of the harmonic cavity;
- ▶ Modes 167–170 are excited by the undamped HOMs in the main RF cavities.

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Summary

- ▶ Low-pass differentiator has been deployed in the longitudinal plane at the ALS since September 2022;
- ▶ Successfully deployed at the APS-U in December 2025;
- ▶ In routine operation at the MAX IV 3 GeV ring since this summer;
- ▶ I'd like to thank Ryan Lindberg and Michael Borland for initiating discussions of the low-pass differentiator approach!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Summary

- ▶ Low-pass differentiator has been deployed in the longitudinal plane at the ALS since September 2022;
- ▶ Successfully deployed at the APS-U in December 2025;
- ▶ In routine operation at the MAX IV 3 GeV ring since this summer;
- ▶ I'd like to thank Ryan Lindberg and Michael Borland for initiating discussions of the low-pass differentiator approach!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Summary

- ▶ Low-pass differentiator has been deployed in the longitudinal plane at the ALS since September 2022;
- ▶ Successfully deployed at the APS-U in December 2025;
- ▶ In routine operation at the MAX IV 3 GeV ring since this summer;
- ▶ I'd like to thank Ryan Lindberg and Michael Borland for initiating discussions of the low-pass differentiator approach!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary

Summary

- ▶ Low-pass differentiator has been deployed in the longitudinal plane at the ALS since September 2022;
- ▶ Successfully deployed at the APS-U in December 2025;
- ▶ In routine operation at the MAX IV 3 GeV ring since this summer;
- ▶ I'd like to thank Ryan Lindberg and Michael Borland for initiating discussions of the low-pass differentiator approach!

Motivation

Concept

Surprise Discovery

Some
Observations

Design Procedure

Recent Results

Summary