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

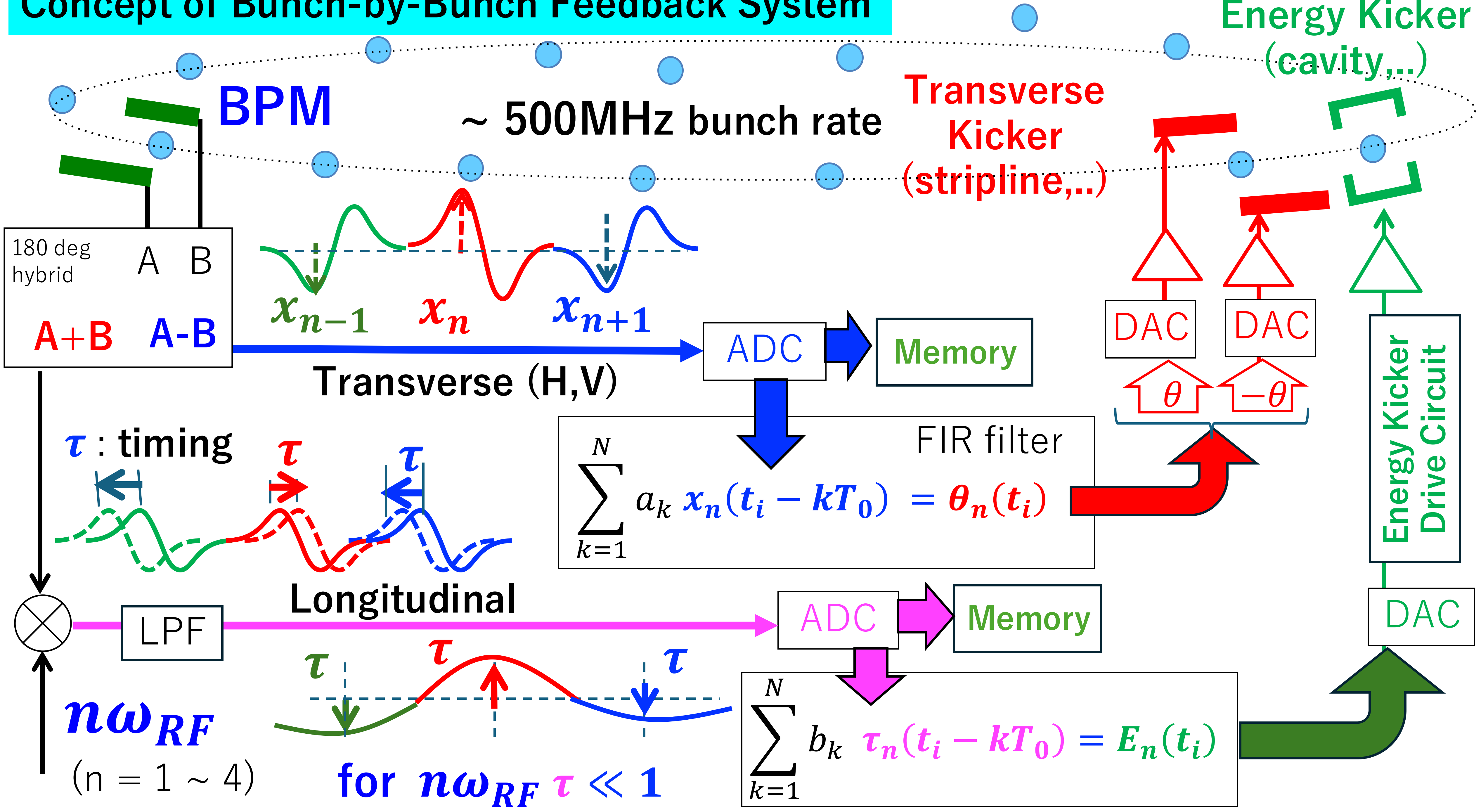
in Bunch-by-bunch base

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

Measurement of Beam Motion:

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

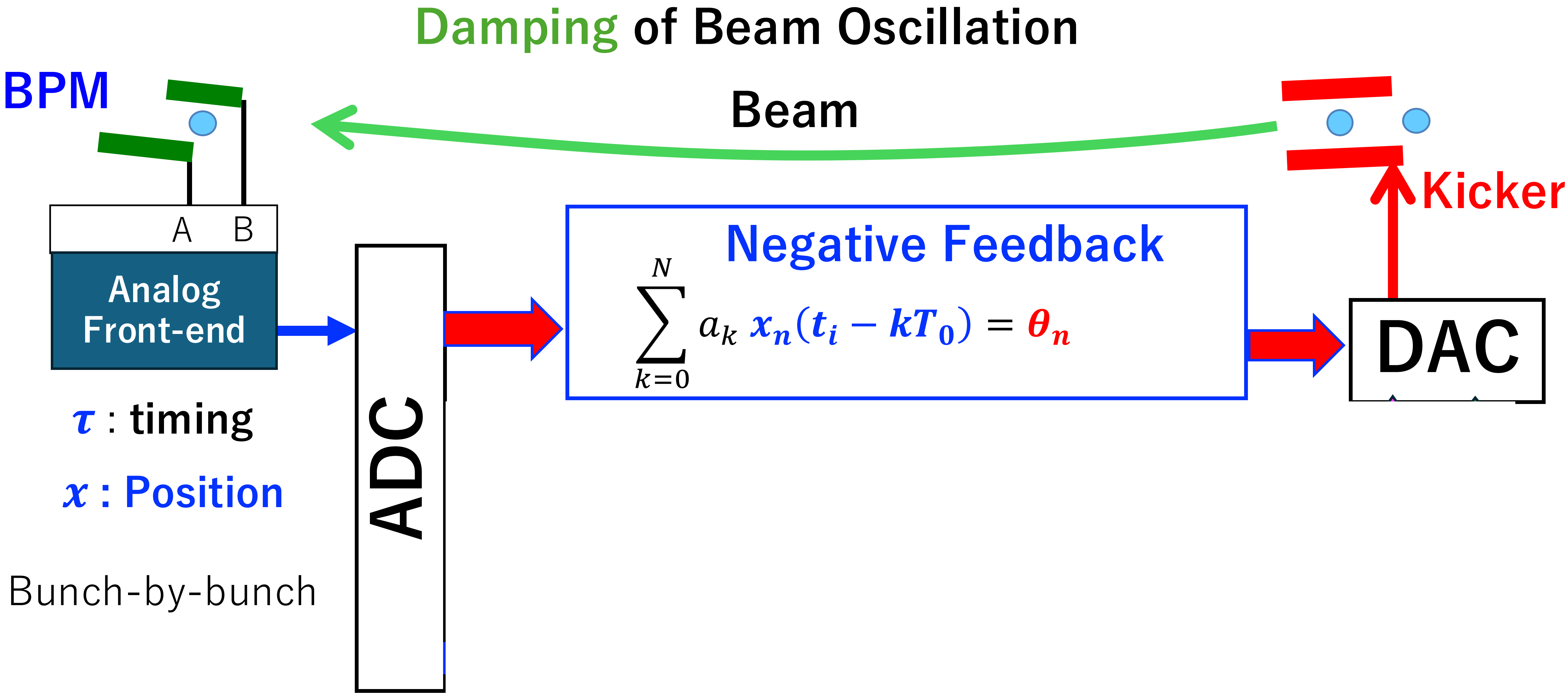
Concept of Bunch-by-Bunch Feedback System



What is **Bunch by bunch feedback ?**

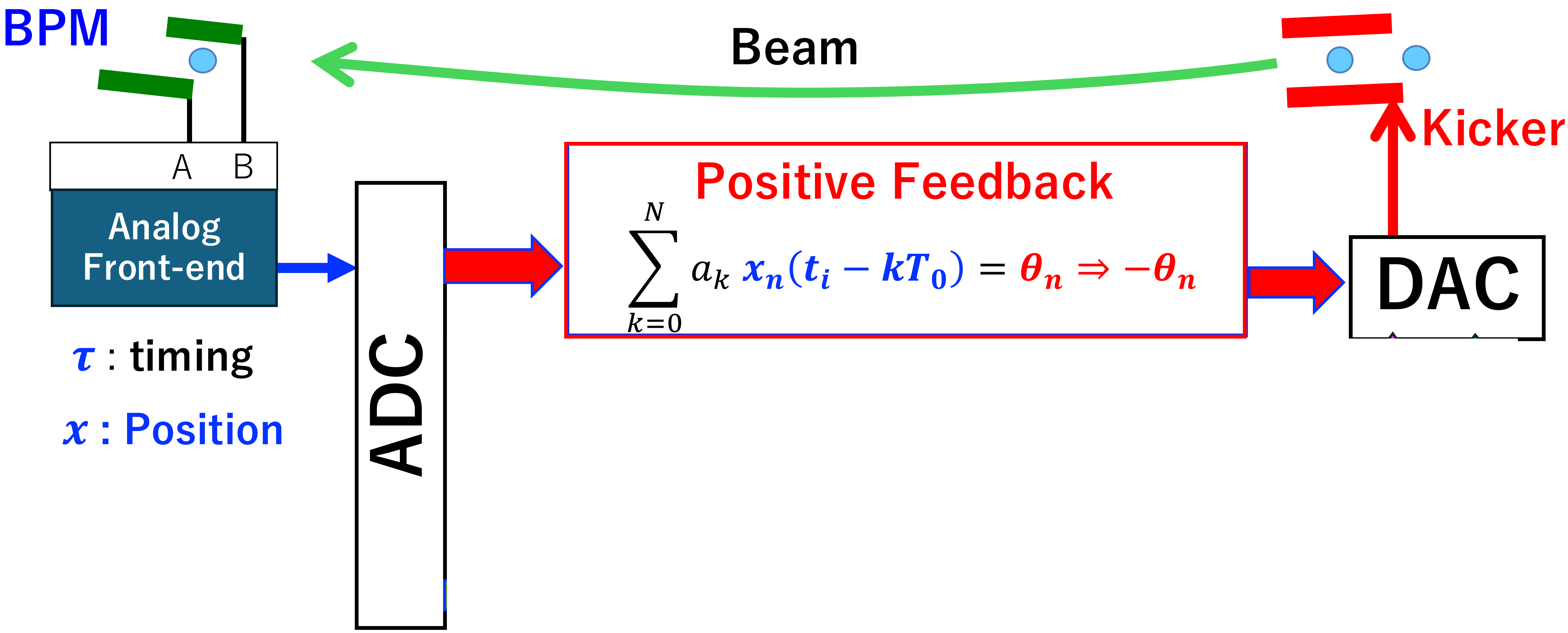
Control : Damping, Anti-Damping, Excitation, ..

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



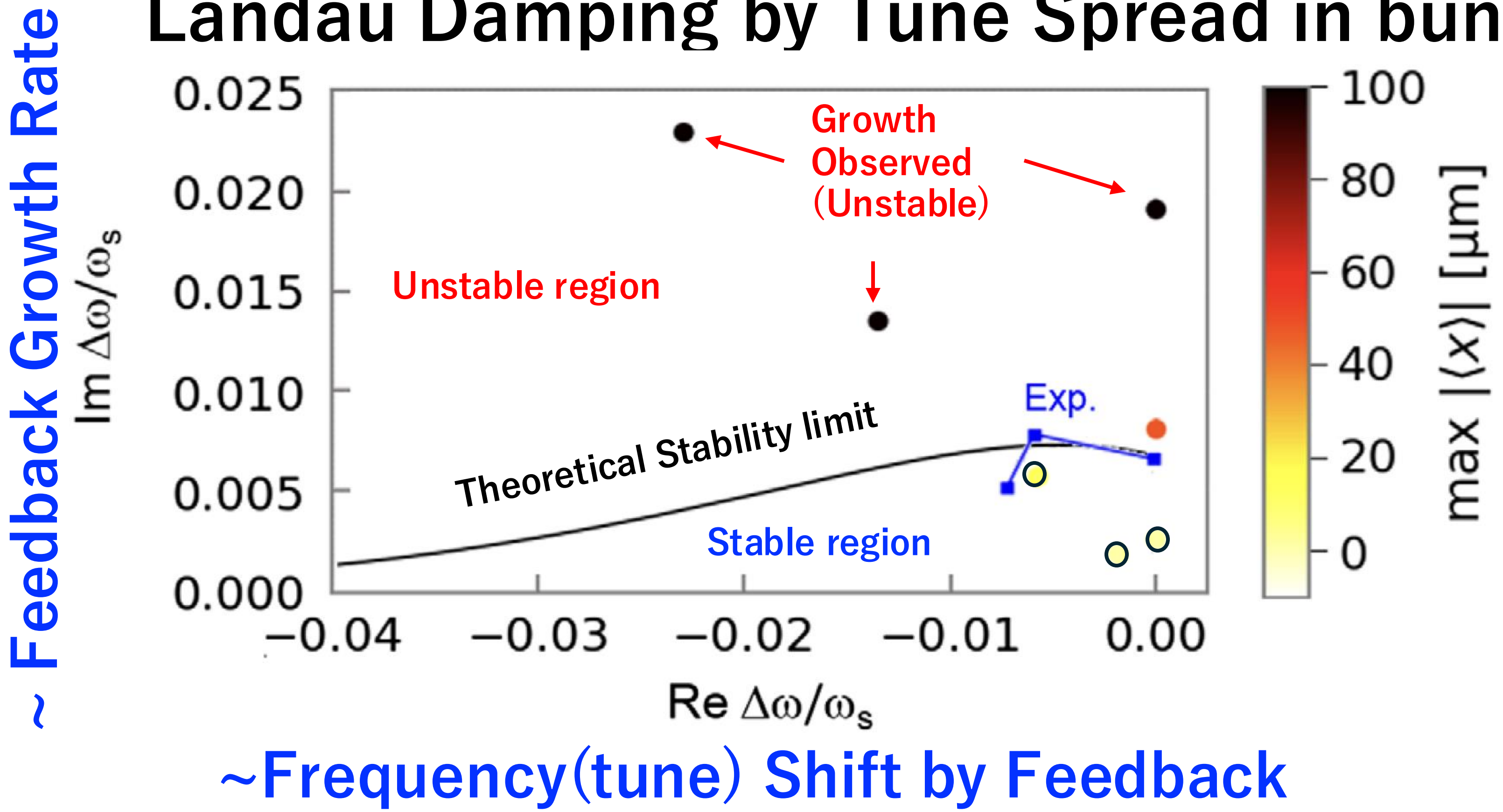
Anti-Damping (Positive Feedback)

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

＝ simulates Instability

Direct Landau Damping measurement (LHC)

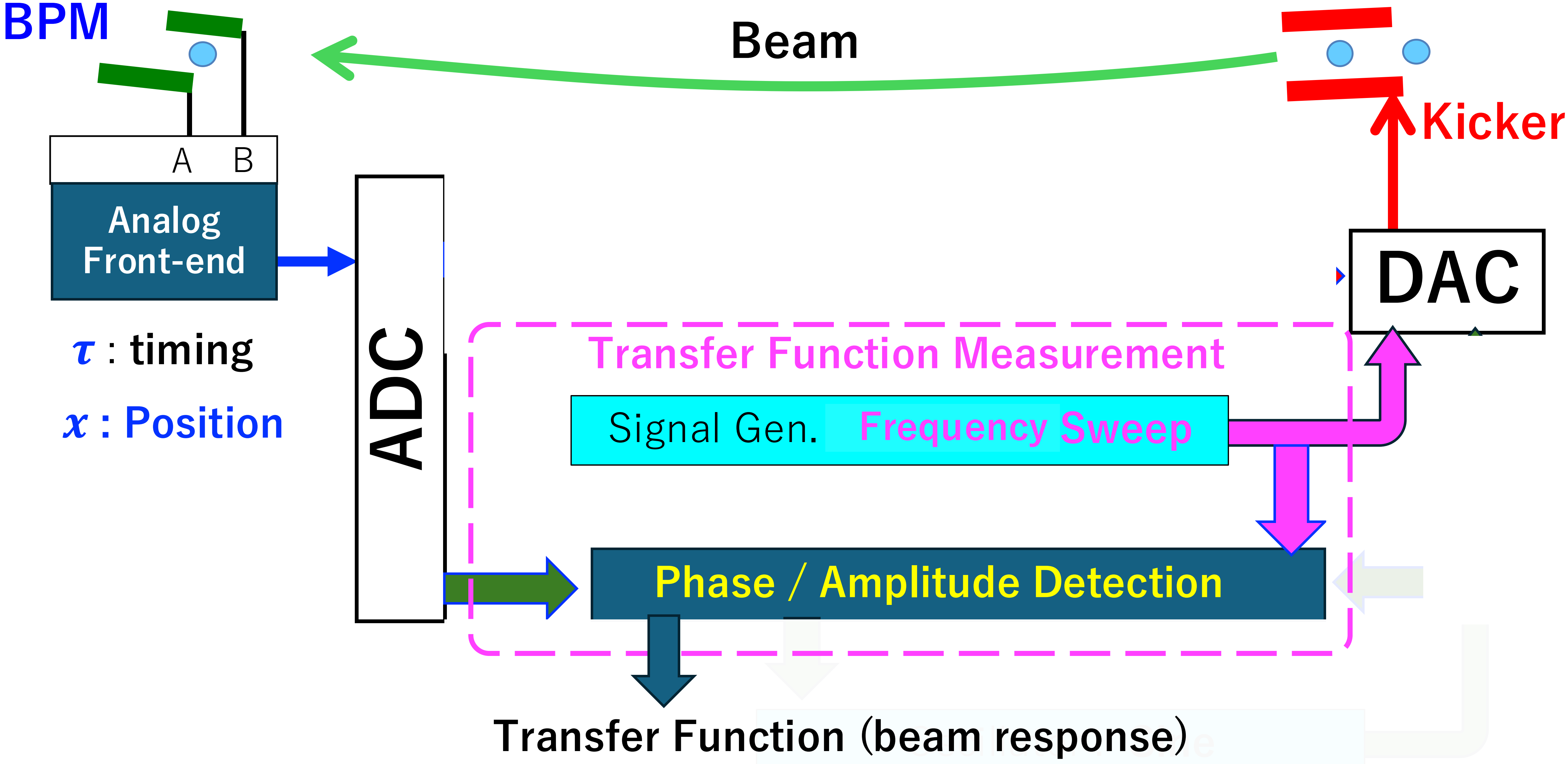
Landau Damping by Tune Spread in bunch <= Octupole



Comparison with Theoretical Stability Diagram

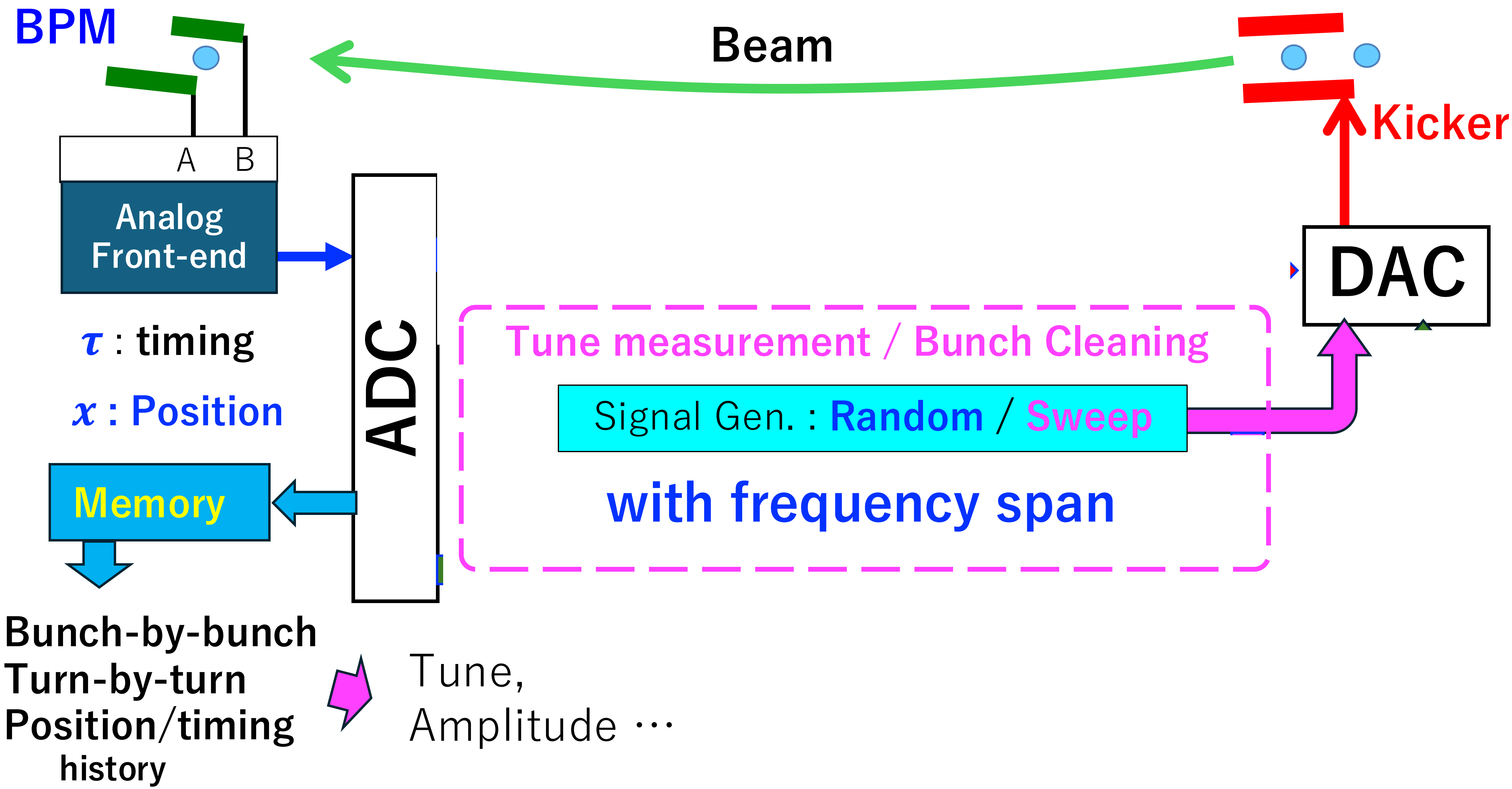
https://indico.scc.kit.edu/event/3742/contributions/15394/ LHC

Excitation (Transfer function) of Beam Oscillation



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

Excitation of Beam Oscillation



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 Vertical 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**

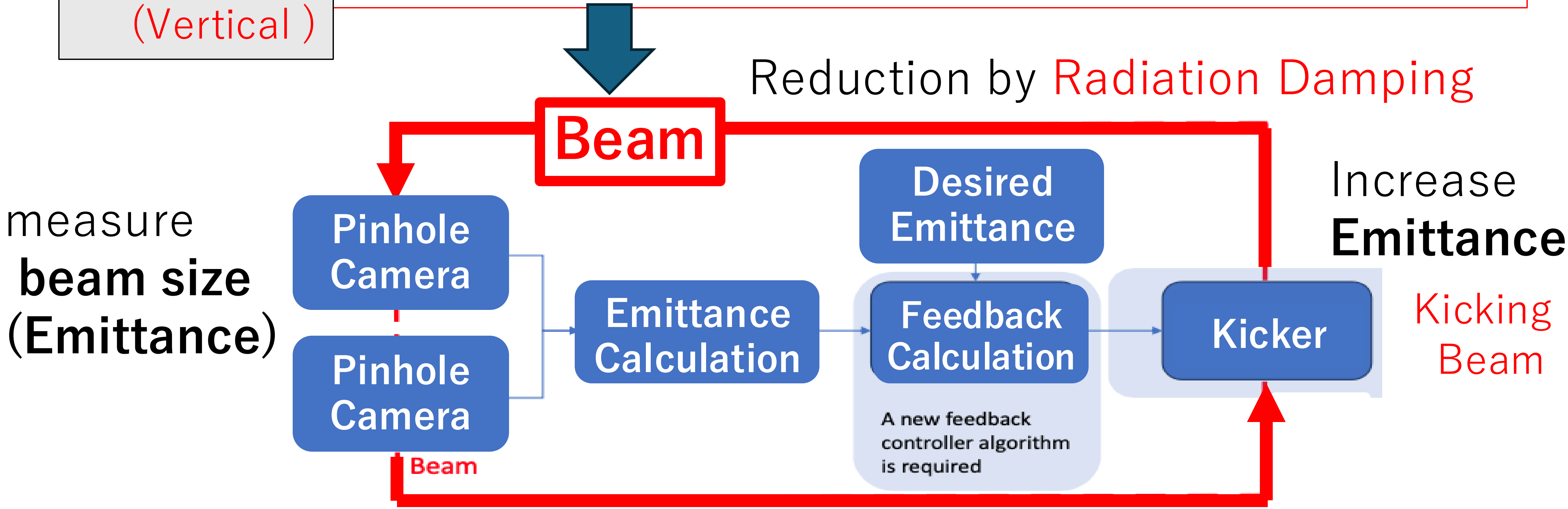
  Coupling measurement : V-emittance / (excited H-emittance) (SOLEIL)
- Smaller effect to Off-Axis Injected Beam (DIAMOND)
- Applicable for Ultra-Low Horizontal Emittance beam

  < but Beam size fluctuation is smaller with Skew Q (SOLEIL) >

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

Emittance Variation Sources (Vertical)

x-y Coupling Strength / Damping time <= ID gap Change
Chromaticity, Tune Shift, Tune Spread, Noise, …

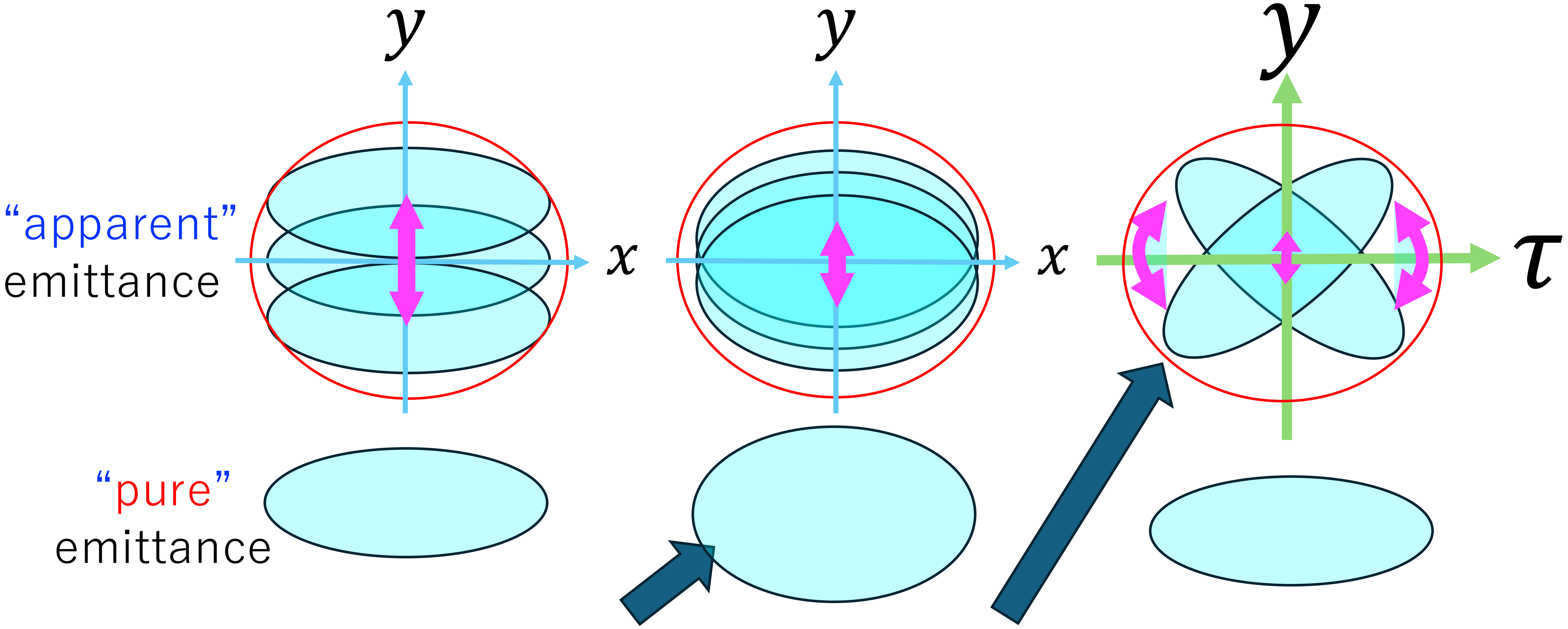


https://indico.scc.kit.edu/event/3742/contributions/15383/ DIAMOND

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

Figure modified from DIAMOND

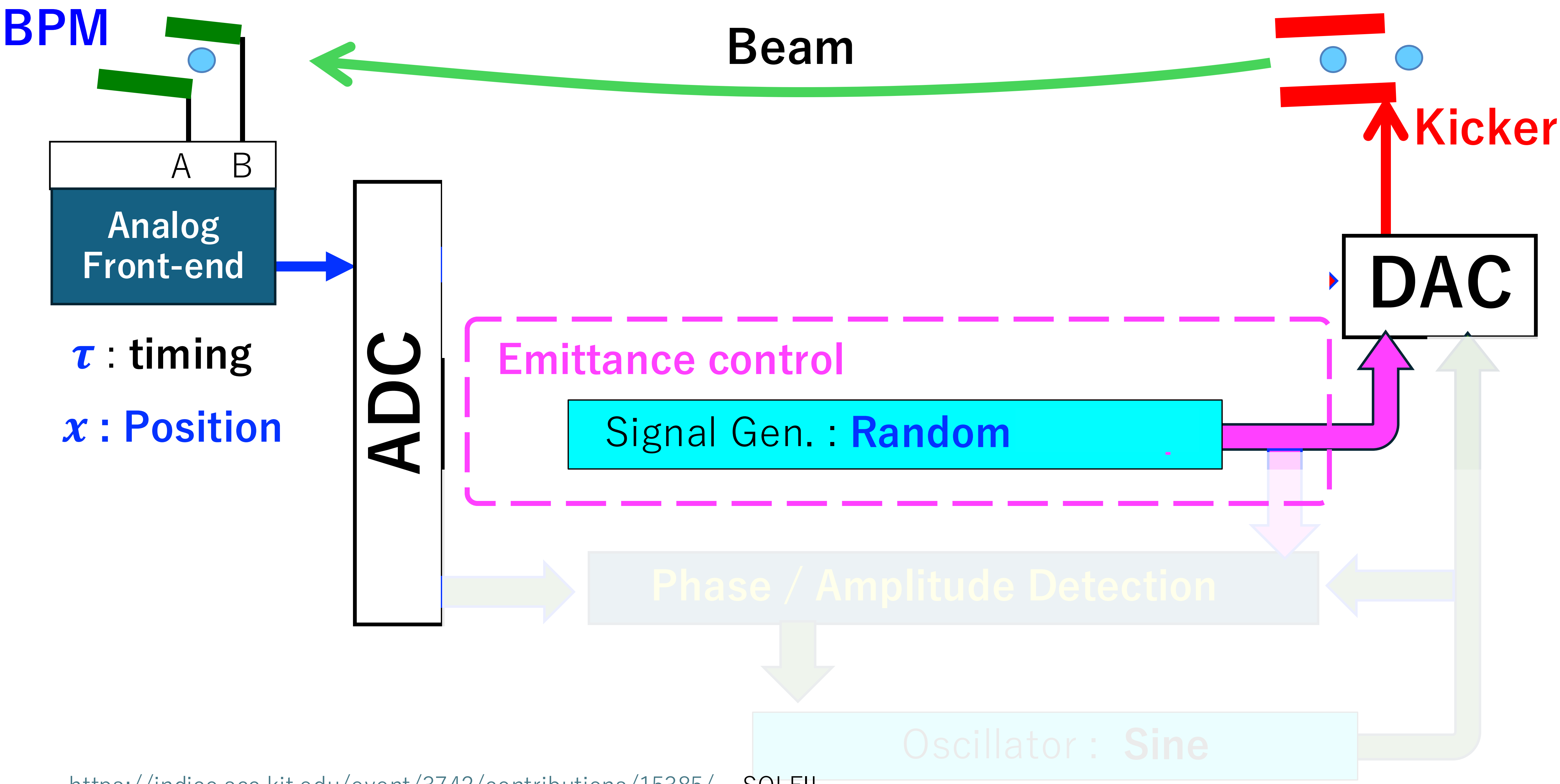
Control of Vertical Beam Size/Emittance (SOLEIL, DIAMOND)



Preferred by Users and lifetime

Preferred by Users (Small CM motion)

Control of Vertical Emittance by Random Kick (SOLEIL)



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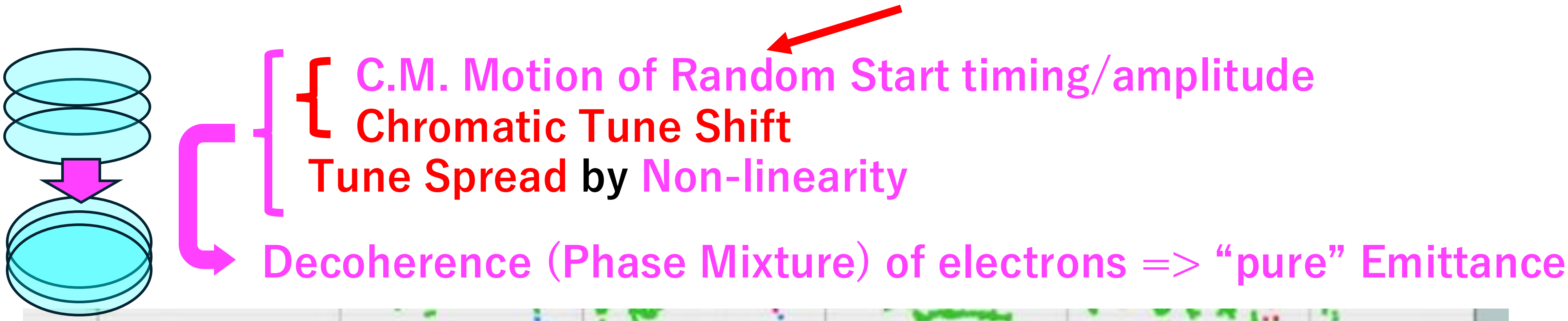

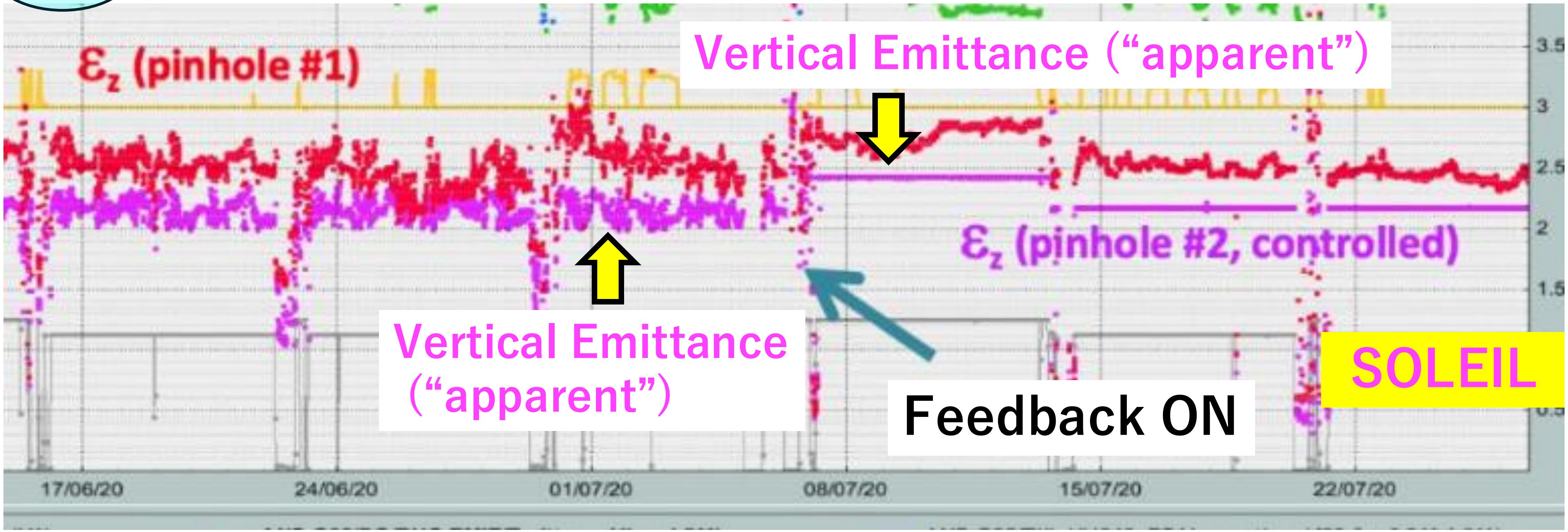

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Control of Vertical Emittance by Random Kick (SOLEIL)

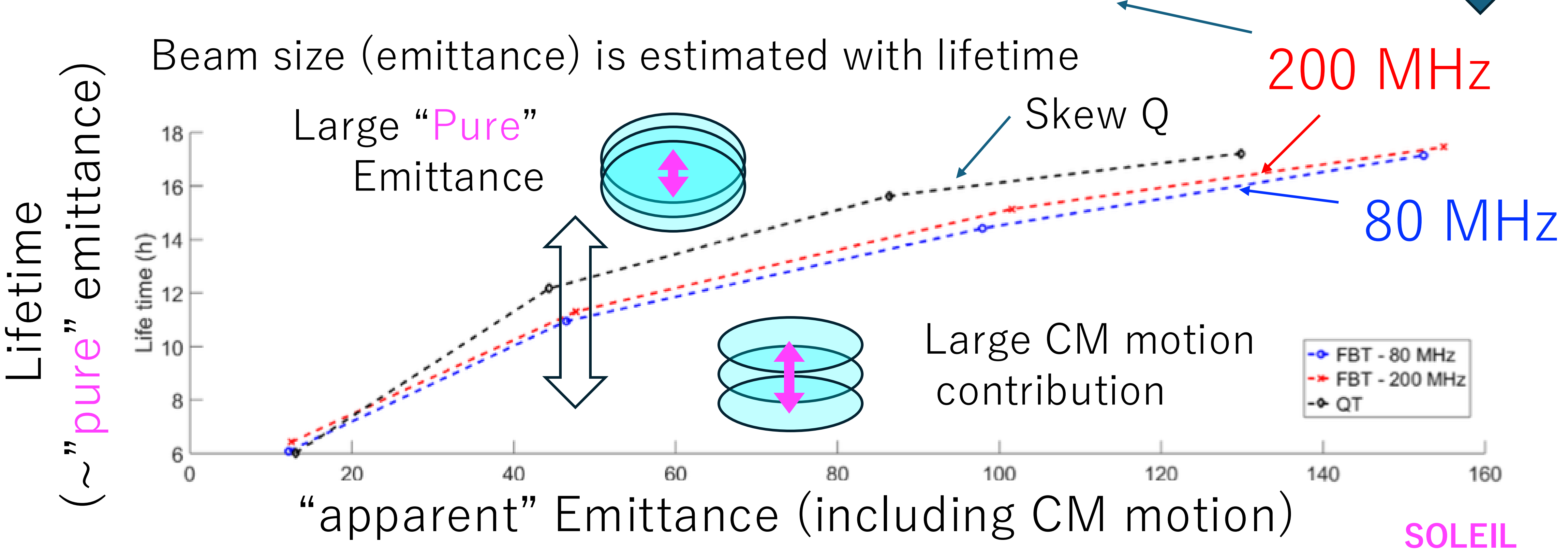
White Noise kick (Random Kick)

Wide Bandwidth (~200MHz) is better :

*** Larger ratio : "Pure" emittance / Center of Mass Motion**

*** Smaller Emittance Jitter (under beam size feedback)**

Beam size (emittance) is estimated with lifetime



SOLEIL

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

Control of Vertical Emittance

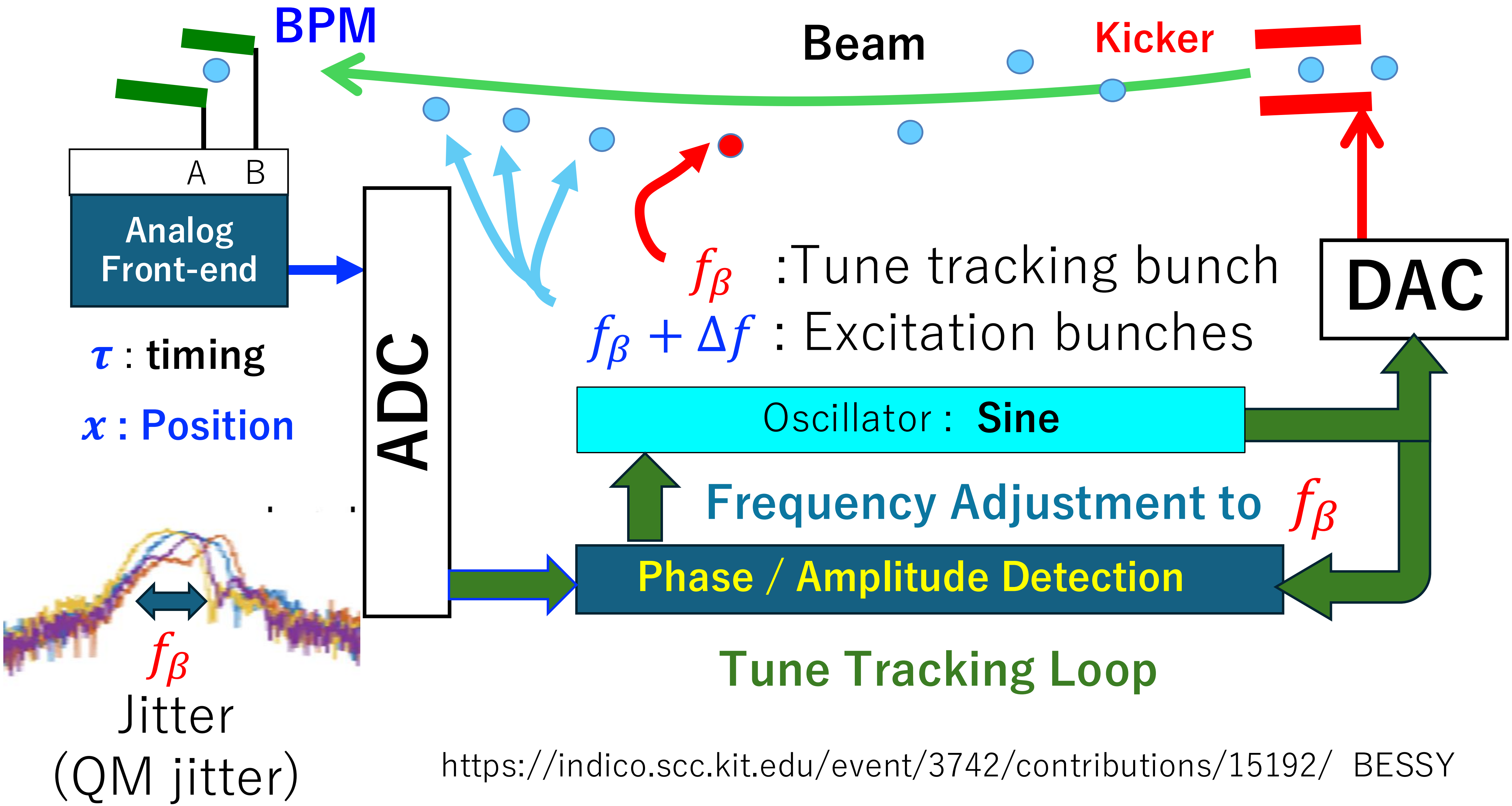
Resonant Excitation at Synchrotron sideband of Betatron peak

BESSY-II, DIAMOND

Before this

Tune Tracking Beam Response Measurement (BESSY)

Tune Tracking Beam Response Measurement (BESSY)



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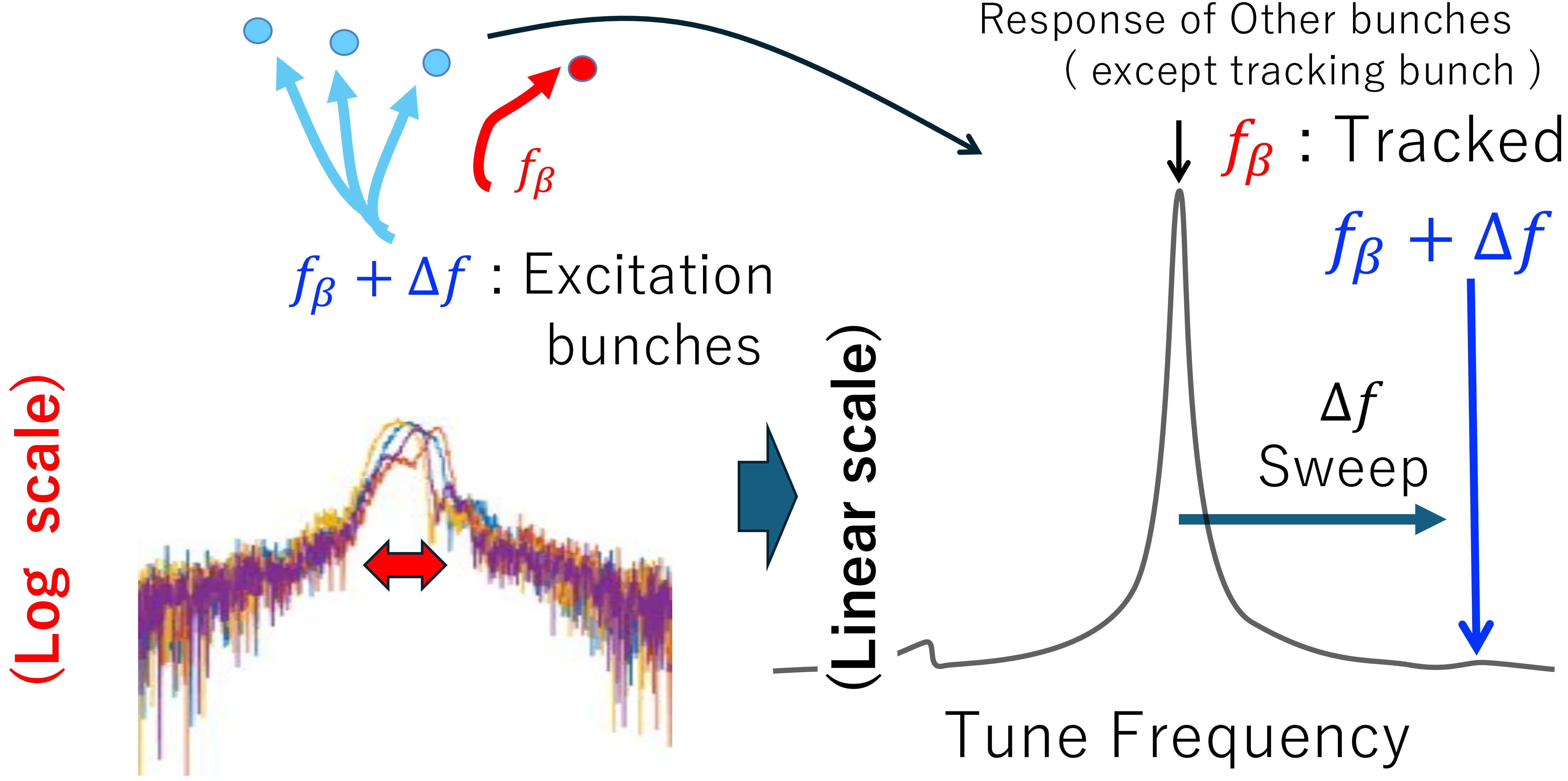
Tune Tracking Beam Response Measurement (BESSY)



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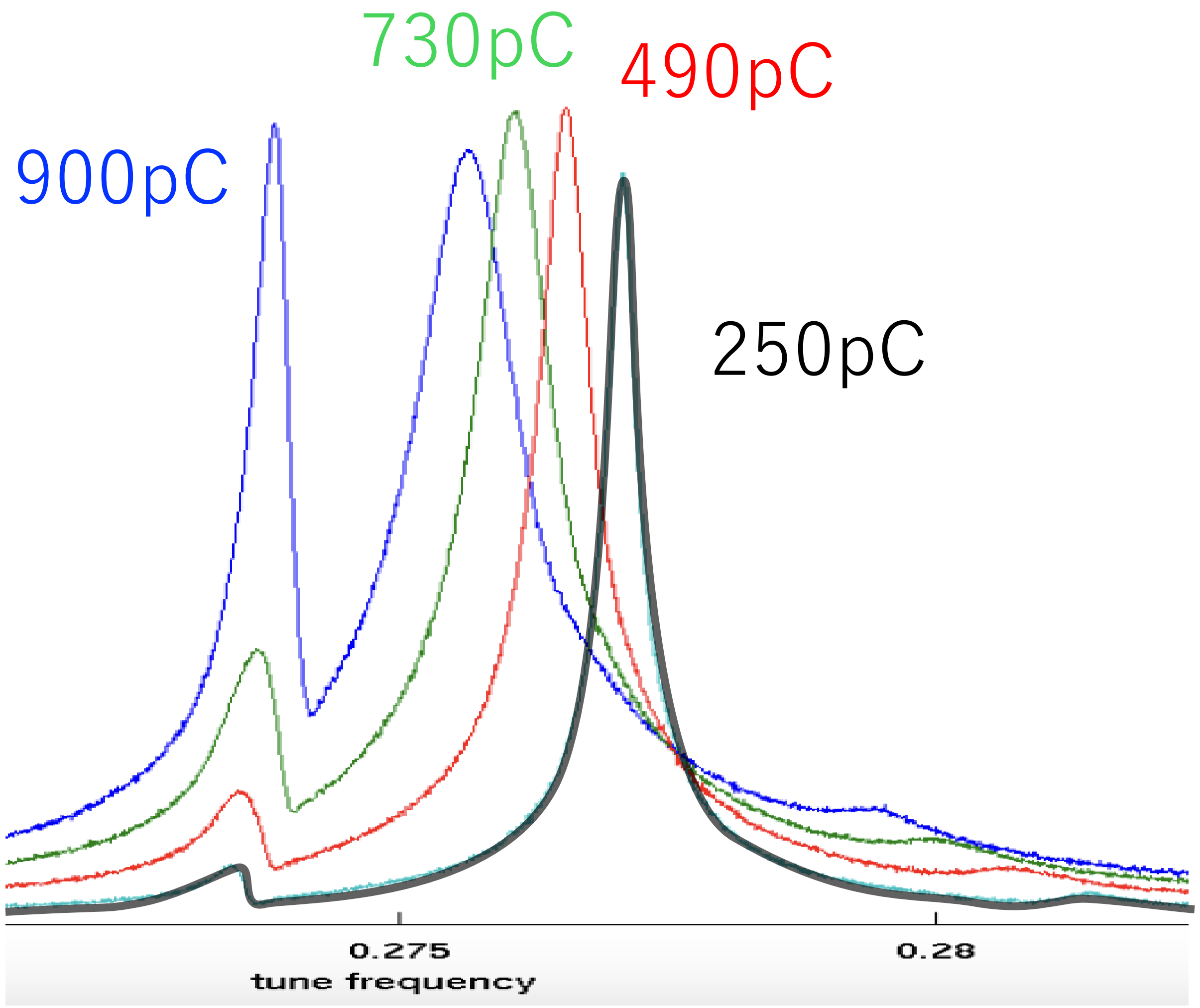
Tune Tracking Beam Response Measurement (BESSY)

Tune Tracking
+
Exciting Shifted Frequency



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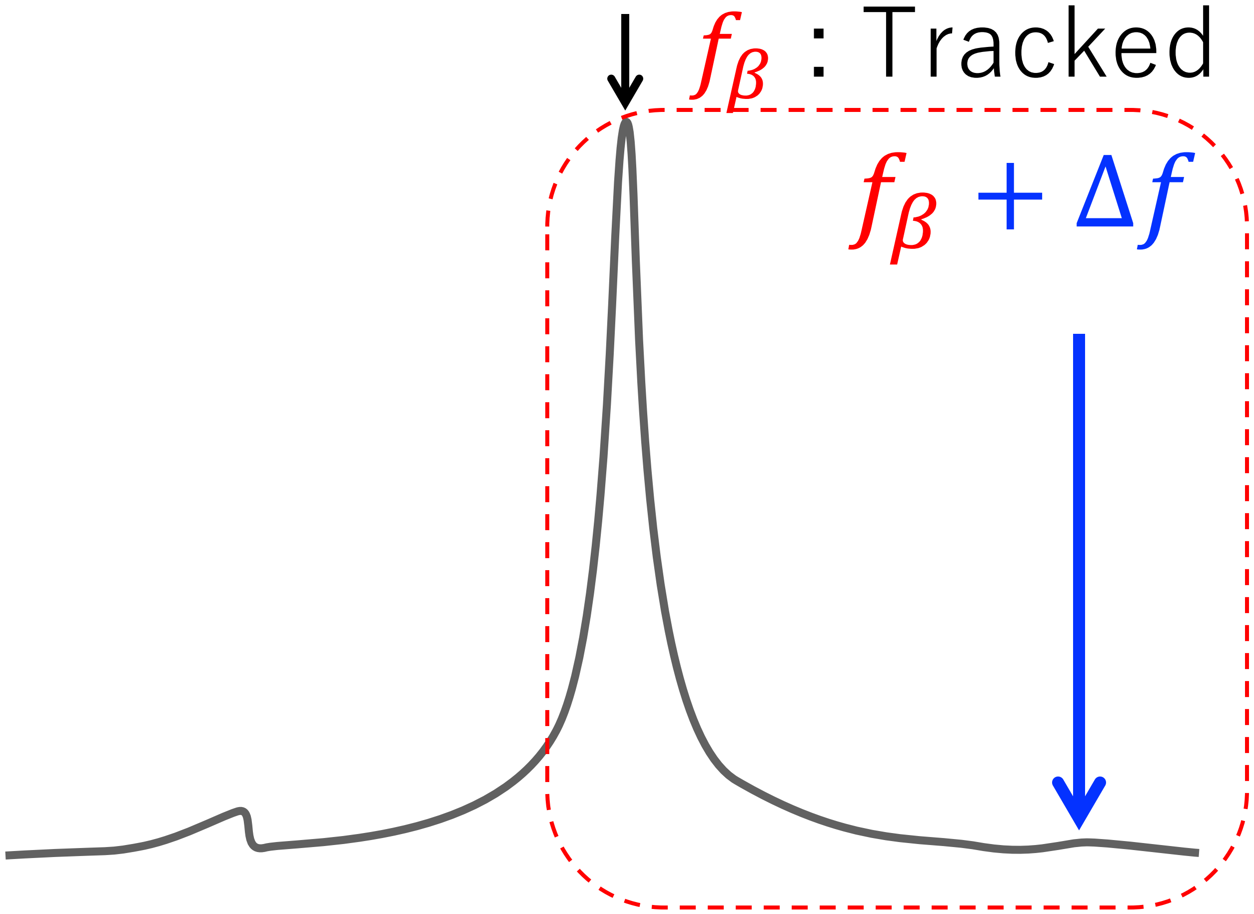
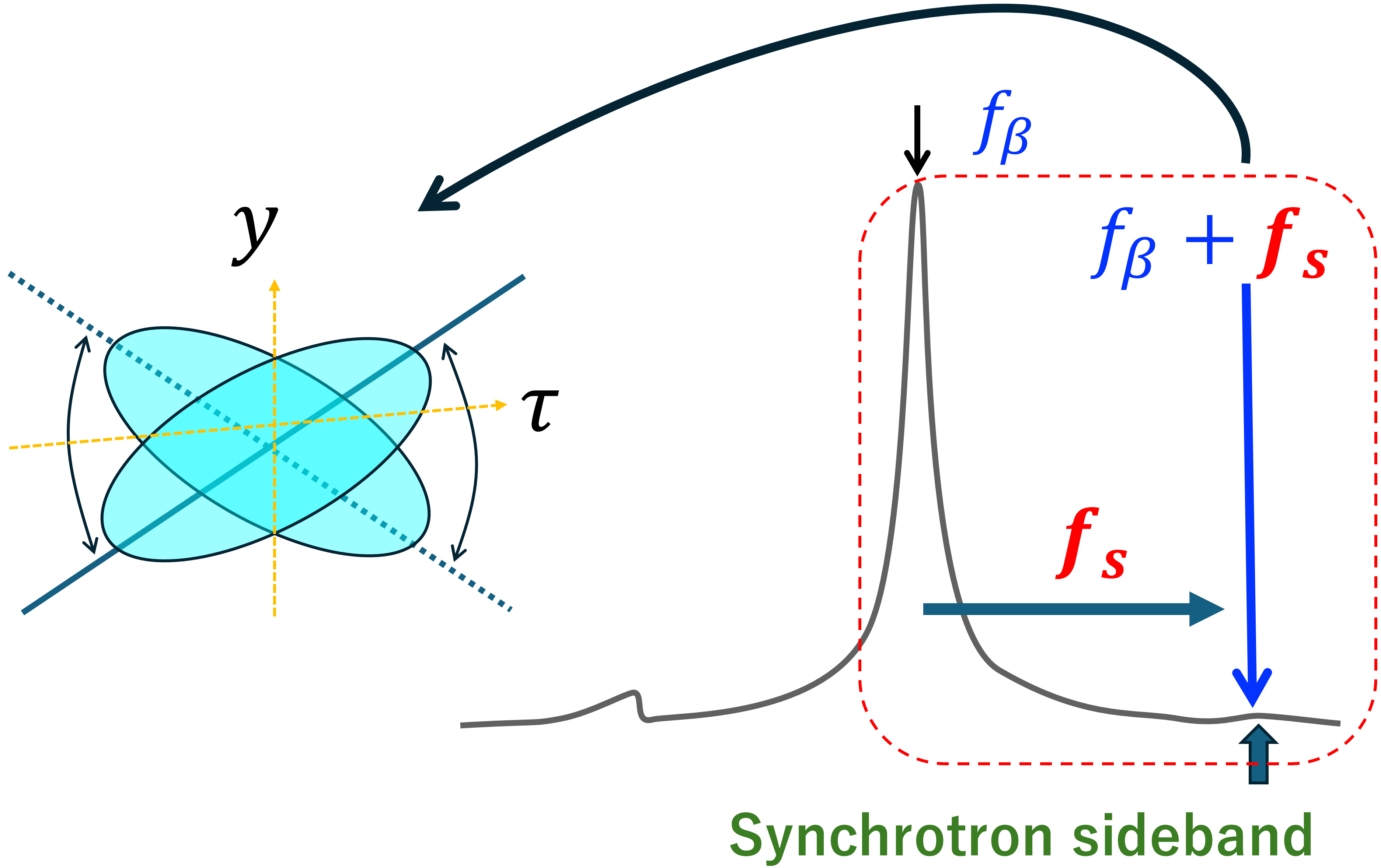


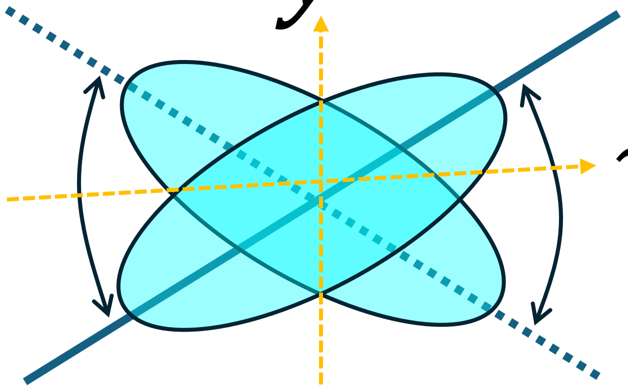
https://indico.scc.kit.edu/event/3742/contributions/15192/ BESSY

Resonant Excitation at Synchrotron sideband of Betatron peak



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

Resonant Excitation at Synchrotron sideband of Betatron peak



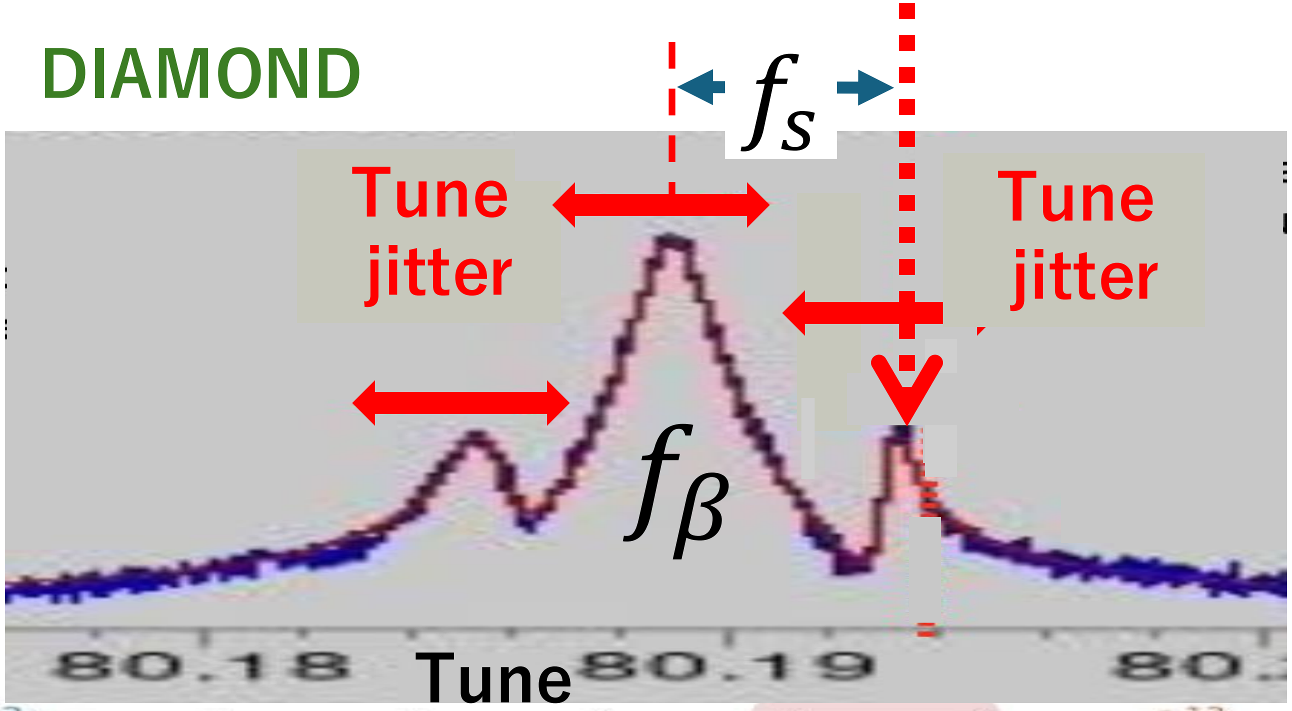
Stronger kick is necessary

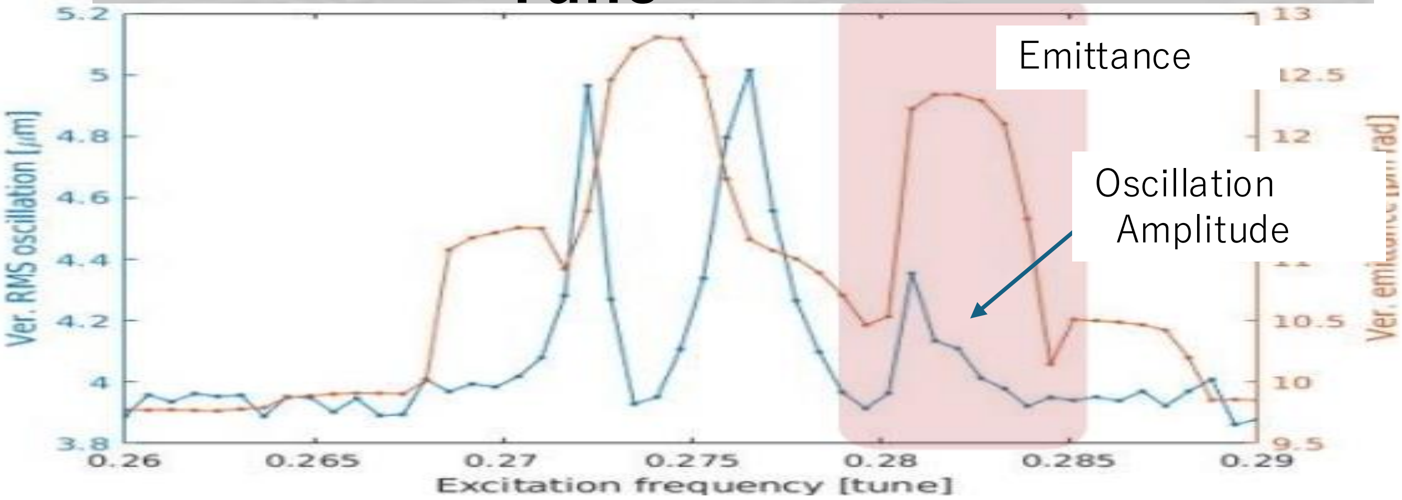
Resonant Excitation with Tune Tracking

||

(On-Resonance Excitation)

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)

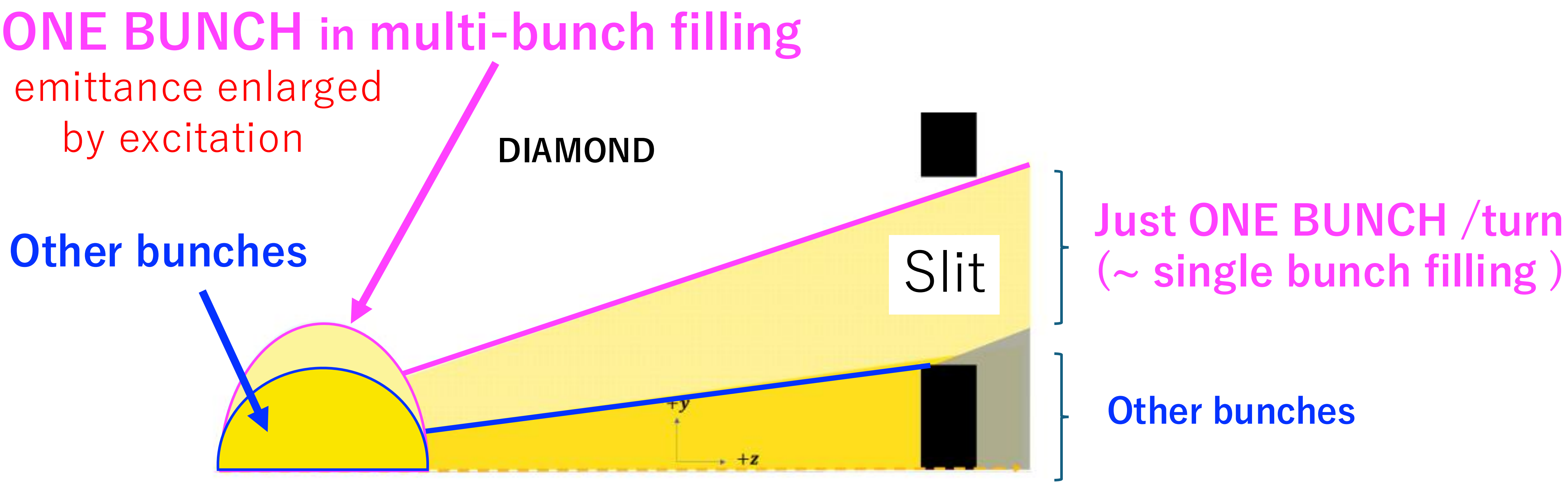
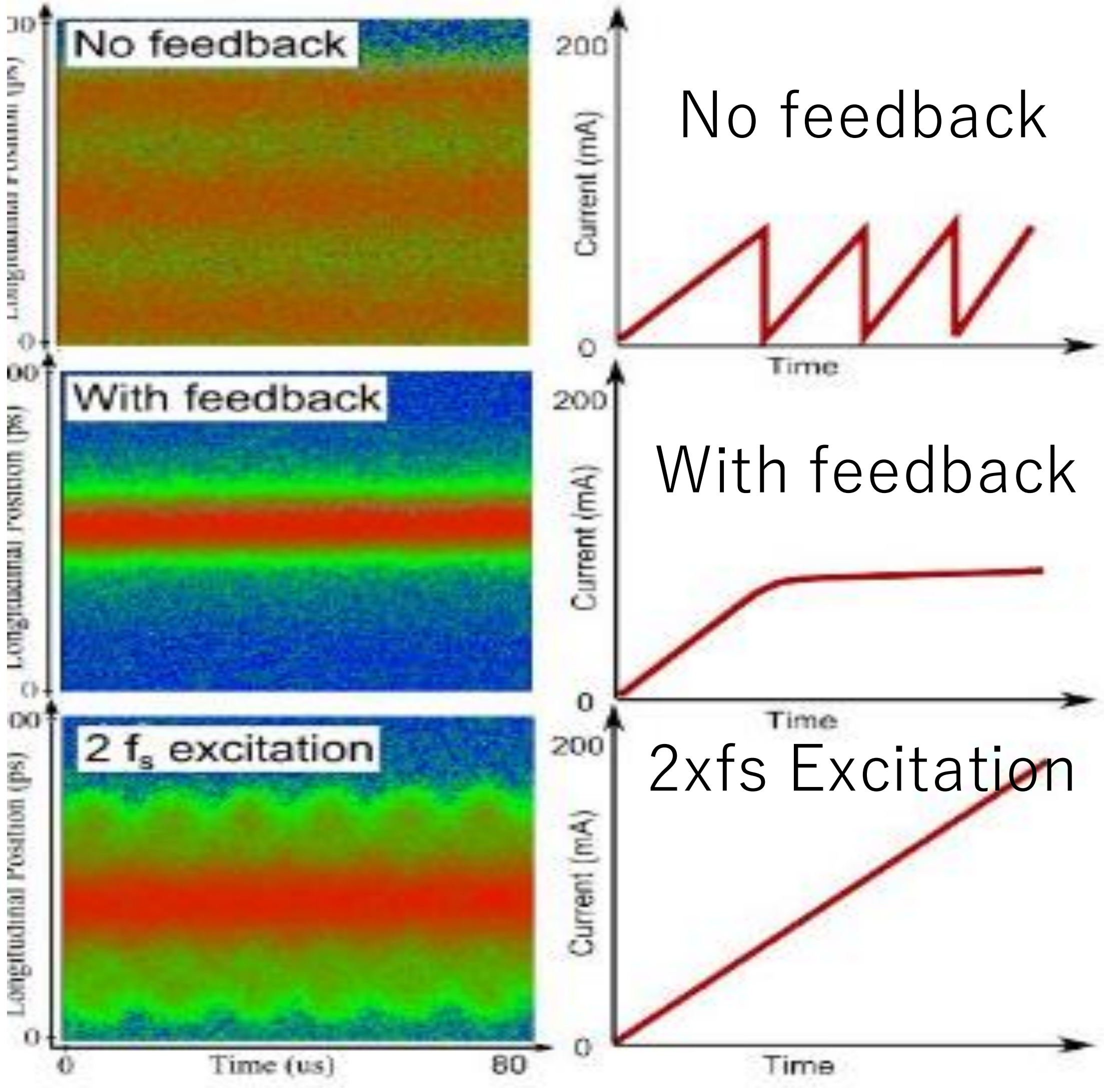


Figure from (modified)

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）



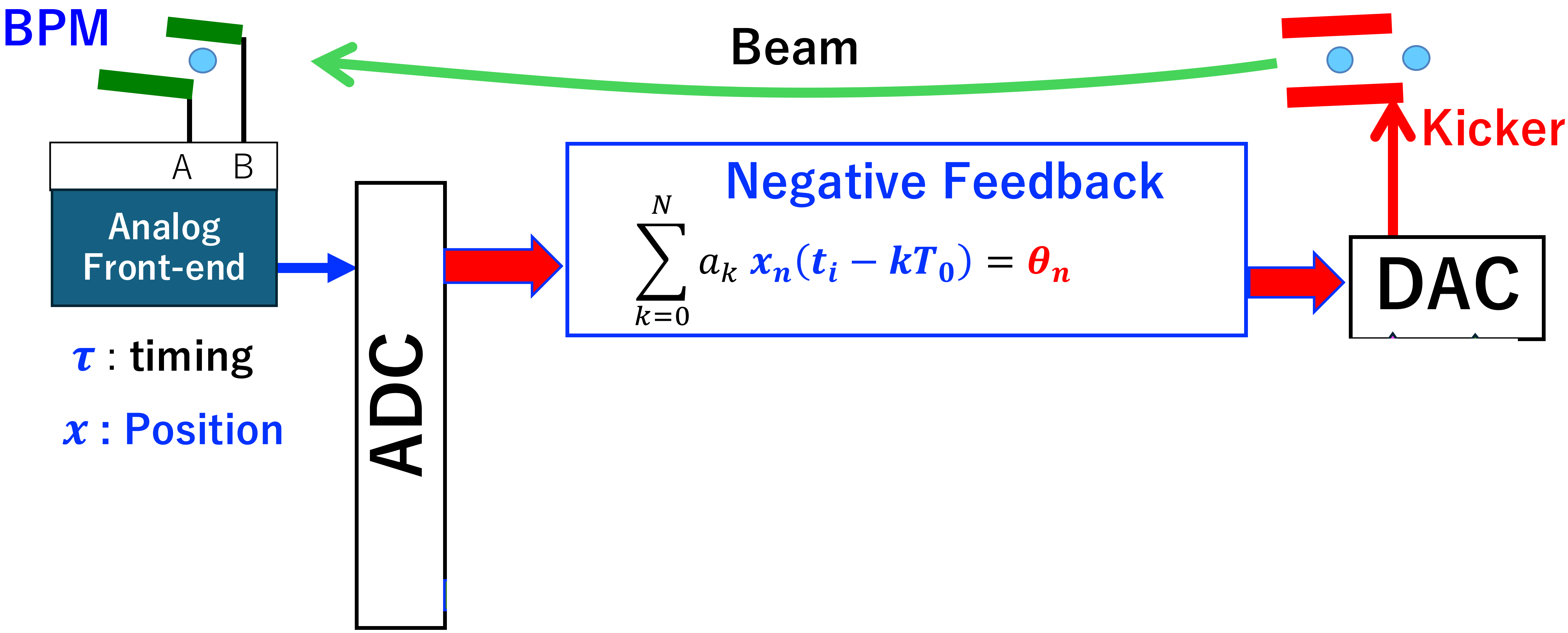
Longitudinal Excitation
of Quadrupole motion with
2 x fs frequency
=> **Lengthen bunches**

suppression of longitudinal instability

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

Negative Feedback for Damping

Damping of Beam Oscillation



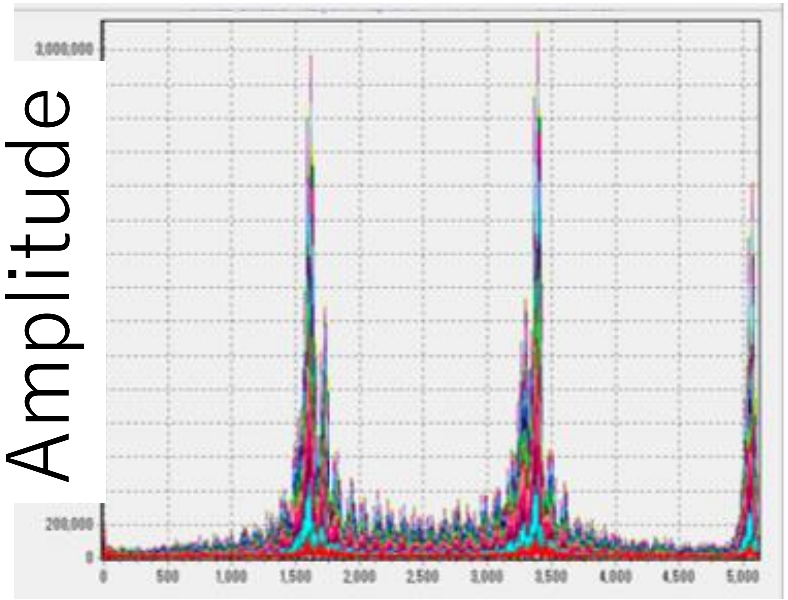
Negative Feedback (Damping)

Grow & Damp Experiment for investigate Instability

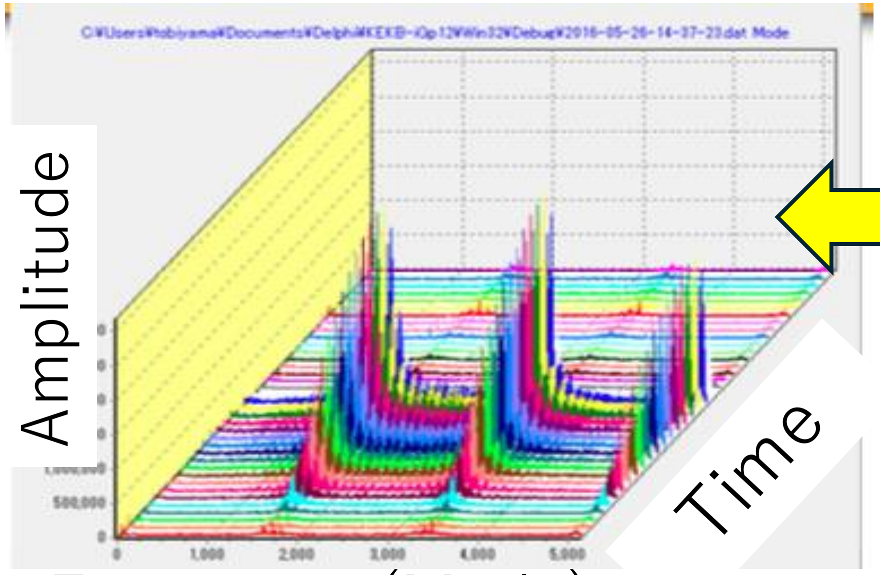
Switch OFF feedback => Growth by Instability => Switch ON feedback

Instability Frequency => source impedance, …z

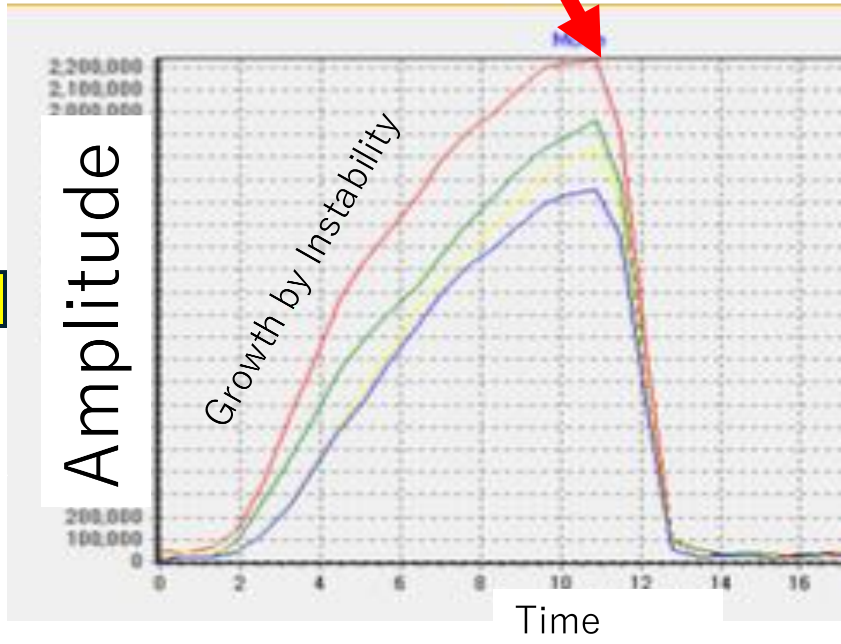
SuperKEKB HER



Frequency
(Instability Mode)



Frequency (Mode)

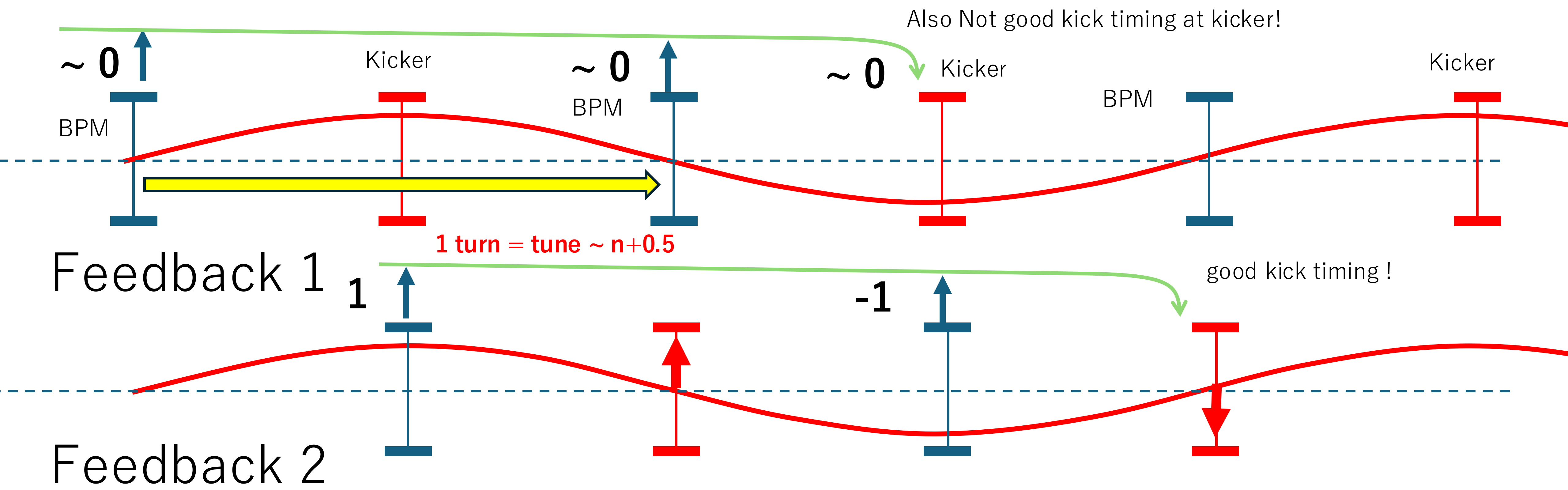


Growth and damping of several Modes

https://indico.scc.kit.edu/event/3742/contributions/15654/ SuperKEKB

Damping

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

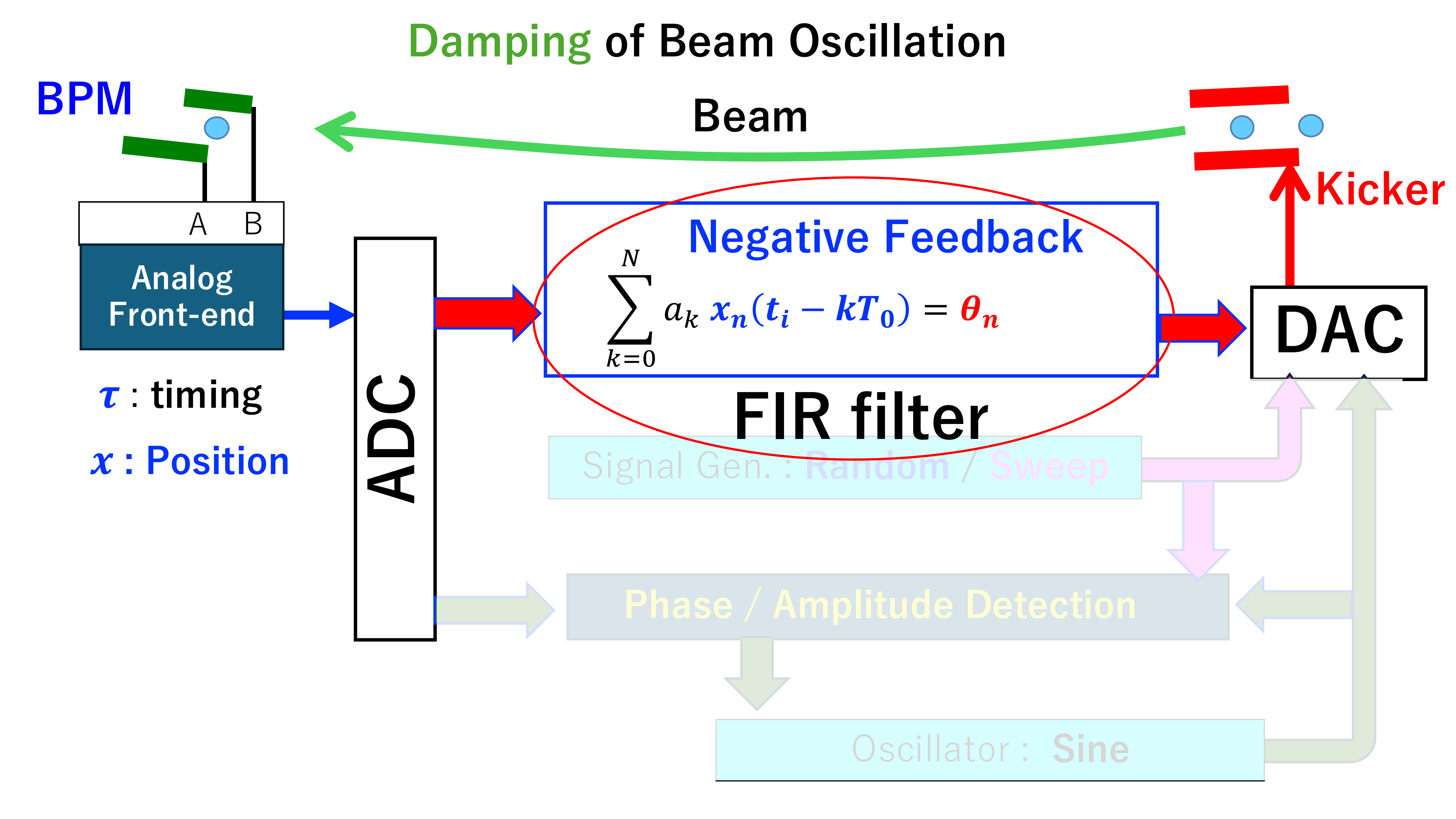


https://indico.scc.kit.edu/event/3742/contributions/15197/ KEK

Negative Feedback (Damping)

Faster Damping of Coherent motion than
Decoherence by **tune spread in bunch**

Coherent Motion =X=> Emittance


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
FIR filter
τ : timing
x : Position
Signal Gen. : Random / Sweep
Phase / Amplitude Detection
Oscillator : Sine

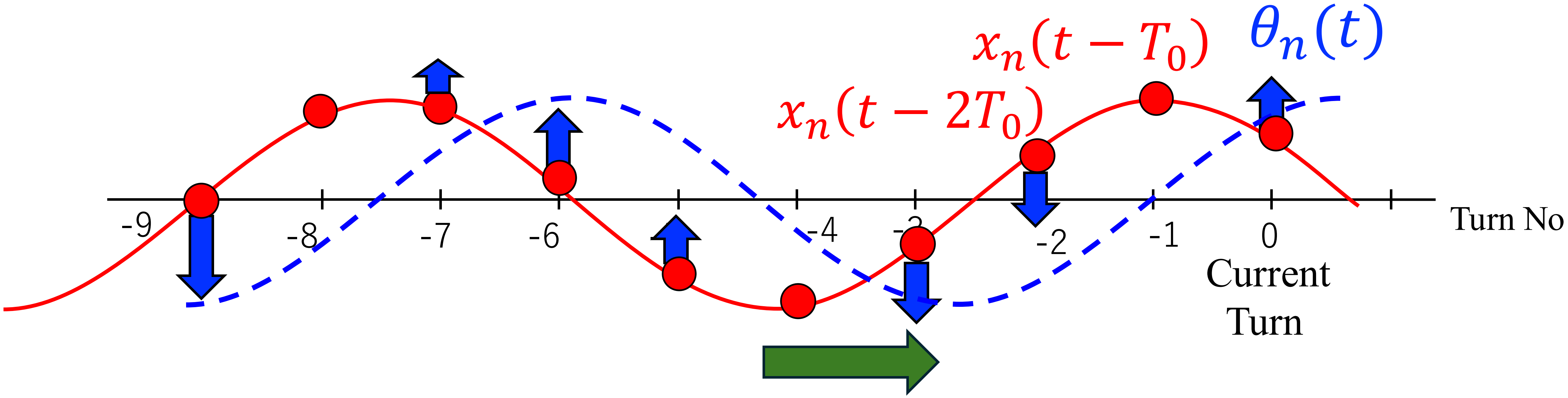
FIR filter

"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

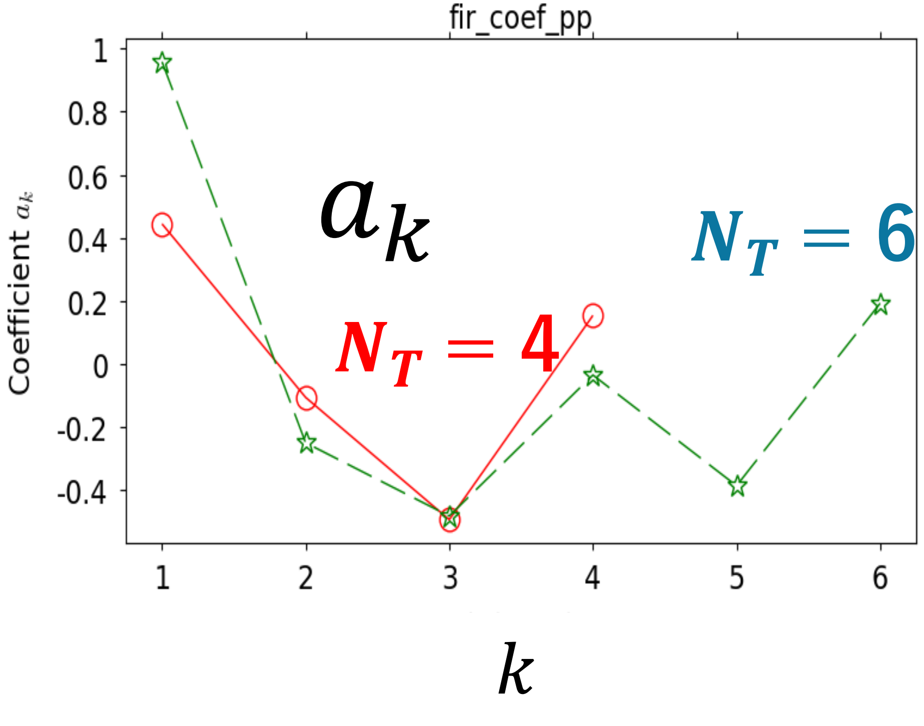


Phase Shift Produced by FIR filter

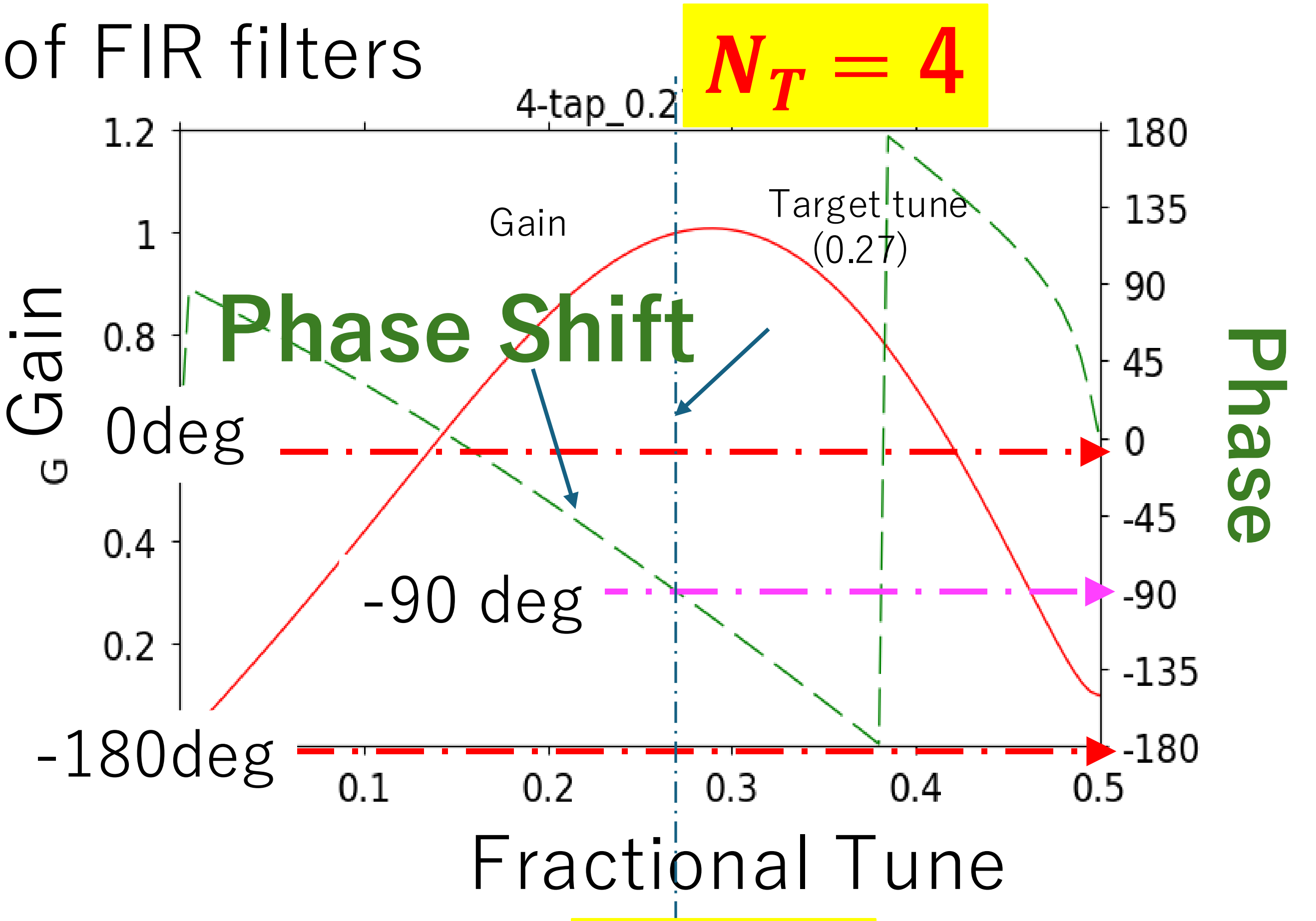
Number of Taps

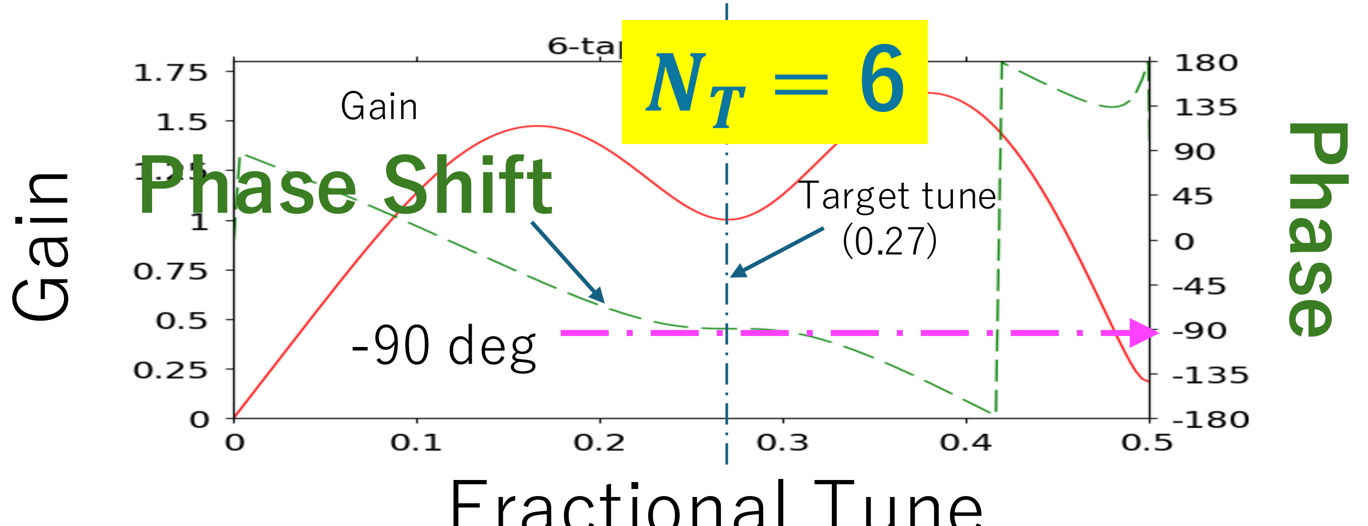
FIR filter

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



Example of FIR filters

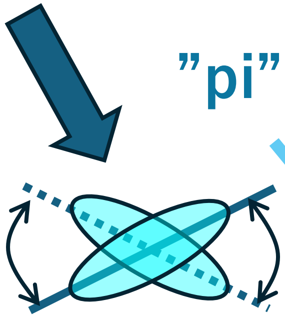




FIR filter for Two Tune Control

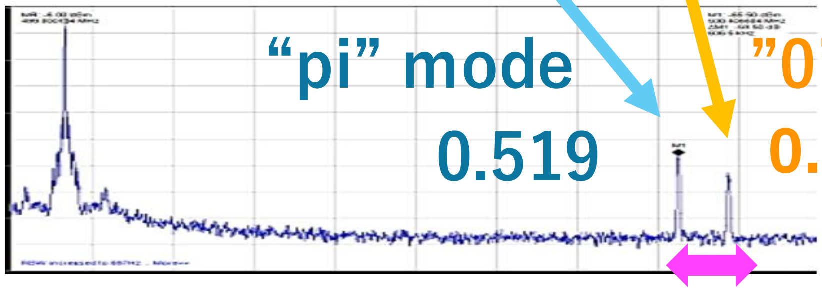
BEPC-II Suppression of Coherent motion by

Synchro-beta Resonances with Beam-Beam effect

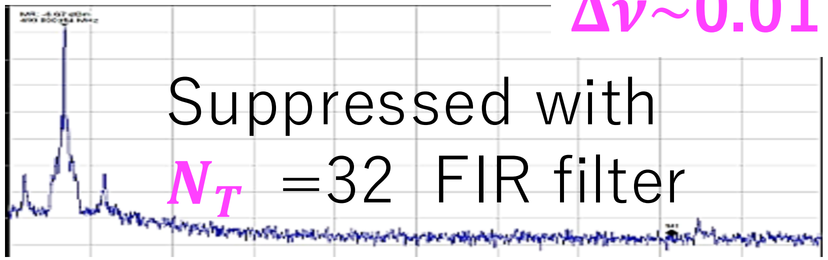


"pi" mode (0.519) : FIR phase -50deg

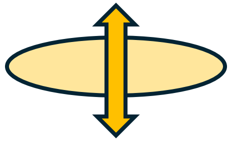
"0" mode (0.508) : FIR phase -140deg



$\Delta\nu \sim 0.01$



Instability



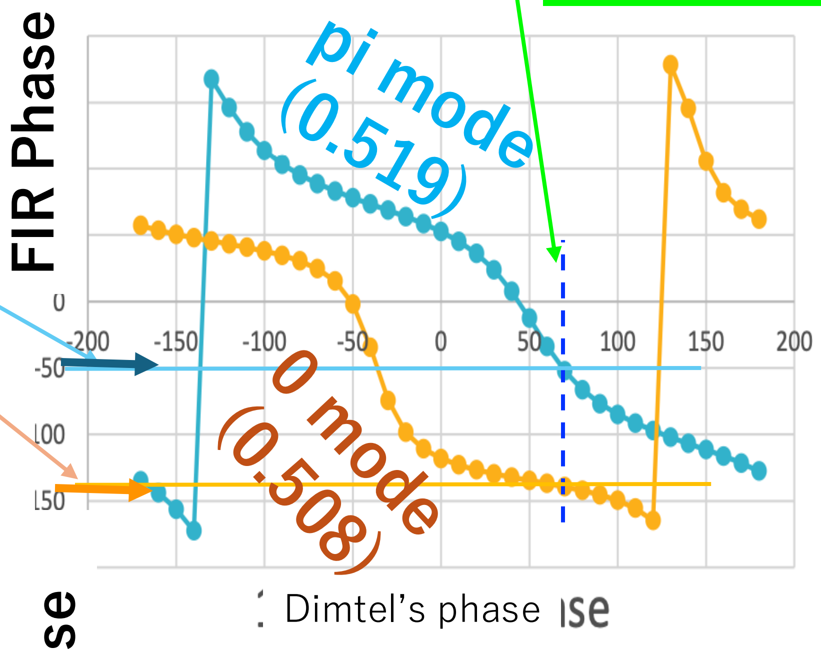
Uncertainity principle

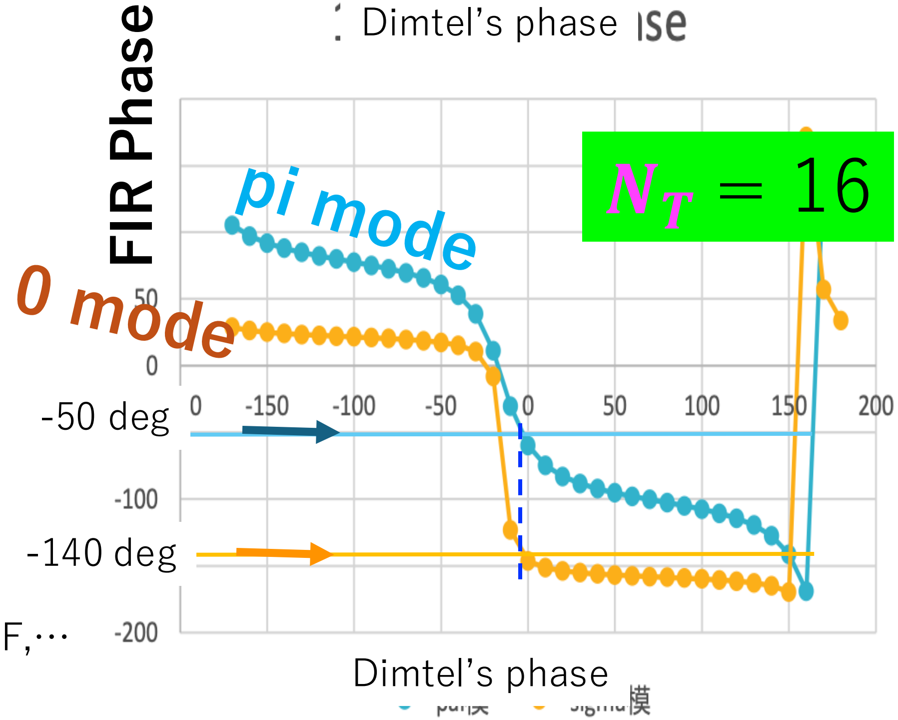
$$1 < N_T \Delta\nu$$

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

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

Selected Filter





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,…

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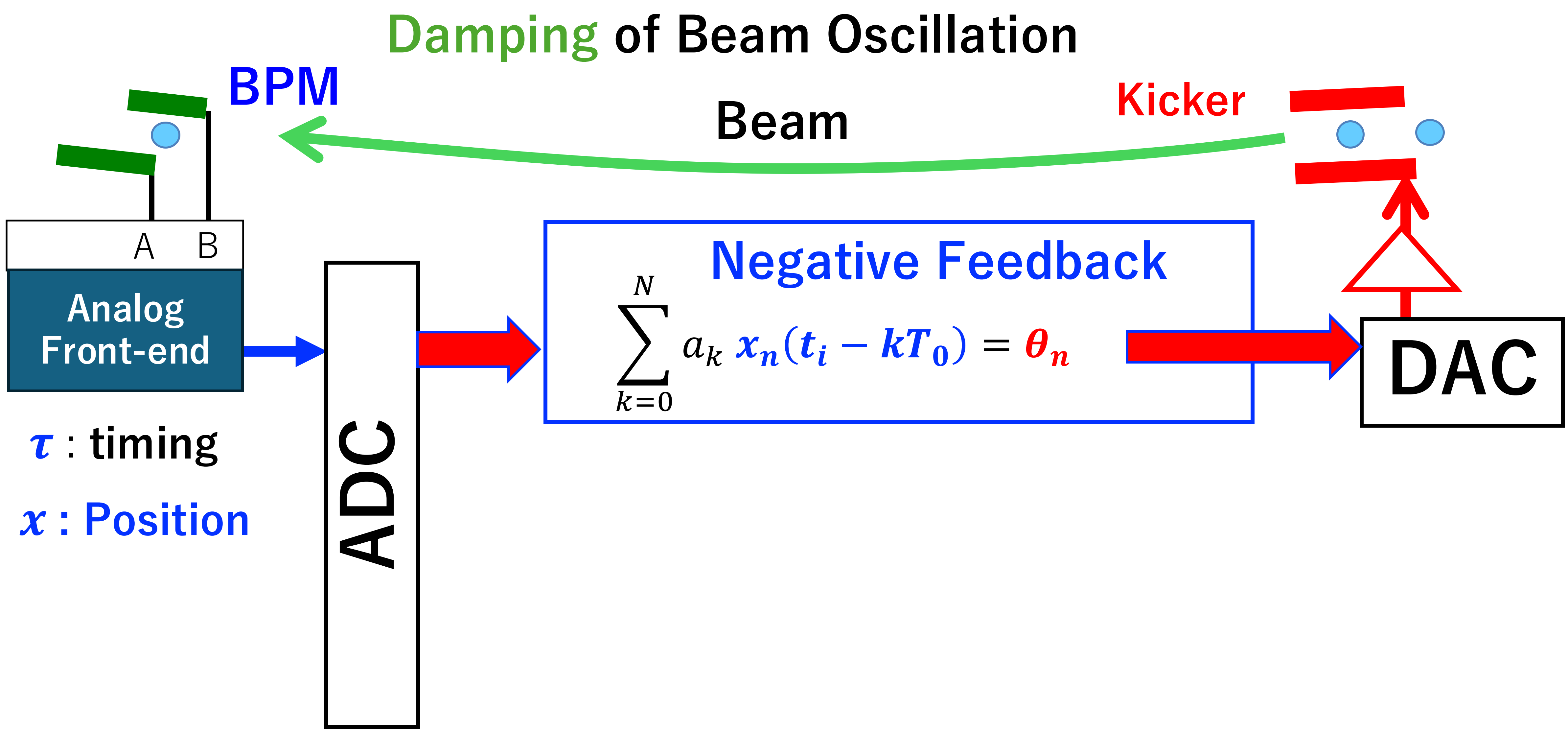
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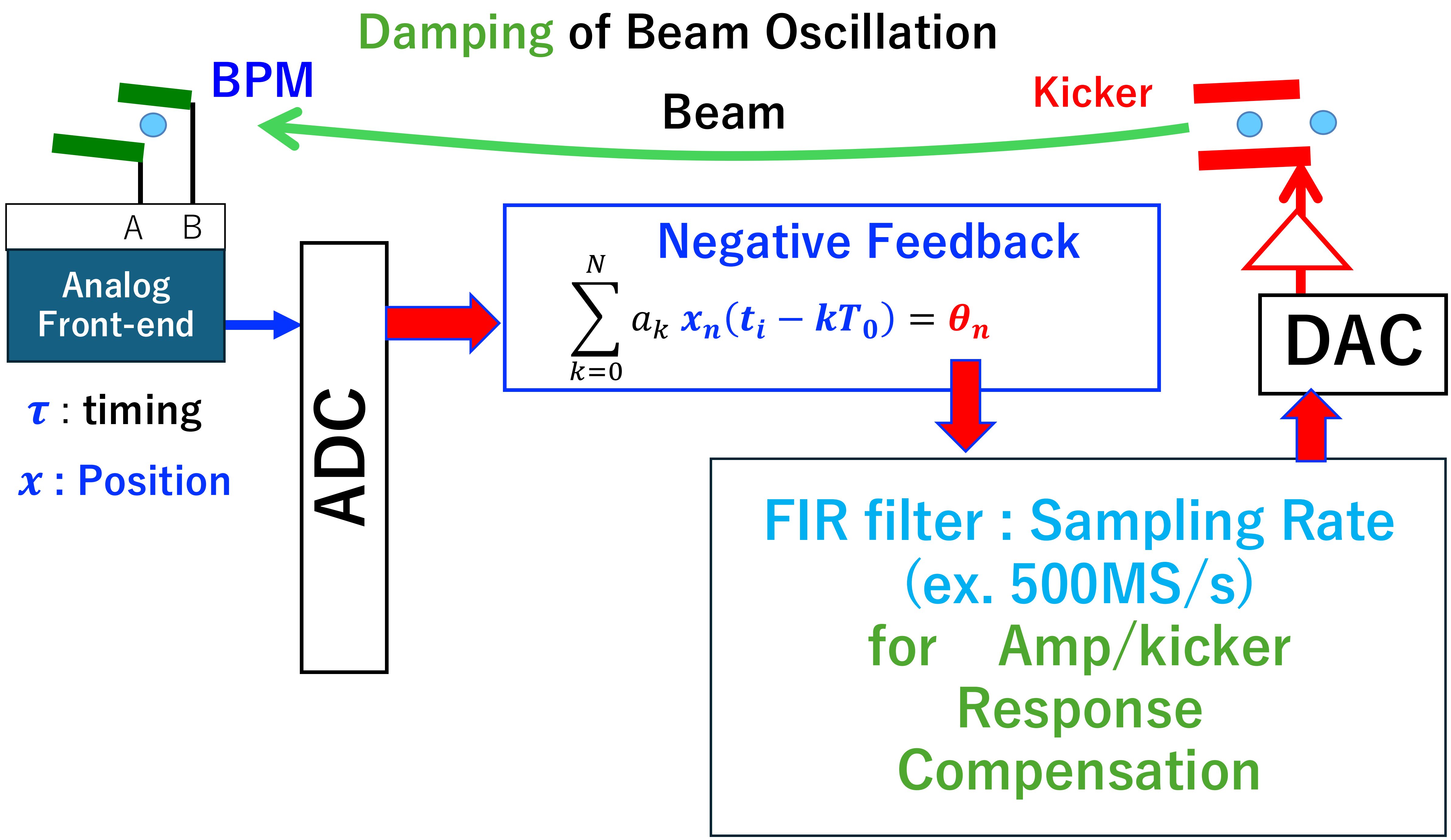
x : Position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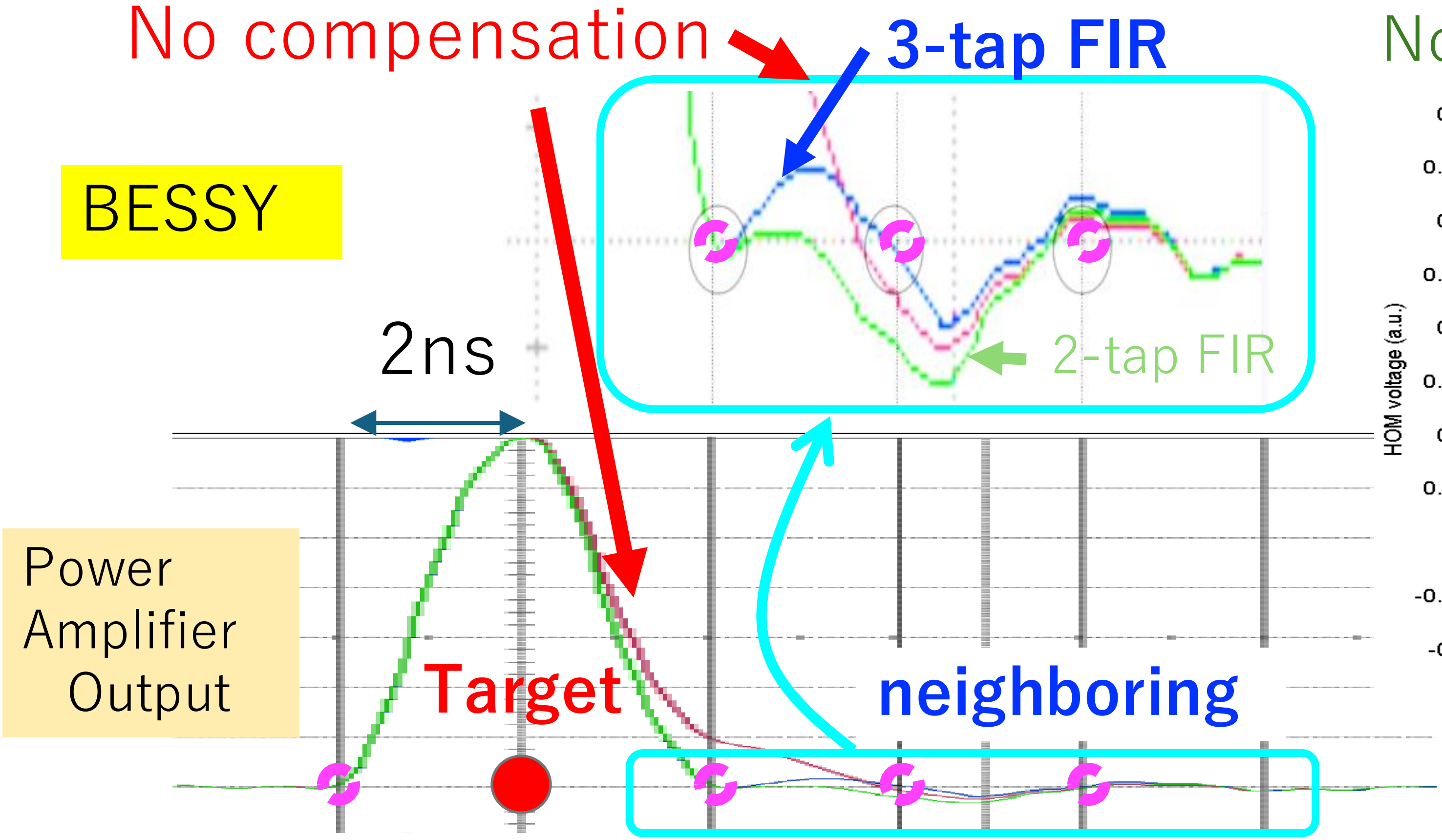
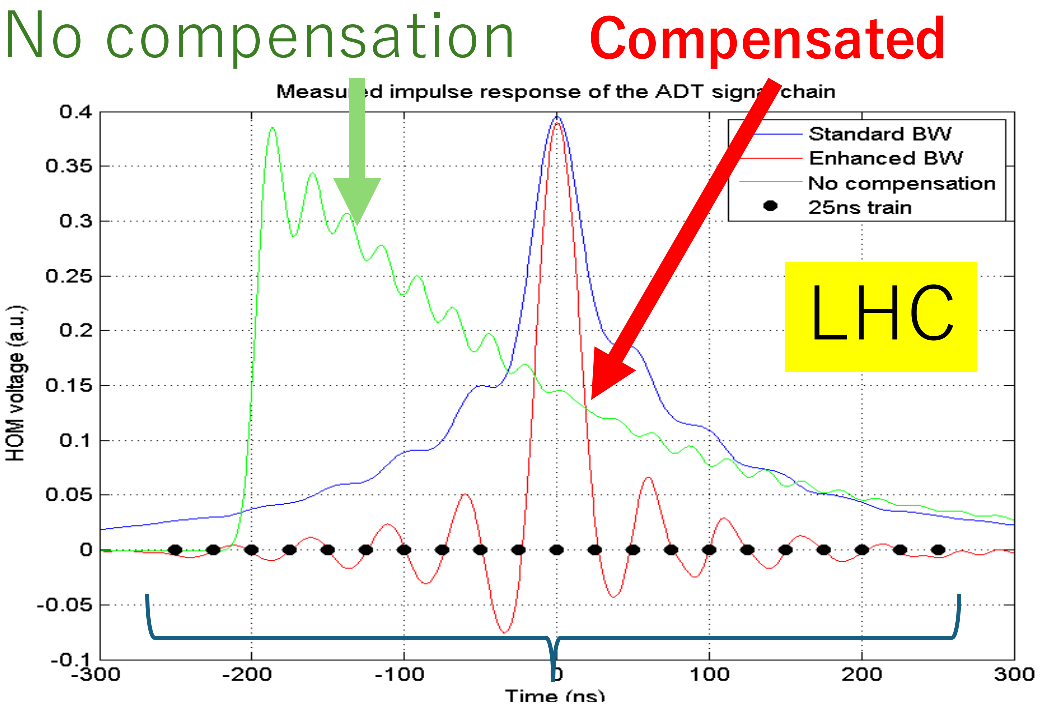
Negative Feedback
$\sum_{k=0}^{N} a_k \, x_n(t_i - kT_0) = \theta_n$
DAC
τ : timing
x : Position
FIR filter : Sampling Rate
(ex. 500MS/s)
for Amp/kicker
Response
Compensation

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

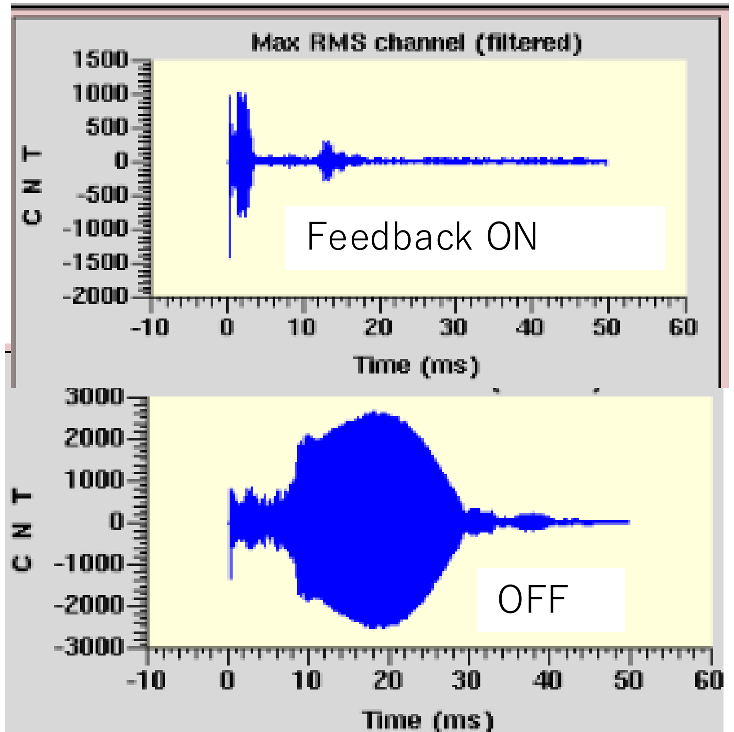
* Cavity voltage Change by beam loading (multi-bunch at high current)

=> 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)

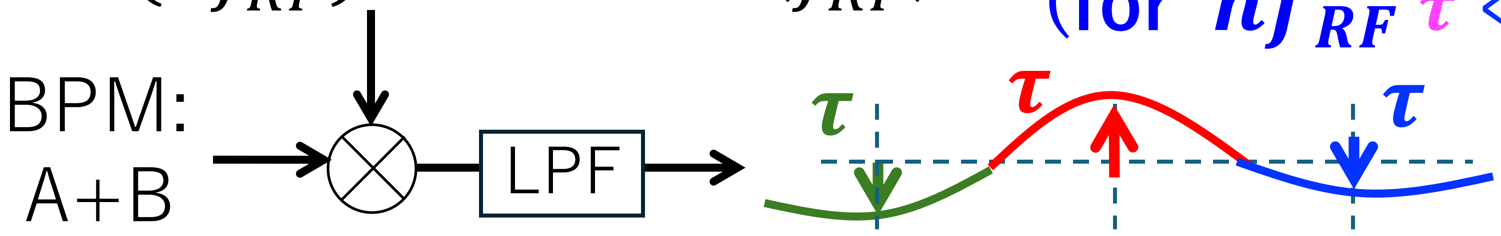


Widening of Acceptance (possible method)

x3 : Acceptance but
1/3 : Phase Sensitivity

$1.5\text{GHz}(3f_{RF}) \Rightarrow 0.5\text{GHz}(f_{RF})$

(for $nf_{RF}\tau \ll 1$)



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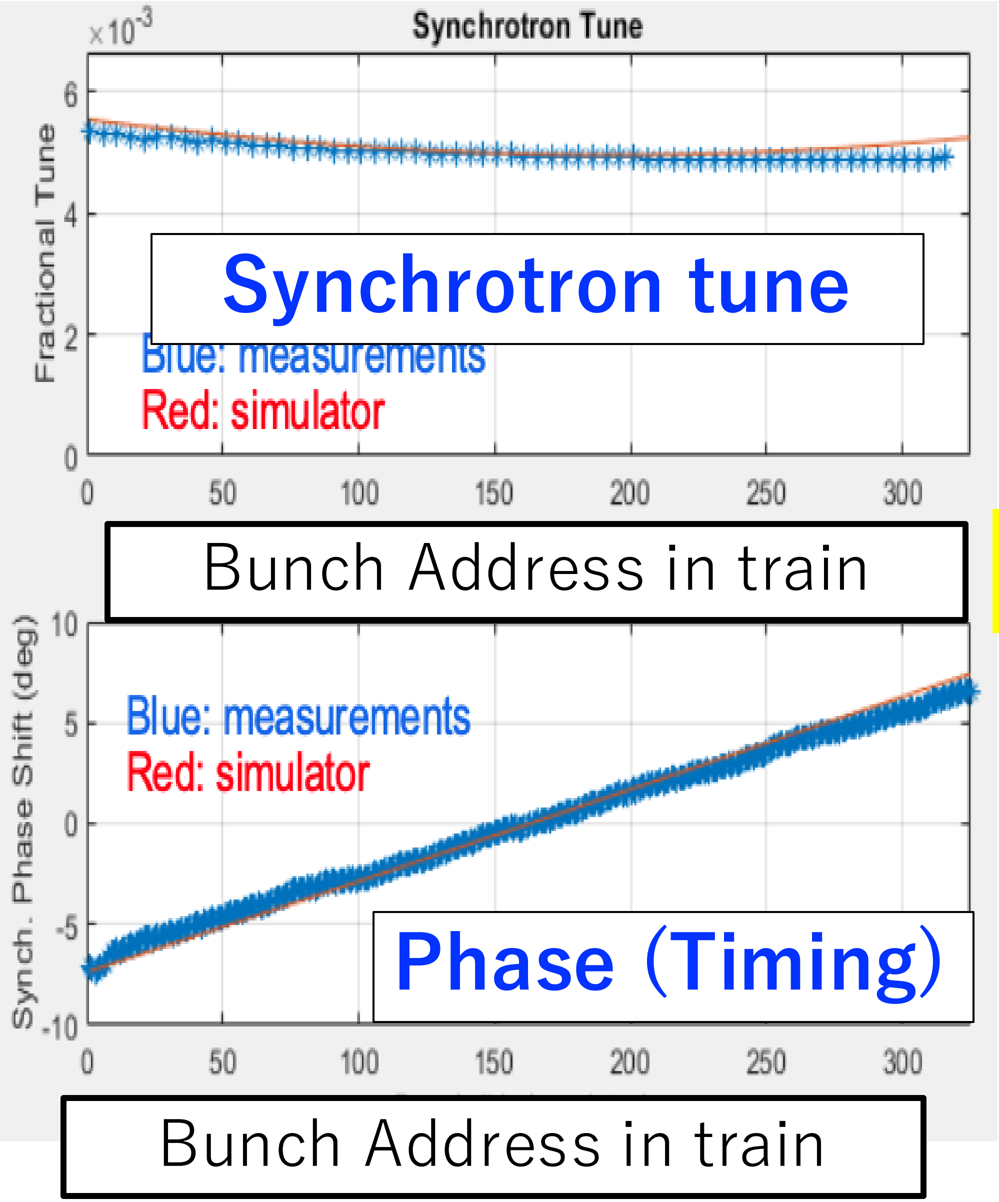
Measurement with Feedback : Synchrotron Tune and Longitudinal Timing Shift



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 = single chip FPGA + ADC + DAC + ARM CPU

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)

See poster WEP55

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

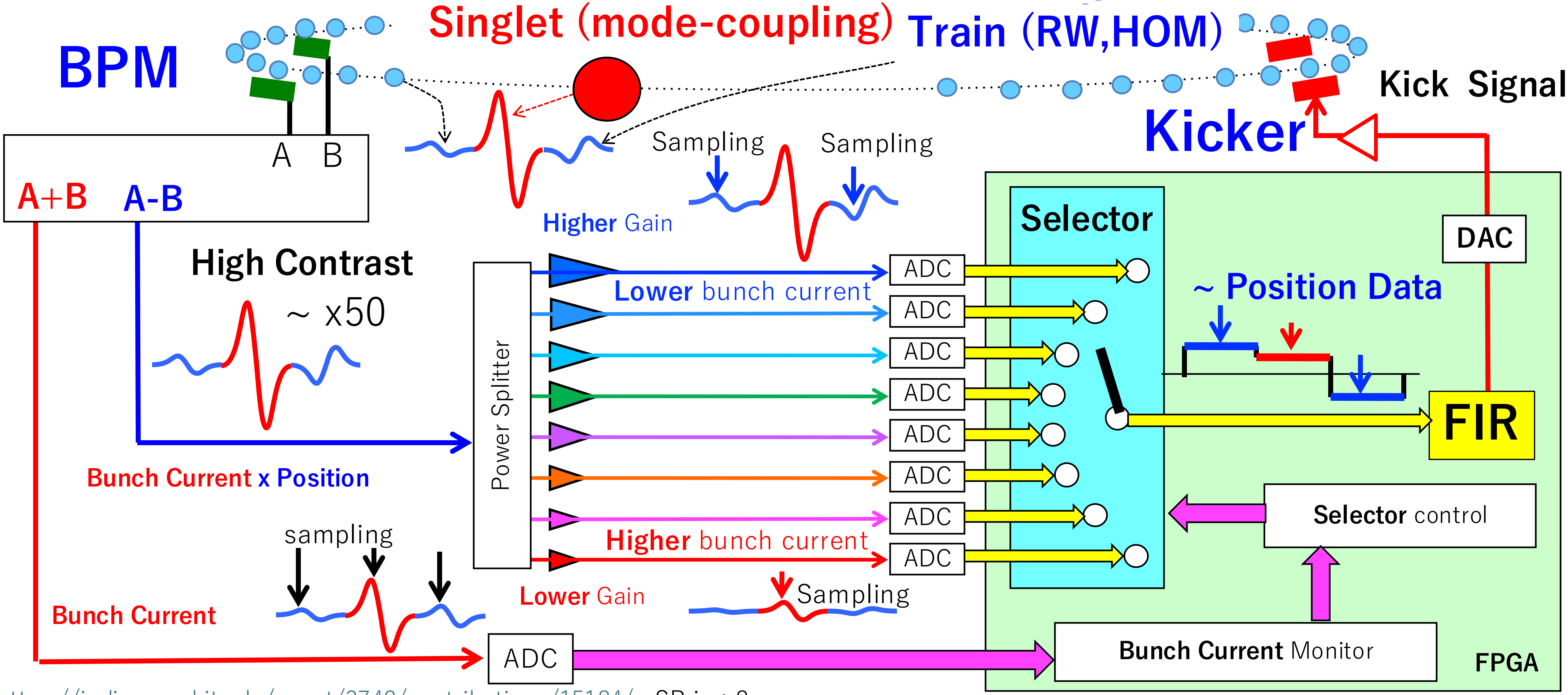
https://indico.scc.kit.edu/event/3742/contributions/15604/ SLS

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)

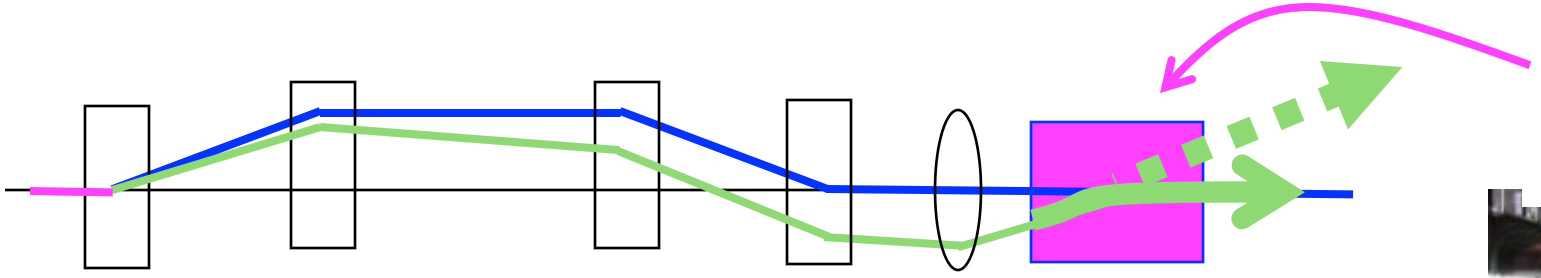


https://indico.scc.kit.edu/event/3742/contributions/15184/ SPring-8

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

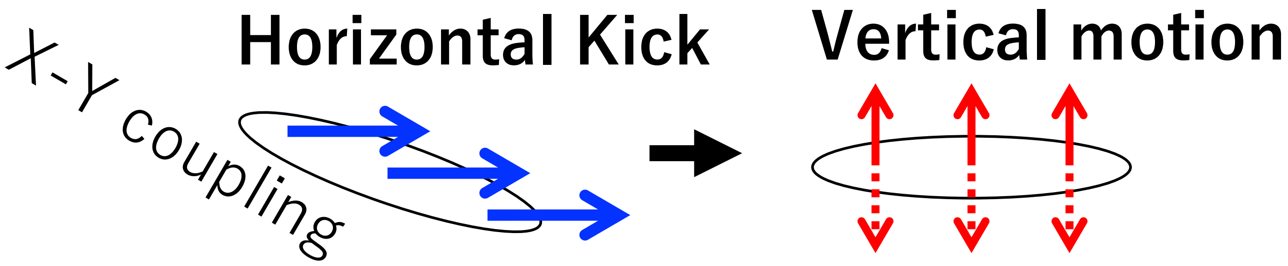
Saturation of Feedback : lower gain -> **Instability**

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

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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)

Main Cavity + Harmonic Cavity + **Bunch Train** + **Gap**

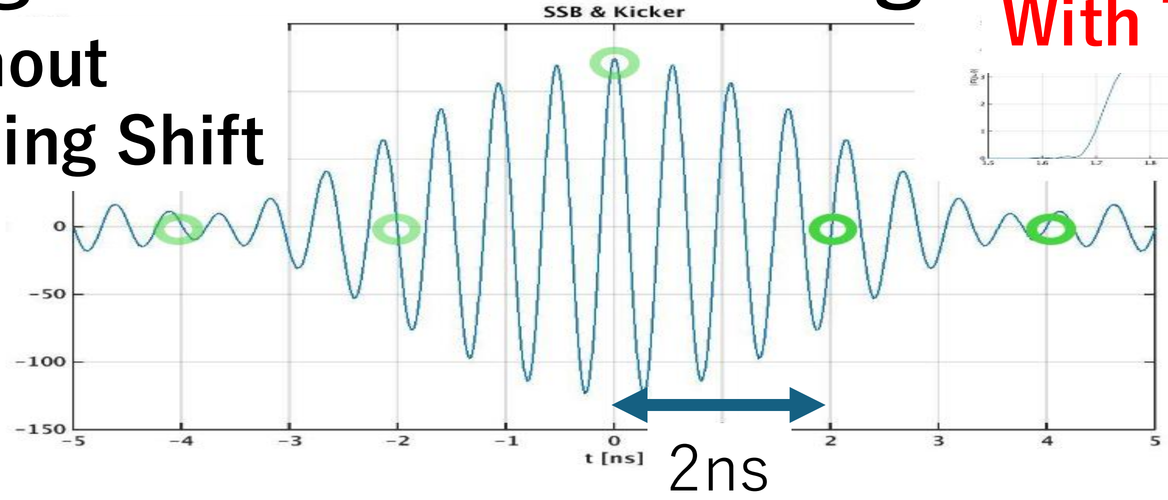
=> Cavity Voltage modulation : Amplitude and Phase

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

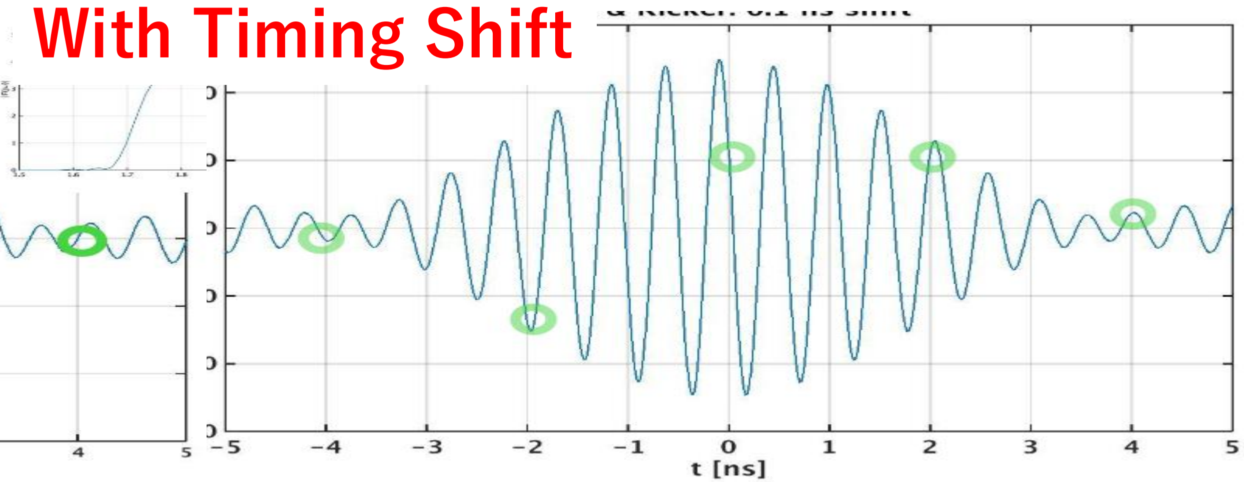
Timing shift : within Front-end acceptance ? => OK

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)

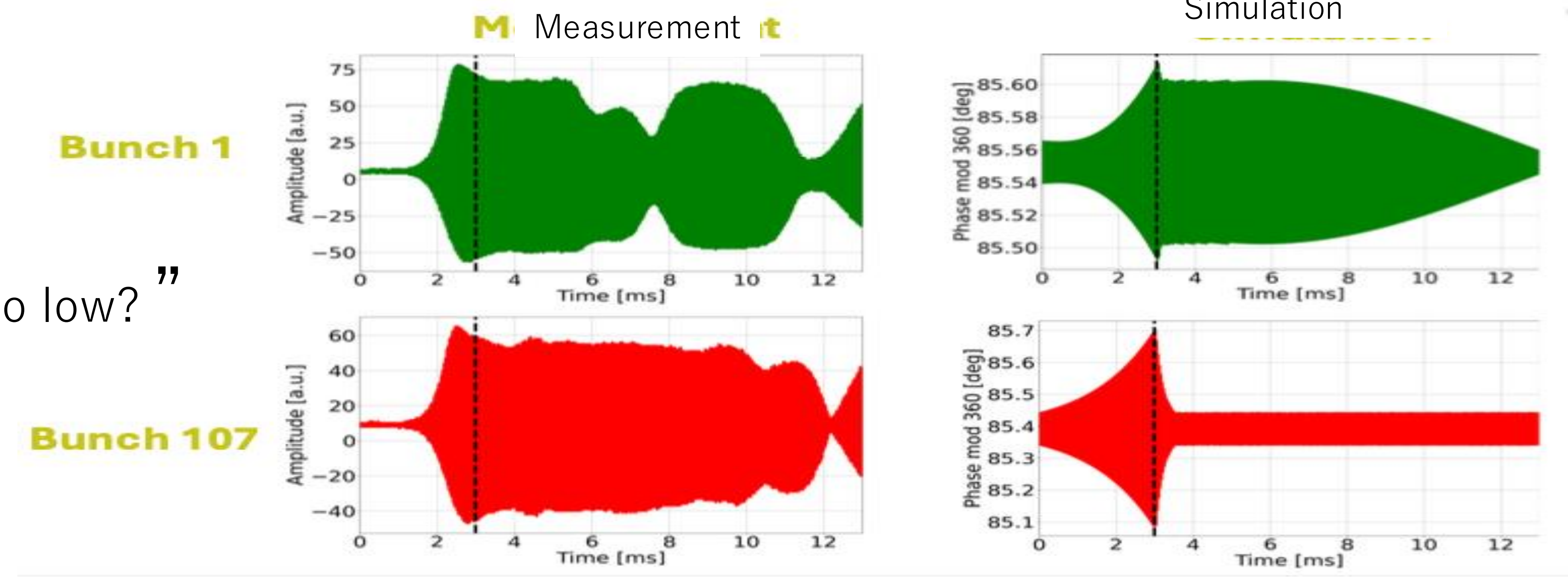
→ Kicker Drive Circuits (SG, QPSK, Drive Signal x DAC (mixer))

→ 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

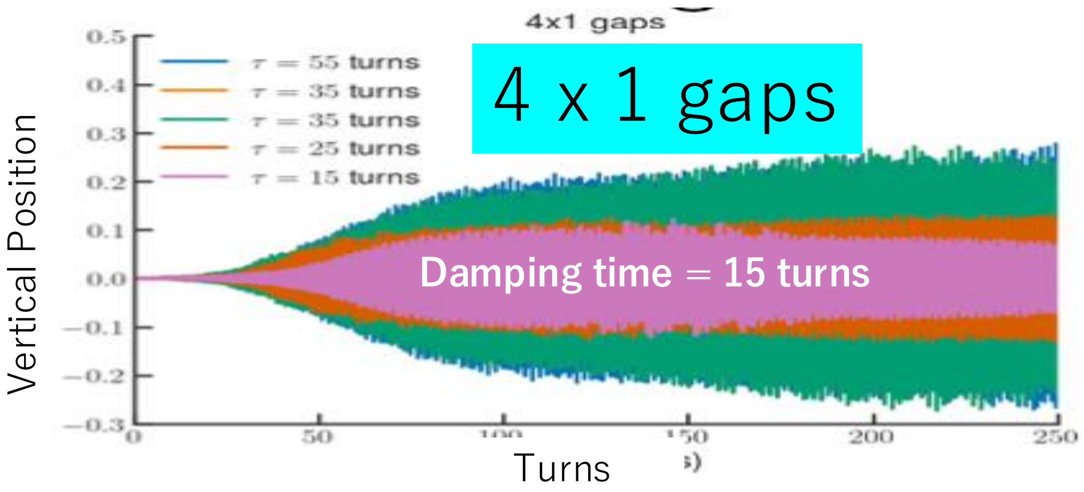
Transverse Coupled-bunch Instability

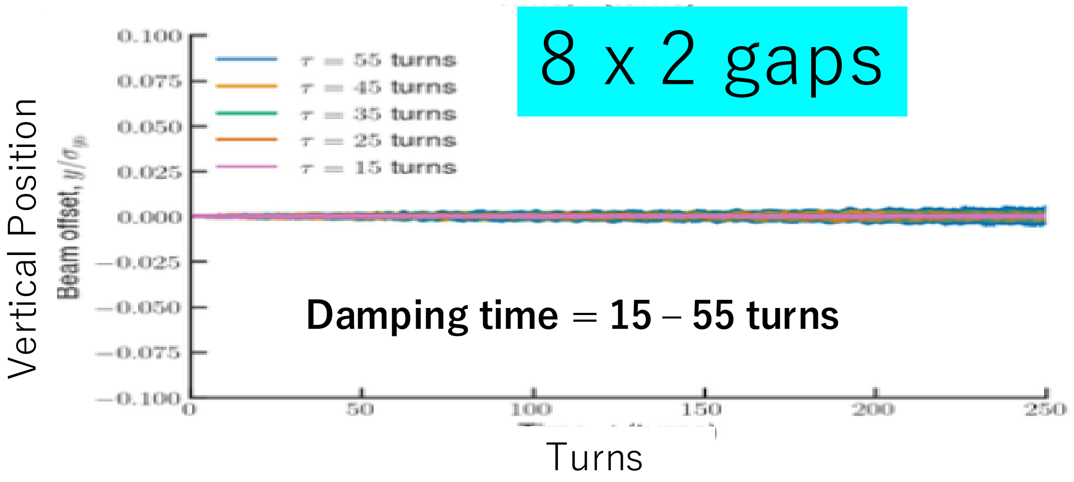
High Chromaticity (~10) may cure => Non-Linear dynamical problem

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

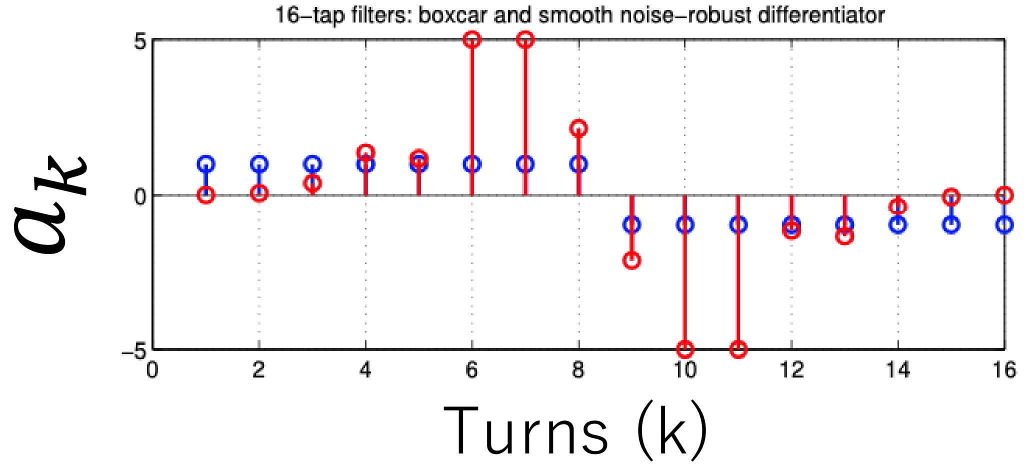
=> **Wide Acceptance of Feedback (FIR Filter)** for synchrotron tune

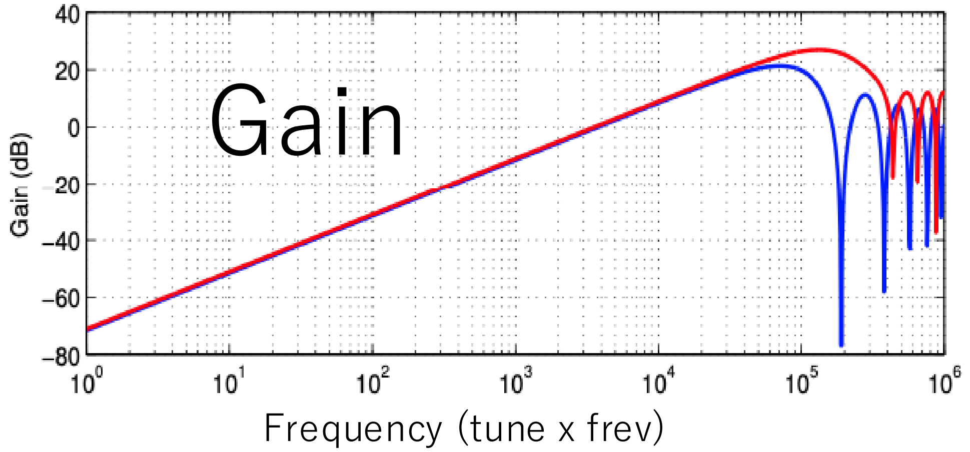
x => dx/dt makes 90 deg at All Freq(tune))

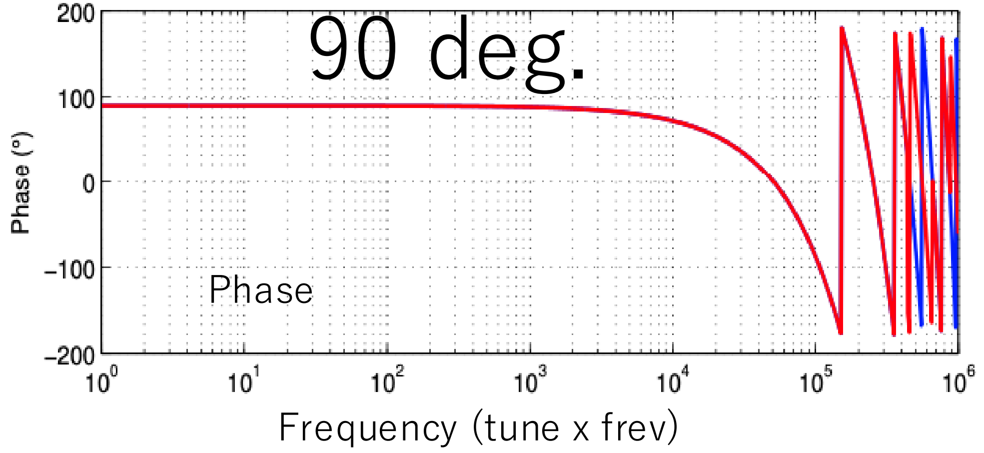
But Gain is proportional to Frequency

FIR filter : Differentiator + Low Pass Filter

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







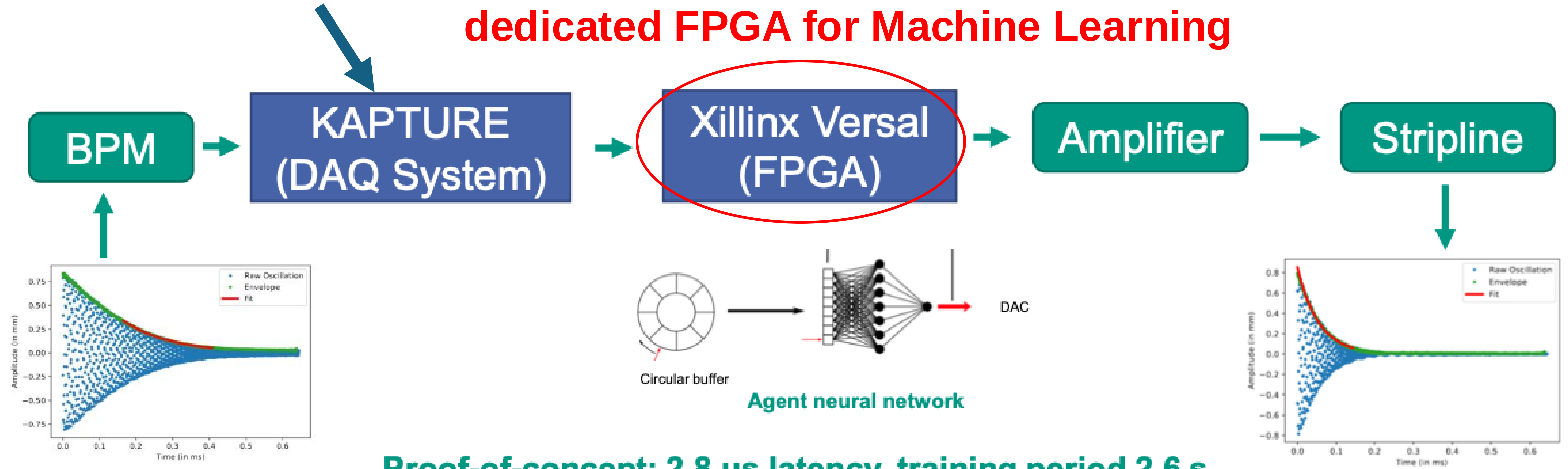
https://indico.scc.kit.edu/event/3742/contributions/15191/ Dimtel

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

dedicated FPGA for Machine Learning



Proof-of-concept: 2.8 μs latency, training period 2.6 s

One-shot Kick

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

Noise

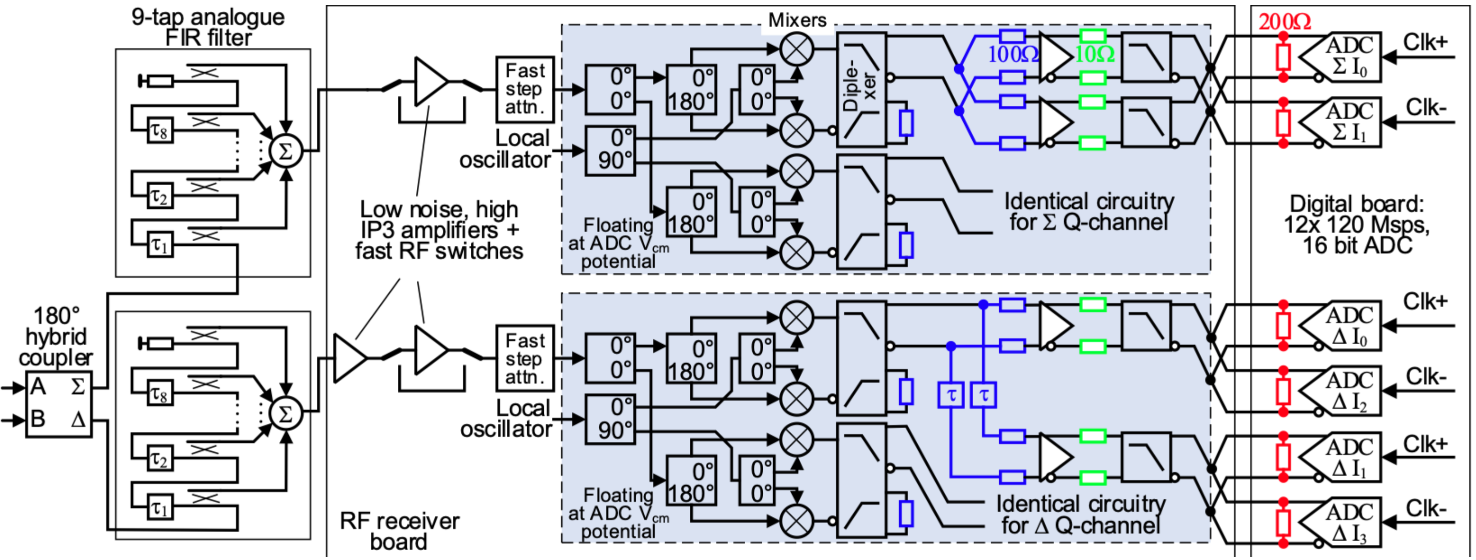
- LHC

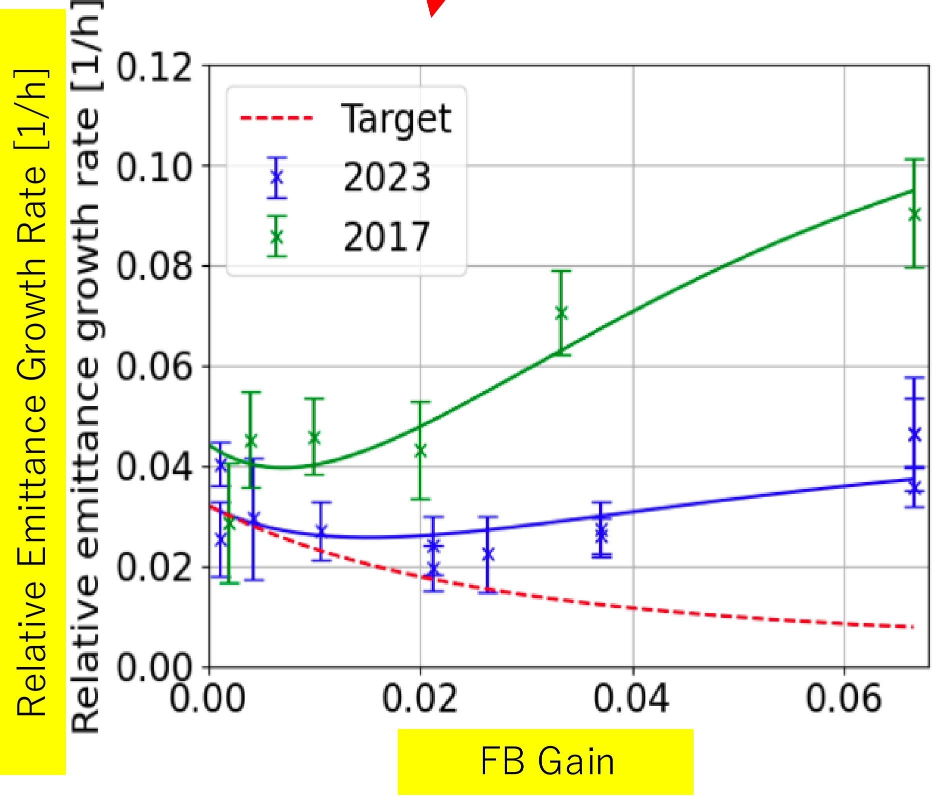
25ns Bunch spacing with 400MHz RF (40MHz bunch rate)
Bunch length 1 – 1.5 ns
1-2e11 protons/bunch （1e9 protons/pilot bunch)
450 GeV => 7 TeV
Filling 20min => energy ramping 20-40min => physics 12-18 hours

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

Other Topics

LHC

Electric field Kicker

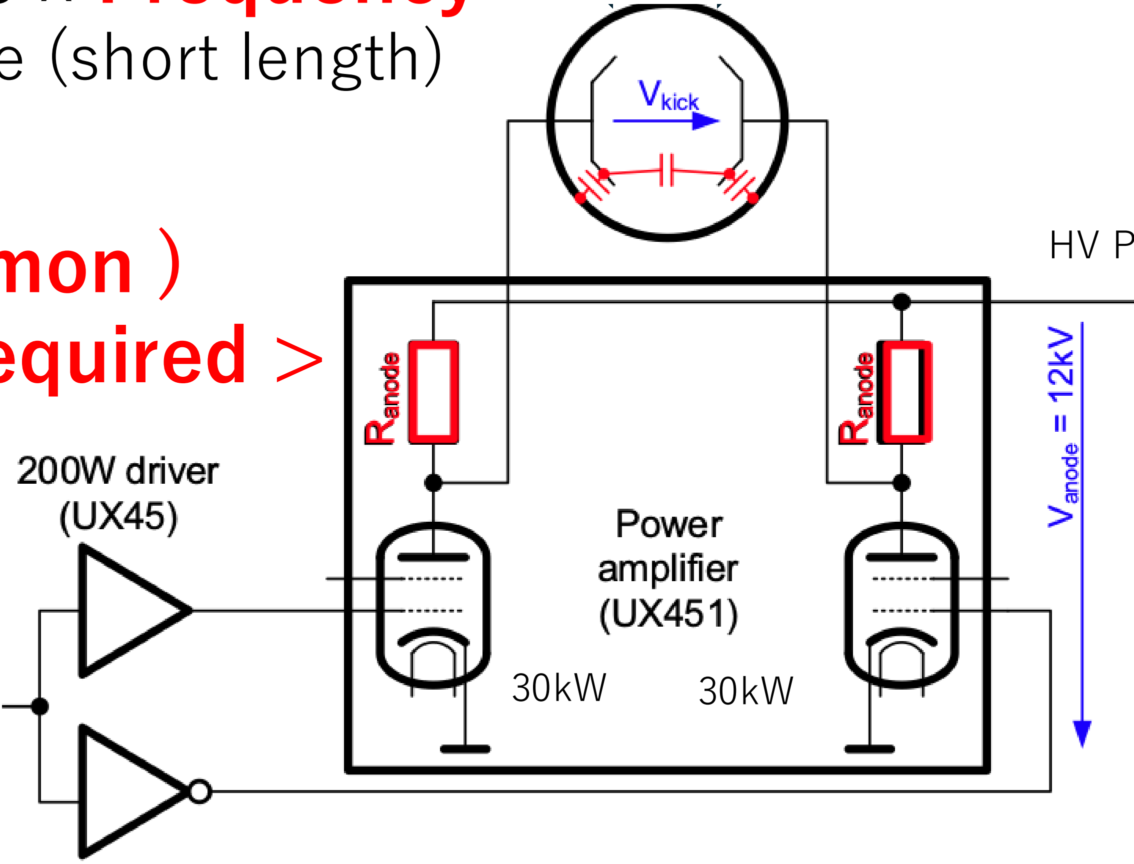
Strong Kick is necessary
Relatively low frequency < 20MHz

Drive current ∝ Kicker Capacitance x Frequency

Capacitance : Kicker electrode + cable (short length)

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

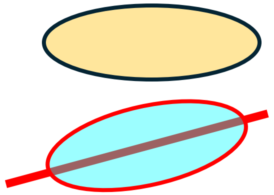
Kick signal from
Feedback processor



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

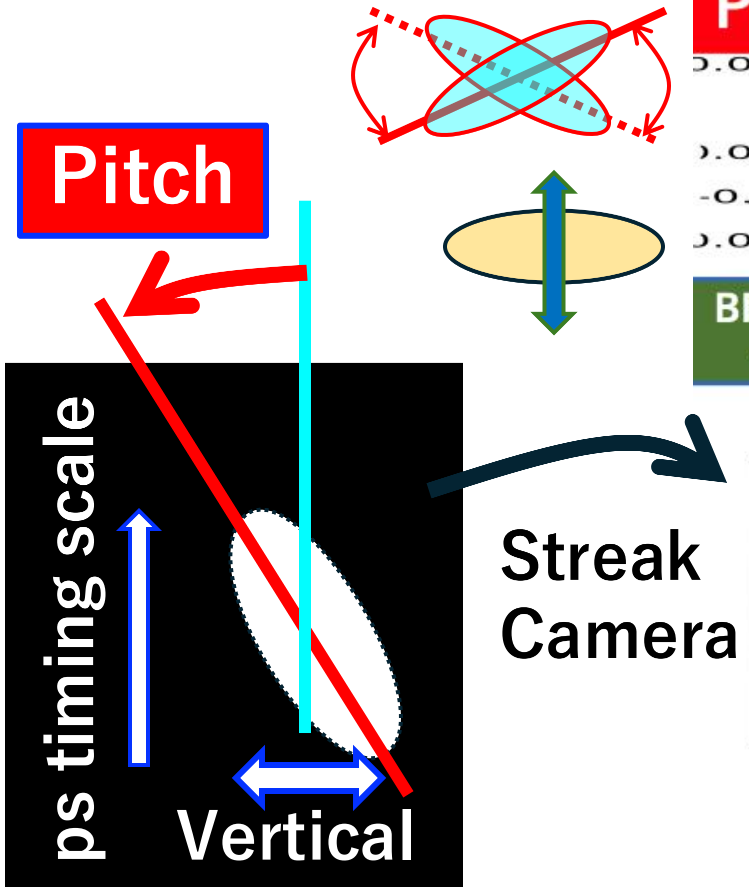
Bunch Pitch/Yaw Monitor Development and Proposal of its Feedback (KEK)
for ps bunch with USUAL button type BPM + SIMPLE Circuit of 1.5GHz band

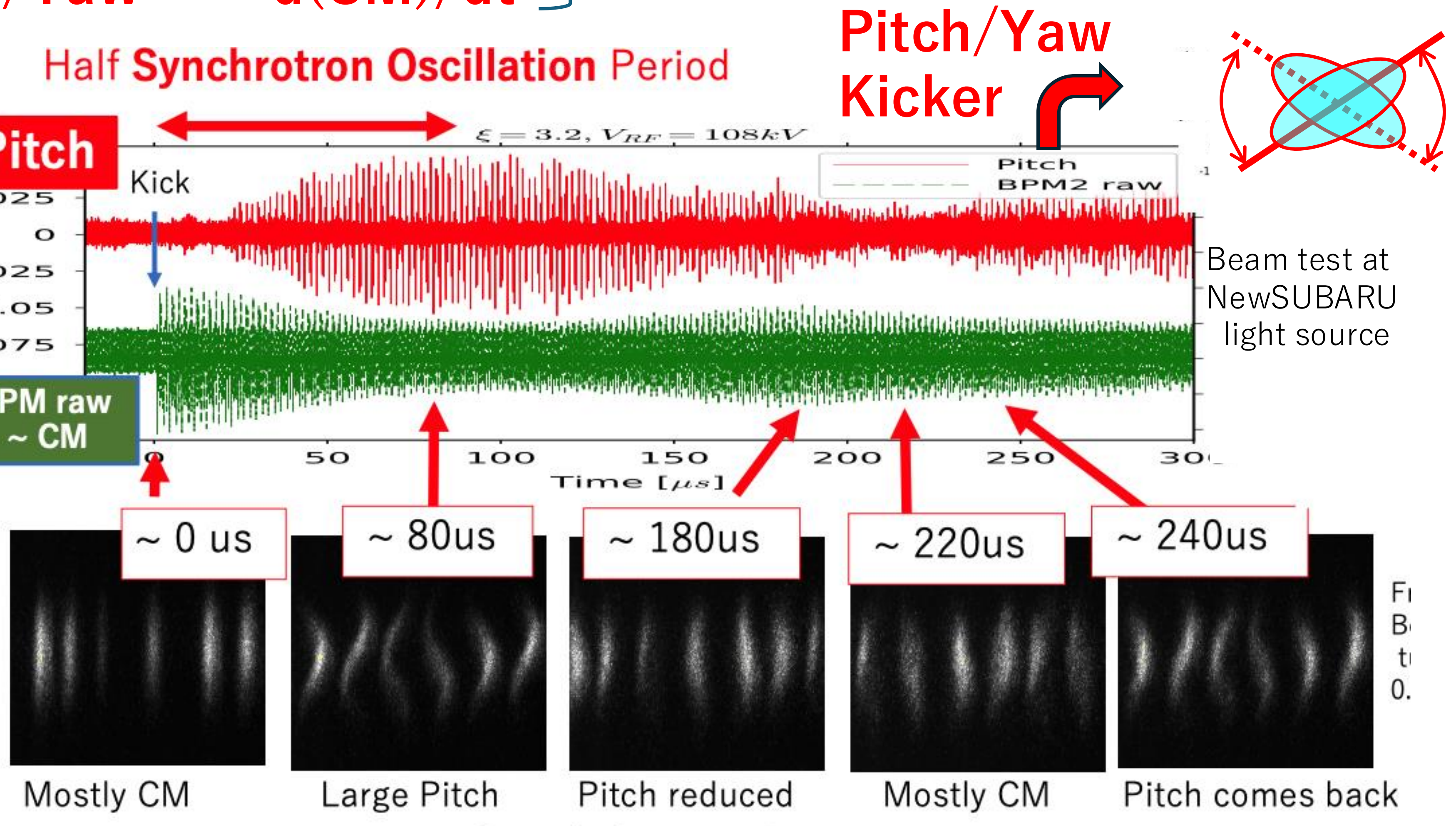
BPM Signal



Center of mass (CM)
Pitch/Yaw ~ d(CM)/dt

90-degree phase Difference at ALL Frequency Components





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

blishment of Common Procedure of Commissioning of Feedback

tance Control by Sideband resonant excitation (tune tracking)

itudinal Feedback with Stripline Kicker at KARA Booster (53MeV)

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

250MHz carrier kick: 4ns spacing bunches (Transverse BBF amp)

.5 GHz carrier kick : 2ns spacing bunches (Longitudinal BBF amp)

izontal Kick at Dispersion => Change of Circumference : worked

ame as Horizontal Feedback (f < 250MHz)

IR filter phase change

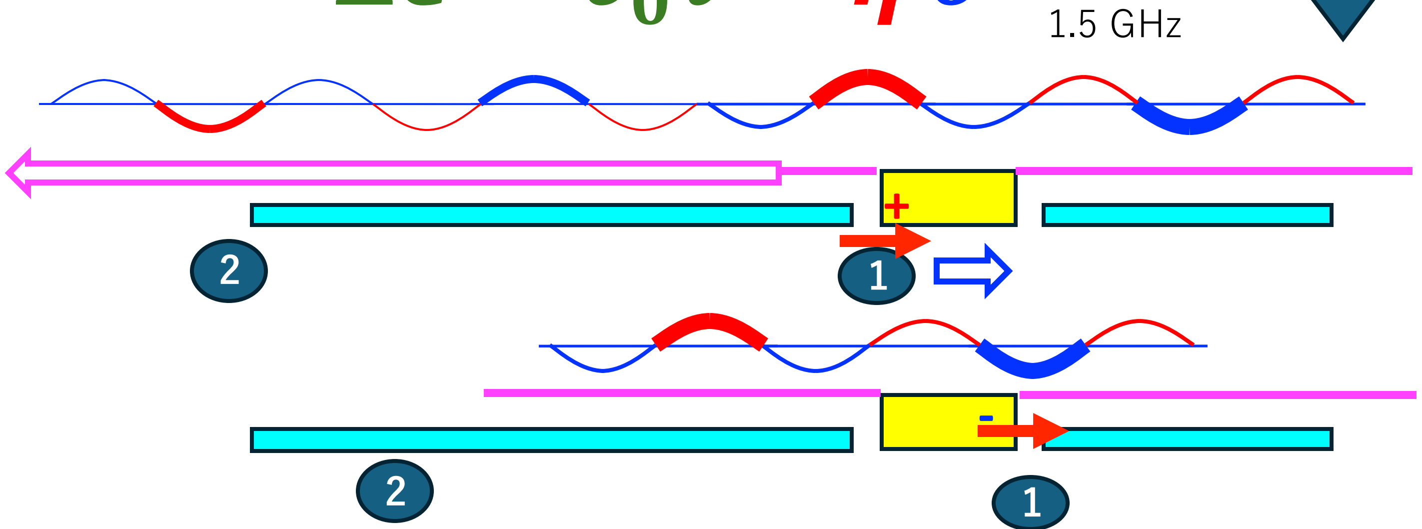
timing monitoring -> timing kick

High Gain required

Dispersion

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

Kick



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