Use of Bunch-by-bunch Feedback Systems for Advanced Beam Control and Diagnostics

Dmitry Teytelman

Dimtel, Inc., San Jose, CA, USA

July 25, 2014
Feedback basics

Outline

1. Introduction
   - Feedback basics
   - Coupled-bunch instabilities and feedback

2. Beam Control
   - Bunch Cleaning
   - Selective Transient Excitation

3. Diagnostics
   - Beam Transfer Function
   - Tune Measurement
Closed-loop Feedback: Structure and Example

- Start with a physical system (plant).

\begin{align*}
\text{Plant} & \quad u \\
         & \quad y
\end{align*}
Closed-loop Feedback: Structure and Example

- Start with a physical system (plant).
- Measure some property of the plant with a sensor.
Closed-loop Feedback: Structure and Example

- Start with a physical system (plant).
- Measure some property of the plant with a sensor.
- Plant behavior (state) can be affected by an actuator.
Closed-loop Feedback: Structure and Example

- Start with a physical system (plant).
- Measure some property of the plant with a sensor.
- Plant behavior (state) can be affected by an actuator.
- Feedback loop is completed by a controller.
Take a household heating system as an example.

Our plant is the house.
Take a household heating system as an example.

- Our plant is the house.
- Actuator - furnace.
Take a household heating system as an example.
- Our plant is the house.
- Actuator - furnace.
- Sensor - thermistor.
Take a household heating system as an example.

- Our plant is the house.
- Actuator - furnace.
- Sensor - thermistor.
- Controller - thermostat.
Closed-loop Feedback: Structure and Example

- Take a household heating system as an example.
  - Our plant is the house.
  - Actuator - furnace.
  - Sensor - thermistor.
  - Controller - thermostat.

- Loop signals
  - Output \( y \) - temperature;
  - Input \( u \) - heated air from the furnace;
  - Reference \( r \) - temperature setpoint.
Dynamic System Descriptions and Models

- Mechanical system: mass on a spring with a damper.
- Described by $M\ddot{x} + \gamma \dot{x} + Kx = F$.
- Differential equation is a time-domain description.
- Frequency domain - Laplace transform.
- Frequency response evaluated at $s = i\omega$. 
Dynamic System Descriptions and Models

- Mechanical system: mass on a spring with a damper.
- Described by $M\ddot{x} + \gamma \dot{x} + Kx = F$.
- Differential equation is a time-domain description.
- Frequency domain - Laplace transform.
- Frequency response evaluated at $s = i\omega$. 

\[ F \rightarrow \frac{1}{Ms^2 + \gamma s + K} \rightarrow x \]
Mechanical system: mass on a spring with a damper.

Described by $M\ddot{x} + \gamma \dot{x} + Kx = F$.

Differential equation is a time-domain description.

Frequency domain - Laplace transform.

Frequency response evaluated at $s = i\omega$. 

$$\frac{1}{-M\omega^2 + \gamma i\omega + K}$$
Introduction

- Feedback basics
- Coupled-bunch instabilities and feedback

Beam Control

- Bunch Cleaning
- Selective Transient Excitation

Diagnostics

- Beam Transfer Function
- Tune Measurement
Consider a single bunch in a lepton storage ring. Centroid motion has damped harmonic oscillator dynamics. Multiple bunches couple via wakefields (impedances in the frequency domain). At high beam currents this coupling leads to instabilities. In modern accelerators active feedback is used to suppress such instabilities.
Coupled-bunch Instabilities

- Consider a single bunch in a lepton storage ring.
- Centroid motion has damped harmonic oscillator dynamics.
- Multiple bunches couple via wakefields (impedances in the frequency domain).
- At high beam currents this coupling leads to instabilities.
- In modern accelerators active feedback is used to suppress such instabilities.
Coupled-bunch Instabilities

Consider a single bunch in a lepton storage ring.

Centroid motion has damped harmonic oscillator dynamics.

Multiple bunches couple via wakefields (impedances in the frequency domain).

At high beam currents this coupling leads to instabilities.

In modern accelerators active feedback is used to suppress such instabilities.
Coupled-bunch Instabilities

- Consider a single bunch in a lepton storage ring.
- Centroid motion has damped harmonic oscillator dynamics.
- Multiple bunches couple via wakefields (impedances in the frequency domain).
- At high beam currents this coupling leads to instabilities.
- In modern accelerators active feedback is used to suppress such instabilities.
Bunch-by-bunch Feedback

**Definition**

In **bunch-by-bunch feedback approach** the actuator signal for a given bunch depends only on the past motion of that bunch.

- Bunches are processed sequentially.
- Correction kicks are applied one or more turns later.
If we consider bunches as coupled harmonic oscillators, a system of $N$ bunches has $N$ eigenmodes.

Without the wakefields these modes have identical eigenvalues determined by the tune and the radiation damping.

Wakefields (impedances) shift the modal eigenvalues in both real part (damping rate) and imaginary part (oscillation frequency).
Within the controller we combine two streams: feedback and excitation;

Bunch-by-bunch masking;

Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.
Within the controller we combine two streams: feedback and excitation;

Bunch-by-bunch masking;

Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.
Within the controller we combine two streams: feedback and excitation;

- Bunch-by-bunch masking;

- Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.
Within the controller we combine two streams: feedback and excitation;

Bunch-by-bunch masking;

Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.
Within the controller we combine two streams: feedback and excitation;

Bunch-by-bunch masking;

Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.
Within the controller we combine two streams: feedback and excitation;
Bunch-by-bunch masking;
Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.
Introduction

Feedback basics
Coupled-bunch instabilities and feedback

Beam Control

Bunch Cleaning
Selective Transient Excitation

Diagnostics

Beam Transfer Function
Tune Measurement
Bunch cleaning capability in a lepton storage ring is a way to remove all charge from an arbitrary subset of RF buckets, without disturbing bunches excluded from such a subset.

Many applications:

- Cleaning up injection errors;
- Controlling diffusion from filled to empty buckets;
- Creating single-bunch fill patterns in storage rings without single-bunch injection capability;
- Creating arbitrary fill patterns for studying detector responses, etc.
Bunch cleaning capability in a lepton storage ring is a way to remove all charge from an arbitrary subset of RF buckets, without disturbing bunches excluded from such a subset.

Many applications:

- Cleaning up injection errors;
- Controlling diffusion from filled to empty buckets;
- Creating single-bunch fill patterns in storage rings without single-bunch injection capability;
- Creating arbitrary fill patterns for studying detector responses, etc.
Definition and Applications

Definition

Bunch cleaning capability in a lepton storage ring is a way to remove all charge from an arbitrary subset of RF buckets, without disturbing bunches excluded from such a subset.

Many applications:

- Cleaning up injection errors;
- Controlling diffusion from filled to empty buckets;
- Creating single-bunch fill patterns in storage rings without single-bunch injection capability;
- Creating arbitrary fill patterns for studying detector responses, etc.
Bunch cleaning capability in a lepton storage ring is a way to remove all charge from an arbitrary subset of RF buckets, without disturbing bunches excluded from such a subset.

Many applications:

- Cleaning up injection errors;
- Controlling diffusion from filled to empty buckets;
- Creating single-bunch fill patterns in storage rings without single-bunch injection capability;
- Creating arbitrary fill patterns for studying detector responses, etc.
Bunch Cleaning

General Approach

- Keep negative feedback on the bunches to retain;
- Turn off the feedback on the bunches to clean;
- Apply to these bunches a swept sinewave excitation centered on the tune frequency;
- When excitation sweeps across the betatron resonance, bunches are driven to large transverse amplitudes and scraped off;
- Excitation frequency sweep must cover the full range of tune variations with beam current and amplitude.
Bunch Cleaning

General Approach

- Keep negative feedback on the bunches to retain;
- Turn off the feedback on the bunches to clean;
- Apply to these bunches a swept sinewave excitation centered on the tune frequency;
- When excitation sweeps across the betatron resonance, bunches are driven to large transverse amplitudes and scraped off;
- Excitation frequency sweep must cover the full range of tune variations with beam current and amplitude.
Bunch Cleaning

General Approach

- Keep negative feedback on the bunches to retain;
- Turn off the feedback on the bunches to clean;
- Apply to these bunches a swept sinewave excitation centered on the tune frequency;
- When excitation sweeps across the betatron resonance, bunches are driven to large transverse amplitudes and scraped off;
- Excitation frequency sweep must cover the full range of tune variations with beam current and amplitude.
General Approach

- Keep negative feedback on the bunches to retain;
- Turn off the feedback on the bunches to clean;
- Apply to these bunches a swept sinewave excitation centered on the tune frequency;
- When excitation sweeps across the betatron resonance, bunches are driven to large transverse amplitudes and scraped off;
- Excitation frequency sweep must cover the full range of tune variations with beam current and amplitude.
General Approach

- Keep negative feedback on the bunches to retain;
- Turn off the feedback on the bunches to clean;
- Apply to these bunches a swept sinewave excitation centered on the tune frequency;
- When excitation sweeps across the betatron resonance, bunches are driven to large transverse amplitudes and scraped off;
- Excitation frequency sweep must cover the full range of tune variations with beam current and amplitude.
Kick a single bucket (2 ns);
DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
Modulation perturbs the bunches we want to keep;
Pre-distort the kick to improve the isolation;
Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kick a single bucket (2 ns);

- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;

- Modulation perturbs the bunches we want to keep;

- Pre-distort the kick to improve the isolation;

- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
**Kicking One Bucket**

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kick a single bucket (2 ns);

- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;

- Modulation perturbs the bunches we want to keep;

- Pre-distort the kick to improve the isolation;

- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Kicking One Bucket

- Kick a single bucket (2 ns);
- DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
- Modulation perturbs the bunches we want to keep;
- Pre-distort the kick to improve the isolation;
- Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.

![Graph showing DAC kick value, kicker voltage, and isolation across bunch numbers.](image-url)
Kick a single bucket (2 ns);
DAC, amplifier and striplines stretch the kick, thus coupling to the neighboring buckets;
Modulation perturbs the bunches we want to keep;
Pre-distort the kick to improve the isolation;
Negative feedback on the neighboring bunches automatically settles on the kick pattern that minimizes the perturbation of these bunches.
Duke SR-FEL: Removing Every Fifth Bunch

- Excitation in the vertical plane;
- Specified cleaning of every fifth bucket.
Duke SR-FEL: Removing Every Fifth Bunch

- Excitation in the vertical plane;
- Specified cleaning of every fifth bucket.
Introduction

Beam Control

Diagnostics

Bunch Cleaning

**MLS: Custom Pattern**

- With the back-end optimized see good isolation bunch-to-bunch;
- Spelling MLS in Morse code here.
Bunch Cleaning

MLS: Custom Pattern

- With the back-end optimized see good isolation bunch-to-bunch;
- Spelling MLS in Morse code here.
With the back-end optimized see good isolation bunch-to-bunch;

- Spelling MLS in Morse code here.
Bunch Cleaning

**MLS: Arbitrary Fill Patterns**

- Adjust the excitation to achieve relatively slow bunch cleaning rate;
- A Matlab script trims the bunches in a controlled manner.
MLS: Arbitrary Fill Patterns

- Adjust the excitation to achieve relatively slow bunch cleaning rate;
- A Matlab script trims the bunches in a controlled manner.
TLS: Bunch Purity Measurements

- Use optical methods (single photon counting) to characterize the purity after bunch cleaning;

- Small peaks are due to multiple light reflections, not satellite bunches.
Use optical methods (single photon counting) to characterize the purity after bunch cleaning;

Small peaks are due to multiple light reflections, not satellite bunches.
Outline

1. Introduction
   - Feedback basics
   - Coupled-bunch instabilities and feedback

2. Beam Control
   - Bunch Cleaning
   - Selective Transient Excitation

3. Diagnostics
   - Beam Transfer Function
   - Tune Measurement
Selective Transient Excitation

General Approach

- Modulate excitation signal on/off together with transient measurements;
- Example from ANKA: 20 bunches driven for 4 ms with feedback turned off;
- Bunch 15 spectrogram;
- Excitation sweeps through the betatron frequency.
Selective Transient Excitation

**General Approach**

- Modulate excitation signal on/off together with transient measurements;
- Example from ANKA: 20 bunches driven for 4 ms with feedback turned off;
- Bunch 15 spectrogram;
- Excitation sweeps through the betatron frequency.
Selective Transient Excitation

**General Approach**

- Modulate excitation signal on/off together with transient measurements;
- Example from ANKA: 20 bunches driven for 4 ms with feedback turned off;
- Bunch 15 spectrogram;
- Excitation sweeps through the betatron frequency.
Selective Transient Excitation

BESSY II Horizontal Grow/Damp Measurement

- Horizontal grow/damp at -3.0 units, 245 mA, no camshaft;
- Mode -1;
- Very fast damping;
- Excellent fit.
Horizontal grow/damp at -3.0 units, 245 mA, no camshaft;
Mode -1;
Very fast damping;
Excellent fit.
Set up constant frequency excitation to drive mode -1;

- Excitation is on during normal running, off during growth period;
- Feedback is also off — measuring open loop trajectory of one mode;
- Can measure slow or stable eigenmodes.
Set up constant frequency excitation to drive mode -1;
Excitation is on during normal running, off during growth period;
Feedback is also off — measuring open loop trajectory of one mode;
Can measure slow or stable eigenmodes.
Measuring Stable Eigenmodes: ANKA X, 2.5 GeV

- Set up constant frequency excitation to drive mode -1;
- Excitation is on during normal running, off during growth period;
- Feedback is also off — measuring open loop trajectory of one mode;
- Can measure slow or stable eigenmodes.
Three transients, modes 0, 91, and -1;
- Fits scaled to the same starting point;
- Expect slower damping for mode -1, driven by the resistive wall impedance;
- Actual data are fairly noisy.
Selective Transient Excitation

Mode to Mode Differences: ANKA X, 2.5 GeV

- Three transients, modes 0, 91, and -1;
- Fits scaled to the same starting point;
- Expect slower damping for mode -1, driven by the resistive wall impedance;
- Actual data are fairly noisy.
Three transients, modes 0, 91, and -1;

- Fits scaled to the same starting point;
- Expect slower damping for mode -1, driven by the resistive wall impedance;
- Actual data are fairly noisy.
Outline

1 Introduction
   - Feedback basics
   - Coupled-bunch instabilities and feedback

2 Beam Control
   - Bunch Cleaning
   - Selective Transient Excitation

3 Diagnostics
   - Beam Transfer Function
   - Tune Measurement
Introduction

Beam Control

Diagnostics

Beam Transfer Function

Measurement Approach

- Single-bunch acquisition engine captures 96k samples for one bunch together with excitation signal;
- From excitation and response signals, frequency domain transfer function can be estimated.

![Image of iGpL2: SB waveforms window showing bunch signal, magnitude, and phase spectra.](image-url)
Single-bunch acquisition engine captures 96k samples for one bunch together with excitation signal;

From excitation and response signals, frequency domain transfer function can be estimated.
A Few Examples from TLS

- Time-domain response, horizontal, open loop
- Frequency domain transfer function
  - Horizontal
  - Vertical
  - Longitudinal
A Few Examples from TLS

- Time-domain response, horizontal, open loop
- Frequency domain transfer function
  - Horizontal
  - Vertical
  - Longitudinal
A Few Examples from TLS

- Time-domain response, horizontal, open loop
- Frequency domain transfer function
  - Horizontal
  - Vertical
  - Longitudinal
A Few Examples from TLS

- Time-domain response, horizontal, open loop
- Frequency domain transfer function
  - Horizontal
  - Vertical
  - Longitudinal
Outline

1. Introduction
   - Feedback basics
   - Coupled-bunch instabilities and feedback

2. Beam Control
   - Bunch Cleaning
   - Selective Transient Excitation

3. Diagnostics
   - Beam Transfer Function
   - Tune Measurement
Parasitic Tune Measurement

- Transverse feedback in DAΦNE operating in the X plane;
- Averaged beam spectrum (lower right) shows a notch;
- This notch is a key to the parasitic tune measurement capability.
Transverse feedback in DAΦNE operating in the X plane;

Averaged beam spectrum (lower right) shows a notch;

This notch is a key to the parasitic tune measurement capability.
Parasitic Tune Measurement

- Transverse feedback in DAΦNE operating in the X plane;
- Averaged beam spectrum (lower right) shows a notch;
- This notch is a key to the parasitic tune measurement capability.
Why Is There a Notch?

Beam response is resonant at the tune frequency;

Attenuation of detection noise by the feedback is proportional to the loop gain;

Transfer gain from noise to the feedback input is \( \frac{1}{1+L(\omega)} \);

Maximum attenuation at the resonance, thus a notch.
Why Is There a Notch?

- Beam response is resonant at the tune frequency;
- Attenuation of detection noise by the feedback is proportional to the loop gain;
- Transfer gain from noise to the feedback input is \( \frac{1}{1 + L(\omega)} \);
- Maximum attenuation at the resonance, thus a notch.
Why Is There a Notch?

- Beam response is resonant at the tune frequency;
- Attenuation of detection noise by the feedback is proportional to the loop gain;
- Transfer gain from noise to the feedback input is $\frac{1}{1+L(\omega)}$;
- Maximum attenuation at the resonance, thus a notch.
Why Is There a Notch?

- Beam response is resonant at the tune frequency;
- Attenuation of detection noise by the feedback is proportional to the loop gain;
- Transfer gain from noise to the feedback input is $\frac{1}{1+L(\omega)}$;
- Maximum attenuation at the resonance, thus a notch.
Bunch-by-bunch Tunes in DAΦNE

- Start from computing bunch spectrum;
- Fit model beam/feedback response to the spectrum;
- Repeat for all filled bunches;
- Convert to fractional tune.
- **Completely parasitic measurement of bunch-by-bunch tunes.**
Bunch-by-bunch Tunes in DAΦNE

- Start from computing bunch spectrum;
- Fit model beam/feedback response to the spectrum;
- Repeat for all filled bunches;
- Convert to fractional tune.
- Completely parasitic measurement of bunch-by-bunch tunes.
Bunch-by-bunch Tunes in DAΦNE

- Start from computing bunch spectrum;
- Fit model beam/feedback response to the spectrum;
- Repeat for all filled bunches;
- Convert to fractional tune.
- Completely parasitic measurement of bunch-by-bunch tunes.
**Bunch-by-bunch Tunes in DAΦNE**

- Start from computing bunch spectrum;
- Fit model beam/feedback response to the spectrum;
- Repeat for all filled bunches;
- Convert to fractional tune.
- Completely parasitic measurement of bunch-by-bunch tunes.
Start from computing bunch spectrum;
Fit model beam/feedback response to the spectrum;
Repeat for all filled bunches;
Convert to fractional tune.

- Completely parasitic measurement of bunch-by-bunch tunes.
Two measurements at 420 mA;
- Horizontal tune spread is $6.5 \times 10^{-3}$;
- Vertical tune spread is $2.8 \times 10^{-3}$.
- Horizontal plane shows evidence of strong electron-cloud instabilities.
**DAΦNE: Horizontal vs. Vertical**

- Two measurements at 420 mA;
- Horizontal tune spread is $6.5 \times 10^{-3}$;
- Vertical tune spread is $2.8 \times 10^{-3}$.
- Horizontal plane shows evidence of strong electron-cloud instabilities.
DAΦNE: Horizontal vs. Vertical

- Two measurements at 420 mA;
- Horizontal tune spread is $6.5 \times 10^{-3}$;
- Vertical tune spread is $2.8 \times 10^{-3}$.
- Horizontal plane shows evidence of strong electron-cloud instabilities.
Tune Tracker: General Approach

- Turn off feedback for one selected bunch;
- Apply low amplitude sinusoidal excitation to that bunch;
- Measure the response and extract phase shift between excitation and response;
- Adjust excitation frequency to keep the phase shift constant;
- At some value of the phase shift we will excite the beam on resonance;
- If the tune changes, closed-loop tune tracker follows;
- Tune tracking can be slow (1-10 Hz) or fast (kHz).
Tune Measurement

Beam Transfer Function and Tracking

- Open loop response has steep phase slope;
- At -90 degrees phase shift excitation is on resonance;
- Negative phase slope — negative phase tracker gain.
Beam Transfer Function and Tracking

- Open loop response has steep phase slope;
- At -90 degrees phase shift excitation is on resonance;
- Negative phase slope — negative phase tracker gain.
Open loop response has steep phase slope;
- At -90 degrees phase shift excitation is on resonance;
- Negative phase slope — negative phase tracker gain.
Tune Tracker: Block Diagram

- DDS-based sinusoidal drive generator
- Drive frequency modulation
- Drive frequency
- Drive amplitude
- A \phi \rightarrow IQ \cos
- A \phi \rightarrow IQ \sin
- CORDIC
- Phase accumulator
- \phi
- Full scale
- Integrator and range limiter
- Phase shift setpoint
- Drive amplitude modulation
- Beam excitation
- Beam
- Beam response
Tune tracking loop closed around −1000 seconds;
- Low gain — slow settling;
- Once settled, the loop maintains stable oscillation amplitude by tracking the variations in the tune.
Tune tracking loop closed around $-1000$ seconds;

- Low gain — slow settling;

- Once settled, the loop maintains stable oscillation amplitude by tracking the variations in the tune.
**Tune Measurement**

**Slow Tune Tracking in NSLS-II**

- Tune tracking loop closed around \(-1000\) seconds;
- Low gain — slow settling;
- Once settled, the loop maintains stable oscillation amplitude by tracking the variations in the tune.
**Slow Tune Tracking in ANKA**

- Slow tracking — $10^4$ turns integration, 120 Hz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- Suggestive of periodic tune variation.
Slow Tune Tracking in ANKA

- Slow tracking — $10^4$ turns integration, 120 Hz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- Suggestive of periodic tune variation.
Fast Tune Tracking in ANKA

- Fast tracking — 200 turns integration, 6 kHz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- 100 Hz tune variation (quadrupole supply ripple).
Fast Tune Tracking in ANKA

- Fast tracking — 200 turns integration, 6 kHz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- 100 Hz tune variation (quadrupole supply ripple).
Fast Tune Tracking in the ALS

- Fast tracking — 500 turns integration, 1.3 kHz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- 60 Hz tune variation.
Fast Tune Tracking in the ALS

- Fast tracking — 500 turns integration, 1.3 kHz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- 60 Hz tune variation.
Modern bunch-by-bunch feedback system is capable of much more than just keeping the beam stable;

Programmable hardware enables a number of experimental techniques for controlling bunch positions and currents;

Modern feedback systems provide multiple ways of monitoring beam dynamics in real time.
Modern bunch-by-bunch feedback system is capable of much more than just keeping the beam stable;
Programmable hardware enables a number of experimental techniques for controlling bunch positions and currents;
Modern feedback systems provide multiple ways of monitoring beam dynamics in real time.
Modern bunch-by-bunch feedback system is capable of much more than just keeping the beam stable;

Programmable hardware enables a number of experimental techniques for controlling bunch positions and currents;

Modern feedback systems provide multiple ways of monitoring beam dynamics in real time.