Bunch-by-bunch feedback systems review

Based on

I.FAST Workshop 2024 on

Bunch-by-Bunch Feedback Systems and Related Beam Dynamics

T. Nakamura (KEK), for the workshop participants, and organizers: led by

Akira Mochihashi,

the Karlsruhe Institute of Technology (KIT) / KARA

I.FAST Workshop 2024 on
Bunch-by-Bunch Feedback Systems and Related Beam Dynamics

I.FAST: Innovation Fostering in Accelerator Science and Technology
https://ifast-project.eu
Great Opportunity for Information Exchange and Discussions
with
Various Machines / Labs / Universities / Companies

What is **Bunch by bunch feedback ?**

Control : **Damping**, **Anti-Damping**, **Excitation**, ..

Betatron (Transverse) Oscillation,

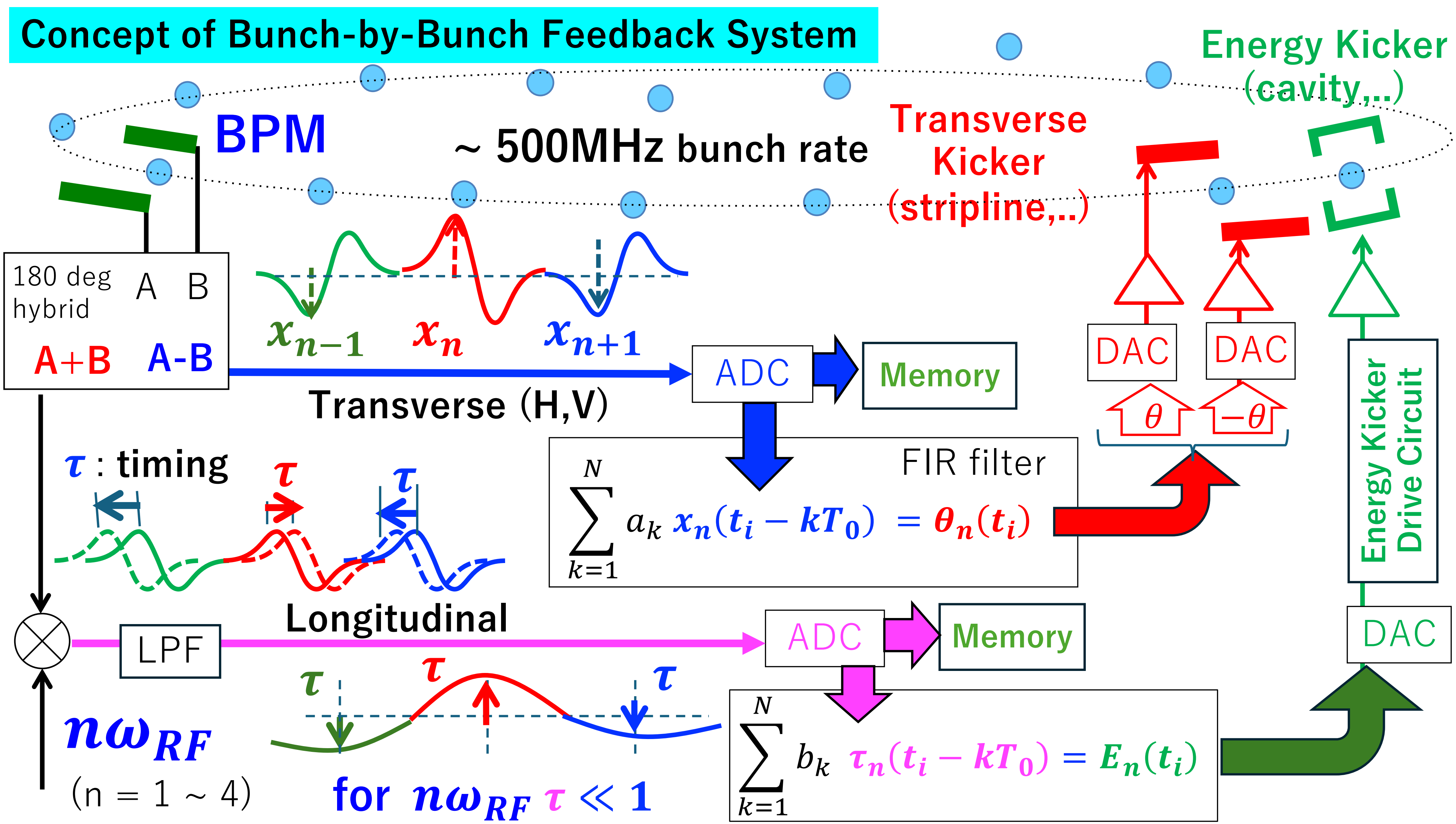
Synchrotron (Longitudinal) Oscillation

in Bunch-by-bunch base

with bunch spacing down to 2ns (~500MHz)

Measurement of Beam Motion:

Bunch-by-Bunch, **Turn-by-Turn** => Memory

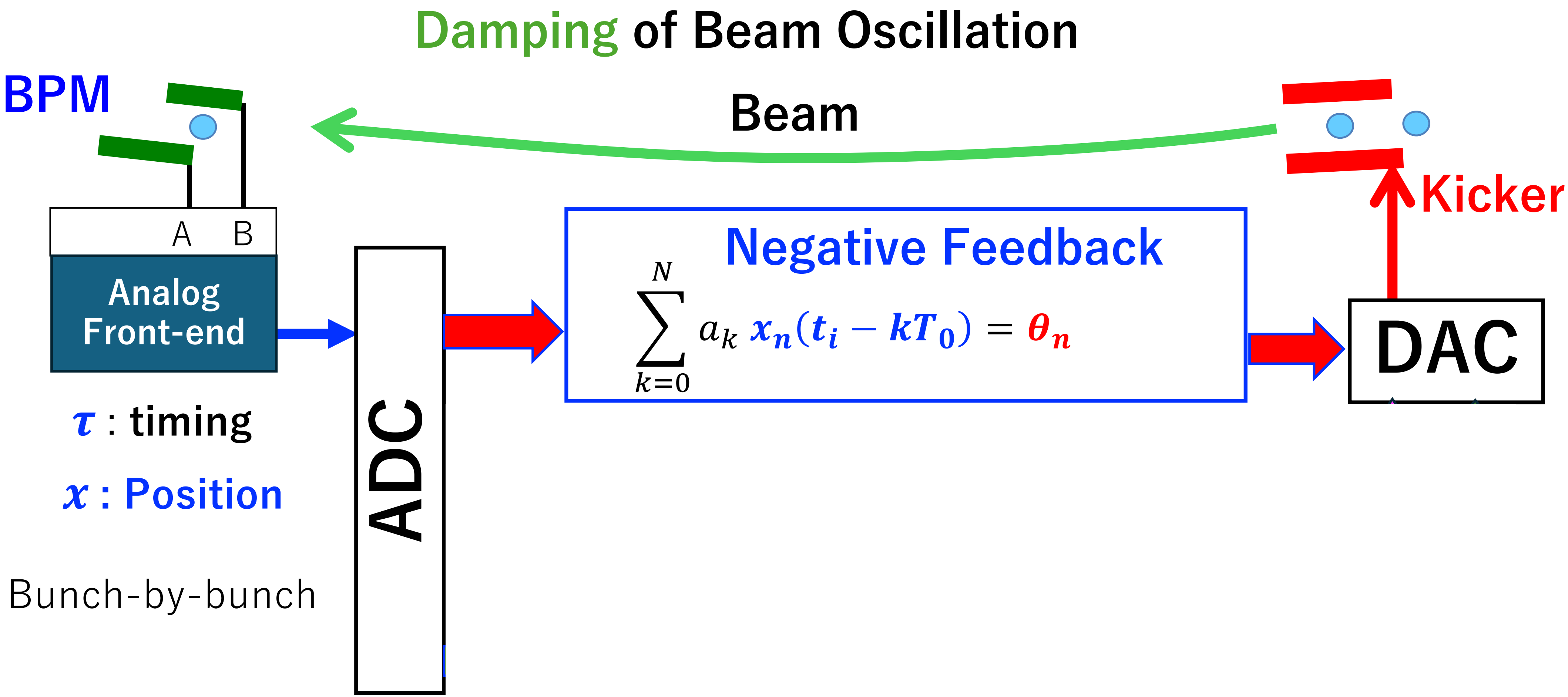


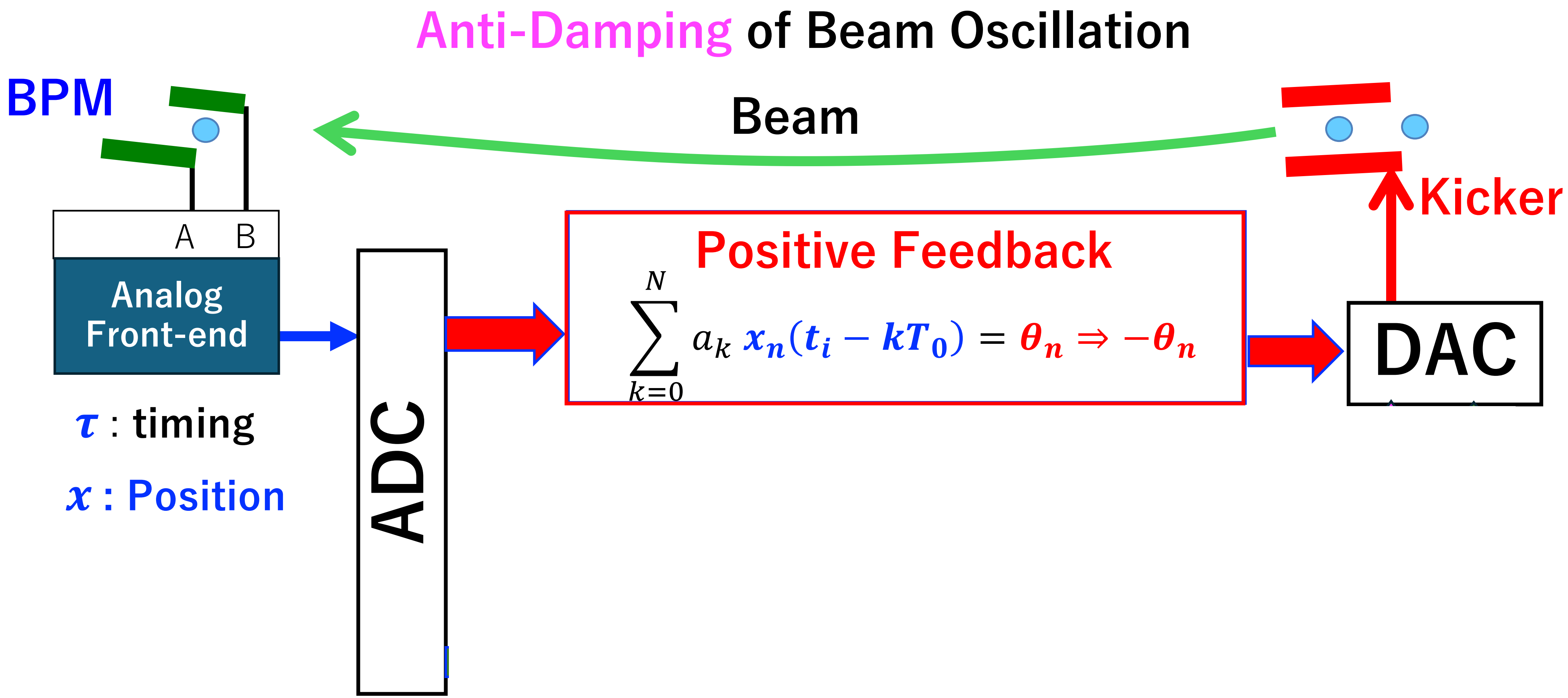
Concept of Bunch-by-Bunch Feedback System
BPM
~ 500MHz bunch rate
Transverse Kicker (stripline,..)
Energy Kicker (cavity,..)
180 deg hybrid
A B
A+B A-B
x_{n-1} x_n x_{n+1}
Transverse (H,V)
ADC
Memory
FIR filter
$\sum_{k=1}^{N} a_k\, x_n(t_i - kT_0) = \theta_n(t_i)$
DAC DAC
θ $-\theta$
Energy Kicker Drive Circuit
DAC
τ : timing
Longitudinal
LPF
ADC
Memory
$\sum_{k=1}^{N} b_k\, \tau_n(t_i - kT_0) = E_n(t_i)$
$n\omega_{RF}$
(n = 1 ~ 4)
for $n\omega_{RF}\,\tau \ll 1$

What is **Bunch by bunch feedback ?**

Control : **Damping, Anti-Damping, Excitation, ..**

We start with


Damping of Beam Oscillation
BPM
Beam
Kicker
A B
Analog Front-end
ADC
Negative Feedback
$\sum_{k=0}^{N} a_k \, x_n(t_i - kT_0) = \theta_n$
DAC
τ : timing
x : Position
Bunch-by-bunch


Anti-Damping of Beam Oscillation
BPM
Beam
Kicker
A
B
Analog Front-end
ADC
Positive Feedback
$\sum_{k=0}^{N} a_k\, x_n(t_i - kT_0) = \theta_n \Rightarrow -\theta_n$
DAC
τ : timing
x : Position

Anti-Damping (Positive Feedback)

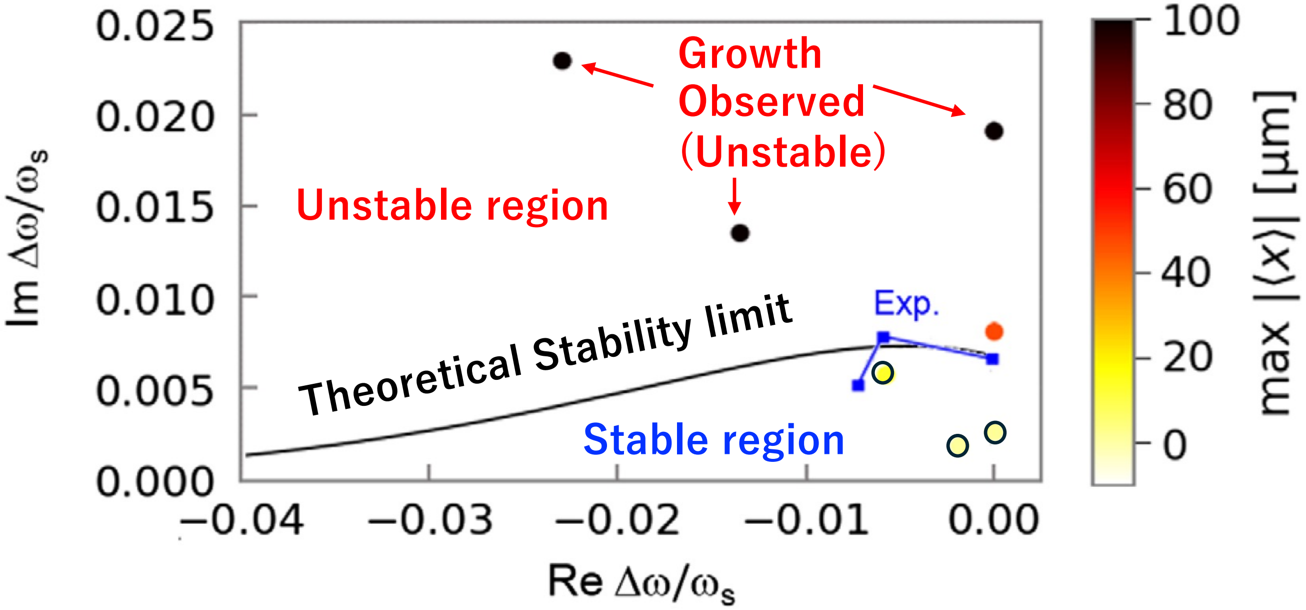
Exponential Growth (Gain) and Tune Shift (Phase) with Feedback

= simulates Instability

⇕ Direct Landau Damping measurement (LHC)

Landau Damping by Tune Spread in bunch <= Octupole

~ Feedback Growth Rate

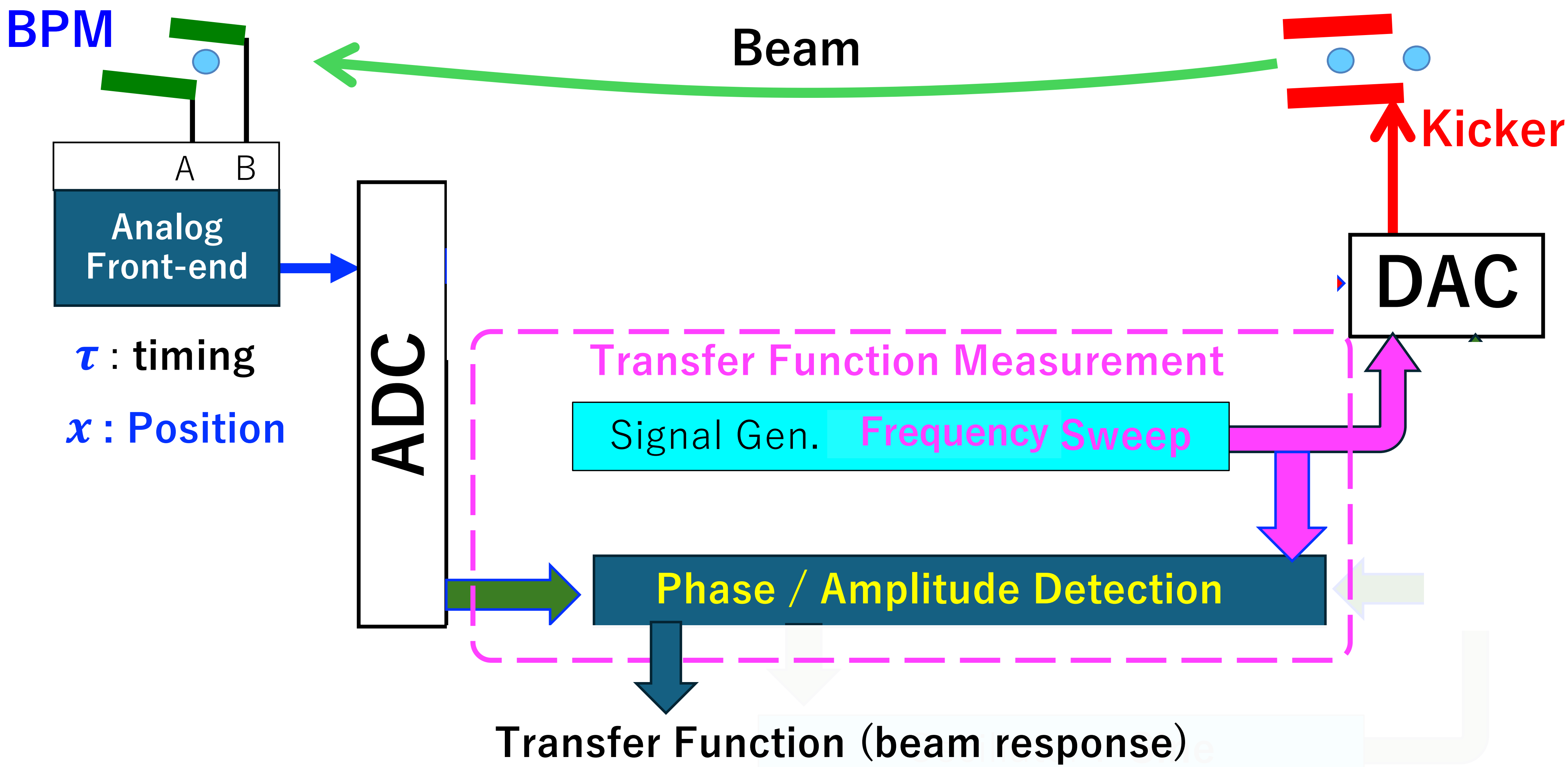


~Frequency(tune) Shift by Feedback

Comparison with Theoretical Stability Diagram

https://indico.scc.kit.edu/event/3742/contributions/15394/ LHC

Excitation (Transfer function) of Beam Oscillation



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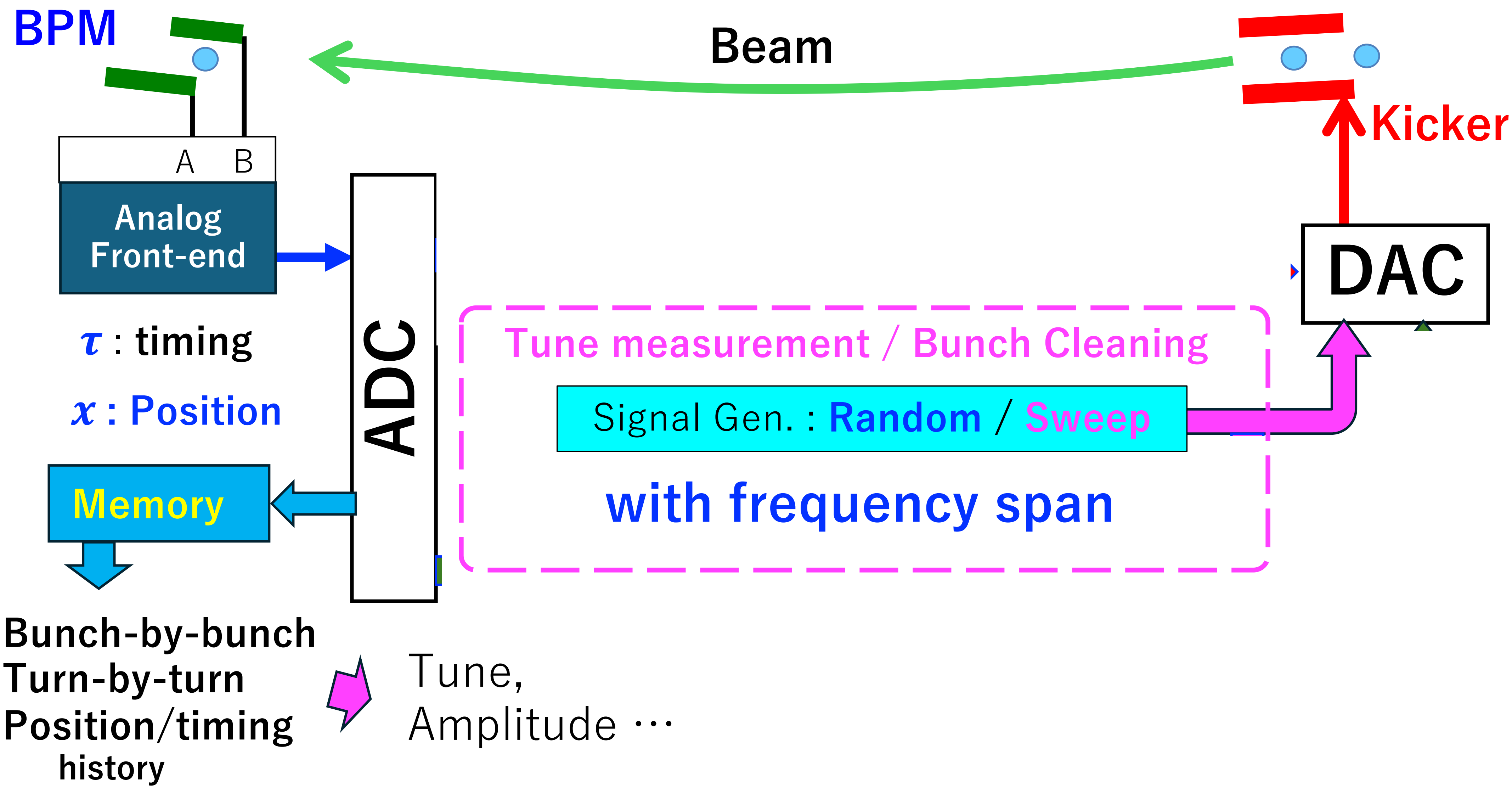
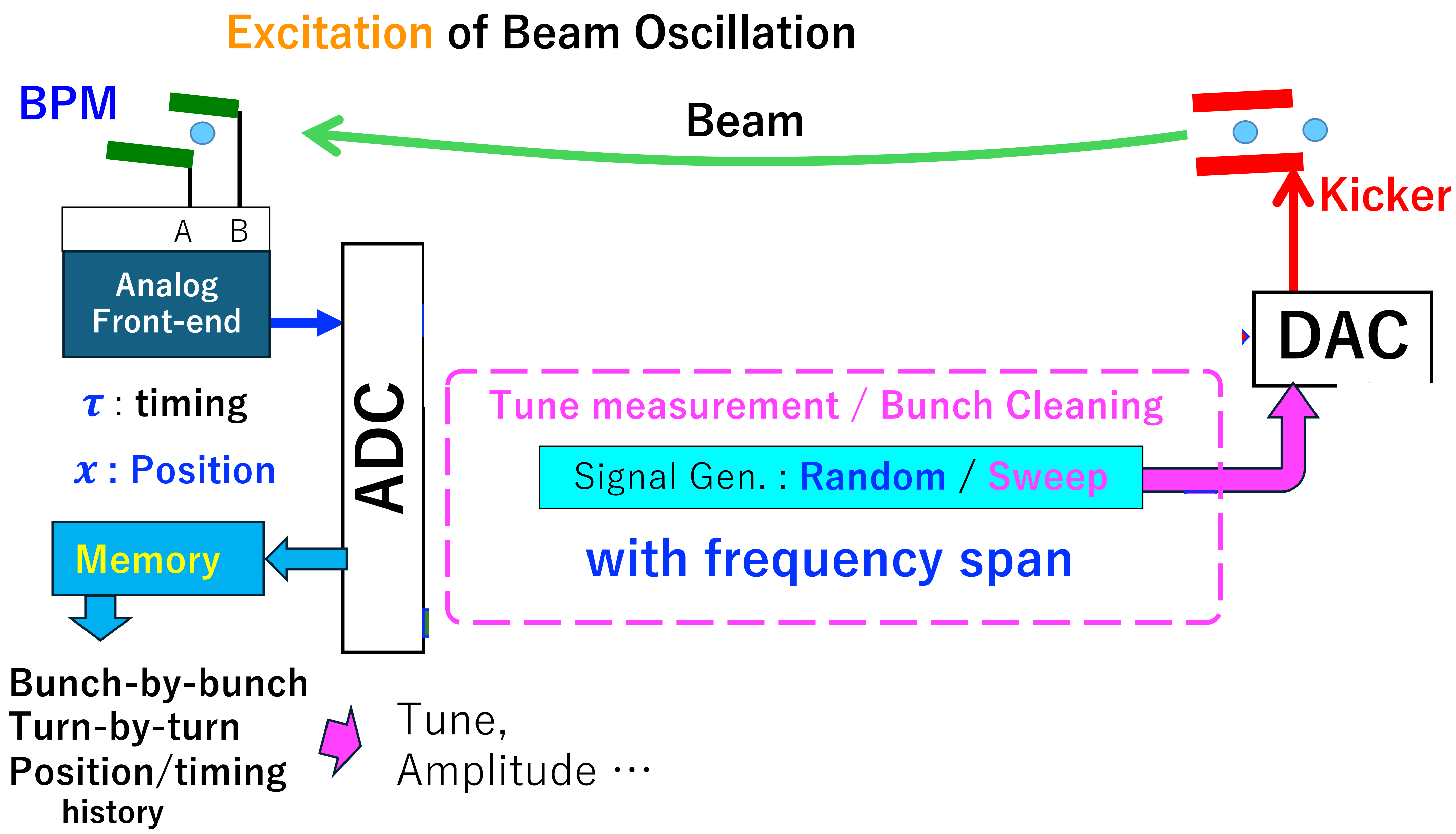
Excitation of Beam Oscillation




Excitation of Beam Oscillation
BPM
Beam
Kicker
A B
Analog Front-end
ADC
DAC
τ : timing
x : Position
Tune measurement / Bunch Cleaning
Signal Gen. : Random / Sweep
with frequency span
Memory
Bunch-by-bunch
Turn-by-turn
Position/timing
history
Tune,
Amplitude …

Excitation by **External Force**

Amplitude to Equilibrium Value controlled by Force Strength

* **Tune Measurement**

Just **One bunch is switched from feedback to excitation**

small effect to users

* **Cleaning of unnecessary bunches in filling gap(s)**

Amplitude Dependent Tune Shift <= catching by Frequency Seep (ELETTRA)

Amplitude	Small	->	Large	
tune	High	->	Low	(Amplitude Dependent tune shift)
Tune Freq.	High	->	Low	<= Sweep with GOOD Direction
Excitation Freq	Low	->	High	**at Lower Betatron Sideband** (ELETTRA)

(tune shift direction is machine/tuning dependent)

Continued . . .

https://indico.scc.kit.edu/event/3742/contributions/15384/ (ELETTRA)

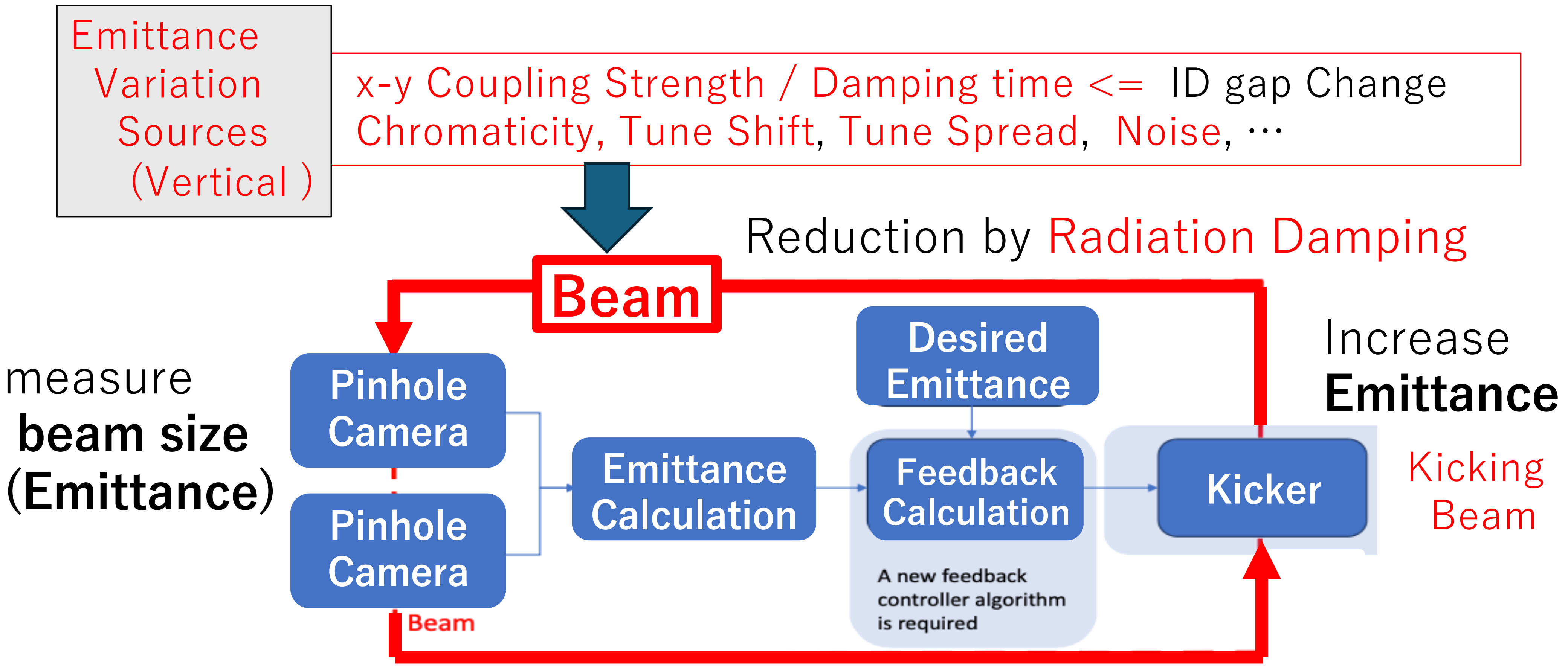
Excitation by **External Force**

* **Control of Transverse Beam Size/Emittance** (SOLEIL, DIAMOND)

Compared with x-y Coupling Control with **Skew Q magnets**

- **Faster** & **Simpler** Control (SOLEIL, DIAMOND)
- **Independent Control for H and V**
  Coupling measurement : V-emittance / (excited H-emittance) (SOLEIL)
- Smaller effect to Off-Axis Injected Beam (DIAMOND)
- Applicable for Ultra-Low Horizontal Emittance beam
  < but Beam size fluctuation is smaller with Skew Q (SOLEIL) >

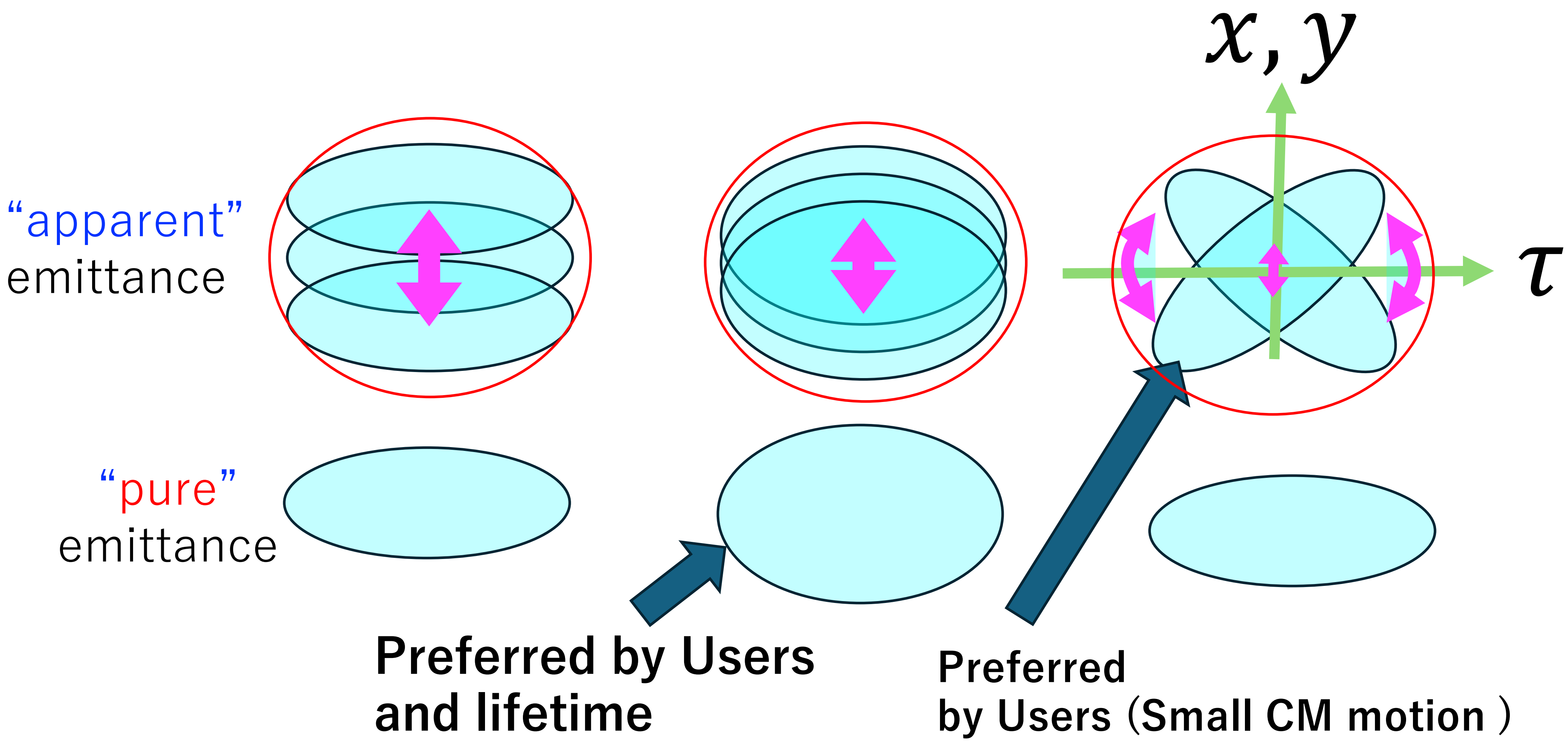
Control of Vertical Beam Size/Emittance (SOLEIL, DIAMOND)



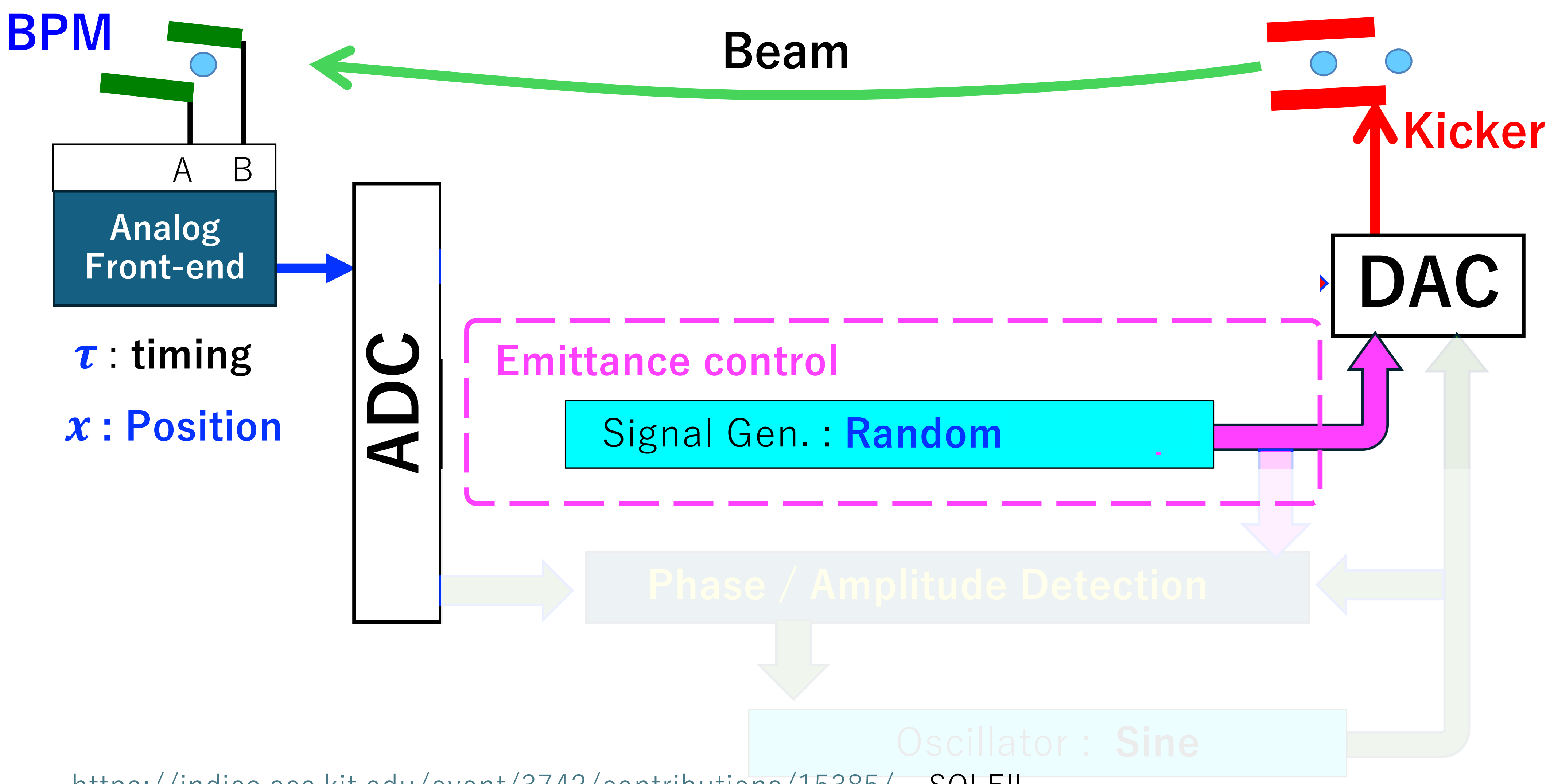
https://indico.scc.kit.edu/event/3742/contributions/15383/ DIAMOND
https://indico.scc.kit.edu/event/3742/contributions/15385/ SOLEIL

Figure modified from DIAMOND

Control of Vertical Beam Size/Emittance (SOLEIL, DIAMOND)



Control of Vertical Emittance by Random Kick (SOLEIL)



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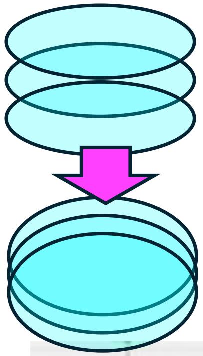
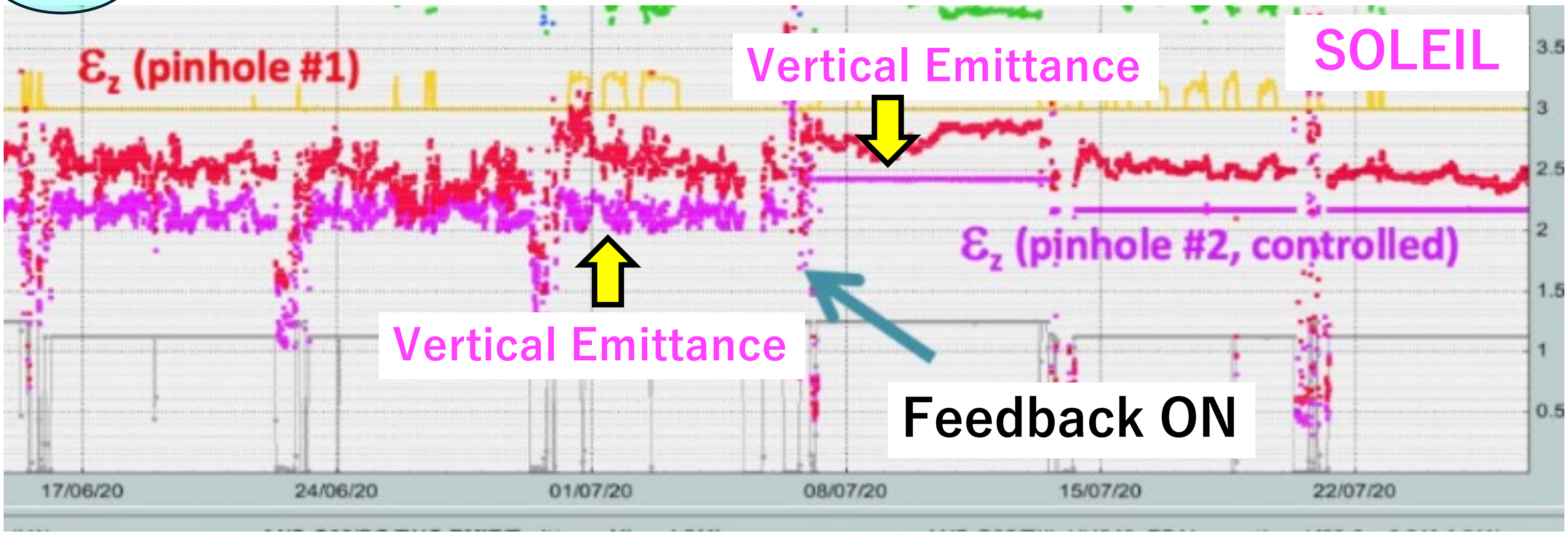


C.M. Motion of Random Start timing/amplitude
Chromatic Tune Shift
Tune Spread by Non-linearity

Decoherence (Phase Mixture) of electrons => "pure" Emittance



https://indico.scc.kit.edu/event/3742/contributions/15385/ SOLEIL

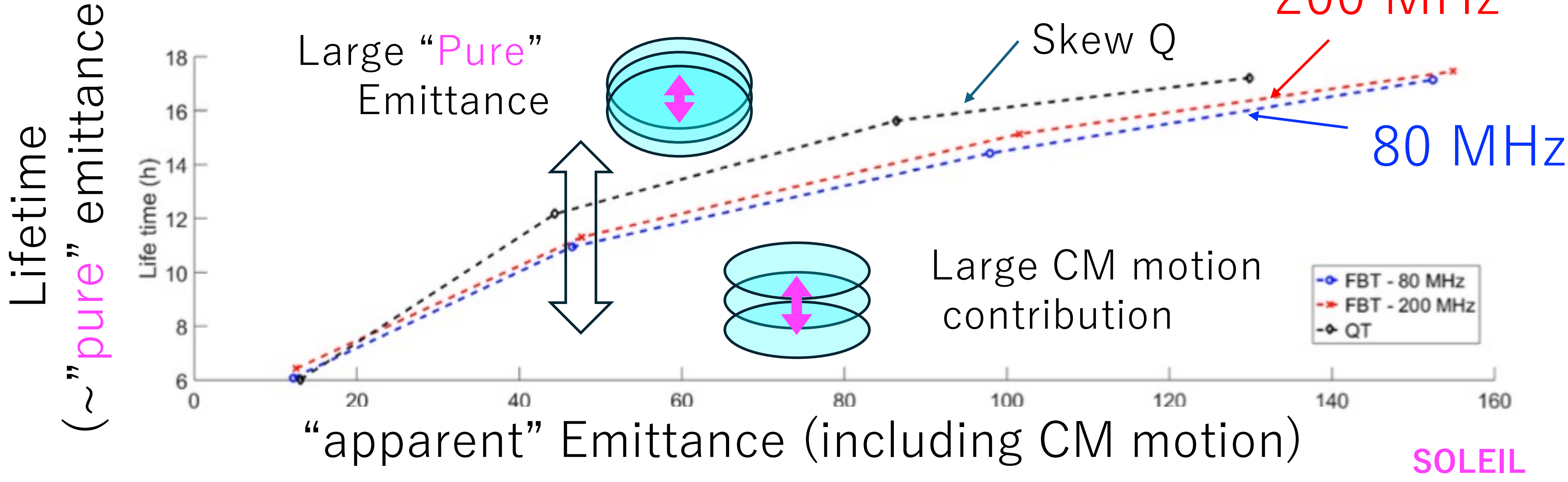
* **Control of Vertical Emittance by Random Kick** (SOLEIL)

Random kick =

White Noise with Wide Bandwidth (~200MHz) is better :

- **“Pure” emittance / Center of Mass Motion**
- **Emittance Jitter (fluctuation under beam size feedback)**

Beam size (emittance) is estimated with lifetime



https://indico.scc.kit.edu/event/3742/contributions/15385/ SOLEIL

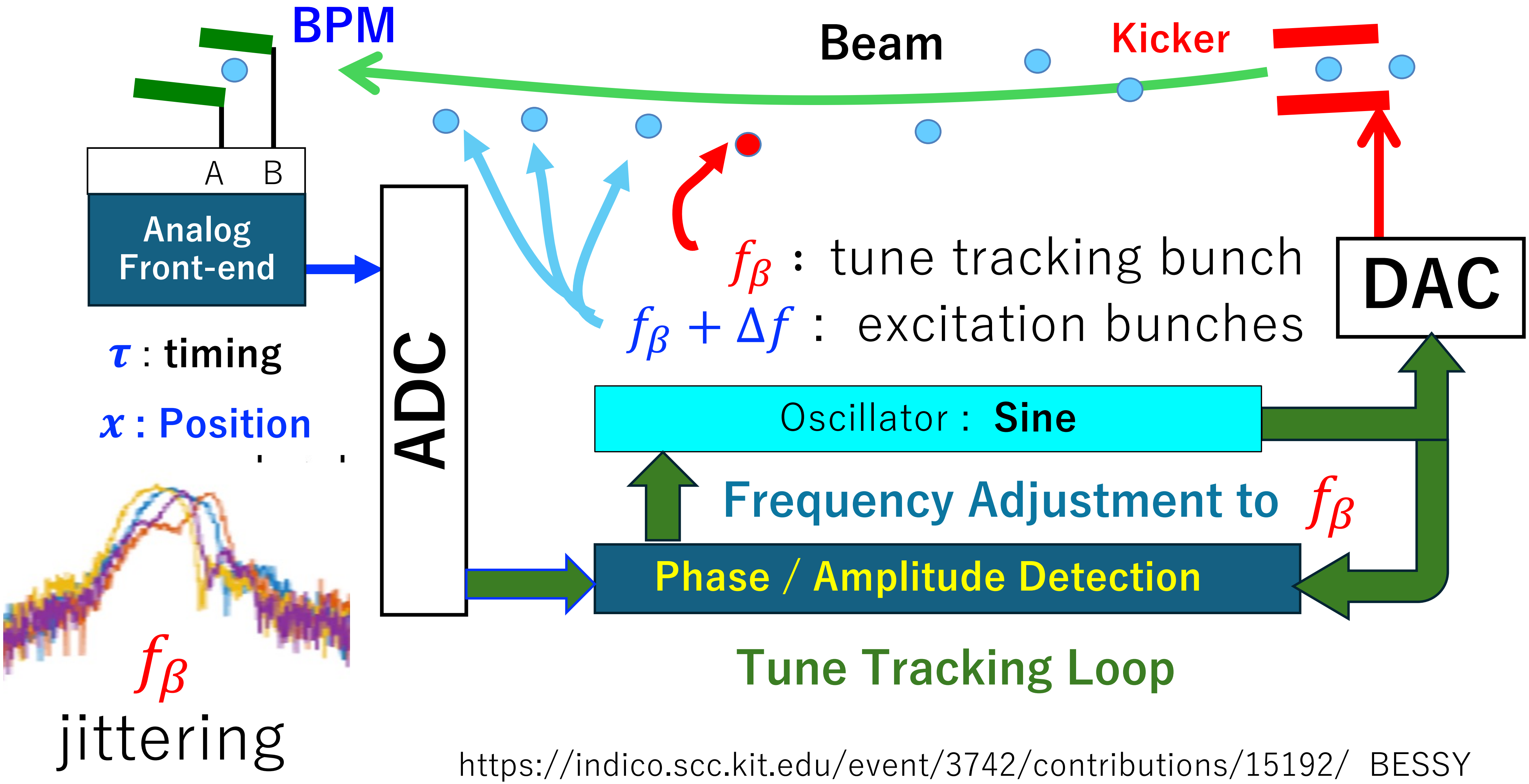
Resonant Excitation at Synchrotron sideband of Betatron peak

BESSY-II, DIAMOND

Before this

Tune Tracking Beam Response Measurement (BESSY)

Tune Tracking Beam Response Measurement (BESSY)



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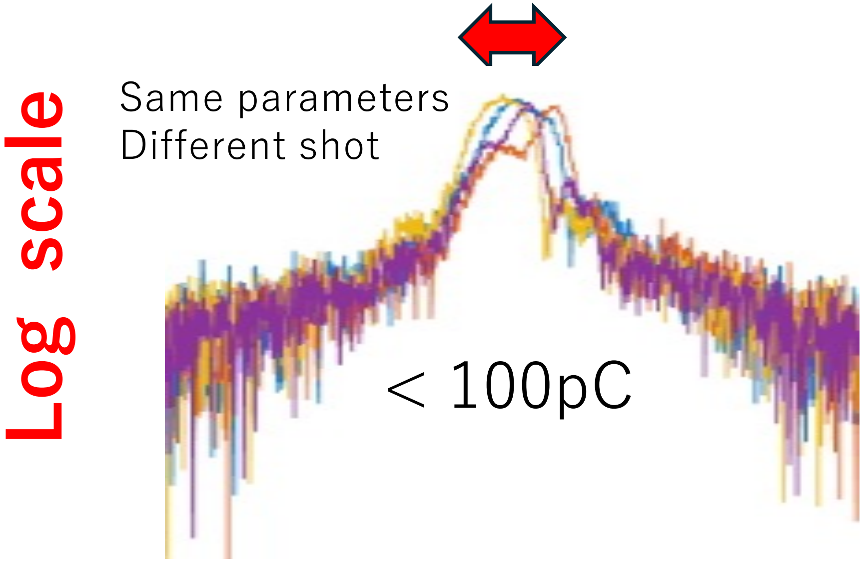
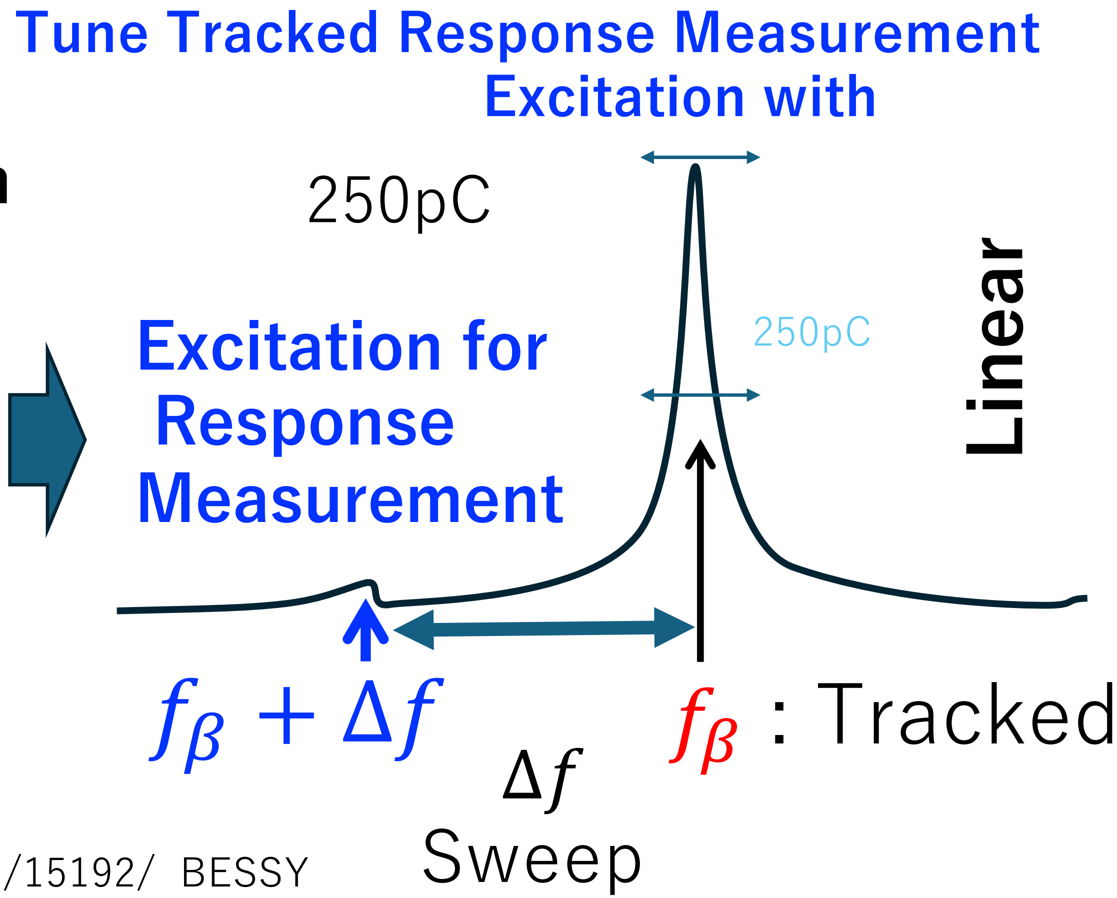
Tune Tracking Beam Response Measurement (BESSY)

Tracking betatron freq. + excitation with shifted frequency

Tune jitter by
Q-mag stability limitation





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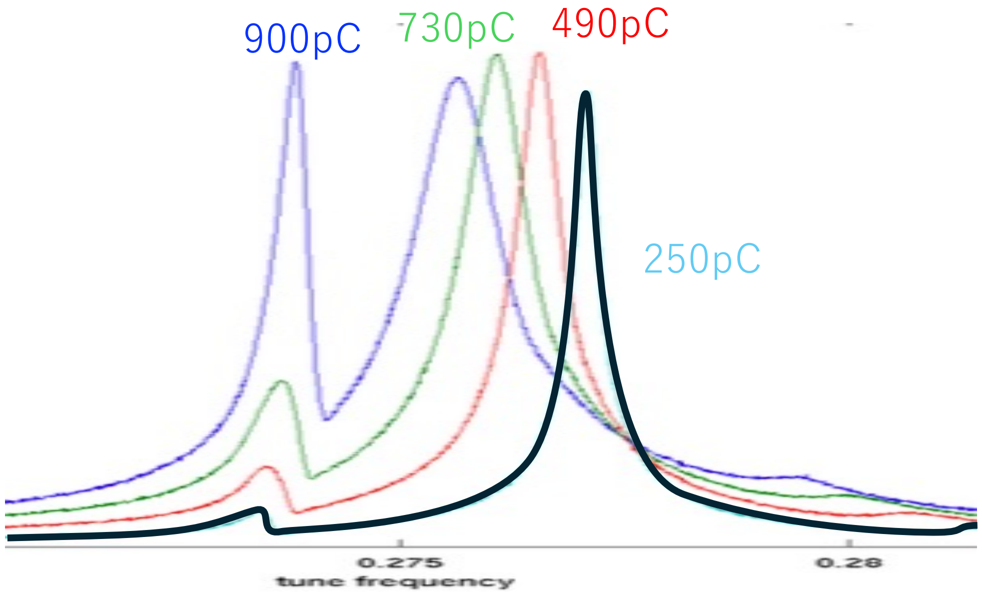
Tune Tracking Beam Response Measurement (BESSY)

Tracking Tune peak

+

Exciting Shifted Frequency



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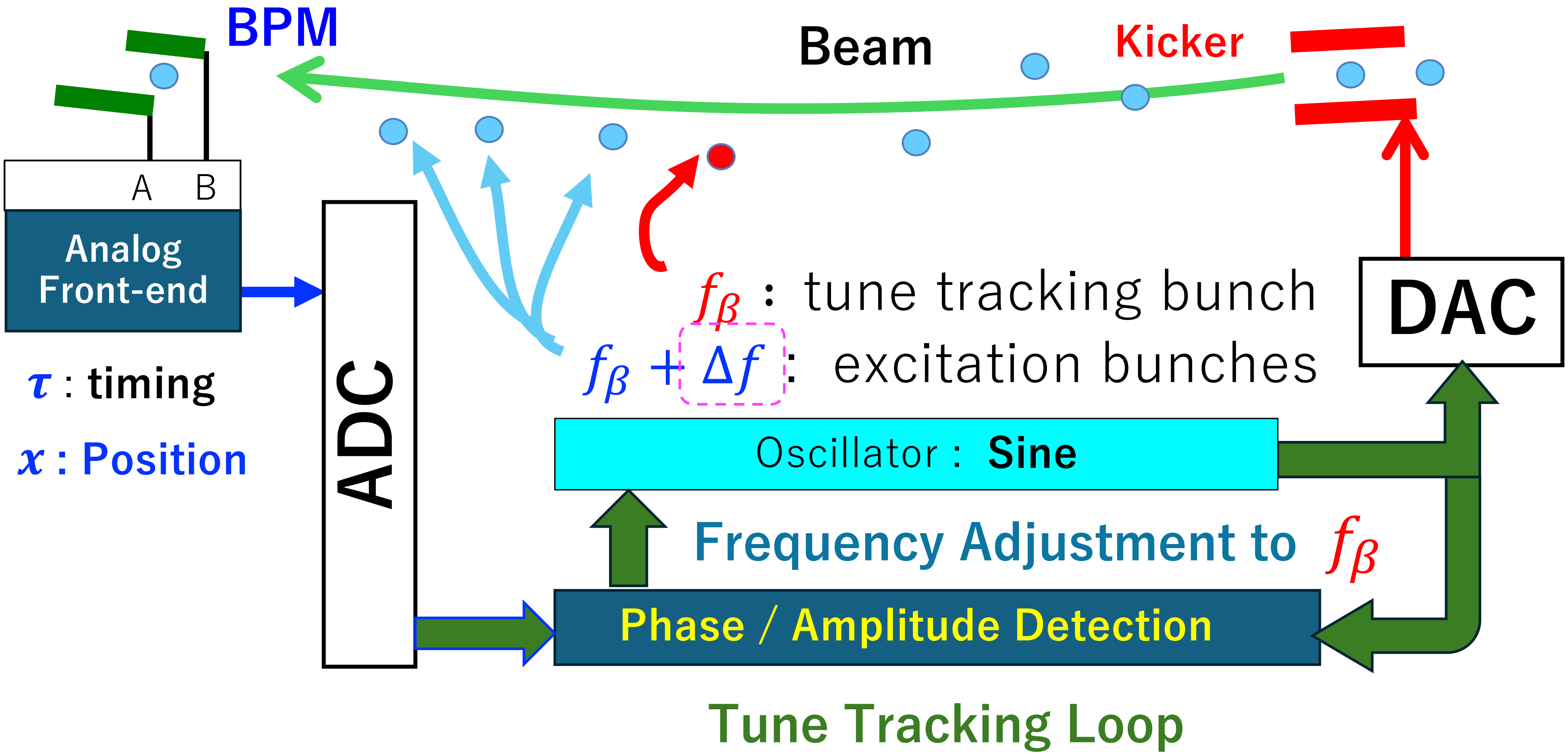
Tune Tracking Beam Response Measurement (BESSY)



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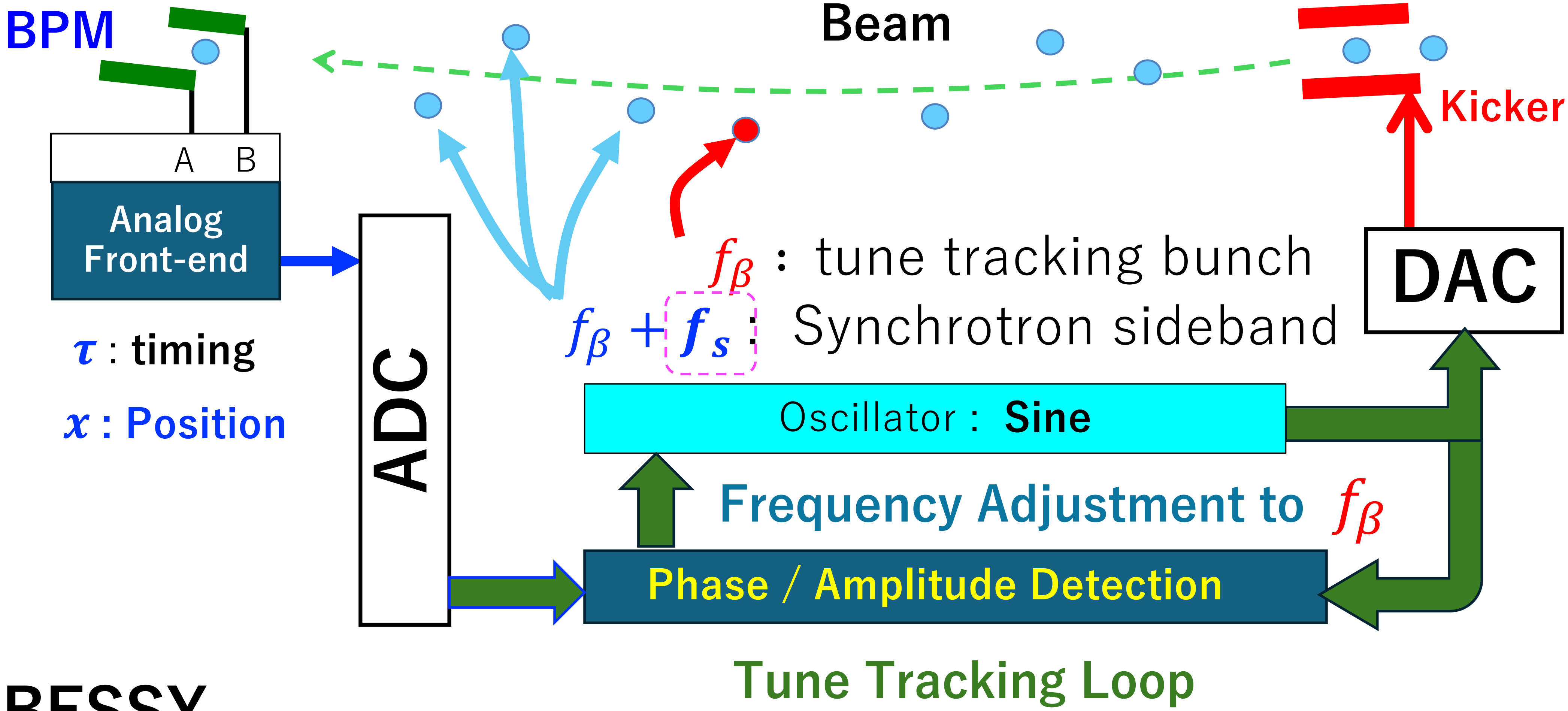
Resonant Excitation at Synchrotron sideband of Betatron peak



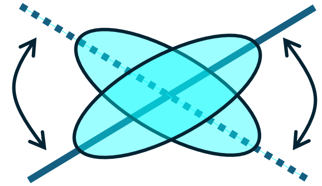
BESSY
DIAMOND

https://indico.scc.kit.edu/event/3742/contributions/15192/ BESSY

https://indico.scc.kit.edu/event/3742/contributions/15383/ DIAMOND

Resonant Excitation at Synchrotron sideband of Betatron peak

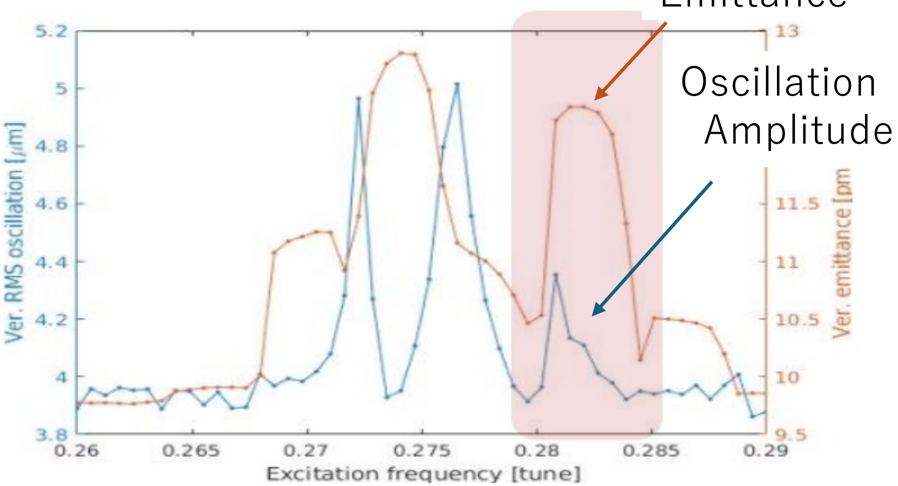
On
Resonance
Excitation



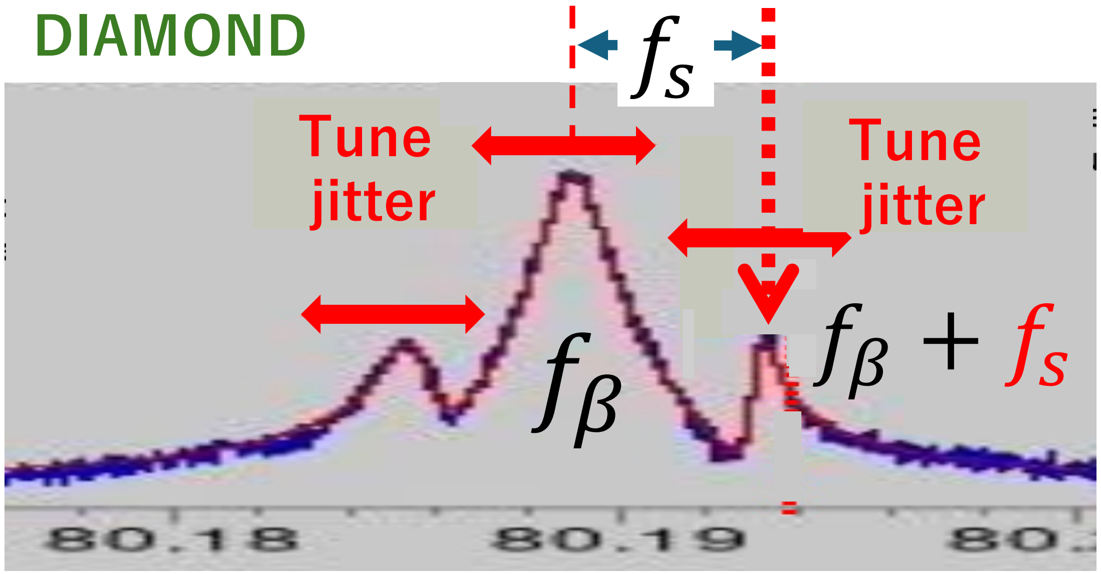
Stronger kick is necessary
than betatron peak

Resonant Excitation with Tune Tracking

Measurement



DIAMOND



https://indico.scc.kit.edu/event/3742/contributions/15383/ DIAMOND

Resonant Excitation at Synchrotron sideband of Betatron peak

Pulse Picking by Resonant Excitation (PPRE) (BESSY-II, DIAMOND)

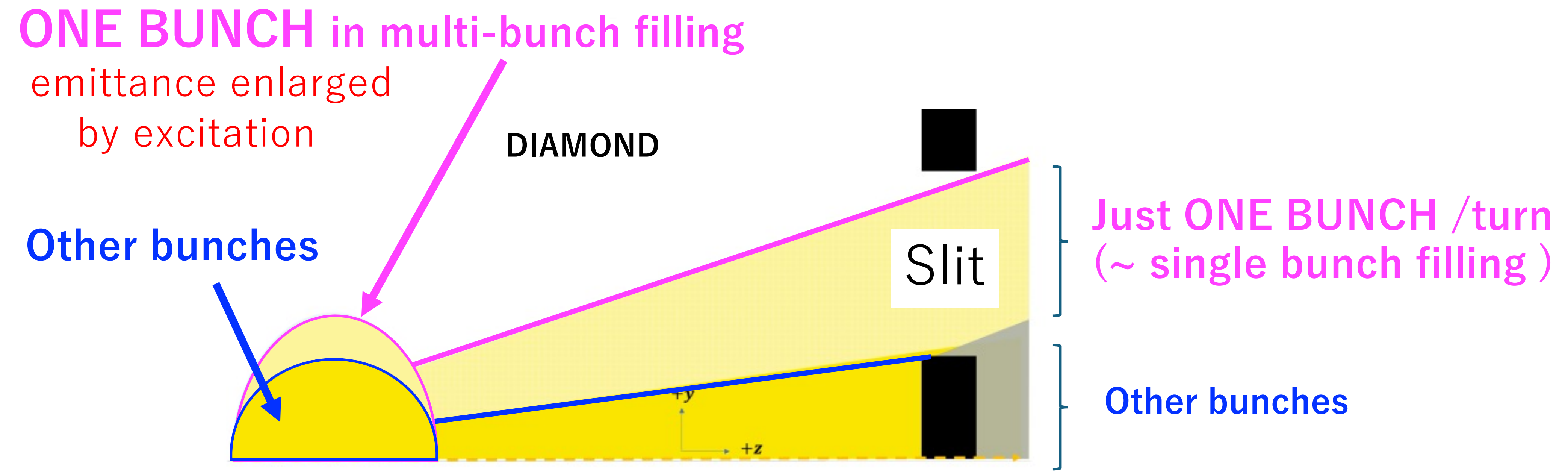


Figure from (modified)

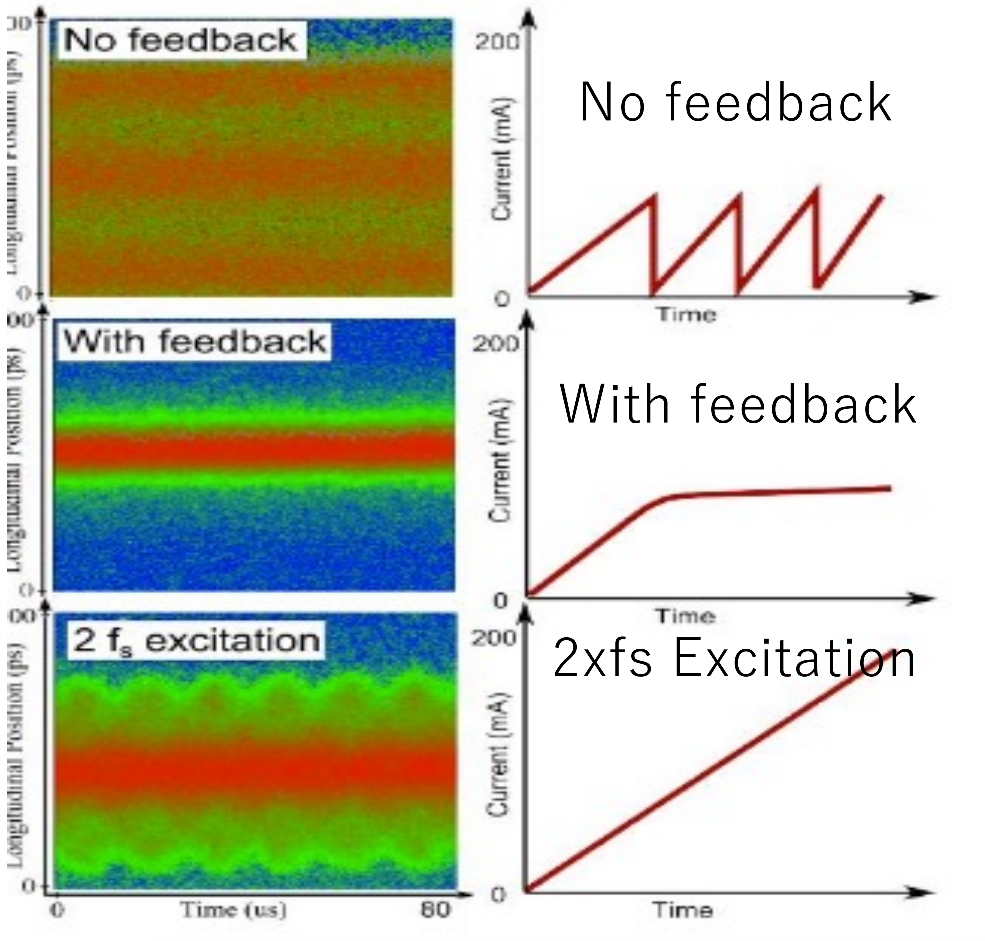
https://accelconf.web.cern.ch/ipac2023/pdf/MOPM037.pdf
"INVESTIGATIONS INTO OPERATING PULSE PICKING BY RESONANT EXCITATION (PPRE) IN THE VERTICAL PLANE" (DIAMOND)

https://indico.scc.kit.edu/event/3742/contributions/15383/ DIAMOND

Resonant Excitation of Synchrotron Oscillation （KARA）

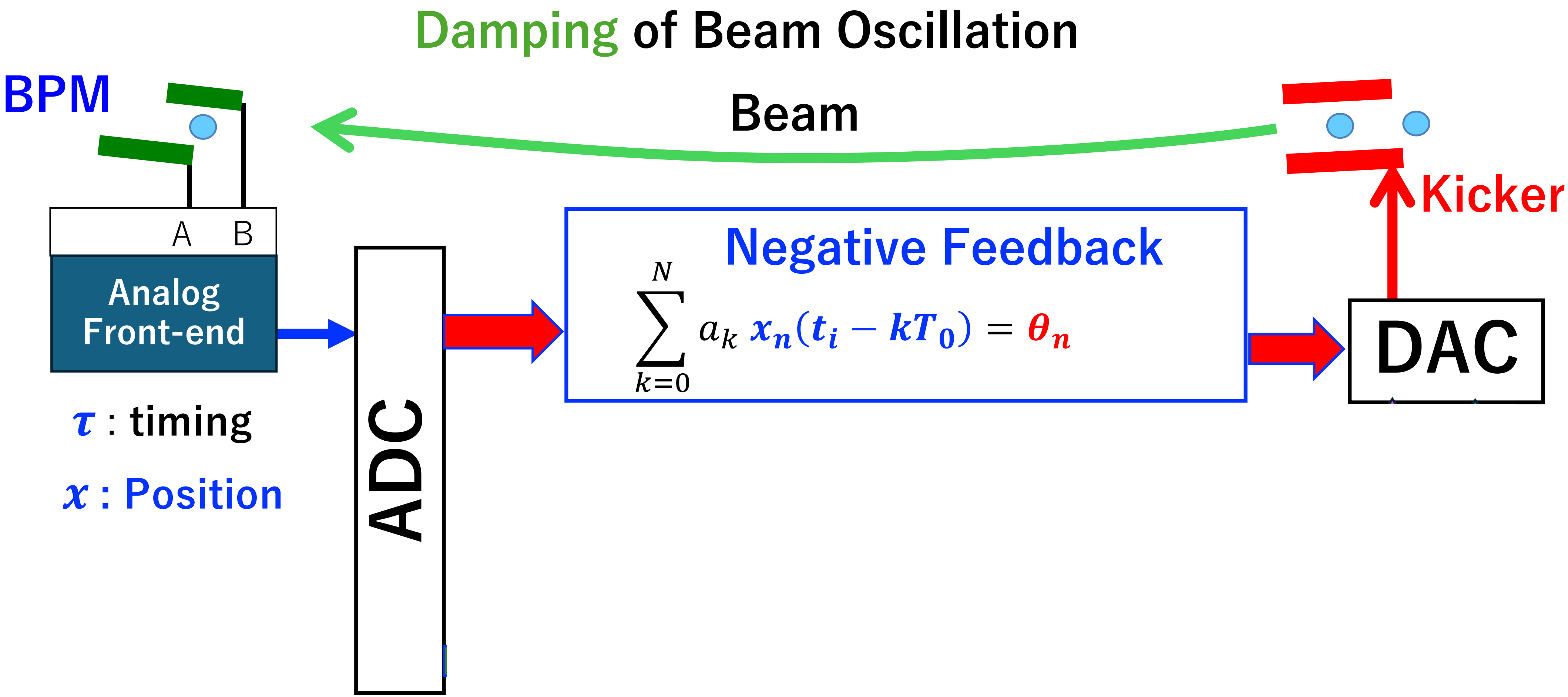
Longitudinal Excitation
of Quadrupole motion with
2 x fs frequency
=> **Lengthen bunches**

suppression of longitudinal instability



https://indico.scc.kit.edu/event/3742/contributions/15188/ KARA

Negative Feedback for Damping



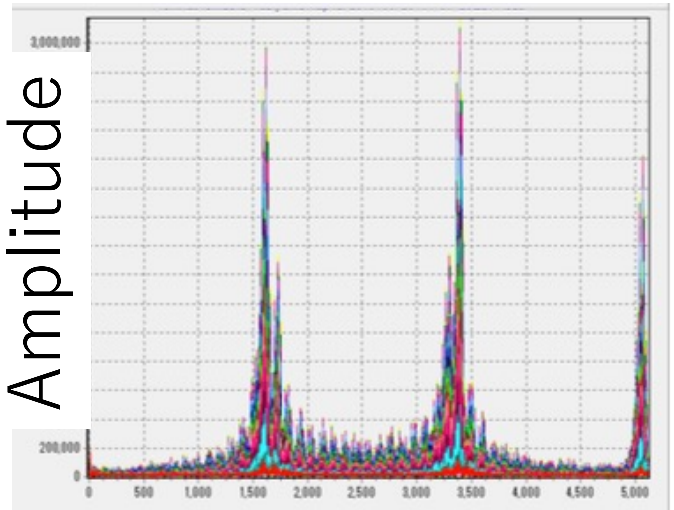
Damping of Beam Oscillation
BPM
Beam
Kicker
A
B
Analog Front-end
ADC
Negative Feedback
$\sum_{k=0}^{N} a_k\, x_n(t_i - kT_0) = \theta_n$
DAC
τ : timing
x : Position

Negative Feedback (Damping)

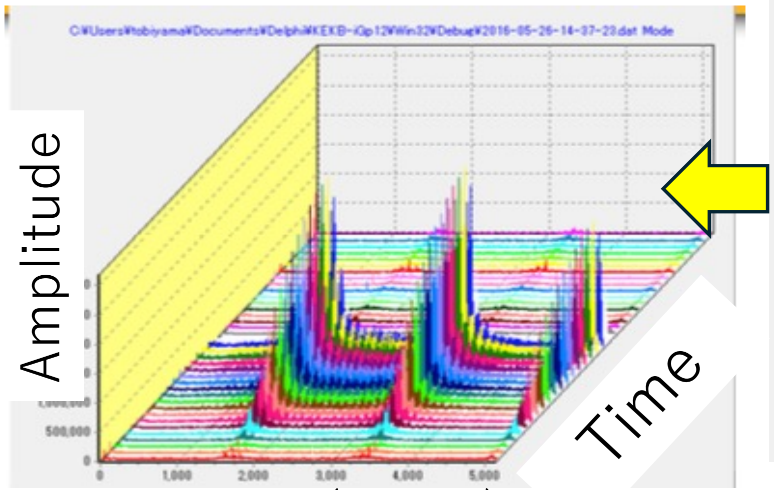
Grow & Damp Experiment for investigate Instability

Switch OFF feedback => Growth by Instability => Switch ON feedback
Instability Frequency => source impedance, …z

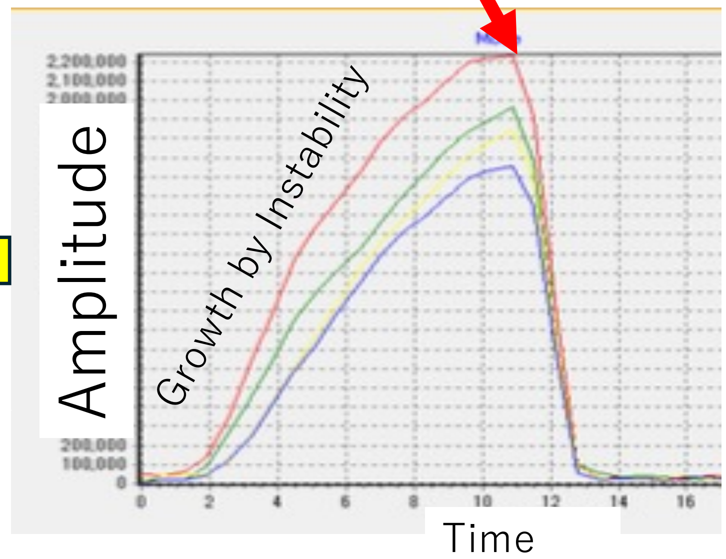
SuperKEKB HER



Frequency
(Instability Mode)



Frequency (Mode)

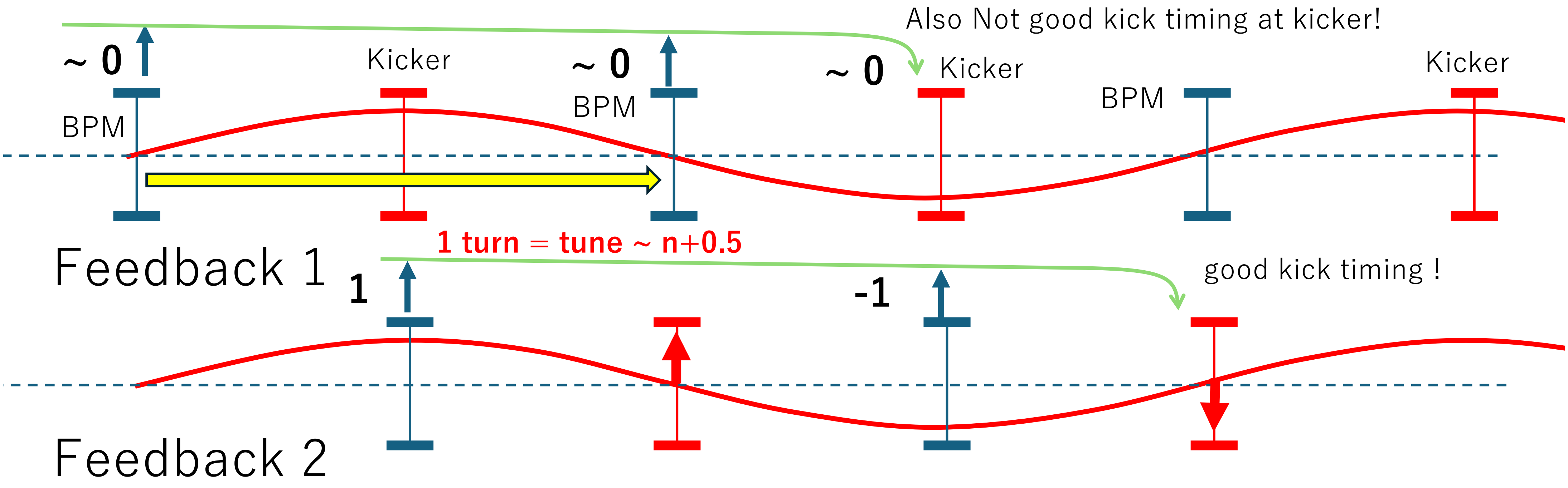


Growth and damping of several Modes

https://indico.scc.kit.edu/event/3742/contributions/15197/ KEK

Damping

* **Fractional Tune ~ 0.5 (SuperKEKB) :**
Two Transverse Feedback with 90 degree betatron phase difference

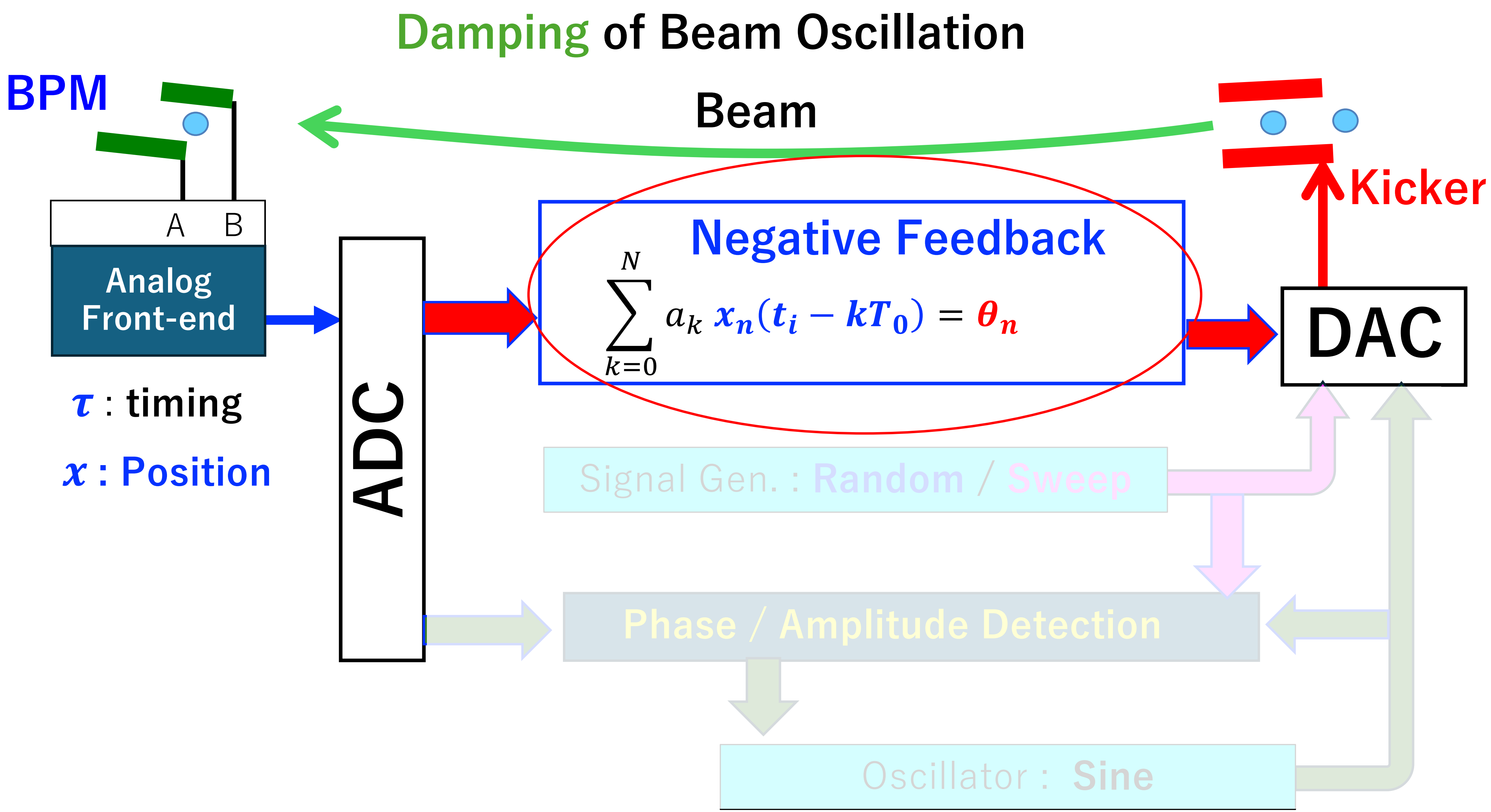


https://indico.scc.kit.edu/event/3742/contributions/15197/ KEK

Negative Feedback (Damping)

Fast Damping of Coherent motion of Stored beam excited at Injection

Fast damping prevents the process :
Coherent Motion =(**Decoherence** by **tune spread in bunch**)=> Emittance produced by, such as Amplitude Dependent Tune Shift



Damping of Beam Oscillation
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Beam
Kicker
A
B
Analog Front-end
τ : timing
x : Position
ADC
Negative Feedback
$\sum_{k=0}^{N} a_k\, x_n(t_i - kT_0) = \theta_n$
DAC
Signal Gen. : Random / Sweep
Phase / Amplitude Detection
Oscillator : Sine

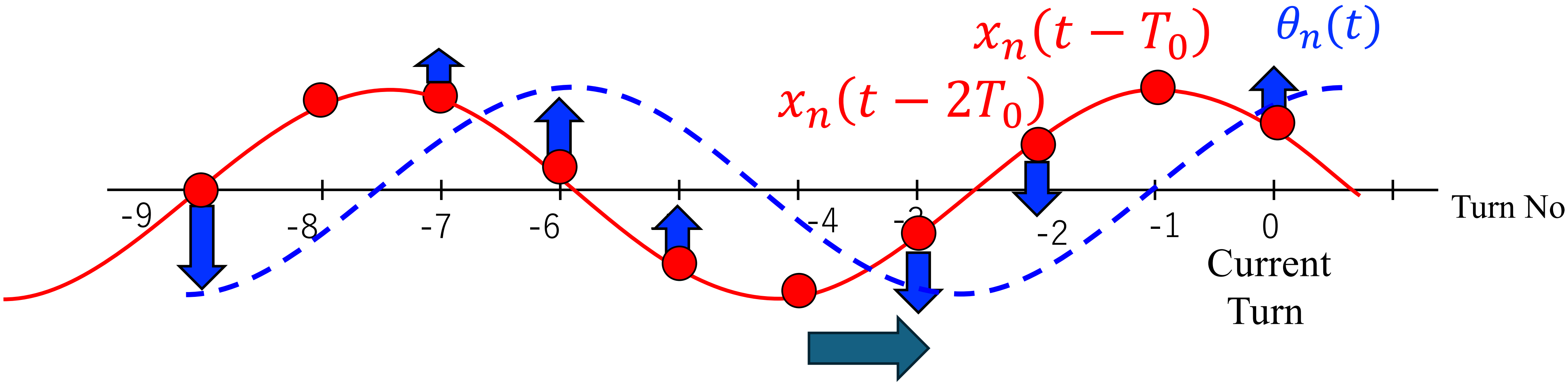
FIR filter

"Number of Taps"

$$\theta_n(t) = \sum_{k=1}^{N_T} a_k \; x_n(t - kT_0)$$

Kick for n-th bunch

Position History of n-th bunch



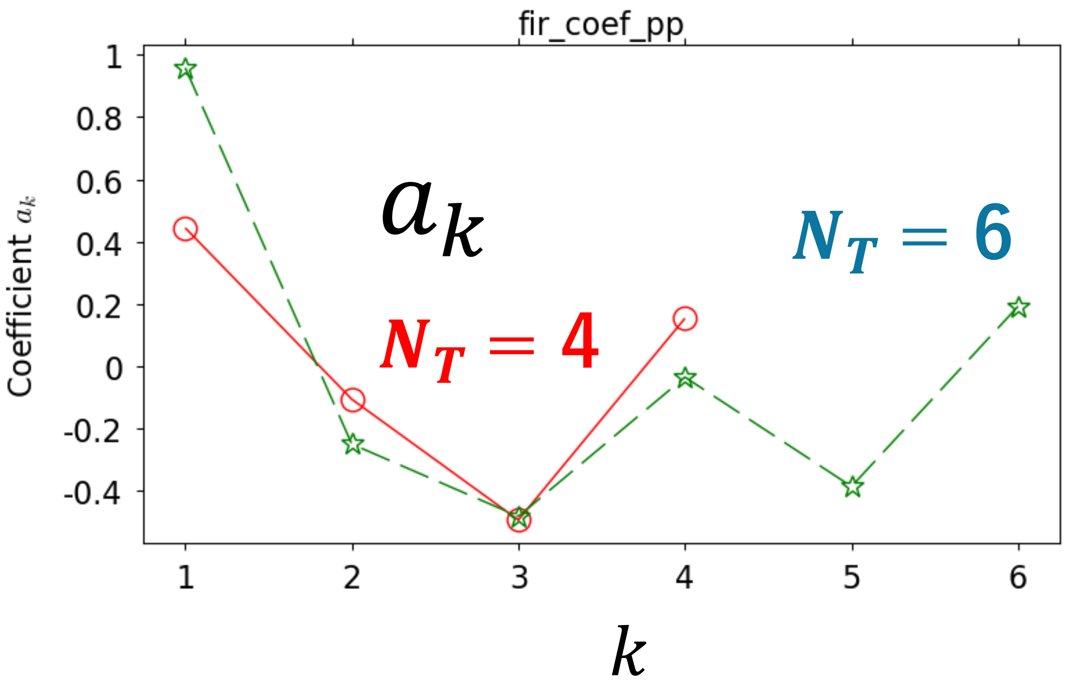
Phase shift Control by FIR filter

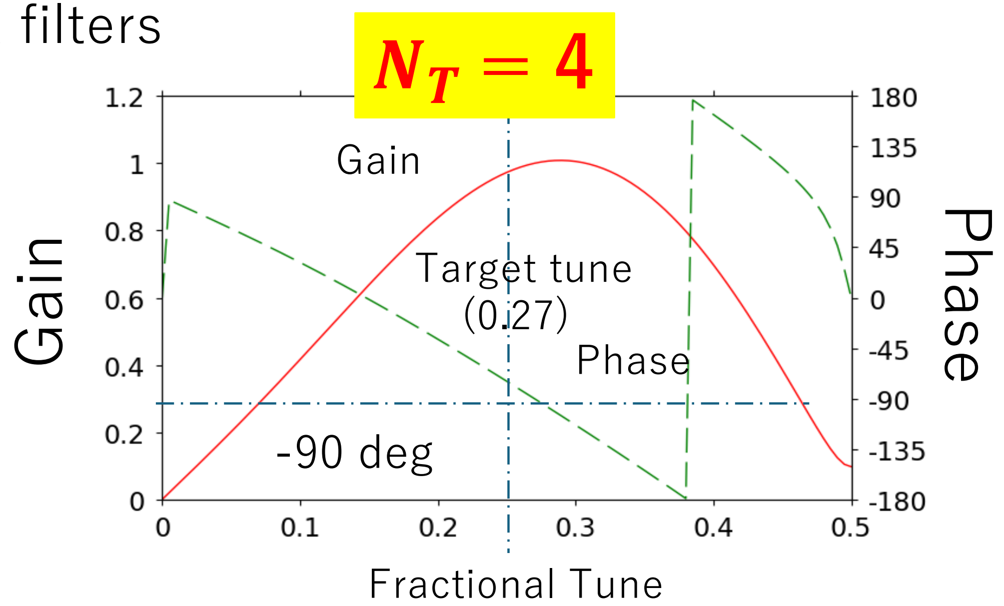
Number of Taps

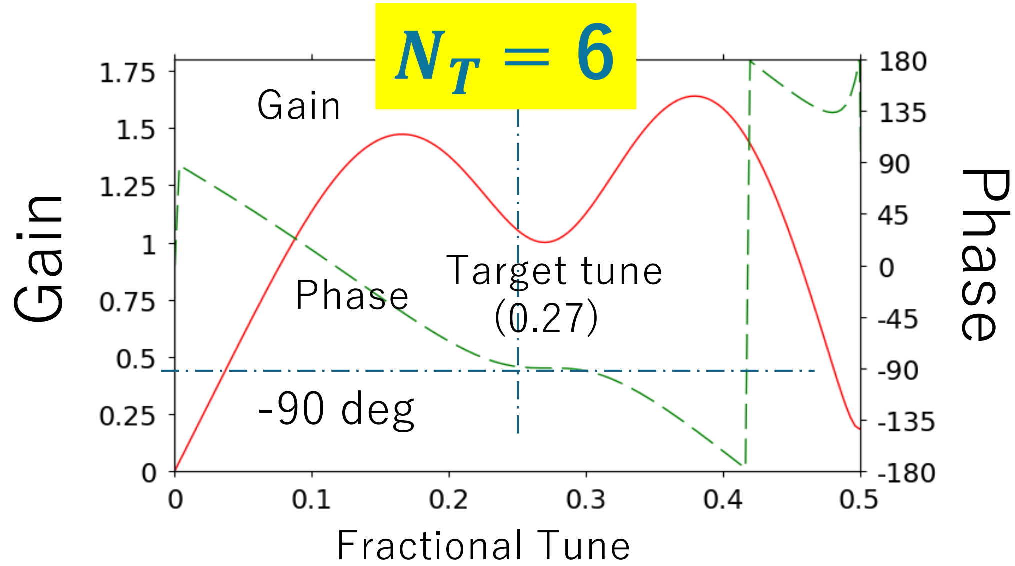
Example of FIR filters

FIR filter

$$\sum_{k=1}^{N_T} a_k \, x_n(t_i - kT_0) = \theta_n(t_i)$$



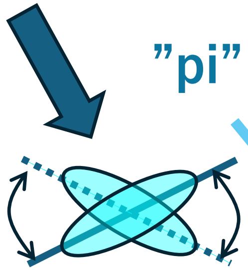


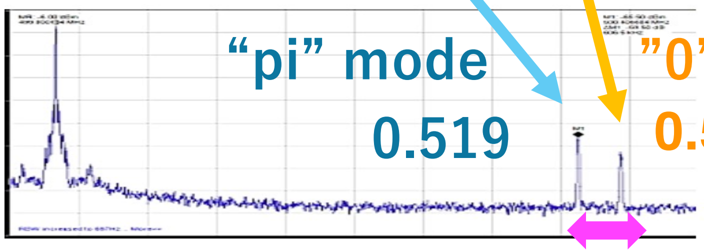


FIR filter for Two Tune Control

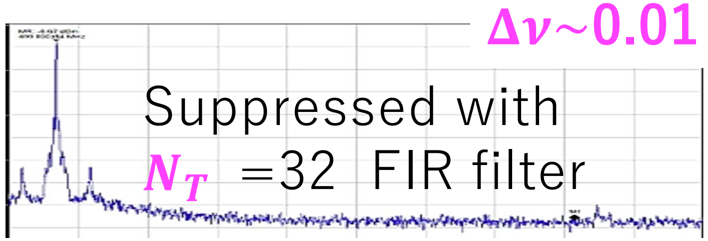
BEPC-II Suppression of Coherent motion by
Synchro-beta Resonances with Beam-Beam effect

"pi" mode (0.519) : FIR phase -50deg
"0" mode (0.508) : FIR phase -140deg

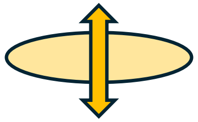




$\Delta\nu \sim 0.01$



Instability

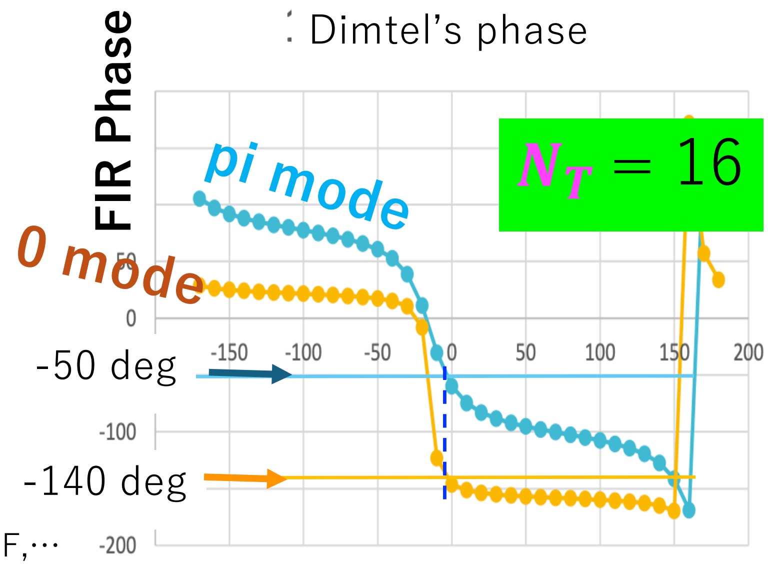


Uncertainity principle

$$1 < N_T \Delta\nu$$

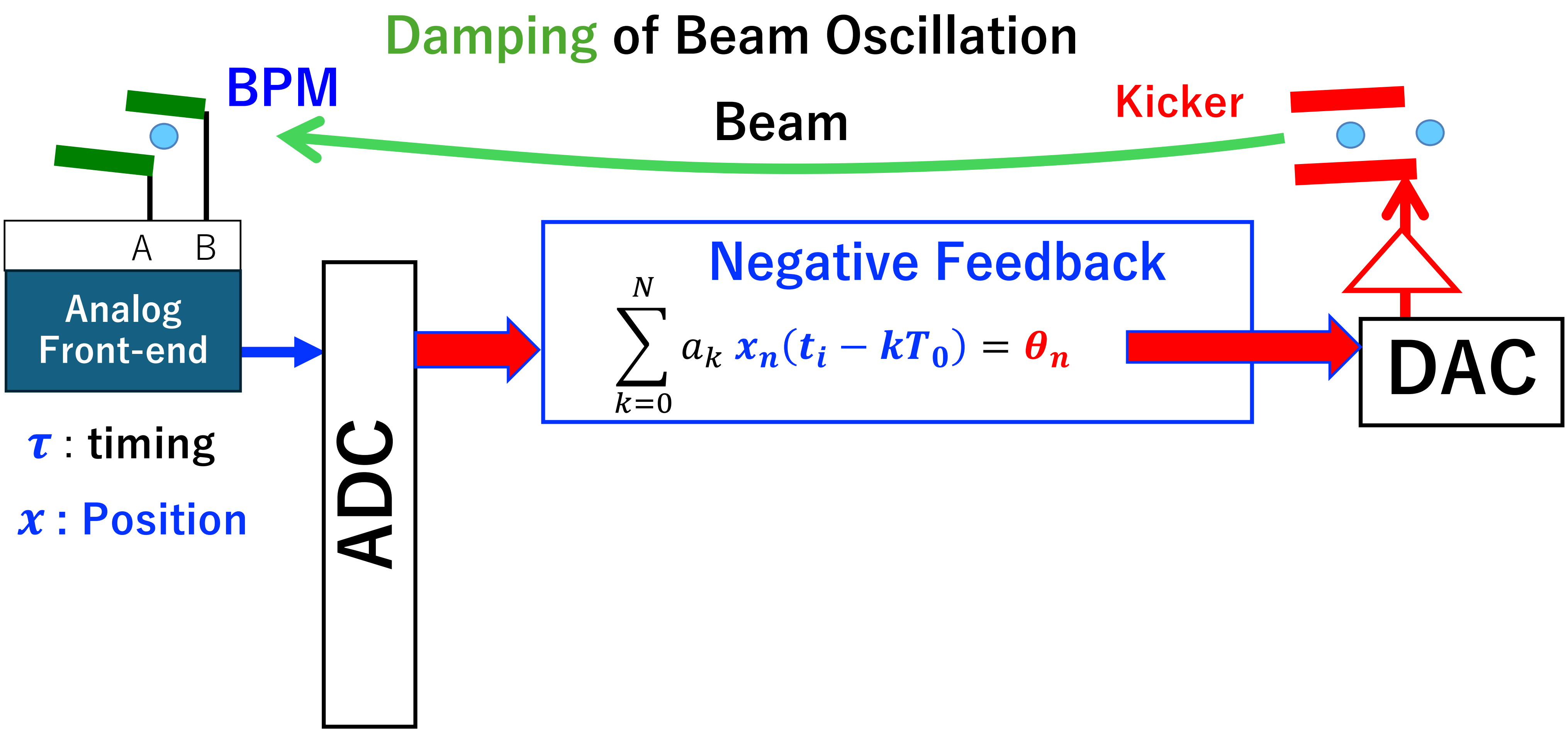
$$\frac{1}{\Delta\nu} < N_T$$

$$\frac{1}{\Delta\nu} = \frac{1}{0.01} = 100 \sim N_T$$



Other "Two tune" control scheme:
- Longitudinal feedback for dipole and quadrupole modes : DAFNE
- Single-loop Horizontal and Vertical feedback (horizontal tune & vertical tune) : SPring-8, PF,…

https://indico.scc.kit.edu/event/3742/contributions/15183/ BEPC-II



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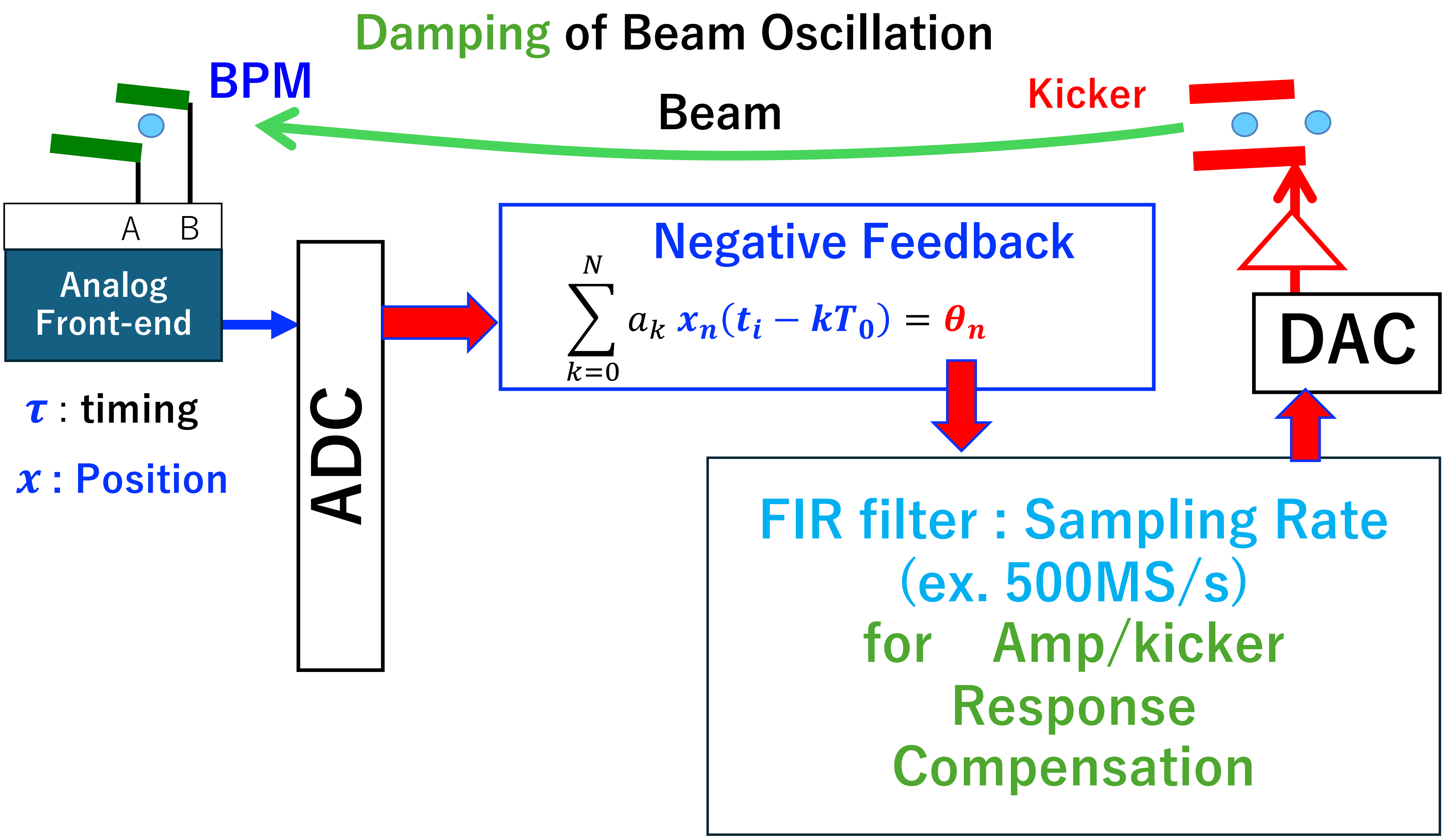
Beam
Kicker
A
B
Analog Front-end
ADC
Negative Feedback
$\sum_{k=0}^{N} a_k x_n(t_i - kT_0) = \theta_n$
DAC
τ : timing
x : Position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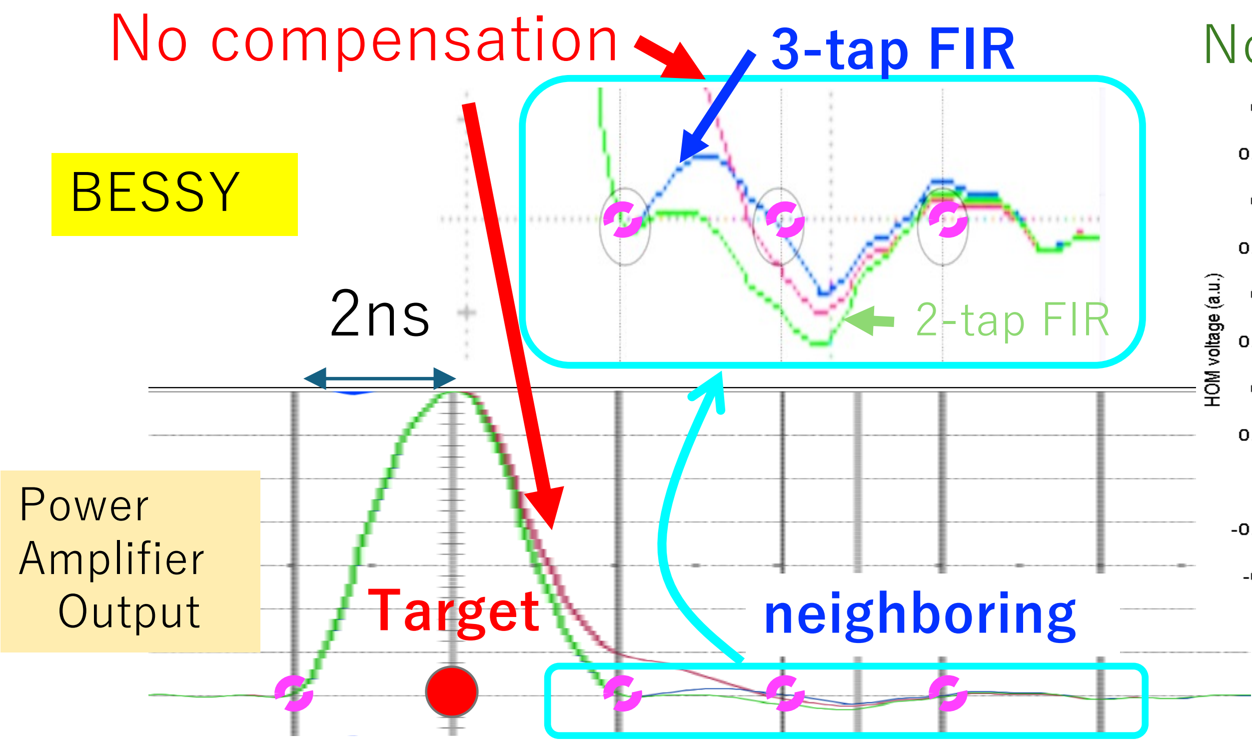
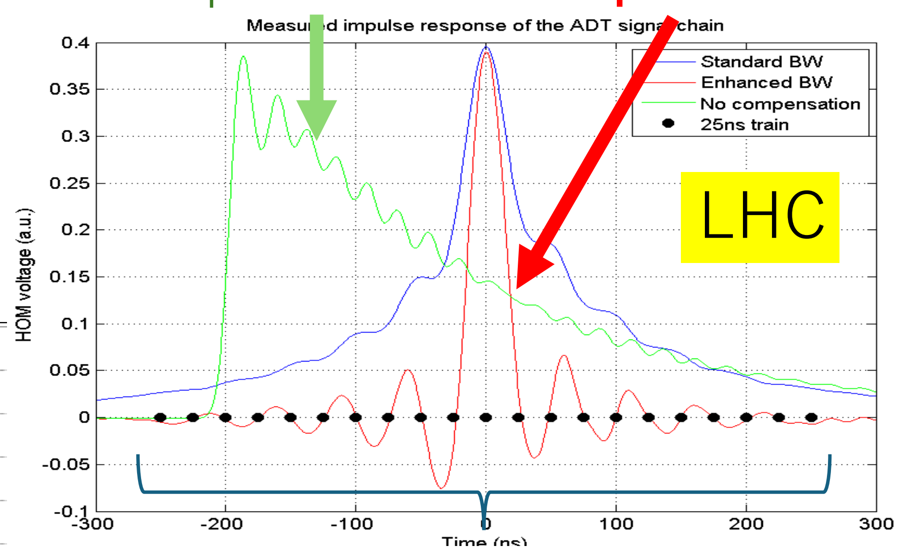
$\sum_{k=0}^{N} a_k x_n(t_i - kT_0) = \theta_n$
DAC
FIR filter : Sampling Rate (ex. 500MS/s)
for Amp/kicker Response Compensation

Kick signal Sampling Rate → FIR filter: Sampling Rate (ex. 500MHz) Amp/kicker Response Compensation → DAC

Reduction of kick on neighboring bunches





Bunches with 25n spacing

Neighboring bunches are at ZERO CROSSING

https://indico.scc.kit.edu/event/3742/contributions/15192/ BESSY

https://indico.scc.kit.edu/event/3742/contributions/15394/ LHC

Timing Jitter at Injection to BESSY-II Booster

Longitudinal Feedback is effective, however,

Timing jitter > Acceptance Longitudinal Feedback in some cases

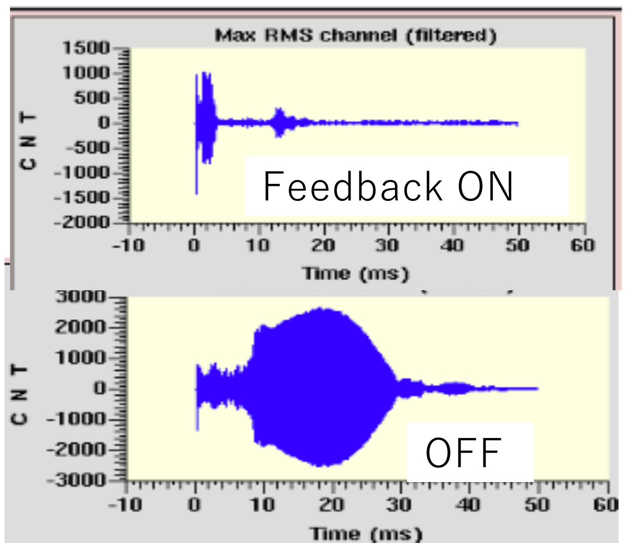
* Cavity voltage Change by beam loading (multi-bunch at high current)

Cured by change injection timing to **dB/dt = 0**

* Injection Beam Timing Jitter <=Transport= Energy jitter by Klystron jitter

=> Feedback is turned on ~3ms after injection

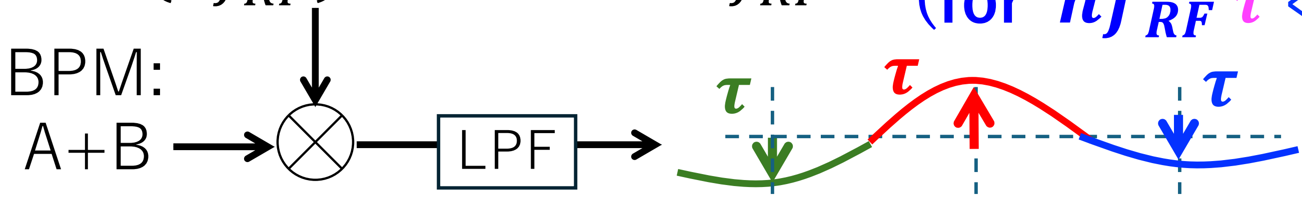
(after Jitter amplitude decreased)



Possible method of Widening of Acceptance

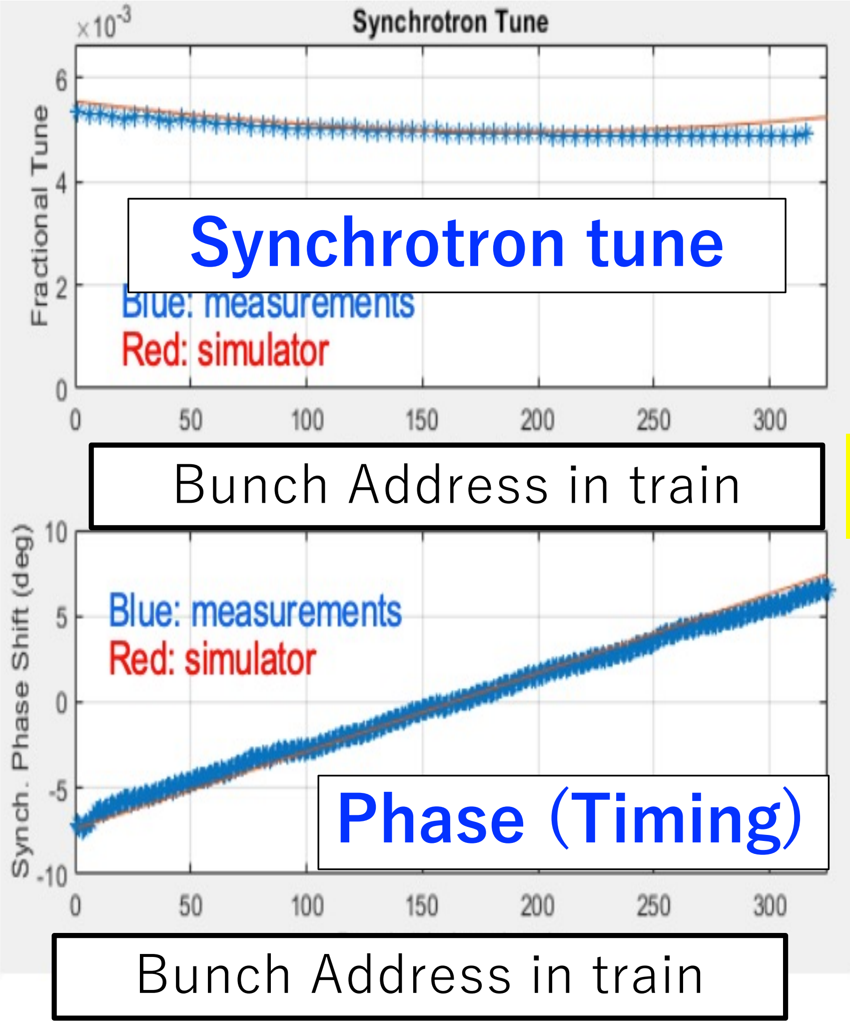
x3 : Acceptance but
1/3 : Phase Sensitivity

1.5GHz($3f_{RF}$) => 0.5GHz(f_{RF}) **(for $nf_{RF}\tau \ll 1$)**



https://indico.scc.kit.edu/event/3742/contributions/15189/ BESSY

Measurement with Feedback : Synchrotron Tune and Longitudinal Timing Shift



Unequal Beam loading by
Main Cavity + (Harmonic Cavity) + Train + Gap
=> Variation of Cavity **Voltage** and **Phase**

⬇

Synchrotron Tune Shift and Bunch Timing Shift

Elettra 2.0

Stable phase of each bunch:

- Measurement with the LMBF front end by scanning of 360° the phase of the detector and recording the acquired signal averaged for each bunch
- The detector phase setting corresponding to the zero crossing for a given bunch is the stable phase of that bunch w.r.t. to the other bunches

https://indico.scc.kit.edu/event/3742/contributions/15384/ ELETTRA

Feedback Processor

Feedback Processors with RFSoC

RFSoC for new feedback processors

RFSoC = (**FPGA** + **ADC** + **DAC** + **ARM CPU**) => **SINGLE CHIP**

SLS-2.0 : AMD ZCU111 Evaluation board : tested in SLS1.0 in transverse BBF

XCZU28DR-2 : 8 x ADC (12-bit 4GS/s) + 8 x **DAC** (14-bit **6.5 GS/s**)

Start-up: Single-board for Longitudinal

Target: X / Y / Longitudinal with Single board

Energy Kicker Direct Drive by DAC :

1.875GHz (280 MHz Bandwidth)

See poster

WEP42

PETRA-IV : MicroTCA.4 board : designing with DESY, …

DAMC-DS5014DR (DESY) for testing

\- candidate -

XCZU47DR-1 : 8 x ADC (14-bit 5GSPS) + 8 x DAC (14-bit 10GSPS)

and several other projects for BBF, LLRF, ... are planning

See poster

WEP55

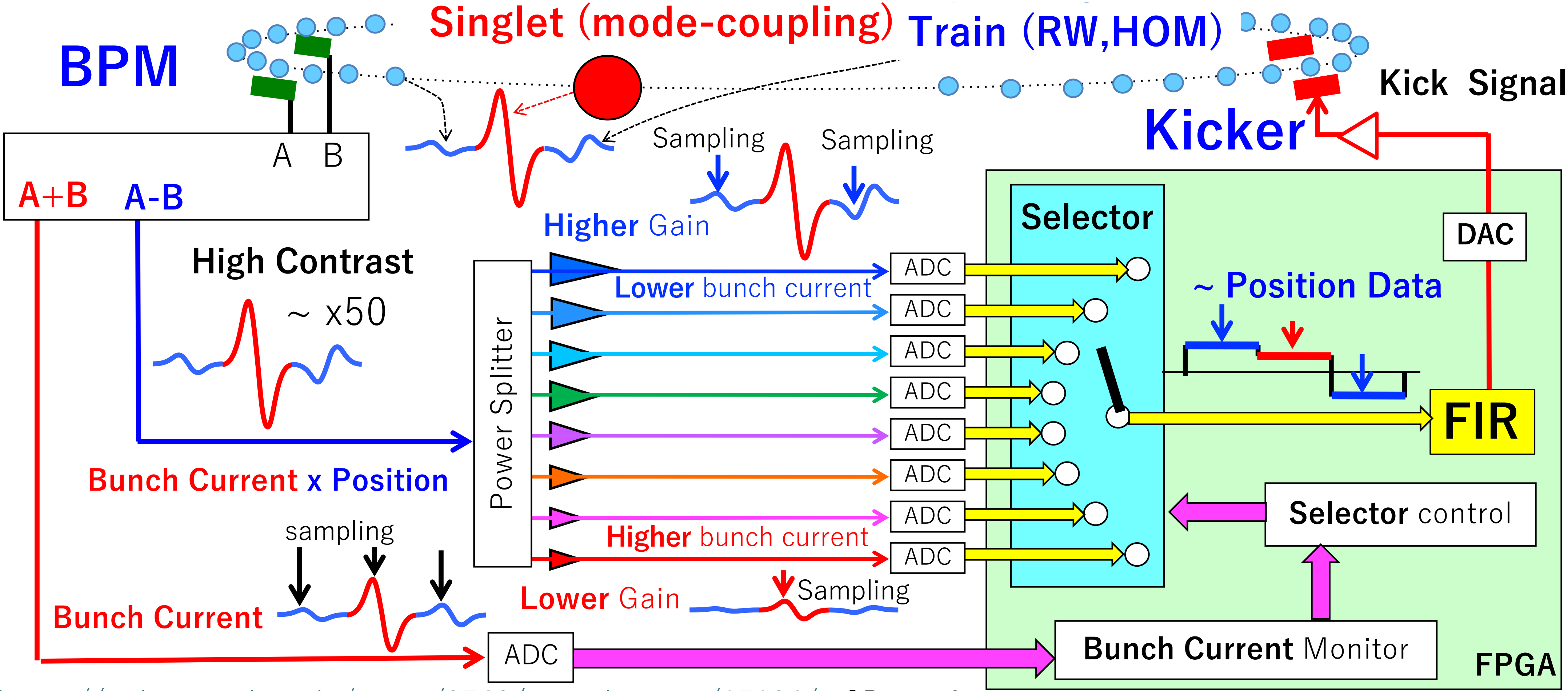
https://indico.scc.kit.edu/event/3742/contributions/15604/ SLS

https://indico.scc.kit.edu/event/3742/contributions/15423/ PETRA

Bunch-by-bunch Feedback for High Contrast Bunch Current

Switching gain : Multiple "Front-end + ADC" with bunch current

(SPring-8, SOLEIL, PAL)

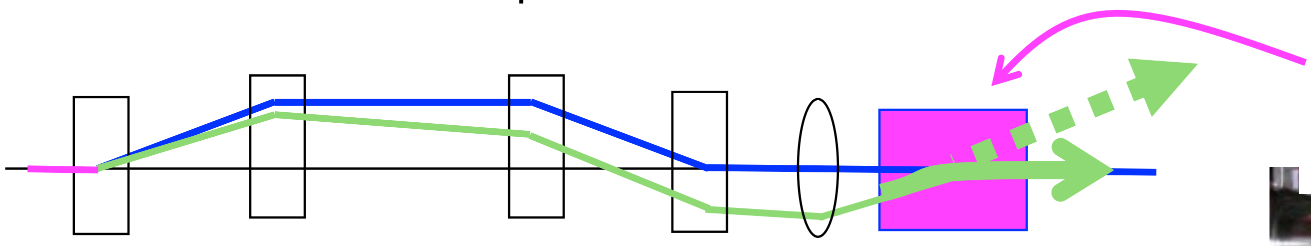


https://indico.scc.kit.edu/event/3742/contributions/15184/ SPring-8

FAST CORRECTION KICKERS (SPring-8) for Reduction of Hori. and Vert. Motion of STORED BEAM at Injection

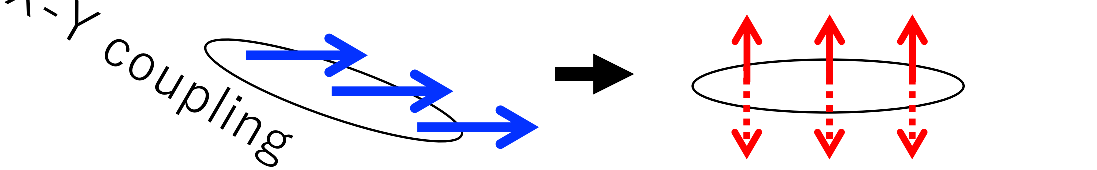
-> Saturation of Feedback : lower gain -> **Instability** ↑

Horizontal : Bump orbit is not closed => Large Oscillation



Fast Horizontal Kicker #

Vertical : local X-Y coupling at Kickers



Fast Vertical Kicker #

C. Mitsuda, K. Fukami, K. Kobayashi, et al., https://accelconf.web.cern.ch/IPAC2014/papers/mopro082.pdf
C. Mitsuda, https://indico.cern.ch/event/635514/contributions/2660454/attachments/1513848/2370449/twiss_2017_v6_pub.pdf

Bump Magnets rotation are optimized with Remotely Controlled Magnet Base* but **Coupling Changes run to run**

*K. Fukami, et al., http://accelconf.web.cern.ch/e08/papers/wepc076.pdf

Simulation / Modeling

Longitudinal Simulation with Harmonic Cavity: the effect of Filling Gap (PSI)

Bunch Train + Gap

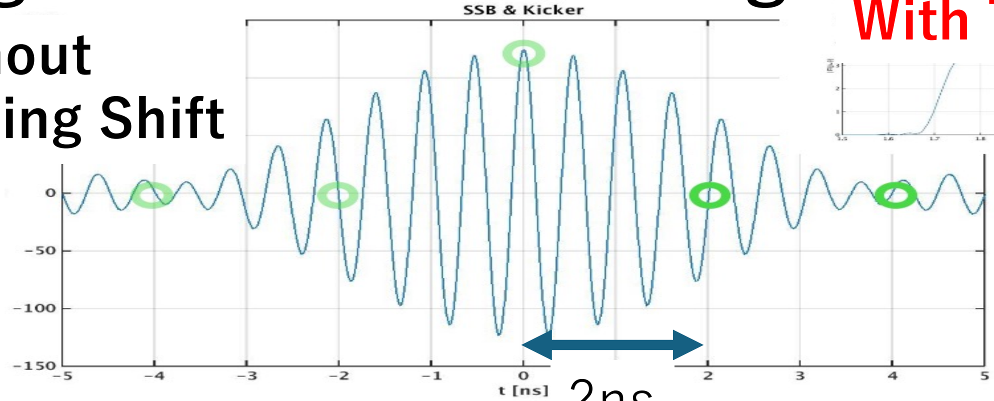
Main Cavity + Harmonic Cavity => Voltage: Amplitude and Phase modulation

=> Synchrotron tune shift : within FIR filter range? => OK

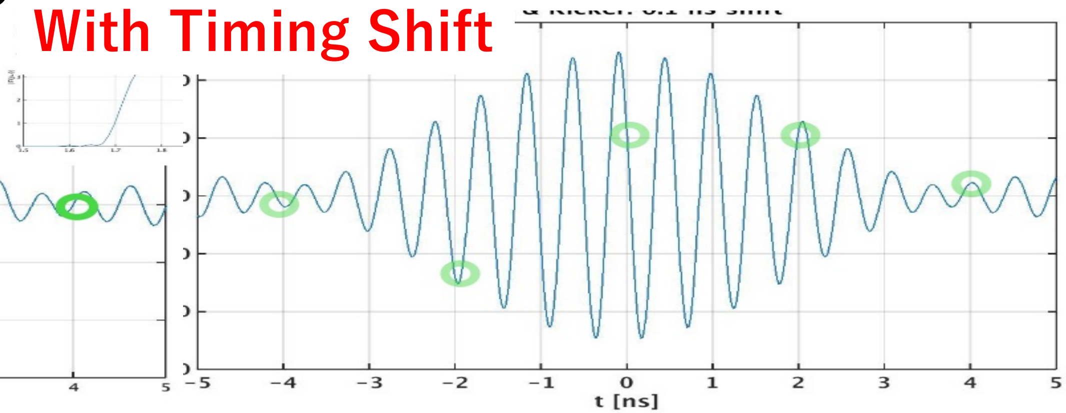
Timing shift : within Front-end acceptance ? => OK

Longitudinal Kicker Voltage

Without Timing Shift



With Timing Shift



all coupled bunch modes => OK

"Basic system for SLS 2.0 shows very satisfying performance, even when taking into account all effects"

https://indico.scc.kit.edu/event/3742/contributions/15196/ SLS

Longitudinal Simulation (DAFNE) for coupled-bunch instability

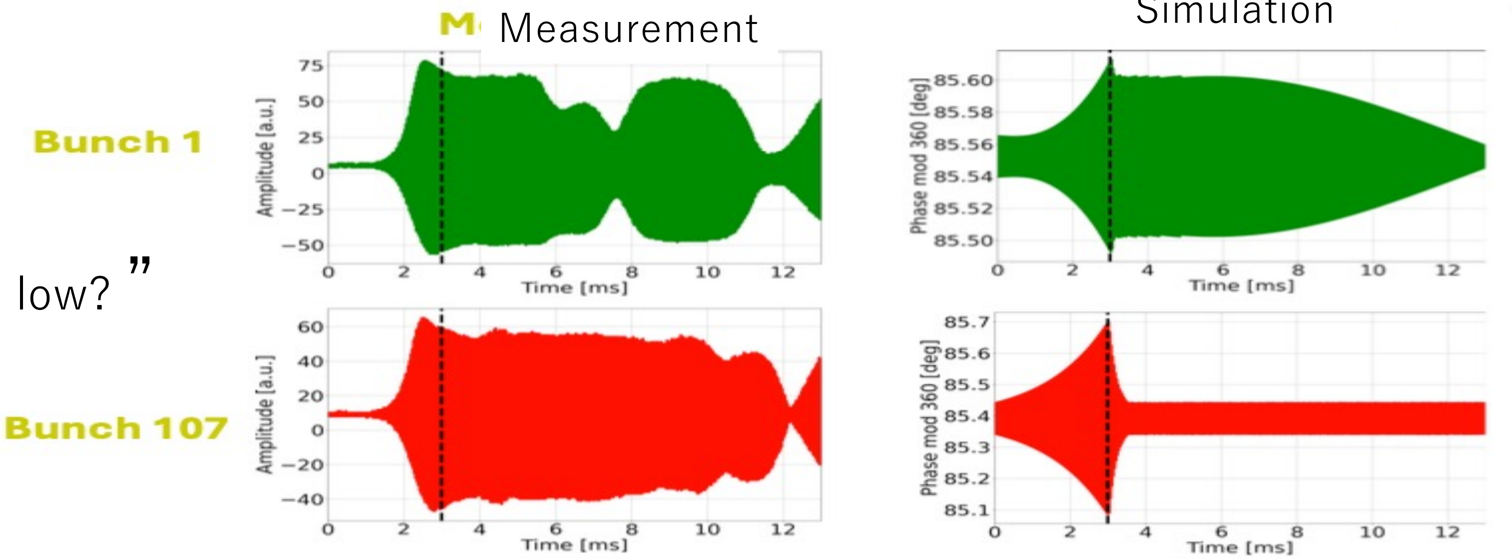
- Cavity response
- Feedback

Analog Front-end (BPM, comb generator)
→ (ADC -> Signal Processing in FPGA -> DAC)
→ Kicker Drive Circuits (SG, QPSK, Drive Signal x DAC (mixer))
→ Cavity Kicker (including beam loading)

Preliminary result

Not damped

“Feedback Gain is too low? ”



https://indico.scc.kit.edu/event/3742/contributions/15423/ DAFNE

Beam Longitudinal Dynamics (BLonD)　(CERN)

(GSI, KIT, KEK, J-PARC, HIAF, Fermilab, Jefferson Lab,..)

written in Python with Object Oriented form with C++/CUDA

Impedance (simulation result, resonators, resistive-wall, constant Im(Z/n))
RF cavity + LLRF + Tuner
RF noise/modulation

Application examples
- Injection
    - Bunch-to-bucket capture
    - Optimization of RF Power
        - detuning, pre-detuning,

https://indico.scc.kit.edu/event/3742/contributions/15644/   CERN

Transverse Simulation for SOLEIL-II

Head-tail Single-bunch instabilities at high bunch current filling

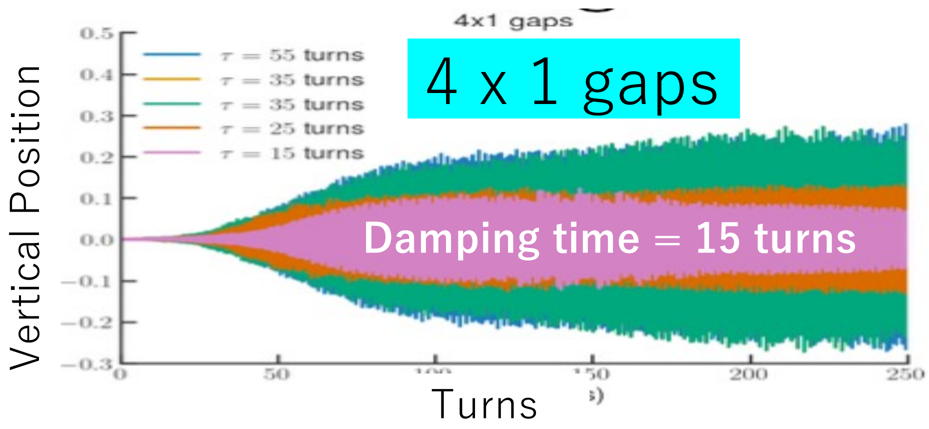
- High Chromaticity ~5 is required => Non-Linear dynamical problem
- Strong feedback damping is necessary
- With Harmonic Cavity : Chromaticity ~ 2 would be OK

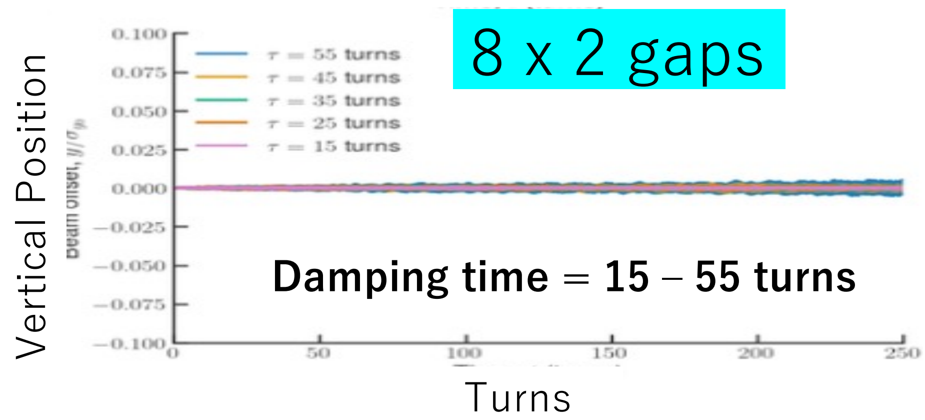
Transverse Coupled-bunch Instability

- High Chromaticity (~10) may cure => Non-Linear dynamical problem
- Feedback System for SOLEIL should be OK

Beam-ion instability

- Increasing number of gaps is Expected to help





https://indico.scc.kit.edu/event/3742/contributions/15195/ SOLEIL

Longitudinal Feedback with Differentiator FIR filter (Dimtel)

Harmonic Cavity + Bunch Train + Gap

=> Wide synchrotron tune spread between bunches

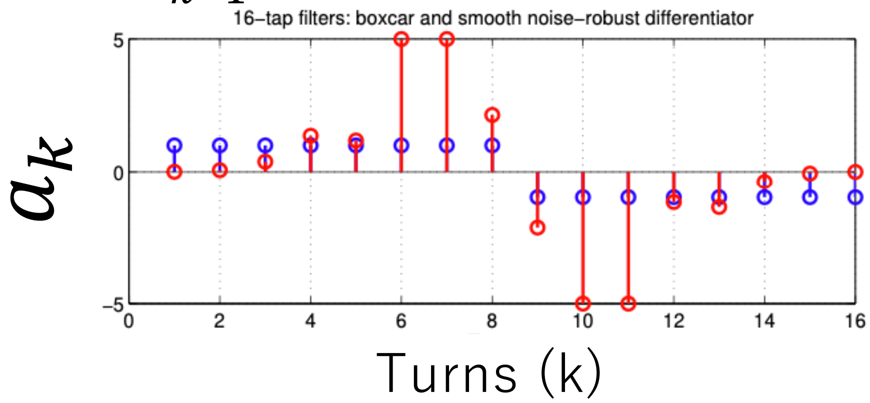
=> **Wide Acceptance of Feedback (FIR Filter)** for synchrotron tune

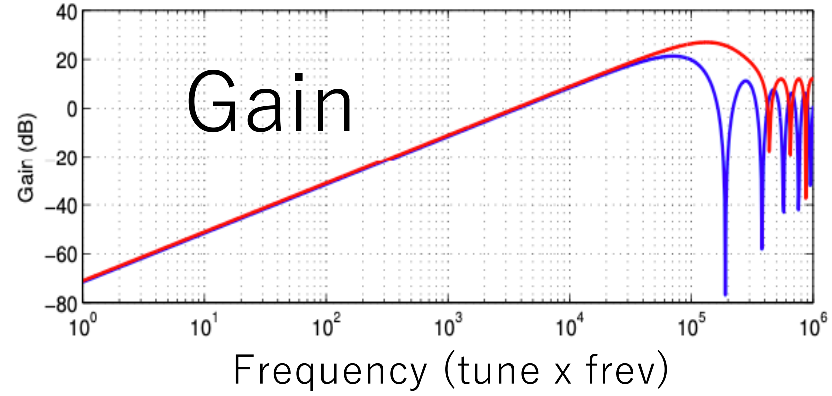
x => dx/dt makes -90 deg at All Freq(tune))

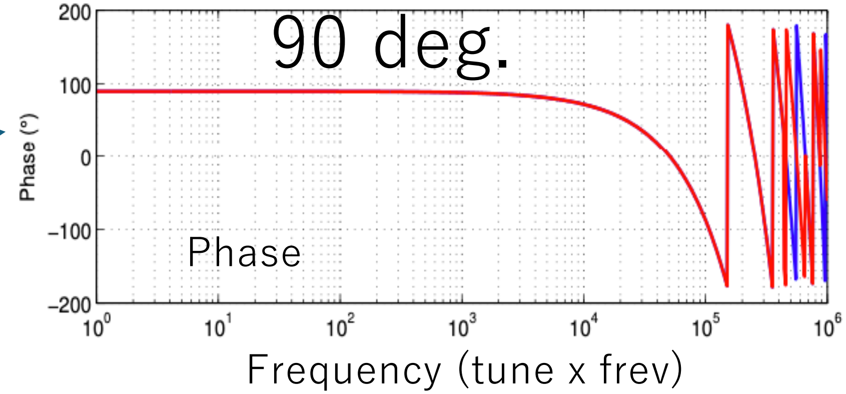
But Gain is proportional to Frequency

FIR filter : Differentiator + Low Pass Filter

$$\sum_{k=1}^{N} a_k \, \boldsymbol{x_n(t_i - kT_0)} = \boldsymbol{\theta_n(t_i)}$$





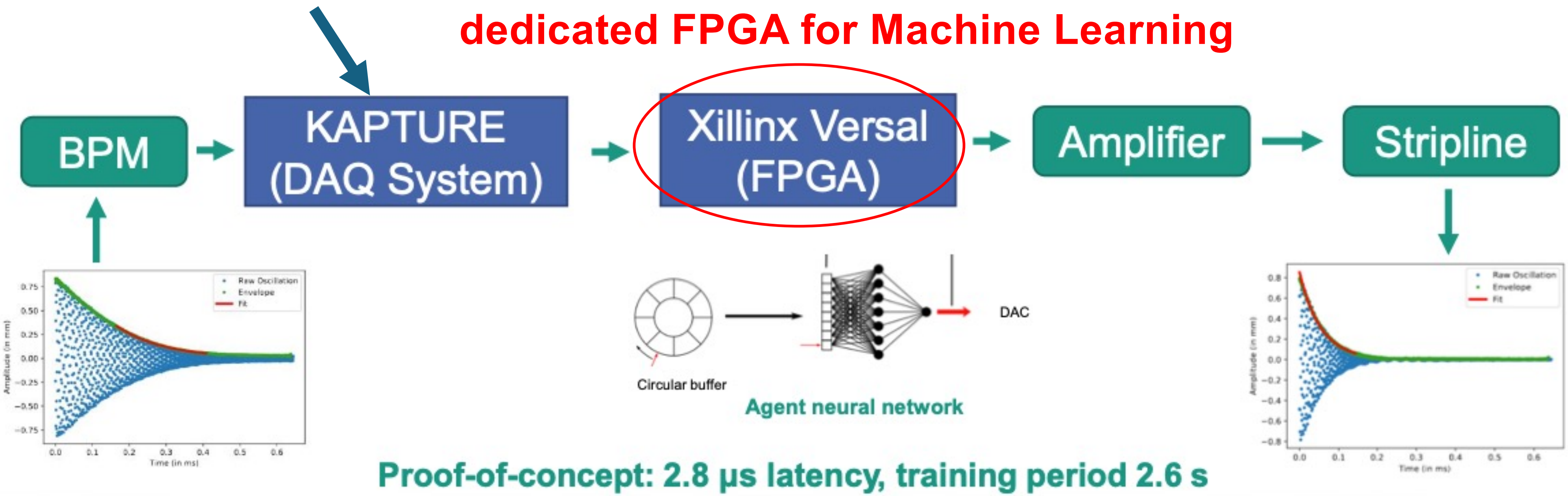


https://indico.scc.kit.edu/event/3742/contributions/15191/ Dimtel

Proposal of Optimization of feedback response with Machine Learning (KARA)

Training of AI (reinforcement learning)?

Karlsruhe **P**ulse **T**aking **U**ltra-Fast **R**eadout **E**lectronics



One-shot Kick

https://indico.scc.kit.edu/event/3742/contributions/15188/ KARA

OtherTopics

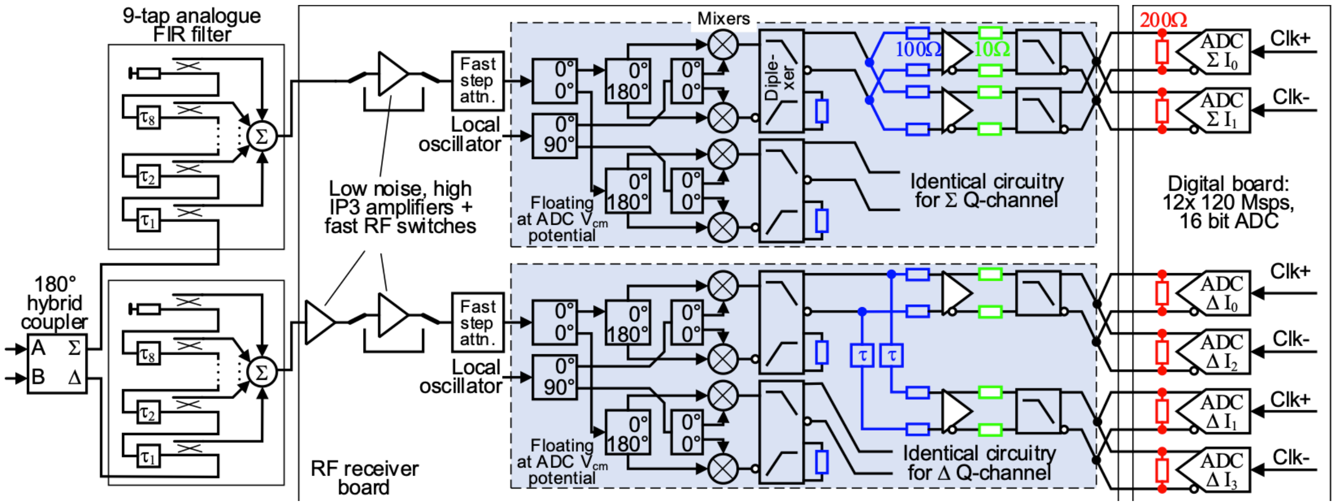
- LHC

  25ns Bunch spacing with 400MHz RF (40MHz bunch rate)
  Bunch length 1 – 1.5 ns
  1-2e11 protons/bunch （1e9 protons/pilot bunch)
  450 GeV => 7 TeV
  Filling 20min => energy ramping 20-40min => physics 12-18 hours

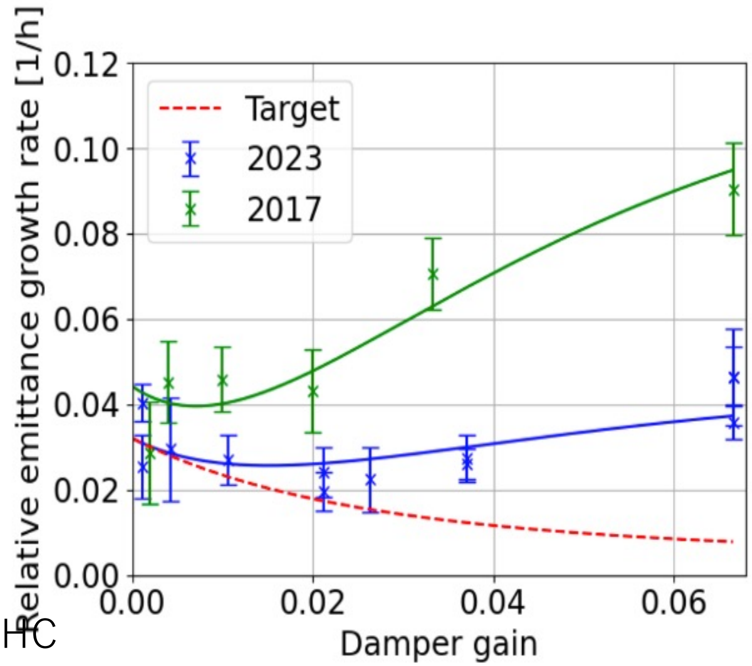
Emittance growth by Transverse Feedback Noise

Low noise Beam Position Monitor Front-end

New Generation, Very Low Noise BPM System for High Lumi LHC



https://indico.scc.kit.edu/event/3742/contributions/15394/ LHC



LHC

Electric field Kicker

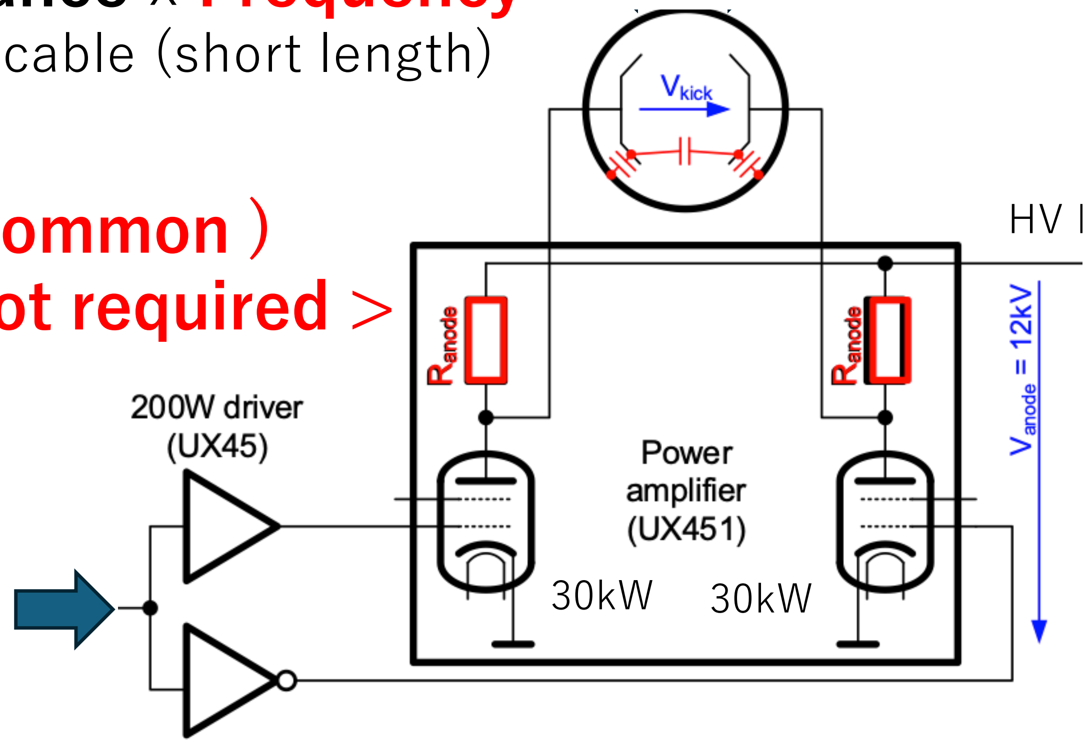
Strong Kick is necessary
Relatively low frequency < 20MHz

Drive current $\propto$ Kicker Capacitance x **Frequency**

Capacitance : Kicker electrode + cable (short length)

Much Less Power than
Stripline kicker (most common)
< high frequency is not required >

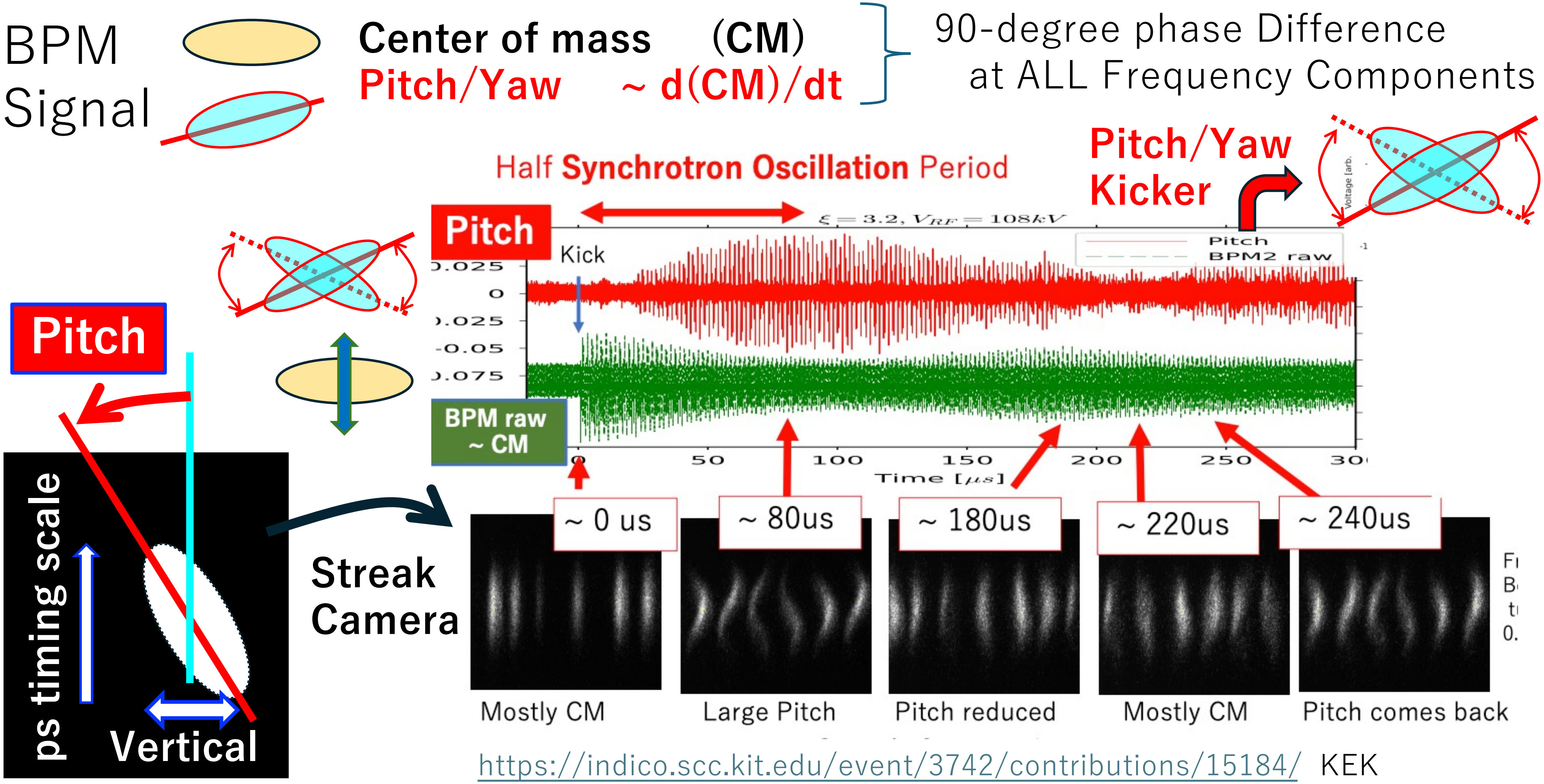
Kick signal from
Feedback processor



https://indico.scc.kit.edu/event/3742/contributions/15394/ LHC

Bunch Pitch/Yaw Monitor Development and Proposal of its Feedback (KEK)

USUAL button type BPM + SIMPLE Circuit of ~1.5GHz band



https://indico.scc.kit.edu/event/3742/contributions/15184/ KEK

Beam Study at KARA
Collaboration of Workshop Attendants

Beam Study : Collaboration of Workshop Attendants at KARA and Booster at KIT

- **Establishment of Common Procedure of Commissioning of Feedback**
- **Emittance Control by Sideband resonant excitation (tune tracking)**
- **Longitudinal Feedback with Stripline Kicker at KARA Booster (53MeV)**

Stripline (L=15cm) as "Drift tube" : worked

250MHz carrier kick: 4ns spacing bunches (Transverse BBF amp)
1.5 GHz carrier kick : 2ns spacing bunches (Longitudinal BBF amp)

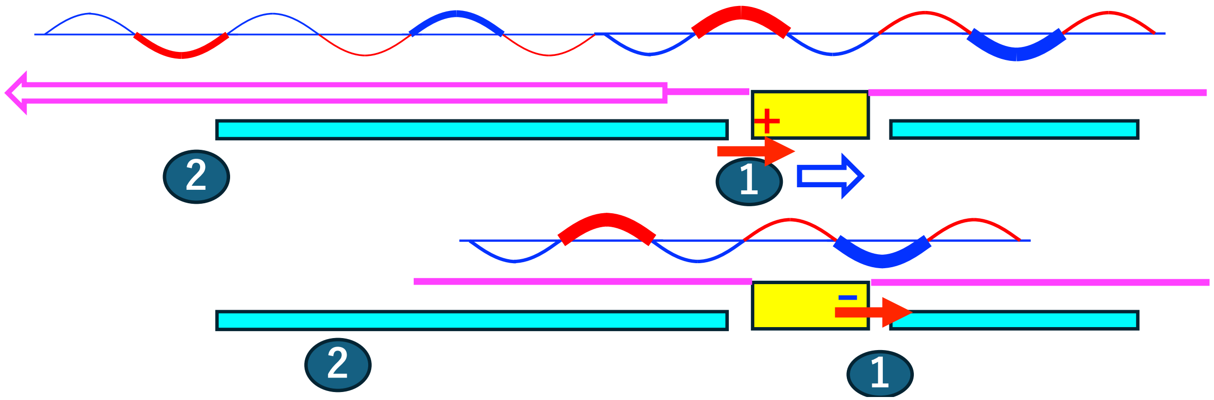
Horizontal Kick at Dispersion => Change of Circumference : worked

Same as Horizontal Feedback (f < 250MHz)
FIR filter phase change
timing monitoring -> timing kick
High Gain required

Dispersion   Kick

$$\Delta C = c_0 \tau = \eta\,\theta$$

1.5 GHz



Summary

I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics

Variety of applications / analysis of bunch-by-bunch feedback

- Damping
  - Cure and Study of beam instabilities
- Anti-Damping
  - Landau Damping Measurement
- Excitation
  - Tune Measurement
  - Bunch Cleaning
  - Tune Tracking Excitation
  - Emittance Control（center of mass，head-tail mode.. ）
- Data taking
  - Bunch-by-bunch, turn-by-turn
- Digital Processing Hardware / Scheme
  - RFSoC, FIR filters, …
- Instrumentation，Theory，Simulation, new scheme, …

Thanks for the participants and organizers of the workshop