Bunch Pitch/Yaw Monitor Development and Proposal of Pitch/Yaw Feedback

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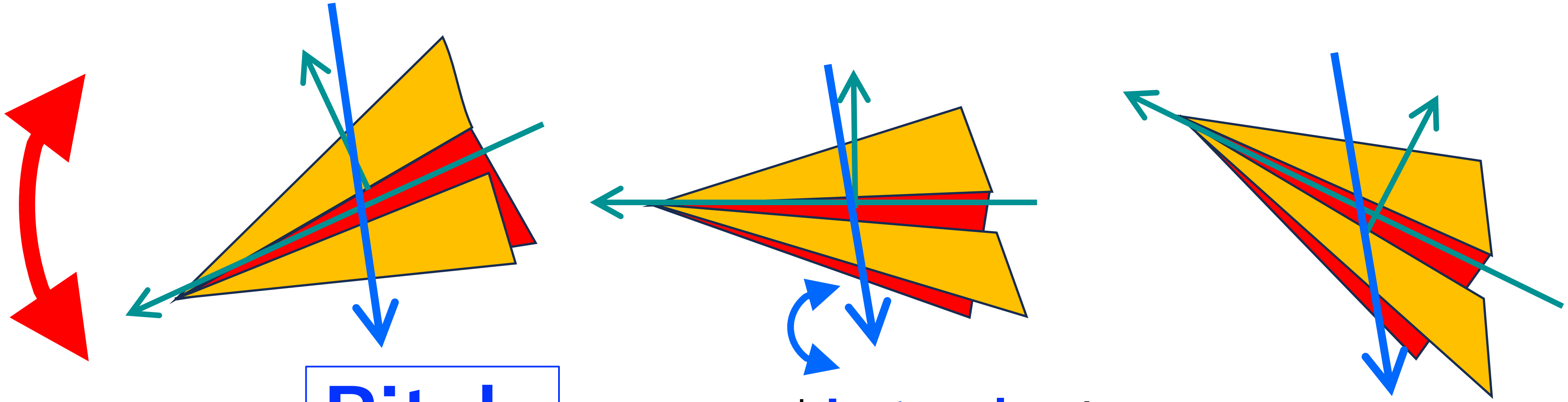
T. Nakamura, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THP0/THP089.pdf
T. Nakamura, https://www.pasj.jp/web_publish/pasj2019/proceedings/PDF/WEPI/WEPI031.pdf

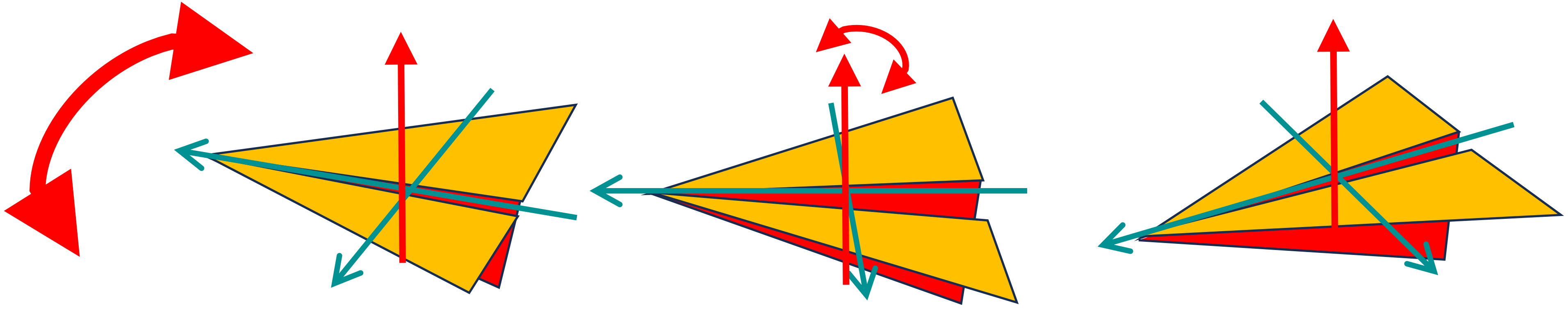
I.FAST workshop on bunch-by-bunch feedback systems, KIT, 05/Mar/2024

Pitch and Yaw Motion



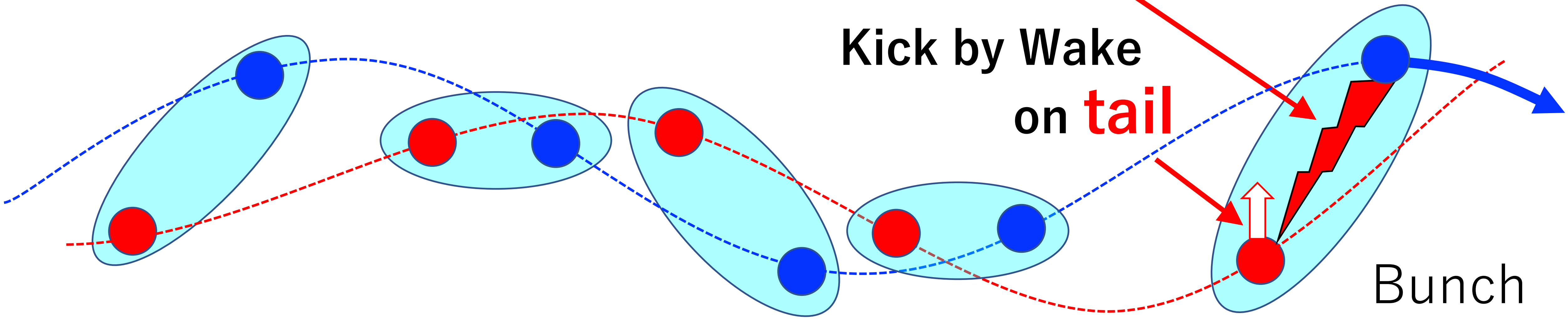
Pitch around **Lateral** axis

Yaw around **Vertical** axis



Single-bunch Instability

Head produces Wake => Kicks Tail
=> Different Orbit (Phase difference) => Pitch



Wake Field produced by
Bunch **head**

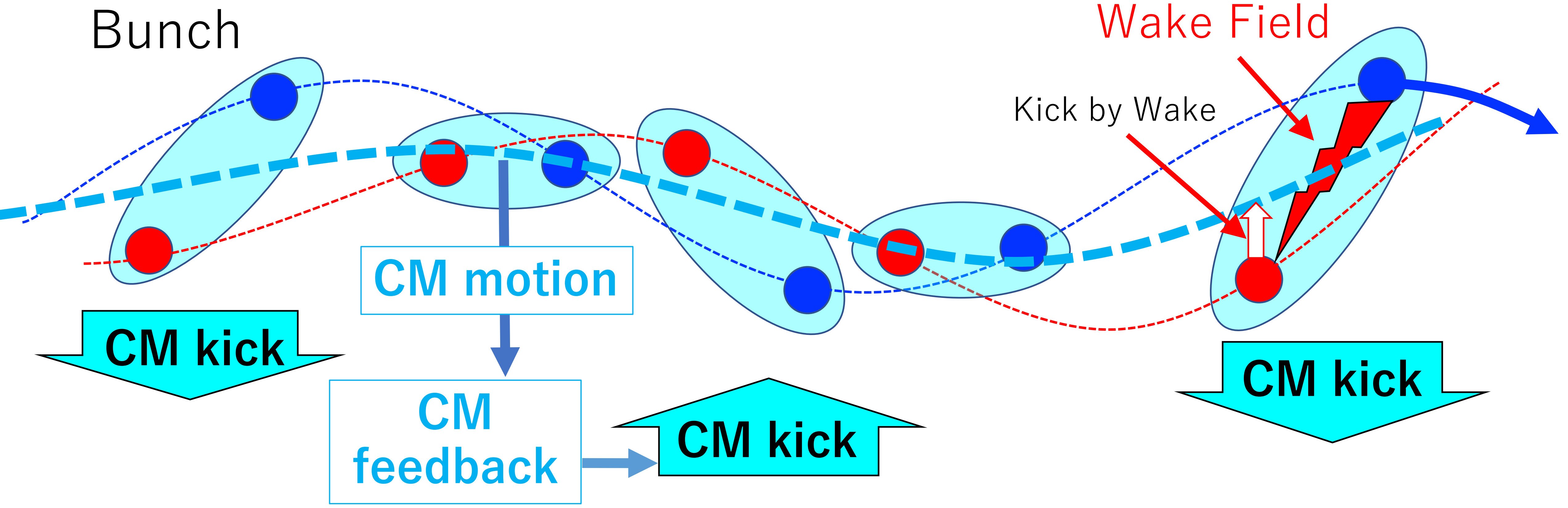
Kick by Wake
on tail

Bunch

This mechanism produces **Single Bunch Instabilities**
or Enlarging beam size (SuperKEKB : e-cloud ?)

Single-bunch Instability

Usual feedback : Center of Mass (CM) motion feedback



Bunch

Wake Field

Kick by Wake

CM motion

CM feedback

CM kick

CM kick

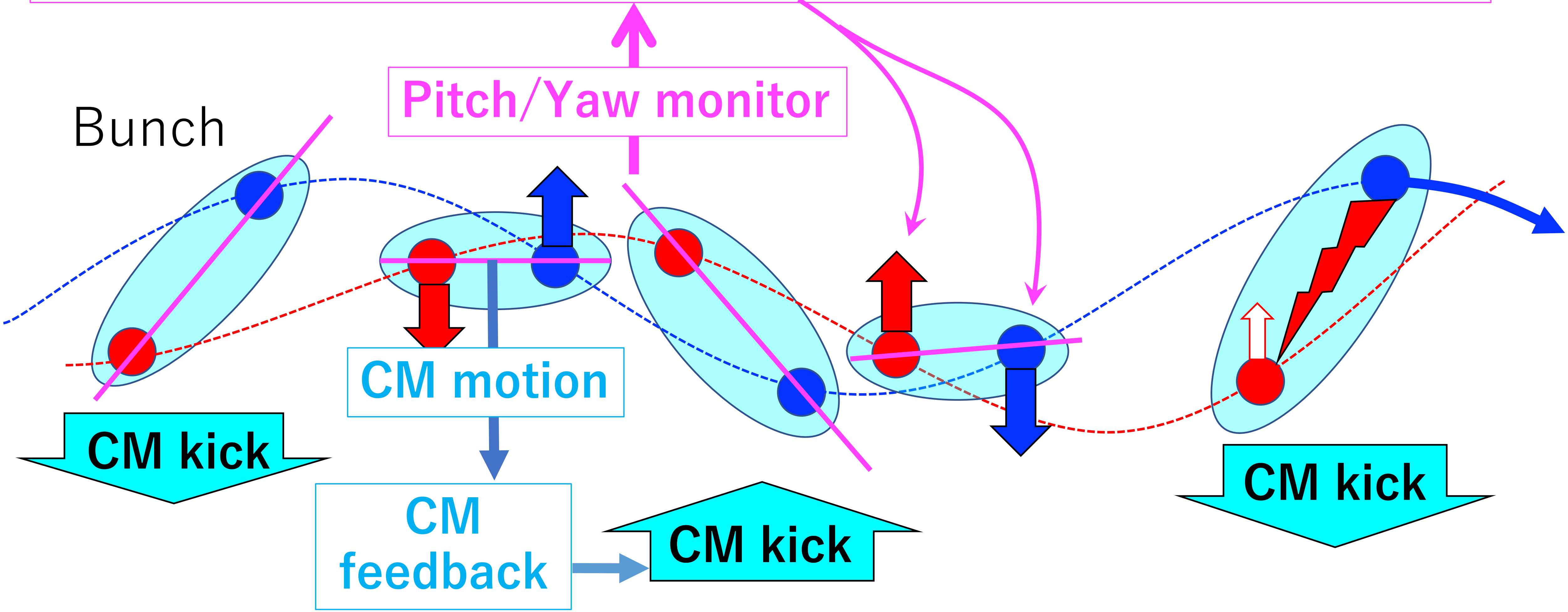
CM kick

Single-bunch Instability

Usual feedback : Center of Mass (CM) motion feedback

+

Pitch/Yaw Feedback (different kick for **head** and **tail)**



Bunch

Pitch/Yaw monitor

CM motion

CM feedback

CM kick

CM kick

CM kick

Single-bunch Instability

Later on, “Pitch” -> Pitch or Yaw

Development of
Bunch Pitch/Yaw Monitor
for pico-second bunch

T. NAKAMURA,　S. TERUI
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T. Nakamura, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THP0/THP089.pdf
T. Nakamura, https://www.pasj.jp/web_publish/pasj2022/proceedings/PDF/TUP0/TUP023.pdf
T. Nakamura, et al., https://www.pasj.jp/web_publish/pasj2023/proceedings/PDF/TWHP/TWHP02.pdf

This work was supported by JSPS KAKENHI Grant Number 23H03667 .

Pitch / Yaw monitor

- Using USUAL BPM electrodes
  - Button, Stripline, ..
- Realtime measurement as usual BPM
  - Bunch-by-bunch, turn-by-turn
- Simple Circuit

⬇

Pitch / Yaw Feedback

Realtime observation of single-bunch instabilities

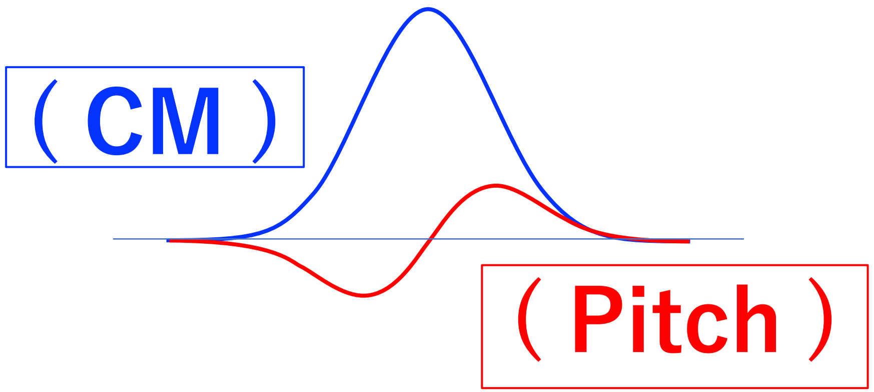
- Mode-coupling, Head-tail, ..

Bunch Charge Transverse Distribution with Pitch

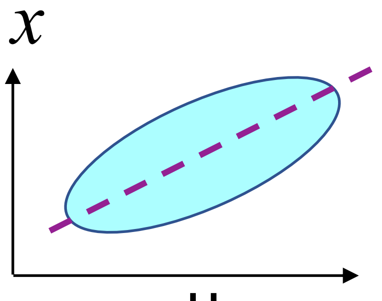
Slice Averaged Position

$$\boxed{\underline{\bar{x}}(t)\,\rho(t) \;\Rightarrow\; BPM}$$

$\bar{x}(t)\,\rho(t)$



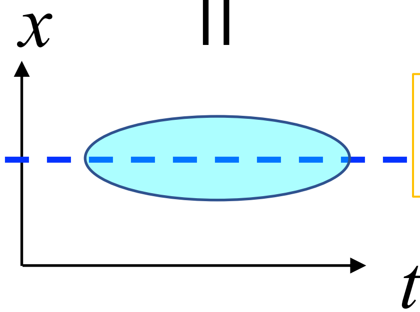
() shows Shape of function



$\boxed{\bar{x}(t)}$

$\boxed{\bar{x}(t)}$ $\boxed{\bar{x}(t)\,\rho(t)}$

$\|$ $\|$ $\|$



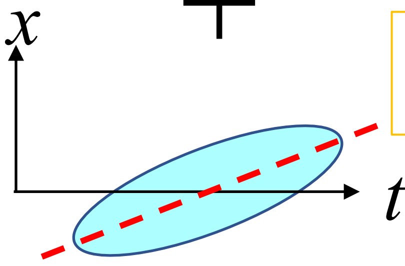
CM

$\boxed{\bar{x}(t)} \Rightarrow \boxed{x_{CM}}$

CM

$\boxed{x_{CM}\,\rho(t)}$

$+$ $+$ $+$



Pitch

$\boxed{\bar{x}(t)} \Rightarrow \boxed{k\,t}$

Pitch

$\boxed{k\,t\,\rho(t)}$

$$(\,k\,t\,\rho(t)\,) \sim \frac{d}{dt}(x_{CM}\,\rho(t))$$

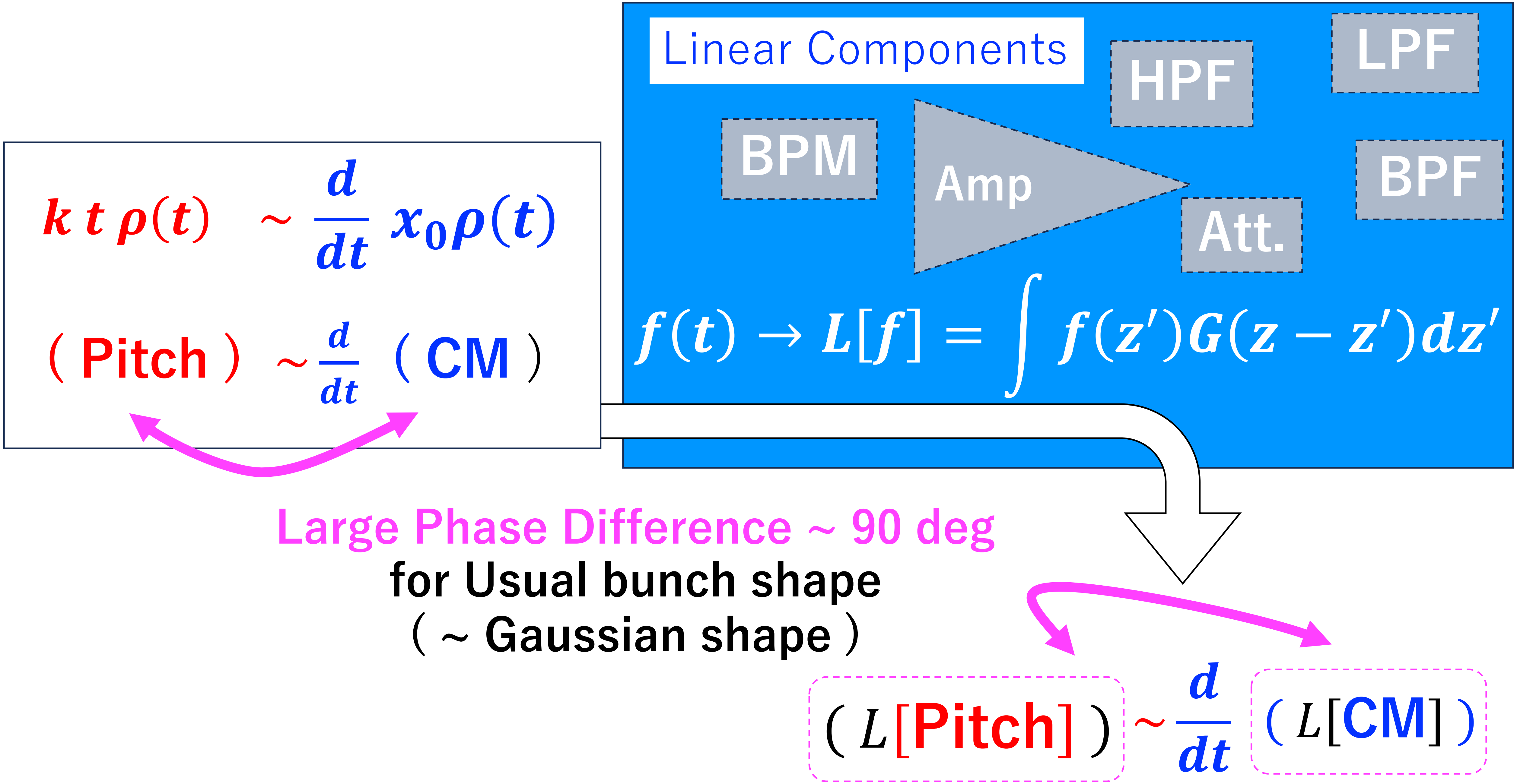
$$(\text{ Pitch }) \sim \frac{d}{dt}\,(\text{ CM })$$

Solution

$\rho(t) \sim A\,e^{-a\,t^2}$

Gaussian Bunch

Head-tail Monitor



$$k\,t\,\rho(t) \sim \frac{d}{dt} x_0\rho(t)$$

$$(\,\text{Pitch}\,) \sim \frac{d}{dt}(\,\text{CM}\,)$$

$$f(t) \to L[f] = \int f(z')G(z-z')dz'$$

Large Phase Difference ~ 90 deg

for Usual bunch shape

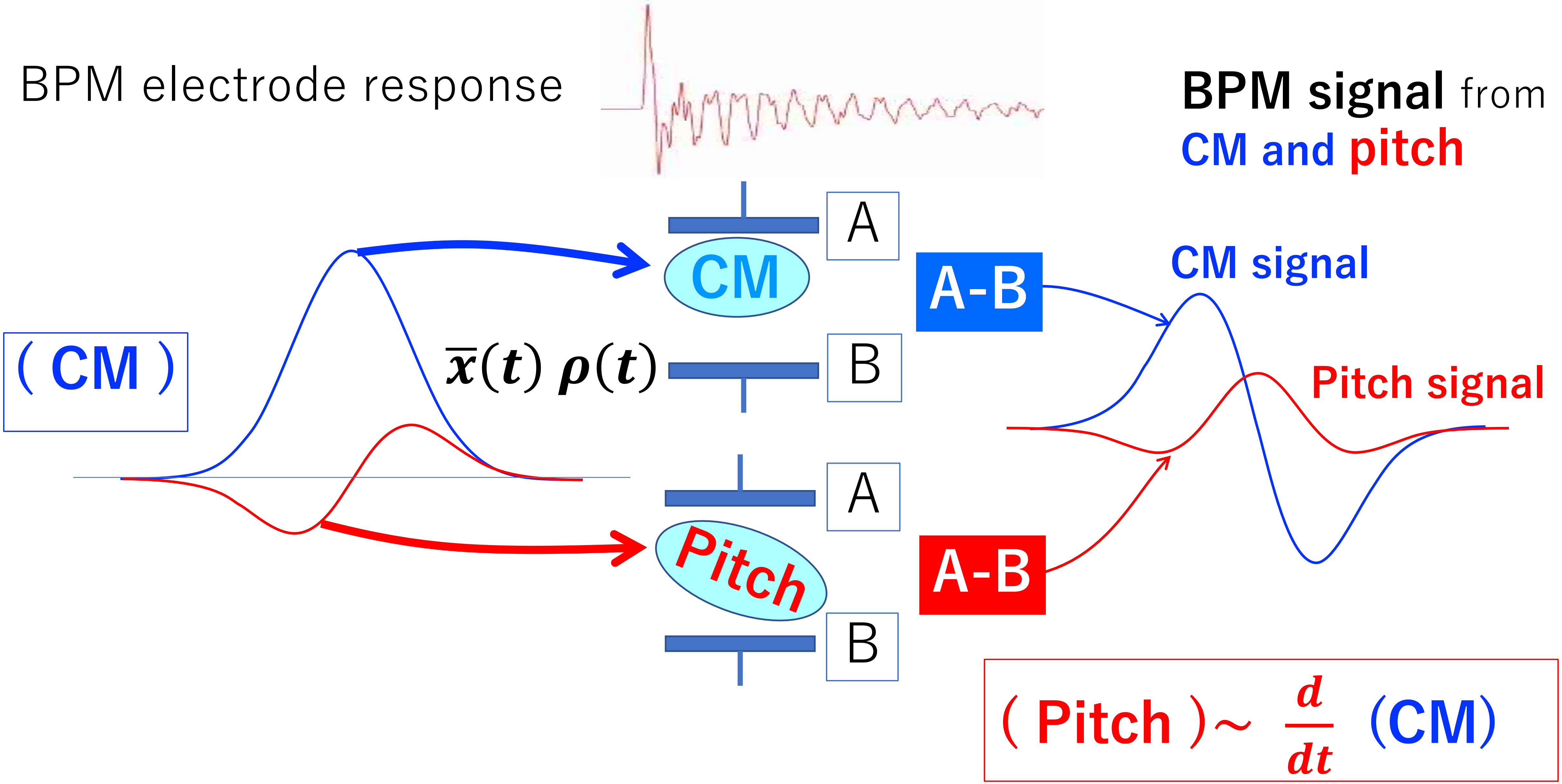
(~ Gaussian shape)

$$(\,L[\text{Pitch}]\,) \sim \frac{d}{dt}(\,L[\text{CM}]\,)$$

Head-tail Monitor

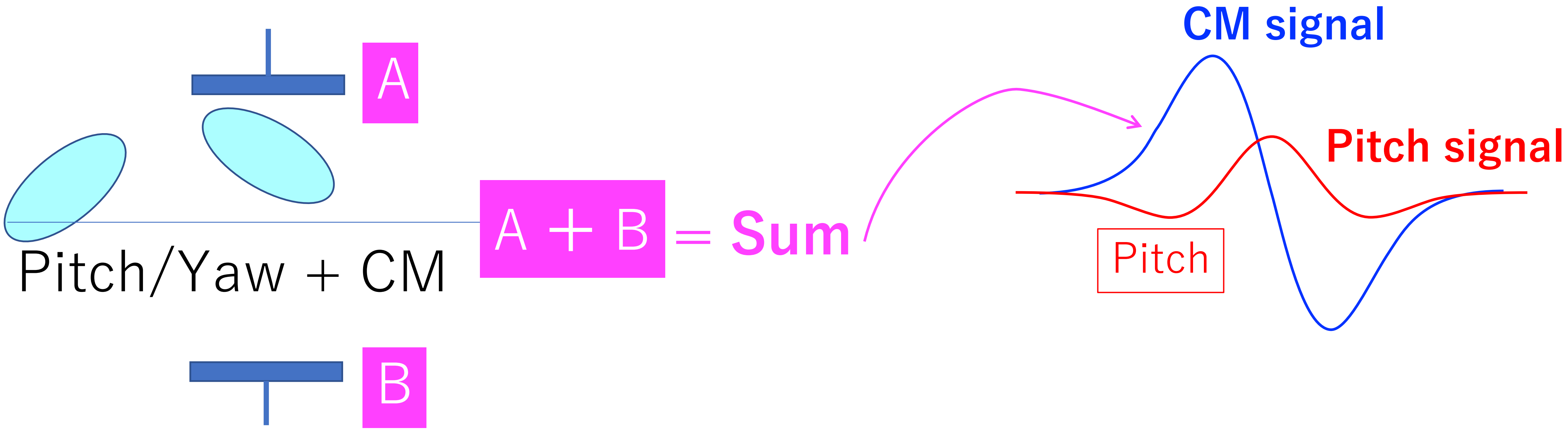
BPM electrode response

BPM signal from
CM and pitch



$$(\text{Pitch}) \sim \frac{d}{dt}(\text{CM})$$

Head-tail Monitor



CM signal $<= x_0\rho(t)$

Sum signal $<= \rho(t)$

(Sum) ~ (CM)

Sum and CM have same shape

Signal Shapes of Pitch, CM and SUM

$$(\text{ CM }) \sim (\text{ Sum })$$

$$(\text{ Pitch }) \sim \frac{d}{dt}(\text{ CM }) \sim \frac{d}{dt}(\text{ Sum })$$

Relation 1

90 degree

(Pitch) ⇐ **Phase shift** ⇒ (CM) and (Sum)

in ALL frequency

Relation 2

$$\int_{Bucket} (\text{ CM }) \times \frac{d}{dt}(\text{ Sum })\, dt \sim 0$$

$$\int_{Bucket} (\text{CM}) \times \frac{d}{dt}(\text{Sum})\, dt \sim \int_{Bucket} (\text{CM }) \times \frac{d}{dt}(\text{CM})\, dt = \int_{Bucket} \frac{1}{2}\frac{d}{dt}(\text{CM})^2 dt = \frac{1}{2}\left[(\text{CM})^2\right]_{bucket\ start}^{bucket\ end} = 0$$

(CM signal(bucket_start) = CM signal(bucket_end) = 0)

Signal Shapes of Pitch, CM and SUM

Relation 2

$$\int_{\boldsymbol{Bucket}} (\,\mathbf{CM}\,) \times \frac{\boldsymbol{d}}{\boldsymbol{dt}} (\,\mathbf{Sum}\,)\, \boldsymbol{dt} \sim \mathbf{0}$$

Pitch Monitor Circuit for 2ns bunch Separation

Pitch Monitor Circuit for 2ns bunch Separation

$$\boxed{\int_{Bucket} (\,\mathrm{CM}\,) \times \frac{d}{dt}\,(\,\mathrm{Sum}\,)\; dt \sim 0}$$

$$\boxed{(\,\mathrm{Pitch}\,) \sim \frac{d}{dt}(\,\mathrm{CM}\,) \sim \frac{d}{dt}(\,\mathrm{Sum}\,)}$$

$$\begin{aligned}
(\mathrm{BPM}) &= A_{CM}\times(\mathrm{CM}) + A_{Pitch}\times(\mathrm{Pitch}) \\
&= A_{CM}\times(\mathrm{CM}) + A_{Pitch}\times D\frac{d}{dt}\,(\mathrm{Sum}) \\
(\mathrm{BPM})\mathrm{x}\frac{d}{dt}(\mathrm{Sum}) &= \underline{A_{CM}\times(\mathrm{CM})\mathrm{x}\frac{d}{dt}(\mathrm{Sum})} + \underline{A_{Pitch}\times D\left(\frac{d}{dt}\,(\mathrm{Sum})\right)^2}
\end{aligned}$$

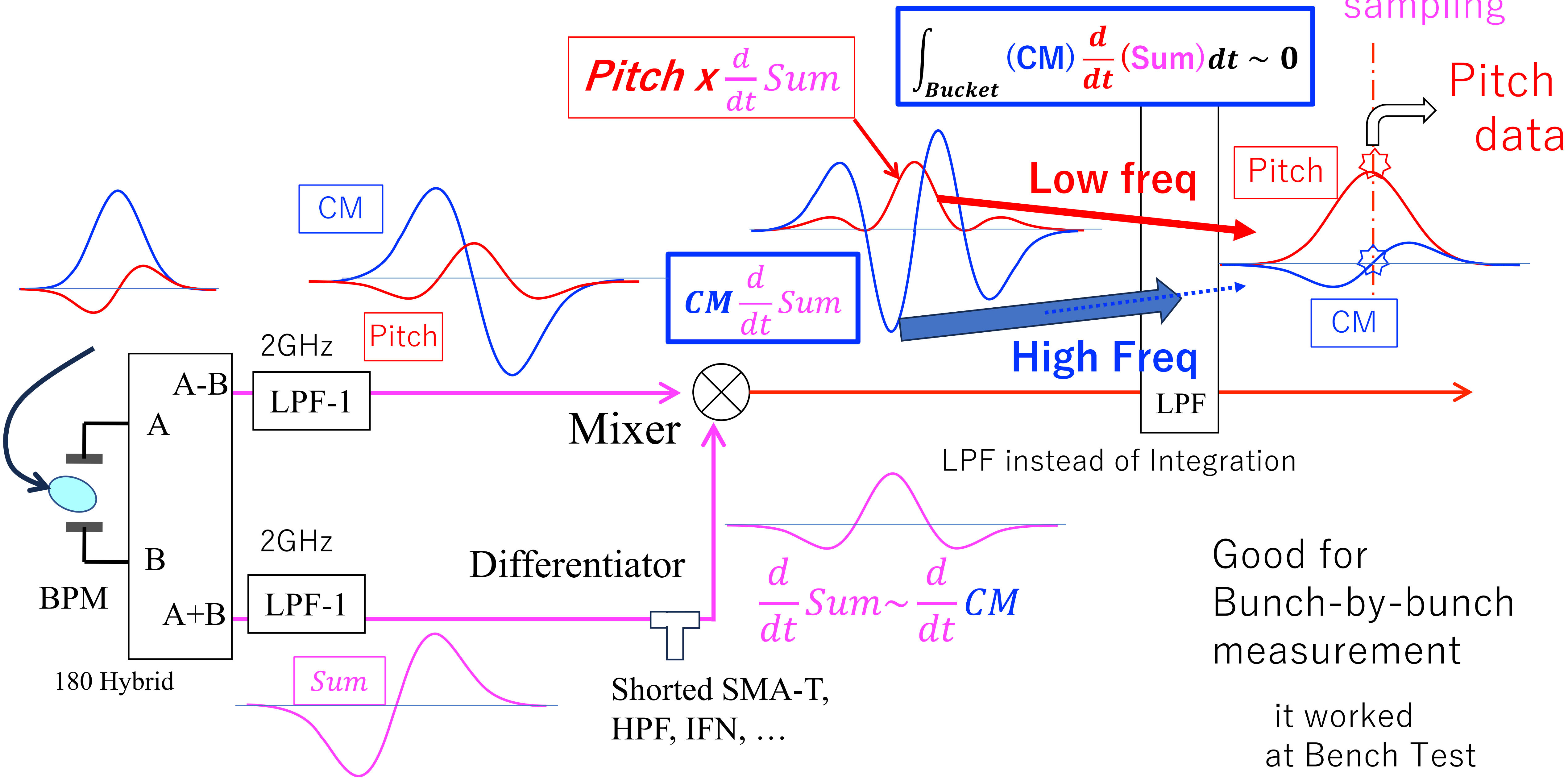
$$\boxed{\int_{Bucket} dt}$$

$$\boxed{\int_{Bucket} (\,\mathrm{CM}\,)\times\frac{d}{dt}\,(\,\mathrm{Sum}\,)\; dt \sim 0}$$

$$\int_{Bucket} (\mathrm{BPM})\mathrm{x}\frac{d}{dt}\,(\,\mathrm{Sum}\,)\; dt = A_{Pitch}\; D\times\int_{Bucket}\left(\frac{d}{dt}\,(\,\mathrm{Sum}\,)\right)^2 dt \;\propto\; \boxed{A_{Pitch}}$$

Suppressing **CM signal** (A_{CM}) => **Pitch signal** (A_{Pitch}) extracted

Pitch Monitor Circuit for 2ns bunch Separation



$\int_{Bucket} (\mathrm{CM}) \frac{d}{dt} (\mathrm{Sum})\, dt \sim 0$

$Pitch\ x\ \frac{d}{dt} Sum$

$CM \frac{d}{dt} Sum$

$\frac{d}{dt} Sum \sim \frac{d}{dt} CM$

LPF instead of Integration

Shorted SMA-T,
HPF, IFN, …

Good for
Bunch-by-bunch
measurement

it worked
at Bench Test

Signal Shapes of Pitch, CM and SUM

$$(\text{CM}) \sim (\text{Sum})$$

$$(\text{Pitch}) \sim \frac{d}{dt}(\text{CM}) \sim \frac{d}{dt}(\text{Sum})$$

⇓

Relation 1

$$(\text{Pitch}) \Leftarrow \begin{array}{c}\textbf{90 degree}\\ \textbf{Phase shift}\\ \textbf{in ALL frequency}\end{array} \Rightarrow (\text{CM}) \text{ and } (\text{Sum})$$

Relation 2

$$\int_{Bucket} (\text{CM}) \times \frac{d}{dt}(\text{Sum})\, dt \sim 0$$

$$\int_{Bucket} (\text{CM}) \times \frac{d}{dt}(\text{Sum})\, dt \sim \int_{Bucket} (\text{CM}) \times \frac{d}{dt}(\text{CM})\, dt = \int_{Bucket} \frac{1}{2}\frac{d}{dt}(\text{CM})^2 dt = \frac{1}{2}\left[(\text{CM})^2\right]_{bucket\ start}^{bucket\ end} = 0$$

(CM signal(bucket_start) = CM signal(bucket_end) = 0)

Signal Shapes of Pitch, CM and SUM

$$(\text{CM}) \sim (\text{Sum})$$

$$(\text{Pitch}) \sim \frac{d}{dt}(\text{CM}) \sim \frac{d}{dt}(\text{Sum})$$

Relation 1

(Pitch) ⇐ 90 degree Phase shift in ALL frequency ⇒ (CM) and (Sum)

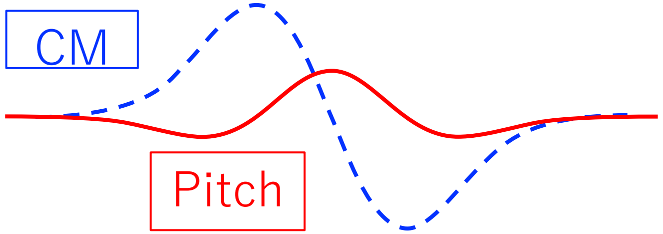
Pitch Monitor Circuit for ~ 6-8ns Bunch Separation

but rather Easy

Pitch Monitor Circuit for ~ 6-8ns Bunch Separation (but Easy)

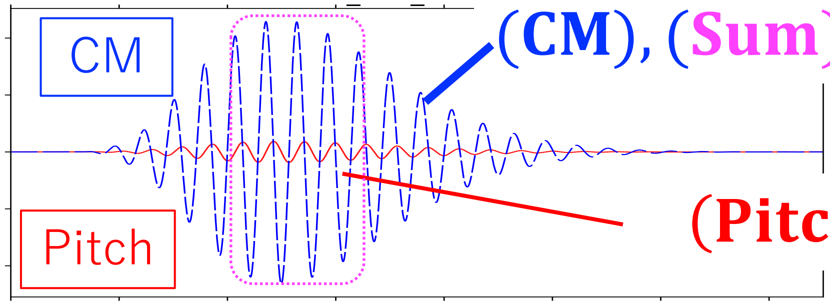
Relation 1

(Pitch) ⇐ ~ 90 degree difference *in ALL Frequency components* ⇒ (CM) and (Sum)



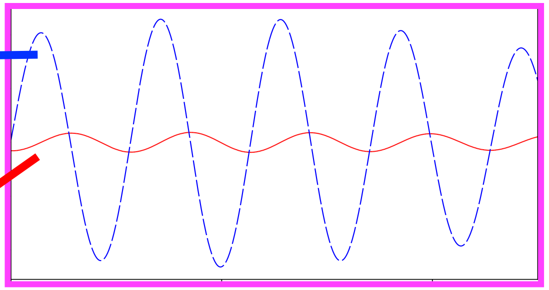
Band Pass Filter (BPF)

90 degree Phase difference



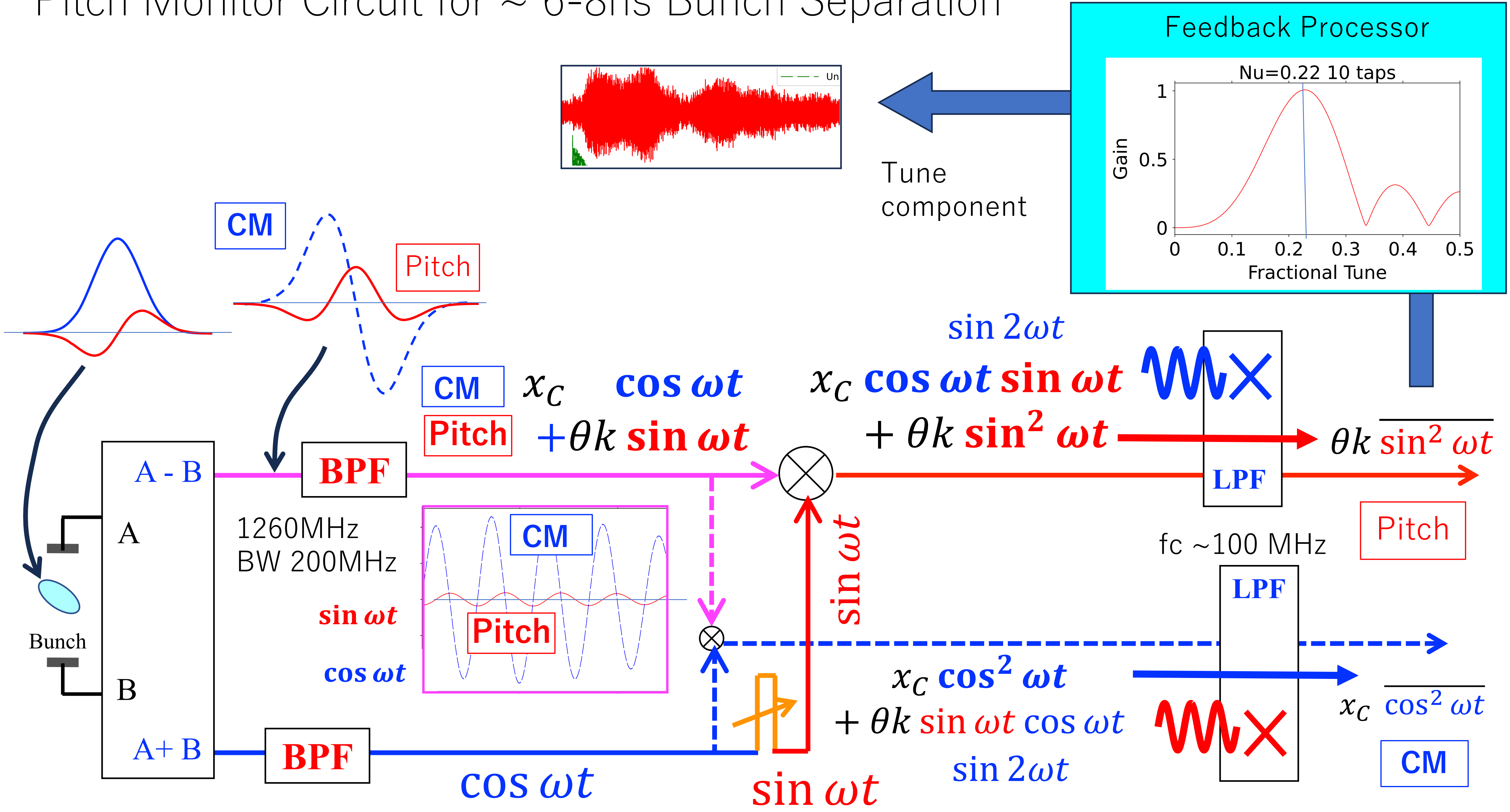
(CM), (Sum) ~ $\cos \omega t$

(Pitch) ~ $\sin \omega t$



BPF[Pitch] ⇐ ~ 90 degree difference *in ALL Frequency components* ⇒ BPF[CM] and BPF[Sum]

Pitch Monitor Circuit for ~ 6-8ns Bunch Separation



Tune component

CM x_c **$\cos\omega t$**

Pitch $+\theta k$ **$\sin\omega t$**

1260MHz
BW 200MHz

$x_c \cos\omega t \sin\omega t$

$+ \theta k \sin^2\omega t$

$\sin 2\omega t$

$\theta k \overline{\sin^2\omega t}$

Pitch

$\sin\omega t$

fc ~100 MHz

$x_c \cos^2\omega t$

$+ \theta k \sin\omega t \cos\omega t$

$\sin 2\omega t$

$x_c \overline{\cos^2\omega t}$

CM

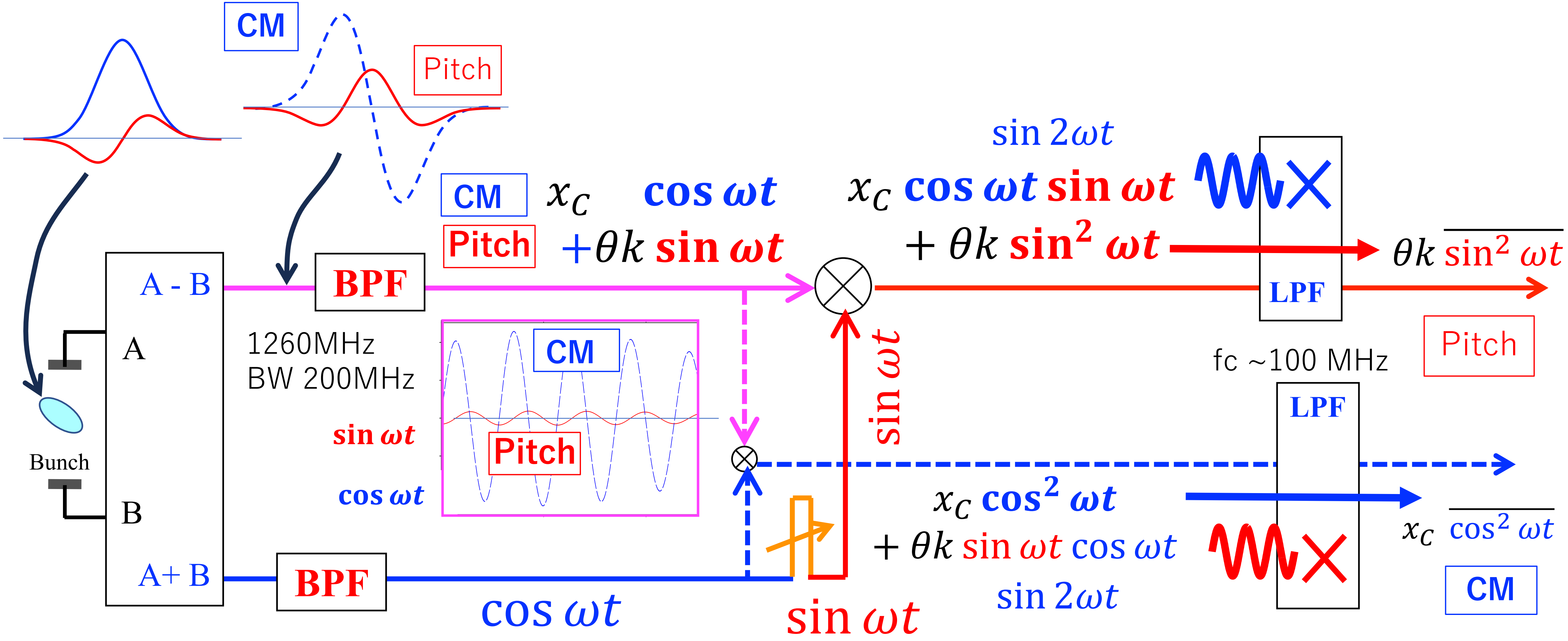
$\cos\omega t$

$\sin\omega t$

Beam Test with

Pitch Monitor Circuit with Relation 1

(Pitch Monitor Circuit for ~ 6-8ns Bunch Separation)



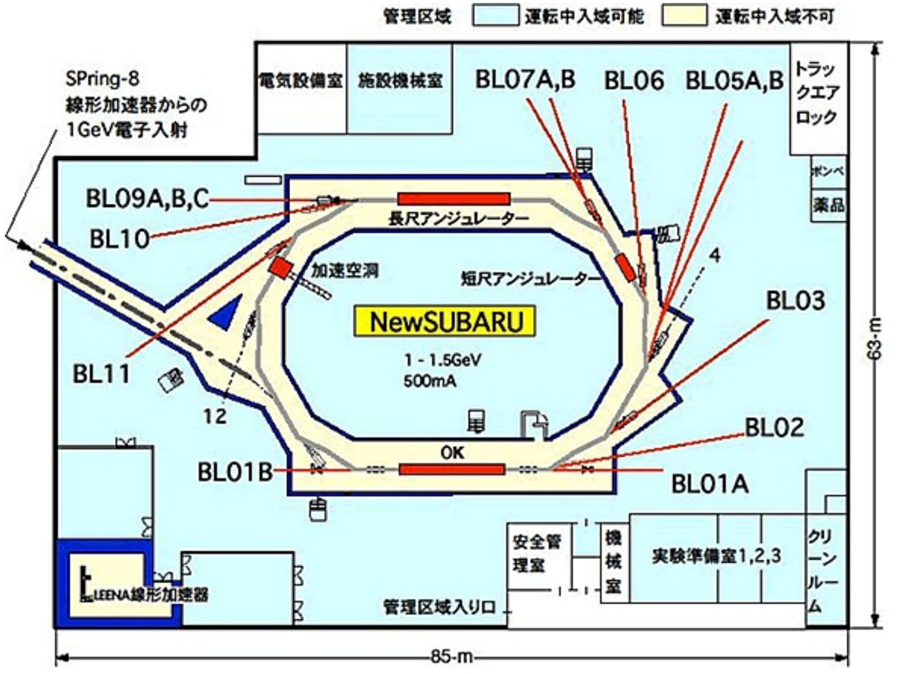
Beam Test with NewSUBARU Electron Storage Ring

Ring Parameters	
Energy	1 GeV
Momentum compaction factor (α)	**1×10^{-3}**
Energy spread (σ_δ)	**0.04 %**
Revolution Frequency (f_0)	2.525 MHz
Vertical tune	2.22
Nominal vertical chromaticity (ξ)	5

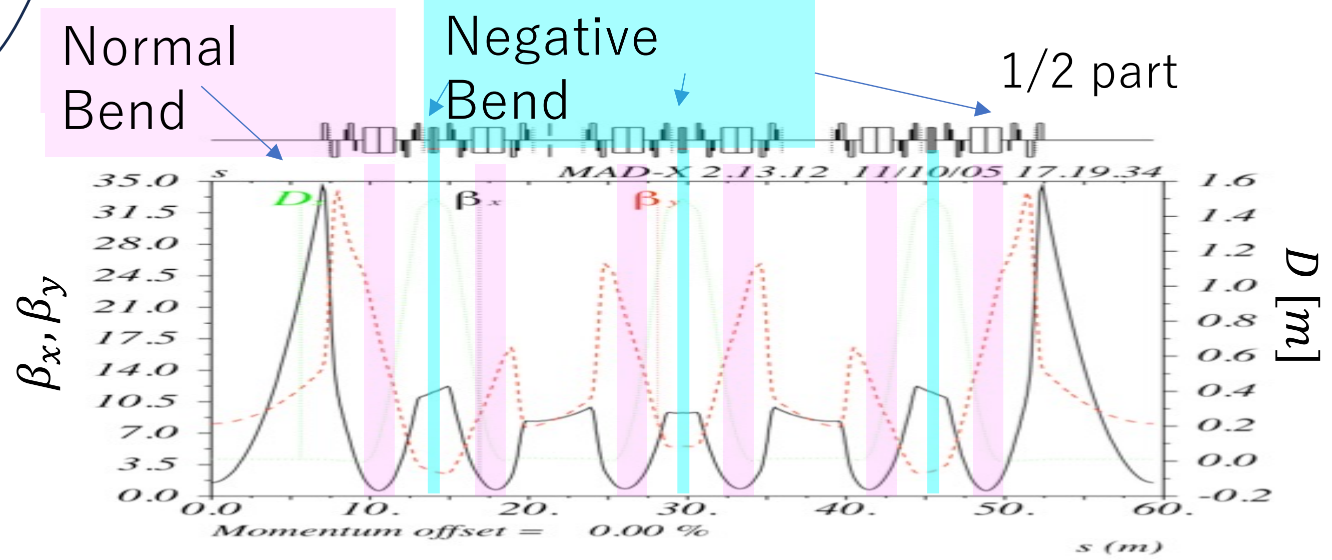
⇒Low Synchrotron Frequency
($f_s \propto \sqrt{\alpha}$)

Univ. of Hyogo
(SPring-8 site)

1-1.5GeV
Light Source



※モーメンタム・コンパクション・ファクター: 運動量圧縮率。異なる運動量の電子を同じ軌道で蓄積周回させる程度を表す。
“0”近くでは短バンチ電子ビームが可能であるが、“0”では不安定となる。



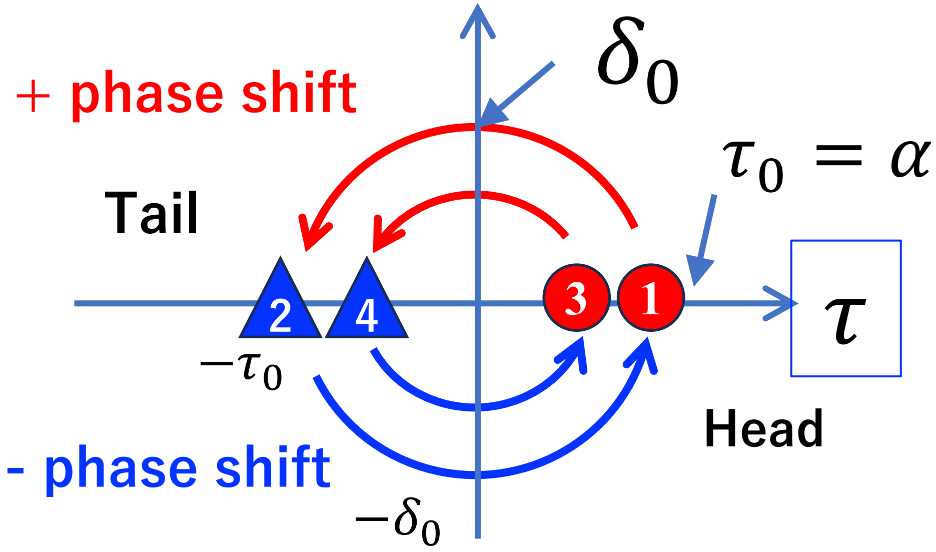
Normal Bend

Negative Bend

1/2 part

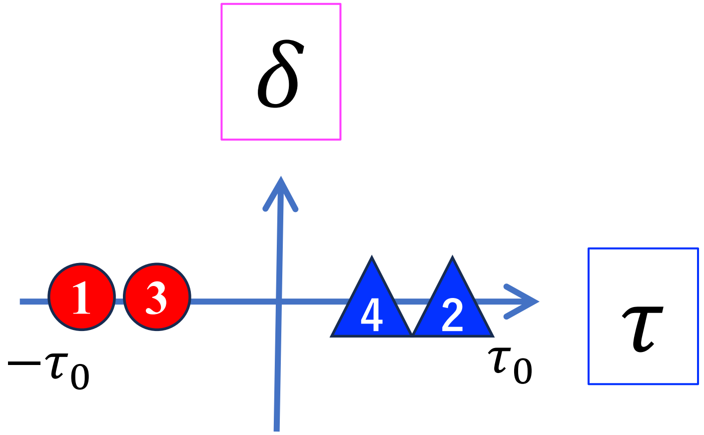
Chromaticity Convert CM motion to Pitch motion

$\delta = \Delta E/E$



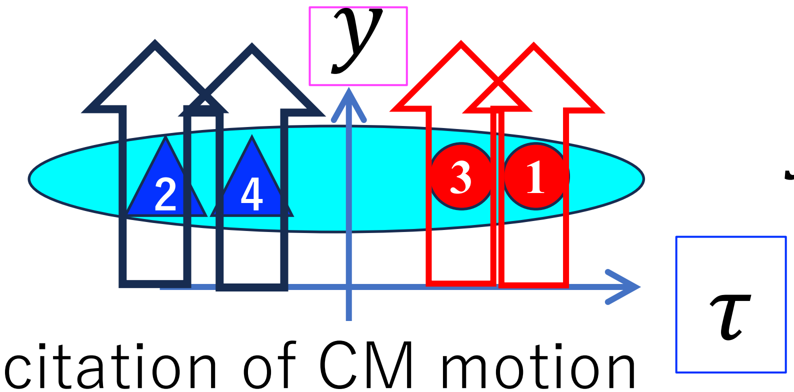
$$\tau_0 = \alpha \frac{\delta_0}{\omega_s}$$

Half Synchrotron Osci. Period



① $\delta(t) = \delta_0 \sin \omega_s t$

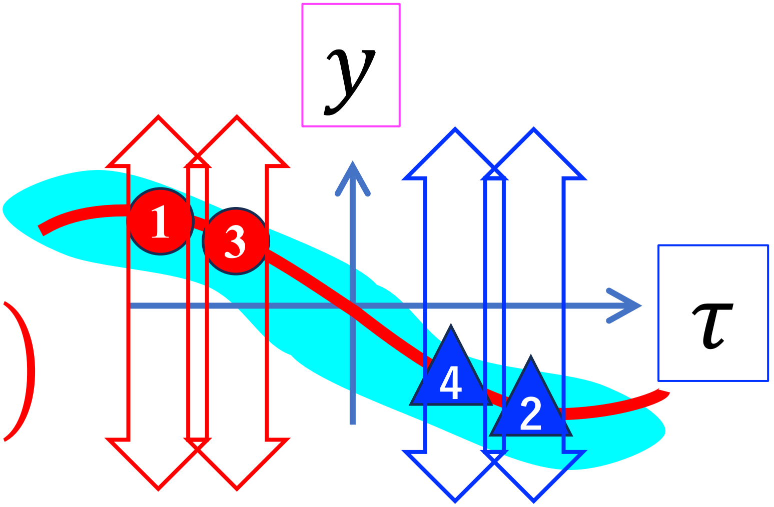
$$\Delta\omega_\beta(t) = \omega_0 \xi \delta(t)$$



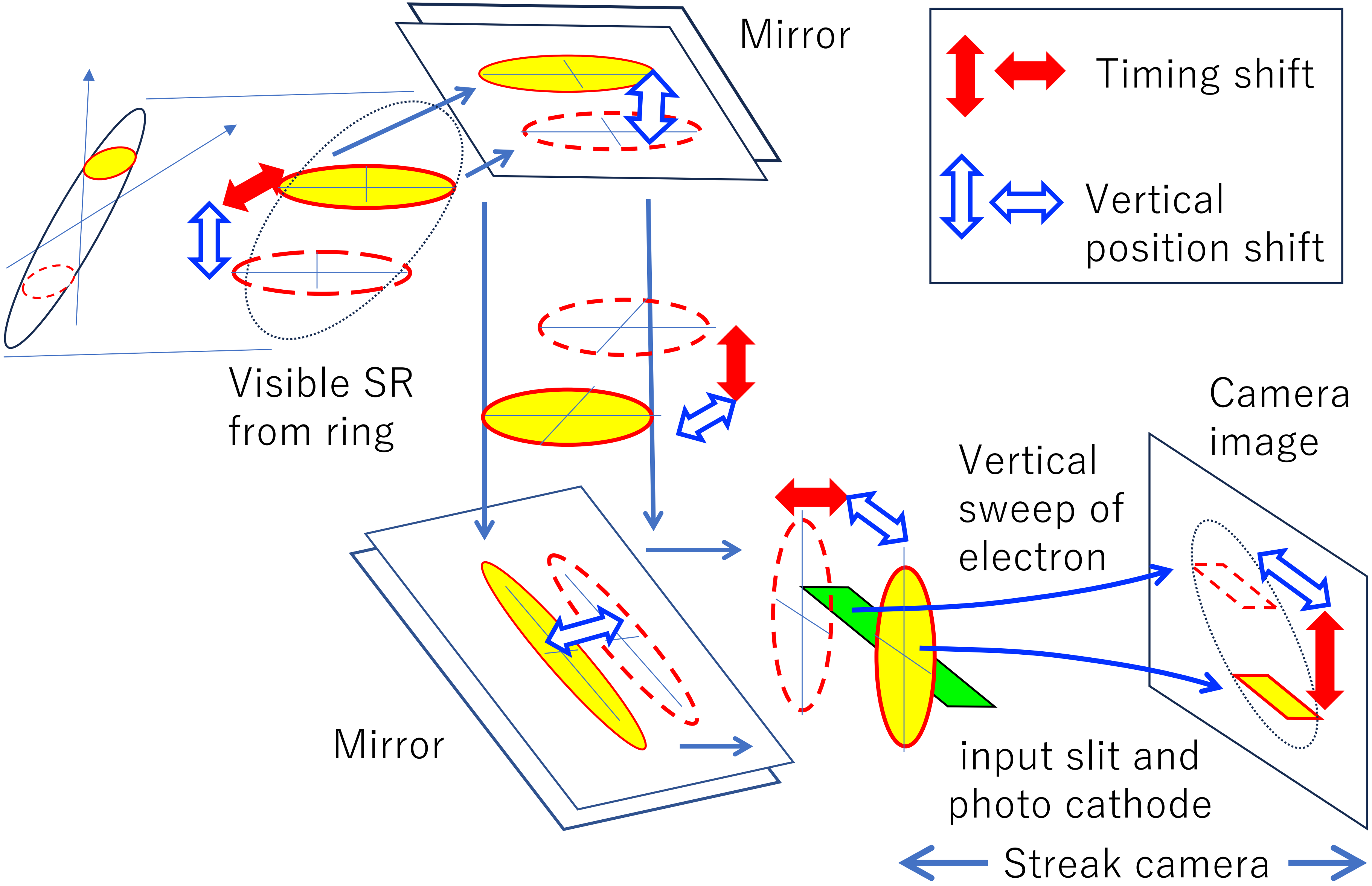
Excitation of CM motion by single kick

$$\int_0^{\frac{T_s}{2}} \Delta\omega_\beta(t)dt = 2\xi\omega_0 \frac{\tau_0}{\alpha}$$

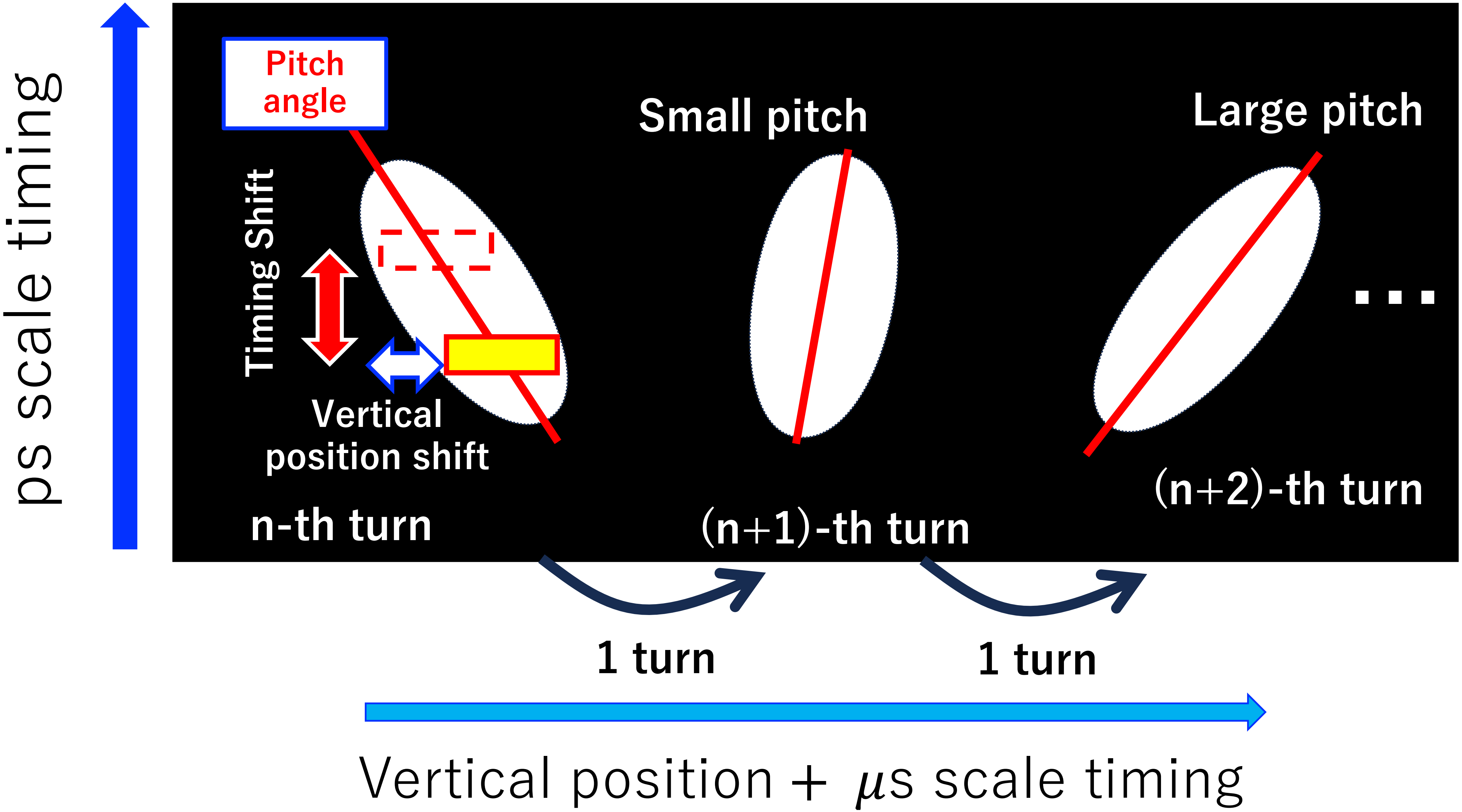
$$y(\tau) \propto \sin\left(2\xi\omega_0 \frac{\tau}{\alpha}\right)$$



Pitch Measurement with Streak Camera



Turn-by-turn Bunch Images in Streak Camera



ps scale timing

Pitch angle

Timing Shift

Vertical position shift

n-th turn

Small pitch

(n+1)-th turn

Large pitch

(n+2)-th turn

. . .

1 turn

1 turn

Vertical position + μs scale timing

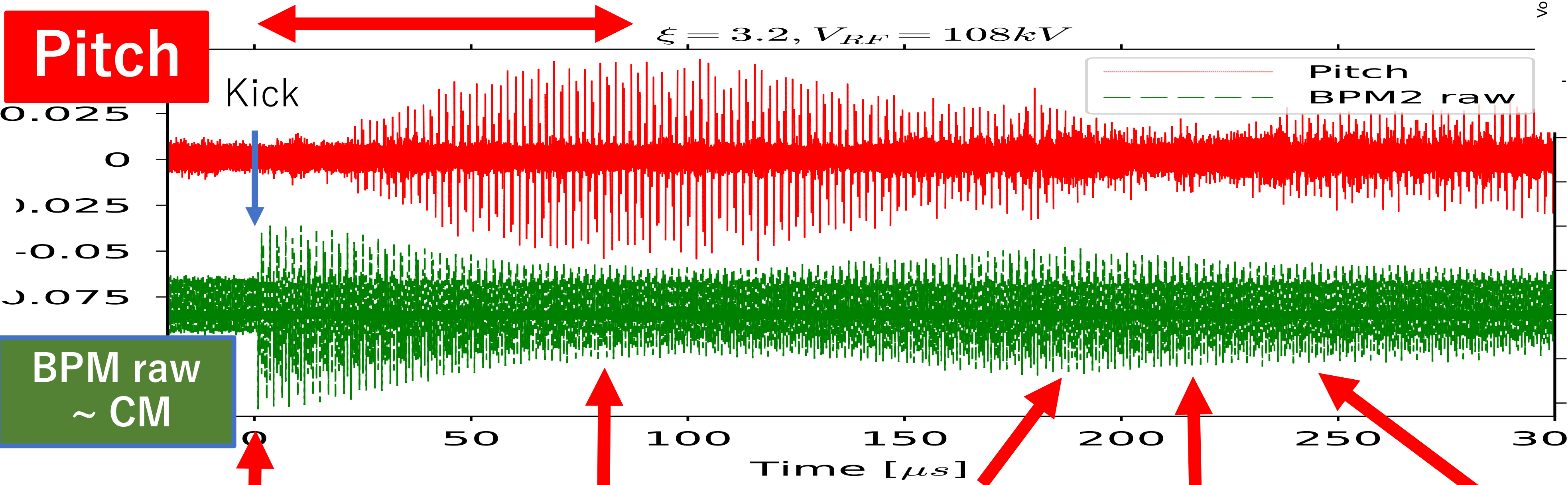
Pitch Monitor Circuit with Relation 1 and Streak Camera Images

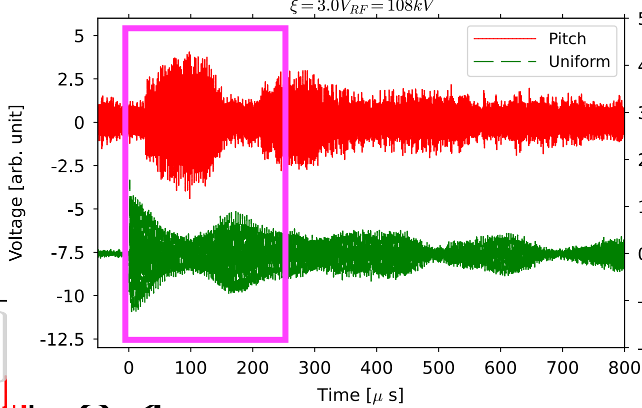
Half **Synchrotron Oscillation** Period

Pitch

Kick

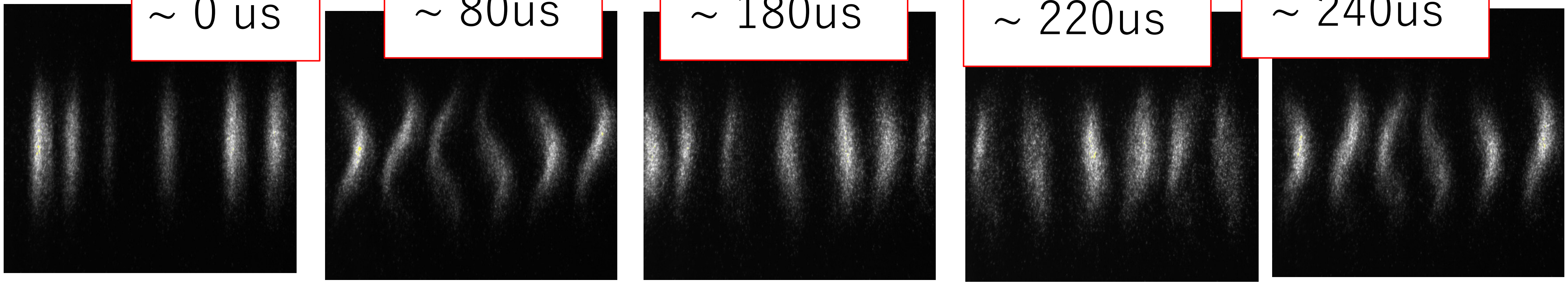
BPM raw ~ CM





VRF = 108kV

Chromaticity ξ= 3.2



~ 0 us

~ 80us

~ 180us

~ 220us

~ 240us

Mostly CM

Large Pitch

Pitch reduced

Mostly CM

Pitch comes back

Fractional Betatron tune 0.22

Streak Camera Images

Measurement

Simulation: ξ and V_{RF} are Adjusted to reproduce data

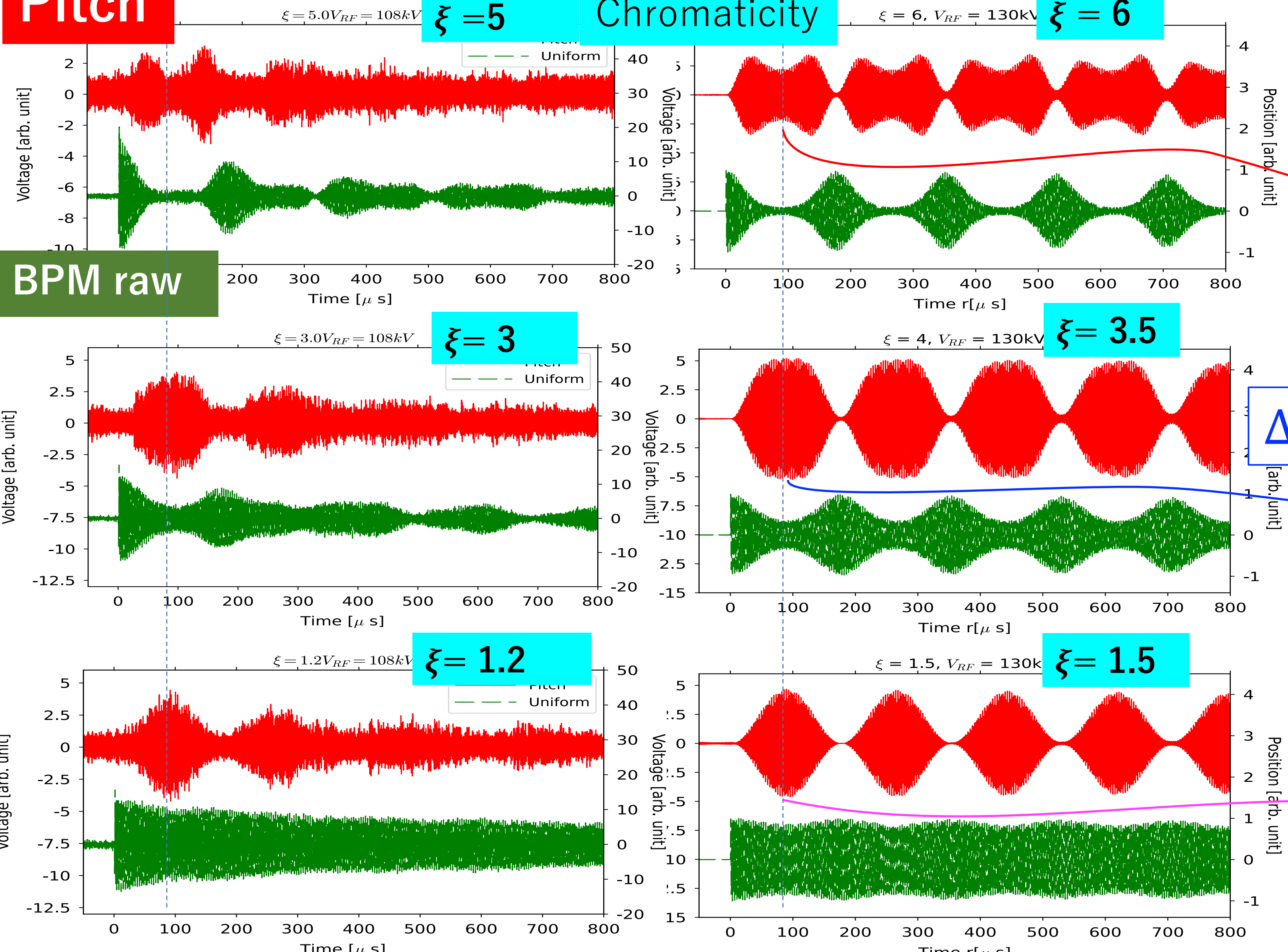
V_{RF} = 108kV

V_{RF} = 130kV

Pitch

BPM raw

Chromaticity



$$\nu_s = 0.0023$$

$$\boxed{\Delta\psi(\sigma_\tau) = 2\xi\omega_0\frac{\sigma_\tau}{\alpha}}$$

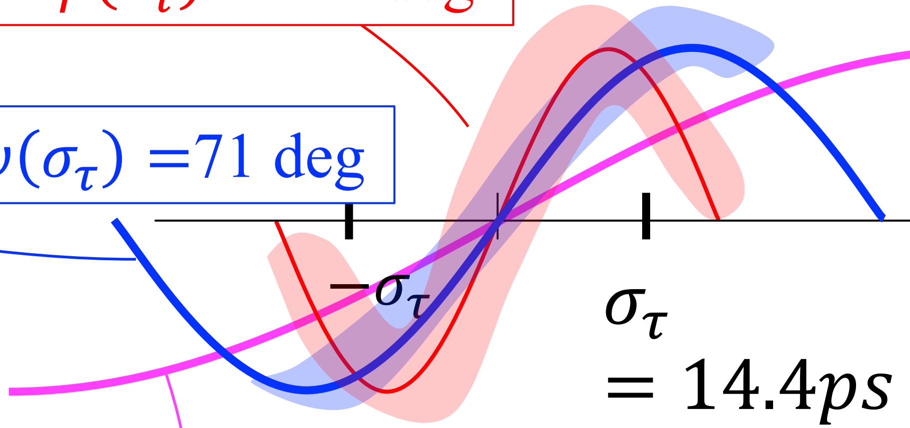
Large tune shift ($\Delta\psi(\sigma_\tau)$)

->

Reduction of Pitch

$\Delta\psi(\sigma_\tau)$ =121 deg

$\Delta\psi(\sigma_\tau)$ =71 deg



$\Delta\psi(\sigma_\tau)$ = 30 deg

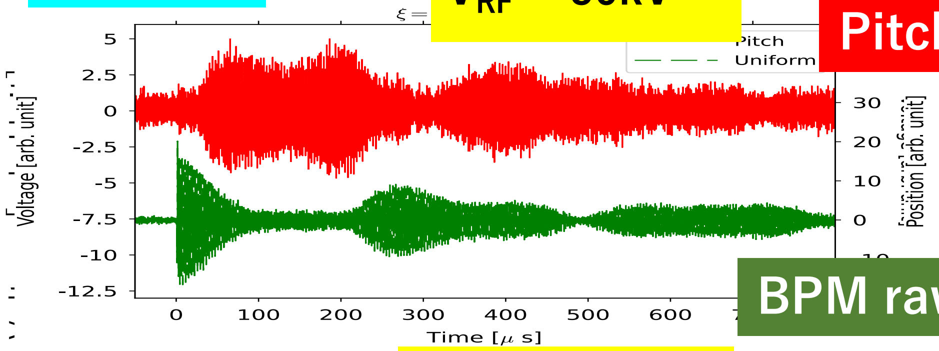
Chromaticity : Fix

Pitch Monitor Circuit with Relation 1

Simulation: ξ and V_{RF} are Adjusted to reproduce data

Measurement

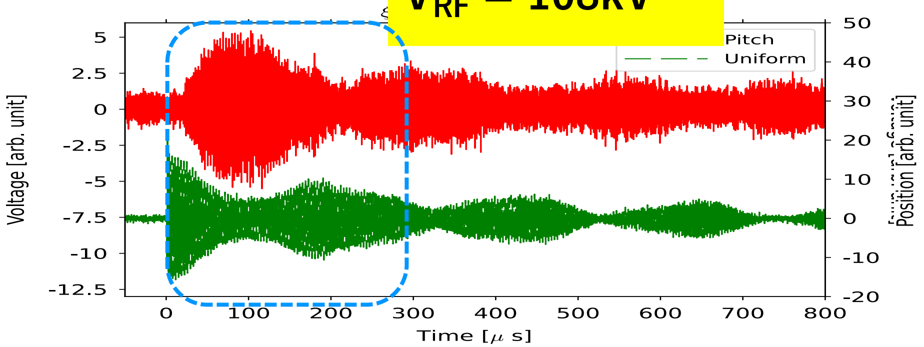
$\xi = 3.2$



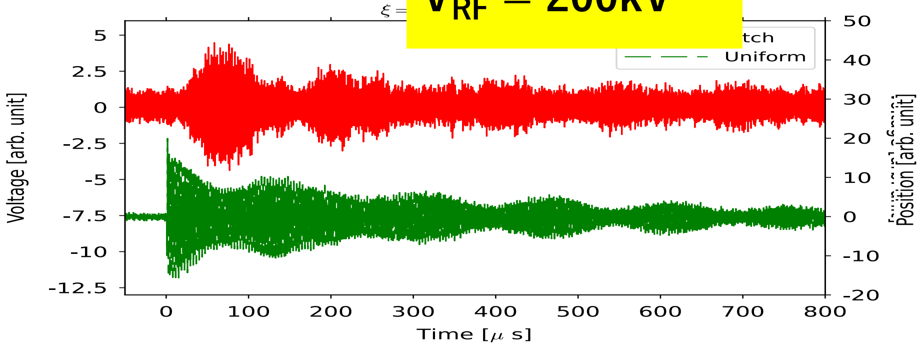
V_{RF} = 50kV

Pitch

BPM raw

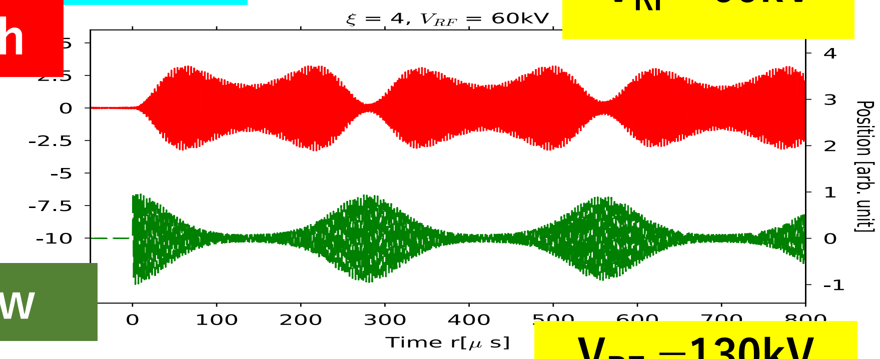


V_{RF} = 108kV

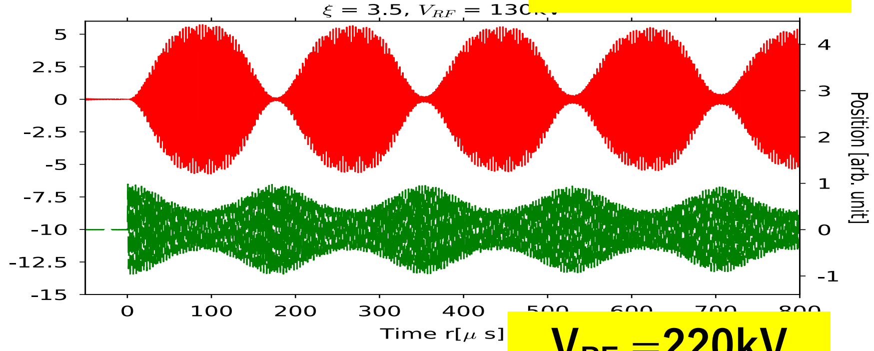


V_{RF} = 200kV

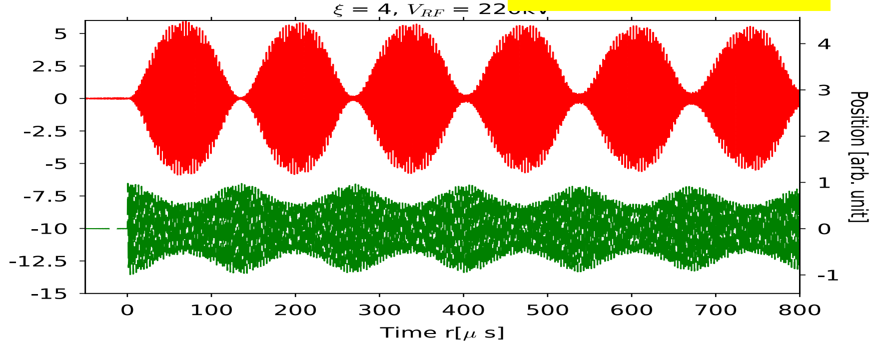
$\xi = 4$



V_{RF} =60kV



V_{RF} =130kV



V_{RF} =220kV

$$\Delta\psi(\sigma_\tau) = 2\xi\omega_0\frac{\sigma_\tau}{\alpha} = 2\xi\frac{\sigma_\delta}{\nu_s}$$

$\nu_s = 0.0014$
$\sigma_\tau = 23\ ps$

$\Delta\psi(\sigma_\tau) = 128$ deg

$\nu_s = 0.0023$
$\sigma_\tau = 14\ ps$

$\Delta\psi(\sigma_\tau) = 81$ deg

$\nu_s = 0.0030$
$\sigma_\tau = 11\ ps$

$\Delta\psi(\sigma_\tau) = 61$ deg

Proposal of Kickers for Pitch Feedback

Kick head and tail with Different Strength

↳ Large Value of $\frac{dV_K(\tau)}{d\tau}$ is Required

1) High Q Resonant Kicker
for **ISOLATED** singlet bunch

2) Low Q Resonant Kicker
for **Bunch-by-bunch** Pitch Feedback

3) Short Stripline Transverse Kicker driven by Multiple-Pulses
for **Bunch-by-bunch** Pitch Feedback

T. Nakamura, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THP0/THP089.pdf
T. Nakamura, https://www.pasj.jp/web_publish/pasj2022/proceedings/PDF/TUP0/TUP023.pdf

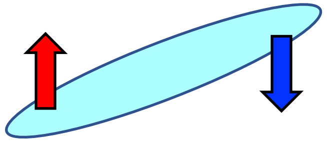
1) High Q Resonant Kicker

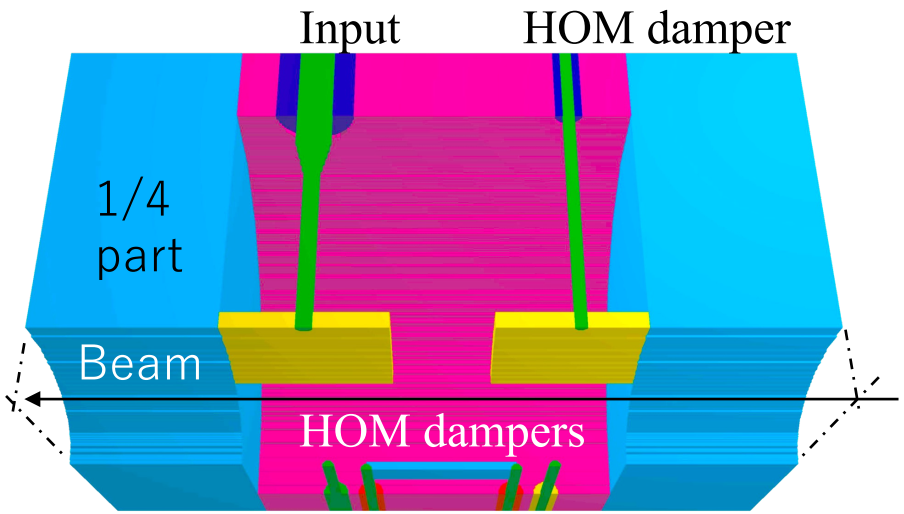
Resonant Kicker

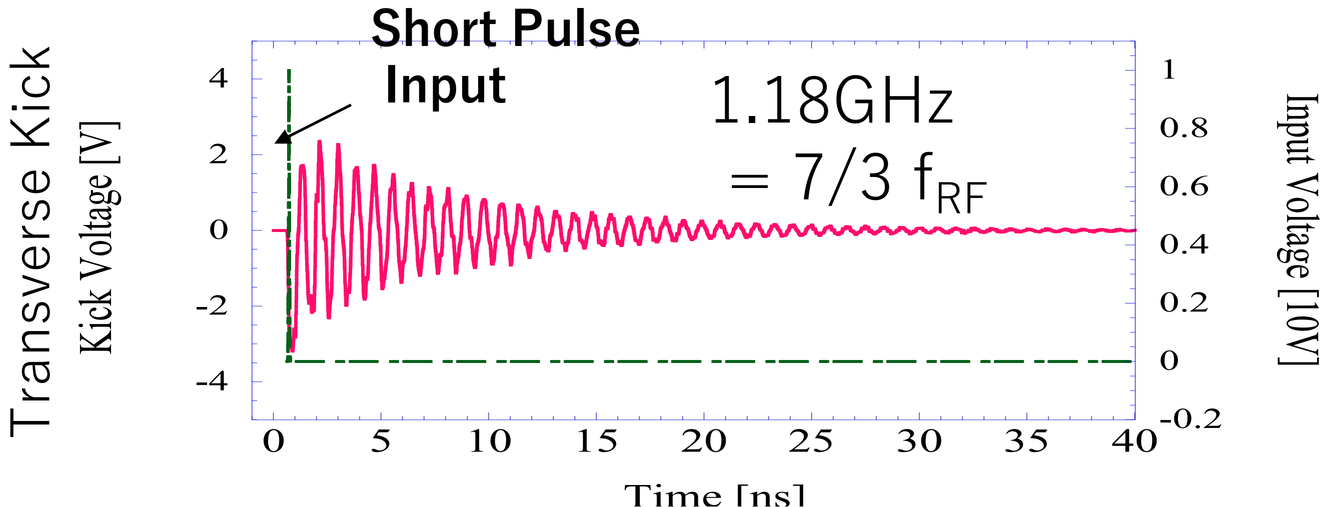
Based on SPring-8 longitudinal kicker*

Different kick for head ant tail

High dV_K/dt

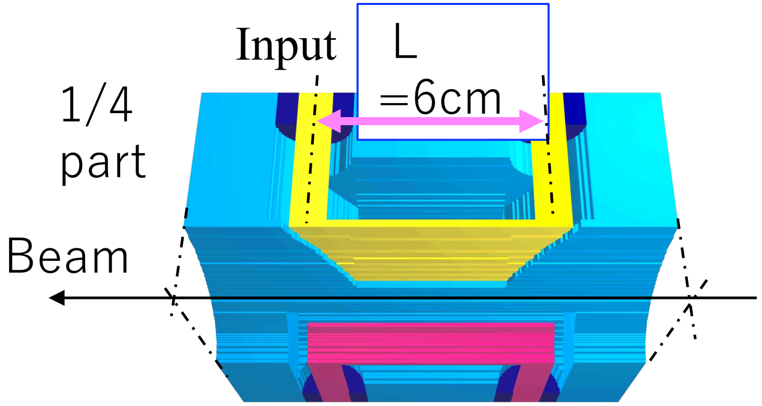


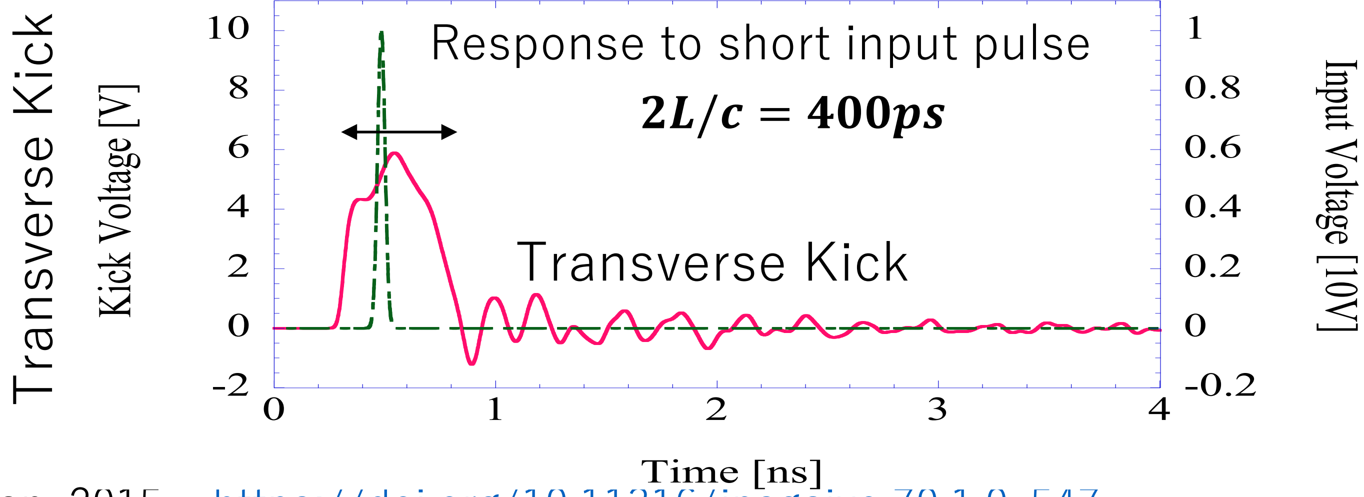




Stripline

< For comparison >





T. Nakamura, Proc. of The Physical Society of Japan, 2015 https://doi.org/10.11316/jpsgaiyo.70.1.0_547

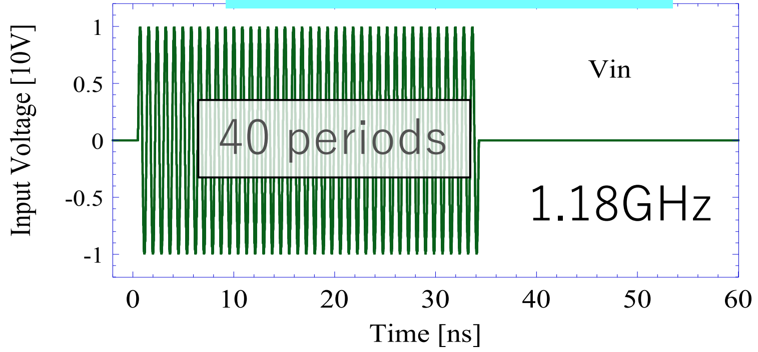
* T. Nakamura, https://accelconf.web.cern.ch/IPAC2011/papers/mopo007.pdf

1) High Q Resonant Kicker

Input

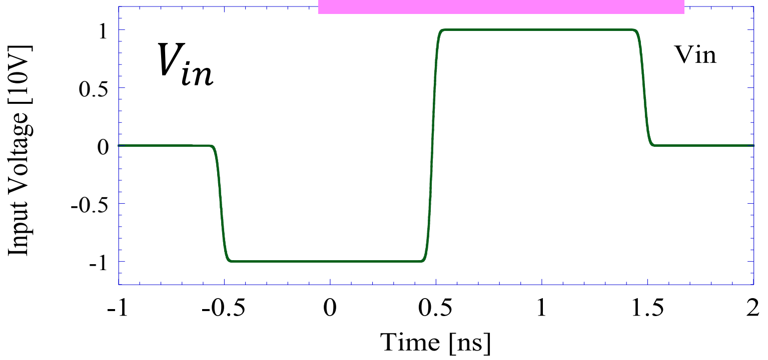
V_{in}

Resonant Kicker



2V

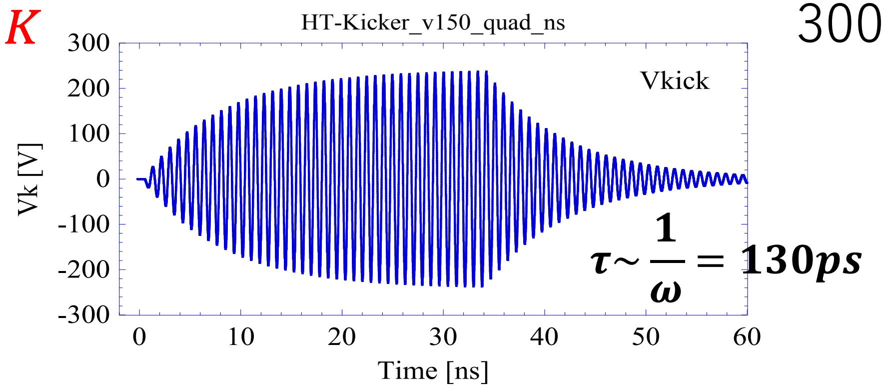
6cm Stripline



V_{in}

Kick Voltage
V_k

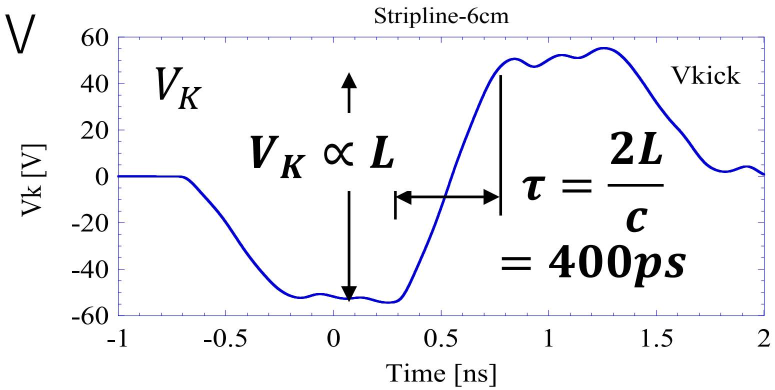
V_K



$$\tau \sim \frac{1}{\omega} = 130ps$$

300V

60V



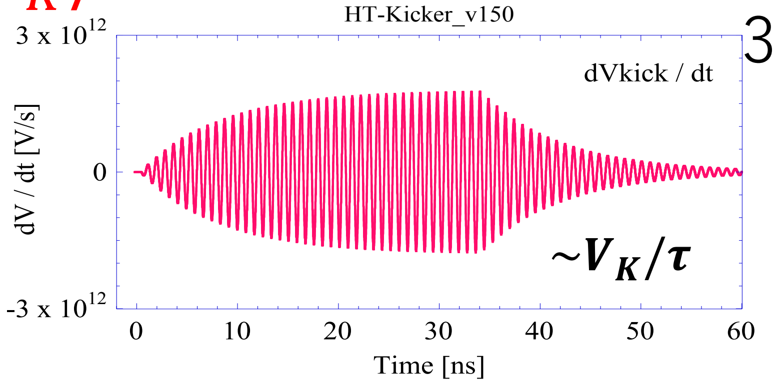
V_K

$$V_K \propto L$$

$$\tau = \frac{2L}{c} = 400ps$$

Time Gradient
$dV_k\ /\ dt$

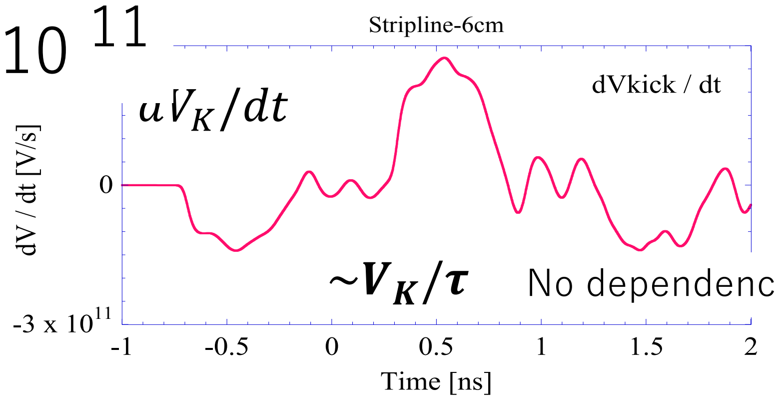
dV_K/dt



$$\sim V_K/\tau$$

$3\text{x}10^{12}$ $3\text{x}10^{11}$

X 6

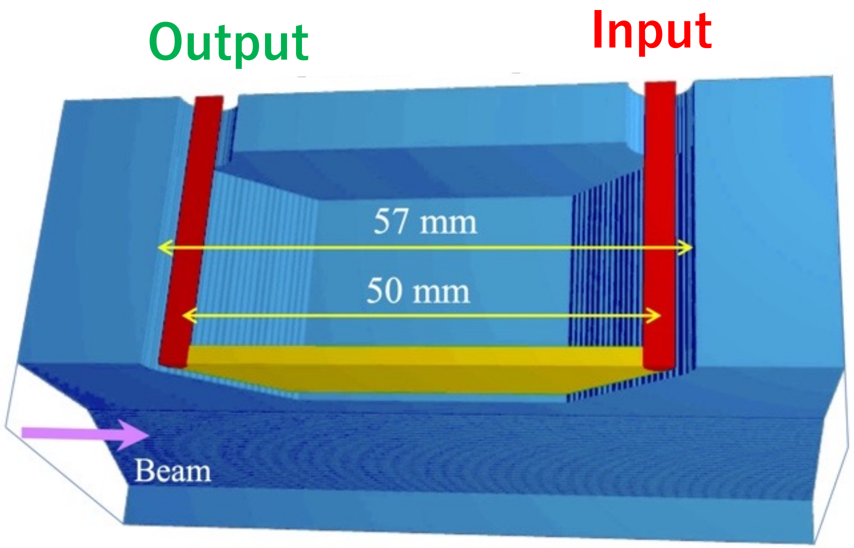


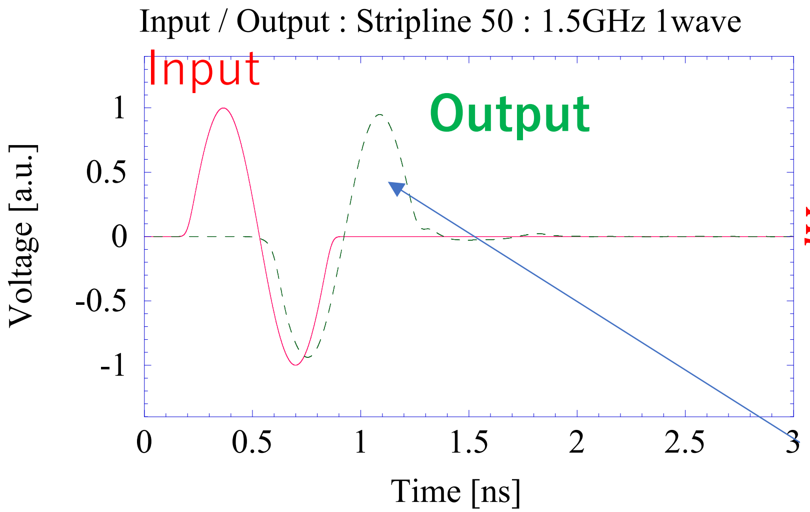
uV_K/dt

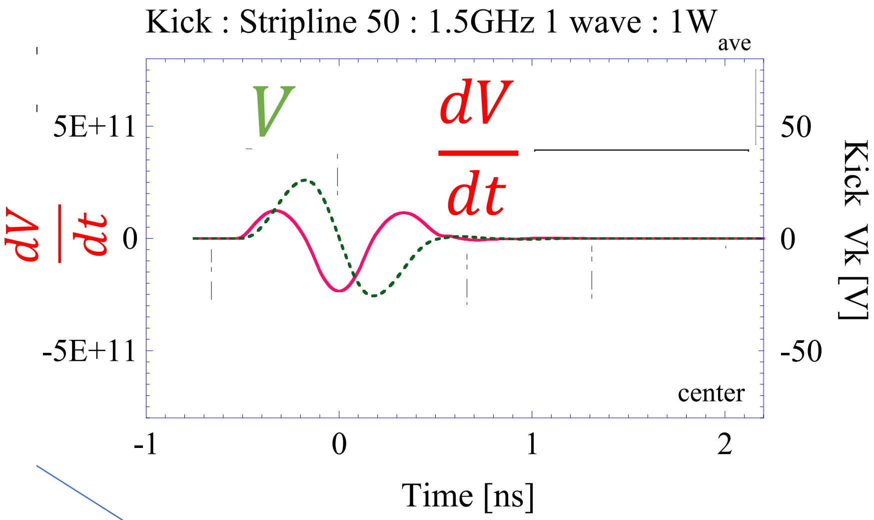
$$\sim V_K/\tau$$

No dependence on L

3) Short Stripline Kicker driven by Multiple-Pulses







$$V(\tau_i) = \int_{-\frac{L}{2}}^{\frac{L}{2}} E(z, t_i(z))dz = E_0 \int_{-\frac{L}{2}}^{\frac{L}{2}} e^{2ikz}z = E_0 L e^{-ikc\tau_i} \frac{\sin kL}{kL}$$

Polarity is the same as Input
Filliping polarity is wrong
(simulation code dependence)

$$\frac{dV_K(\tau)}{d\tau} = -2icE_0 e^{-ikc\tau_i} \sin kL$$

$$\max\left|\frac{dV_K(\tau)}{d\tau}\right| = 2cE_0 \ : \ at\ \ kL = \frac{2\pi}{\lambda}L = \frac{\pi}{2}$$

$$\lambda = 4L$$

Drive Signal Wave-length
for kicker length L

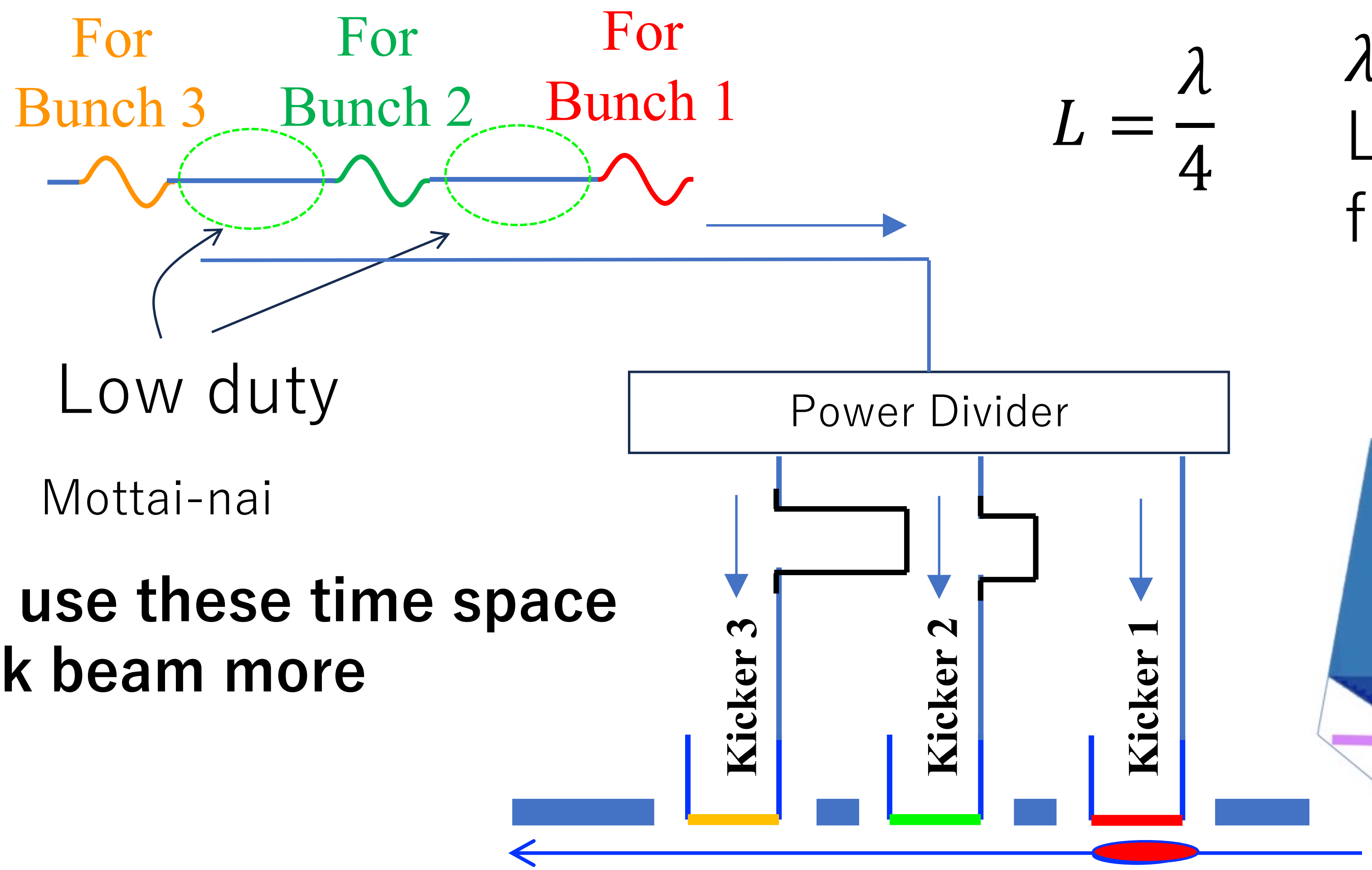
No dependence on length L

We can choose ANY L (kicker length)

Increase Efficiency by adjusting drive pulse order

We can choose ANY L (kicker length)

Choose Short L to set as many kickers for available space



Low duty

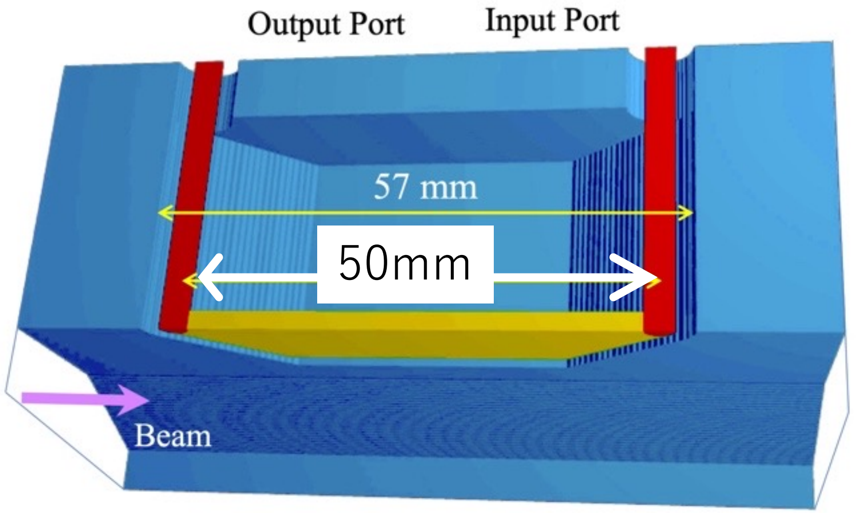
Mottai-nai

$$L = \frac{\lambda}{4}$$

λ = 60cm / 3

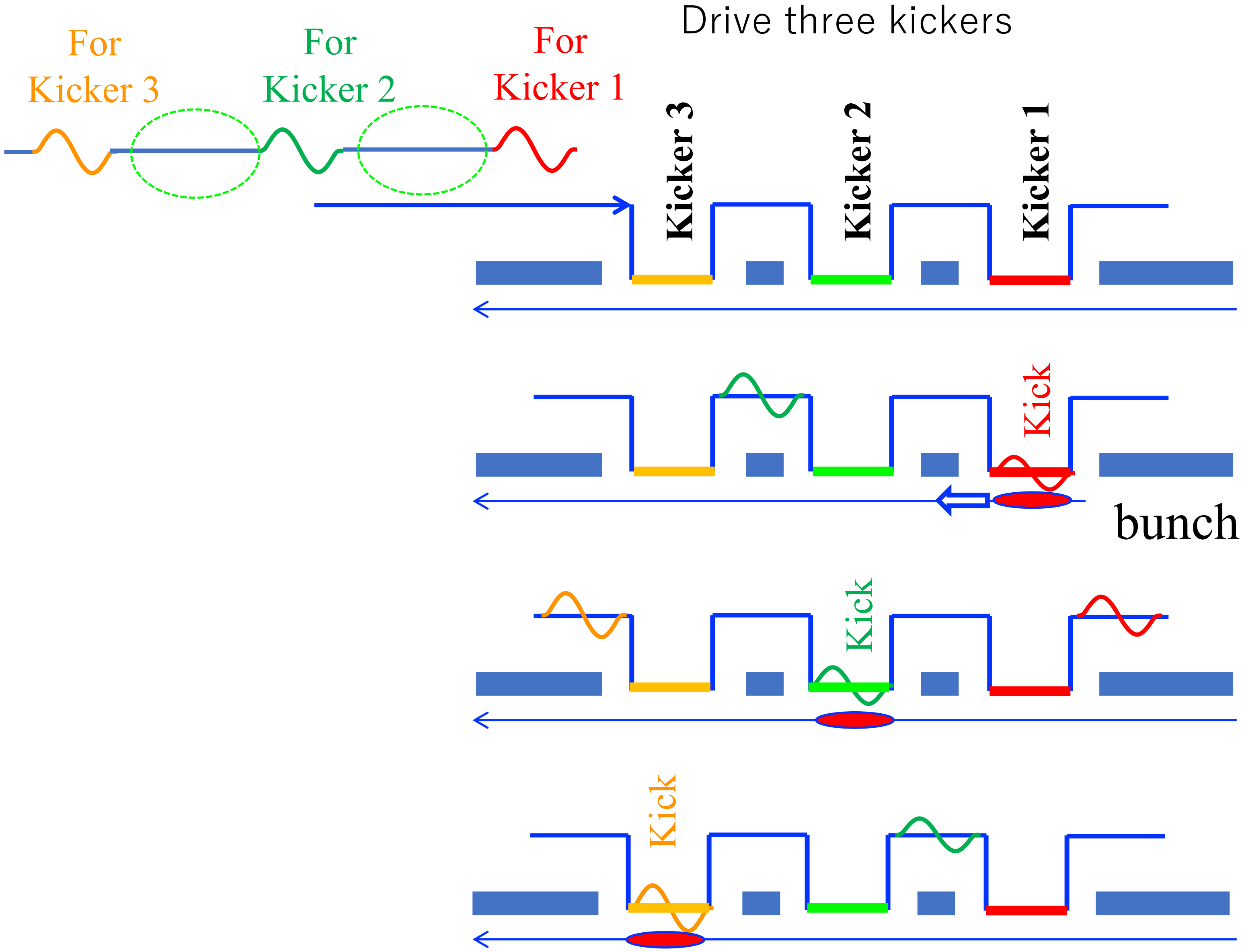
L = 50mm

f = 1.5 GHz

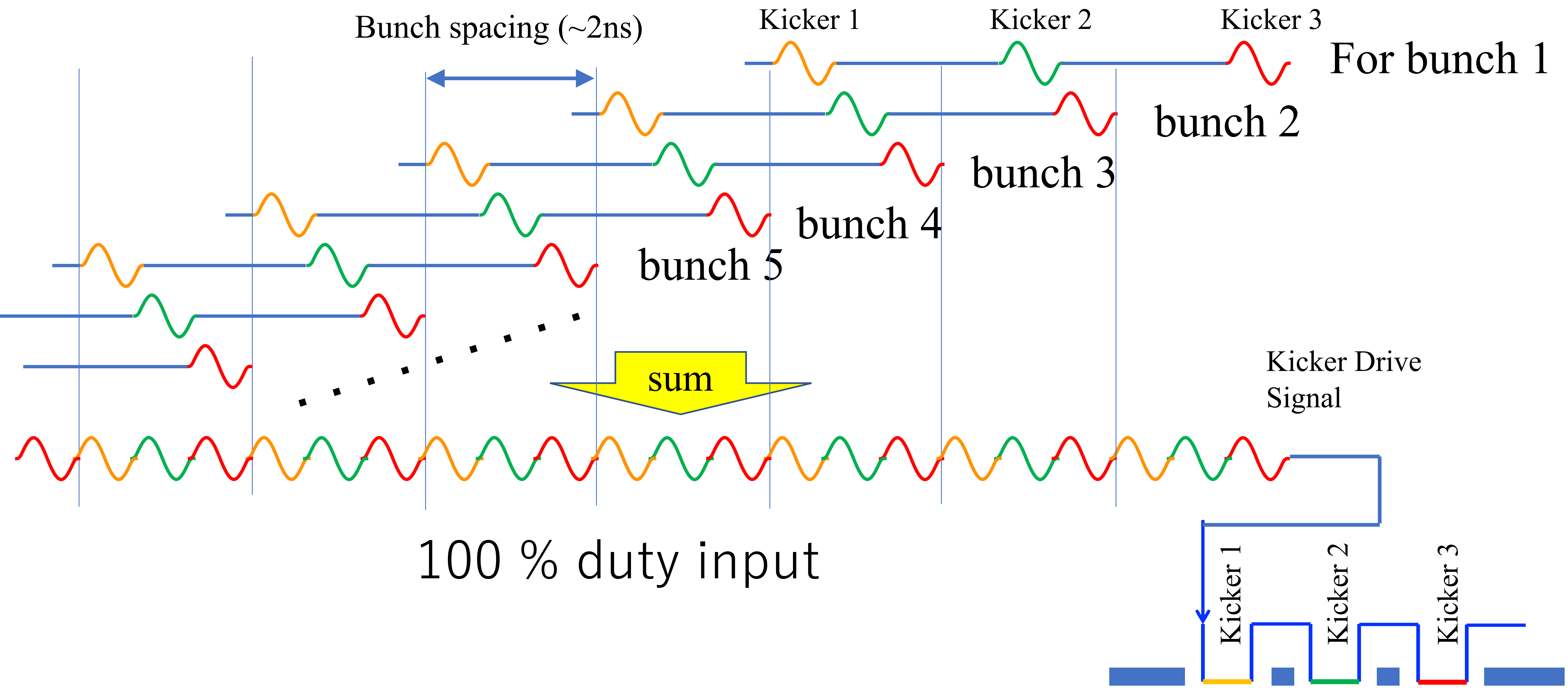


We can use these time space to kick beam more

Increase Efficiency by adjusting drive pulse order



Increase Efficiency by adjusting drive pulse timing



Bunch spacing (~2ns)

Kicker 1

Kicker 2

Kicker 3

For bunch 1

bunch 2

bunch 3

bunch 4

bunch 5

sum

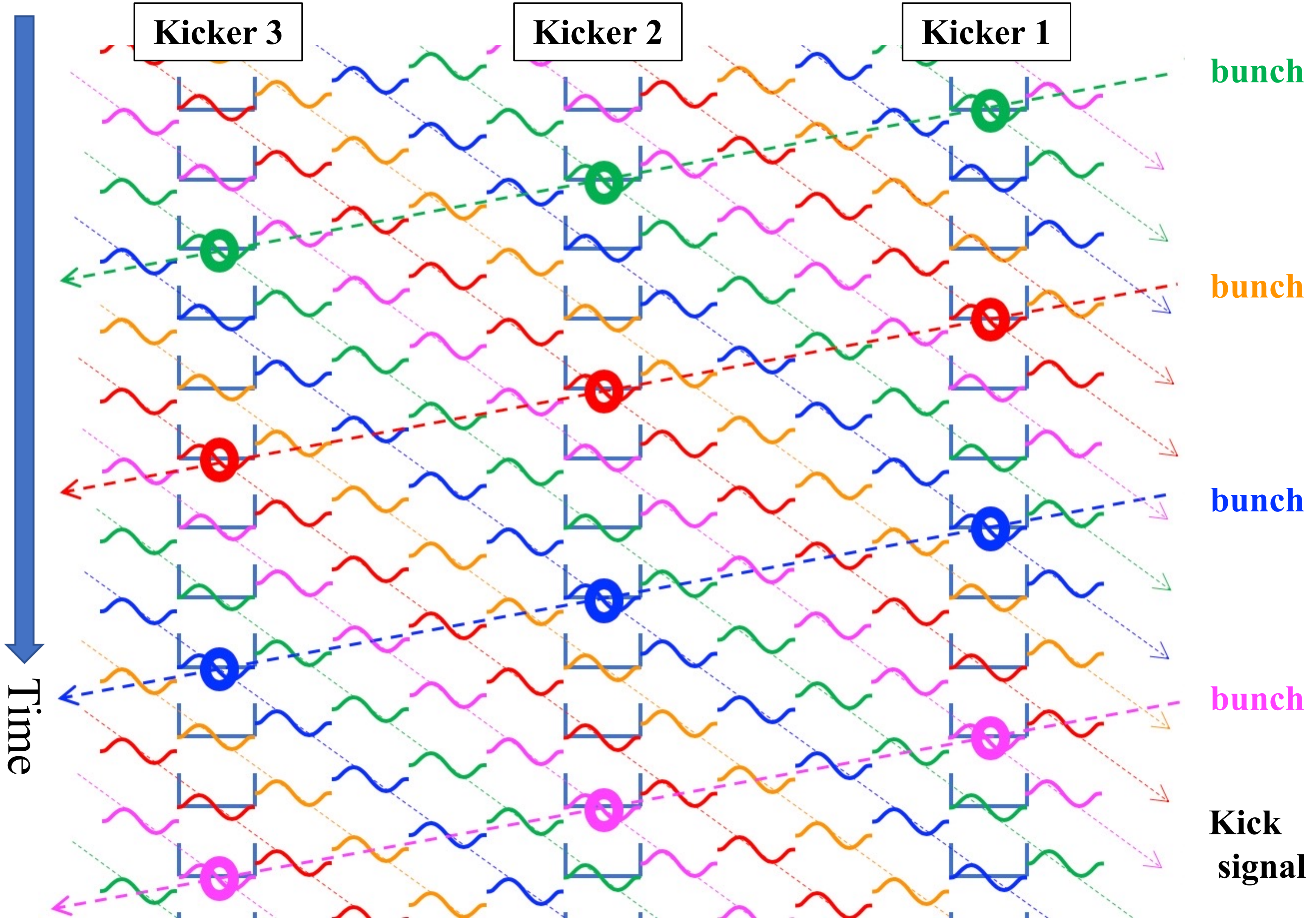
Kicker Drive Signal

100 % duty input

Kicker 1

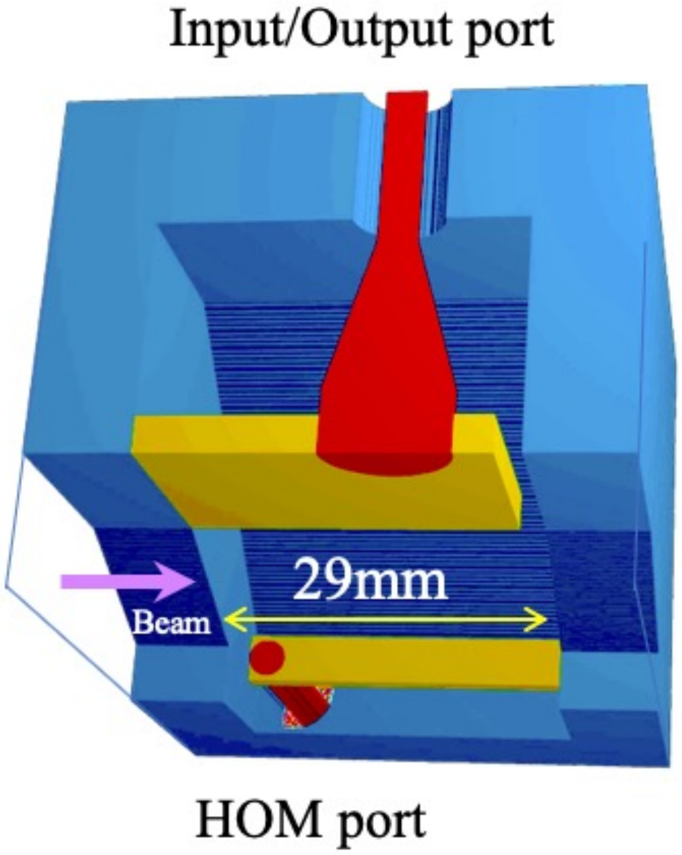
Kicker 2

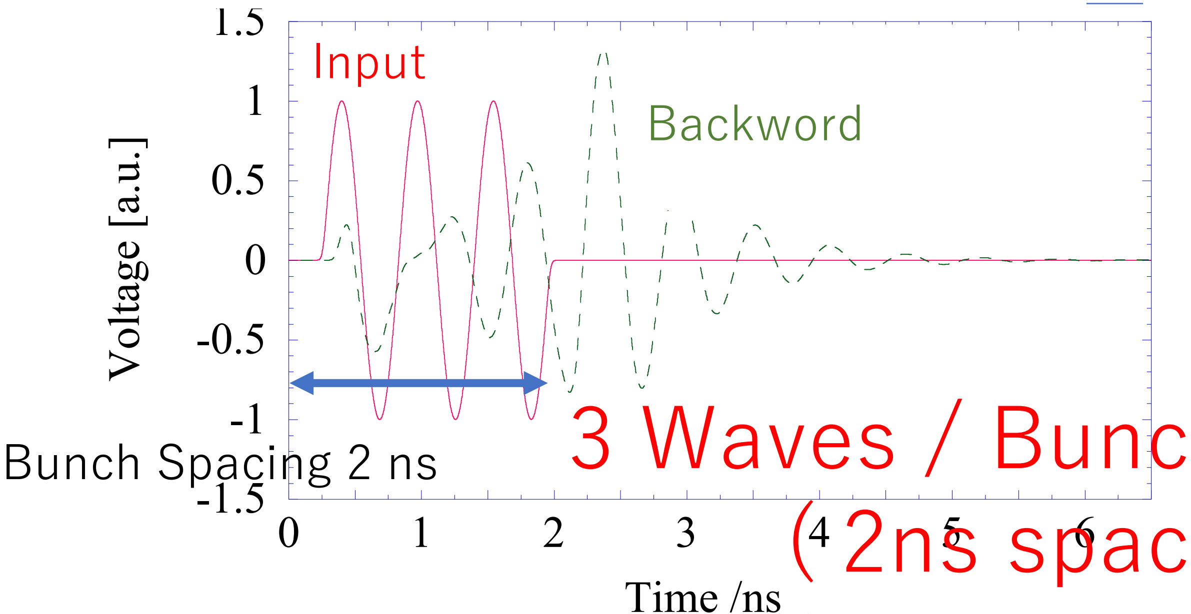
Kicker 3


Kicker 3
Kicker 2
Kicker 1
bunch
bunch
bunch
bunch
Kick signal
Time

3) Shorted Stripline Kicker driven by Multiple-Pulses

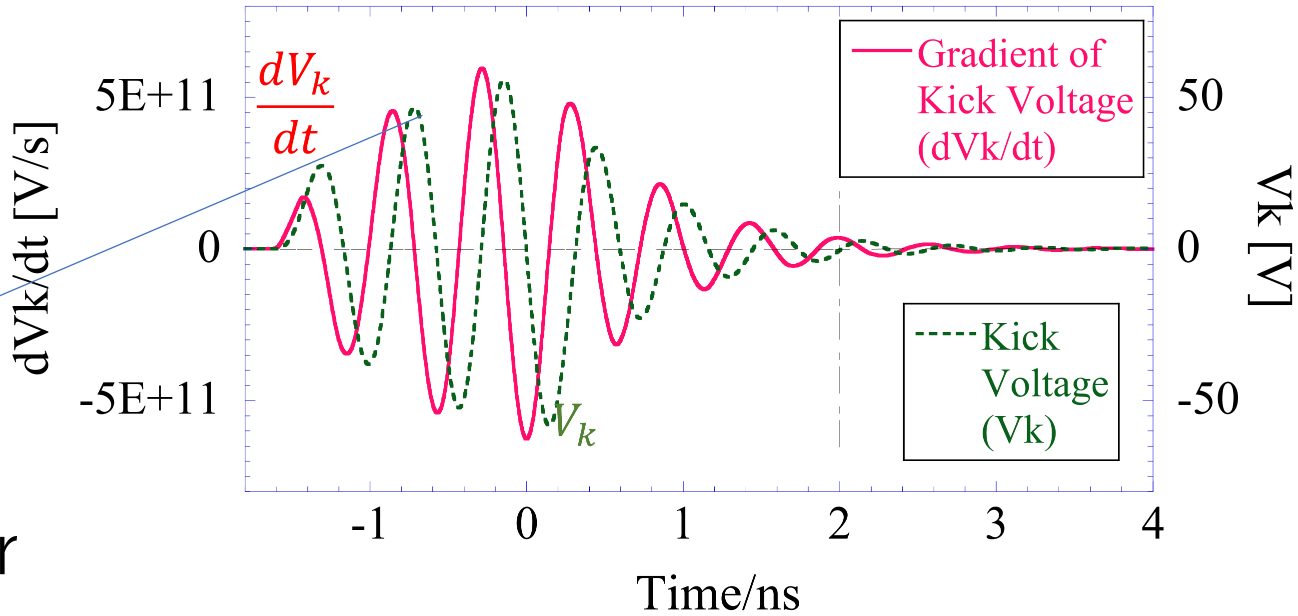
$f_{drive} = 1.75\ \mathrm{GHz}$





3 Waves / Bunch
(2ns spacing)

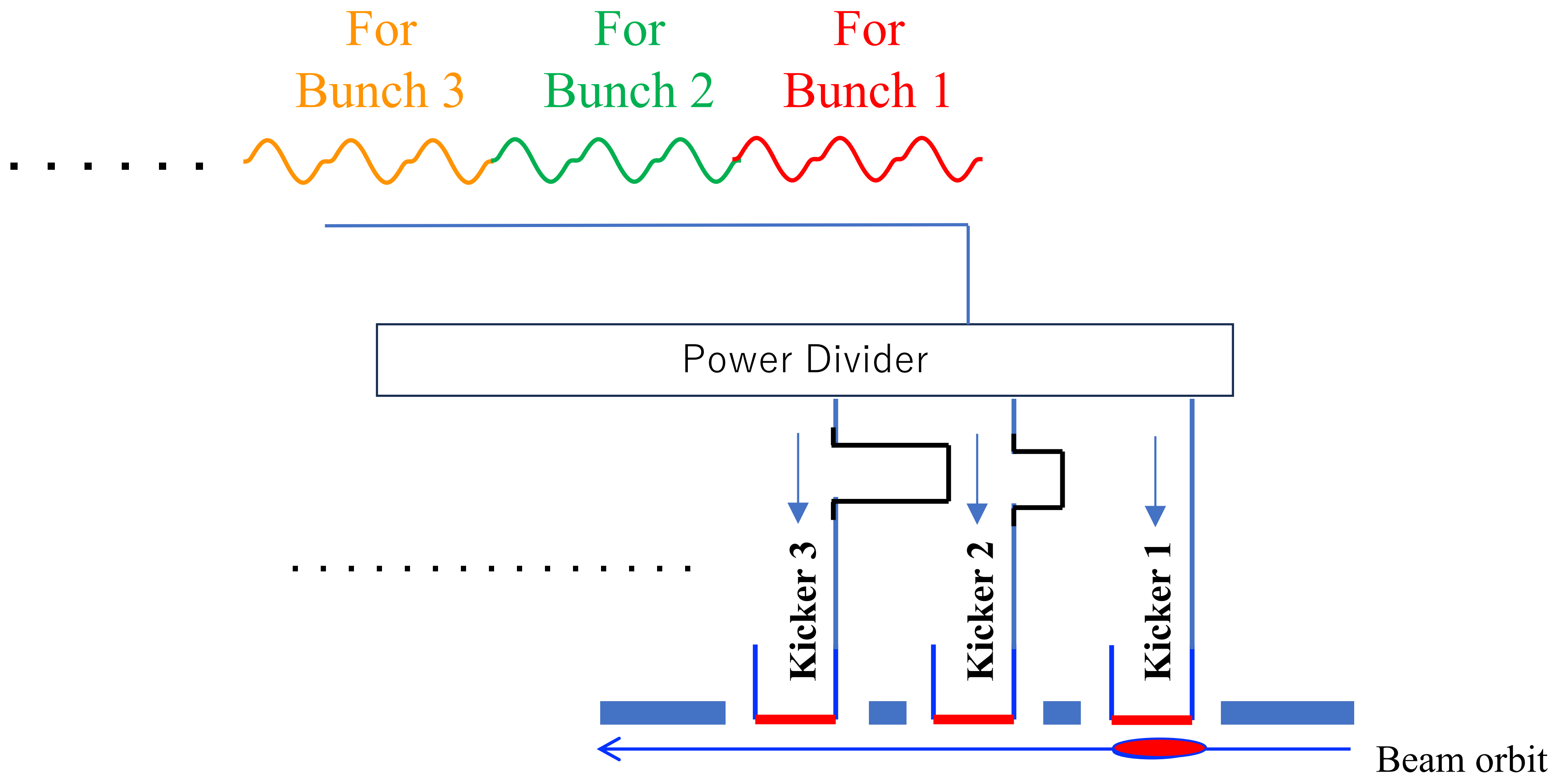
1.75GHz 3 wave drive (1W$_{ave}$)



dVk/dt : x3 of Stripline Kicker

High Duty Input Signal with the kicker

~ 100 % duty

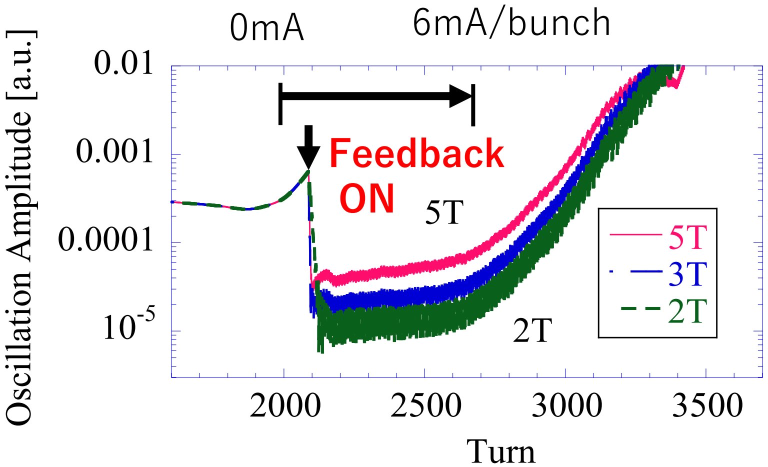


Simulation Results for Head-Tail Feedback with x2 more current than that with CM feedback only

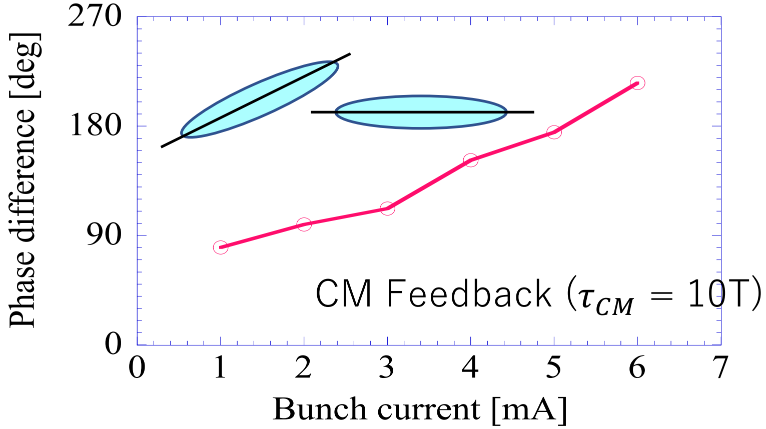
CM feedback only

Feedback
Stability limit ~ 2T (T=turns)

Log scale

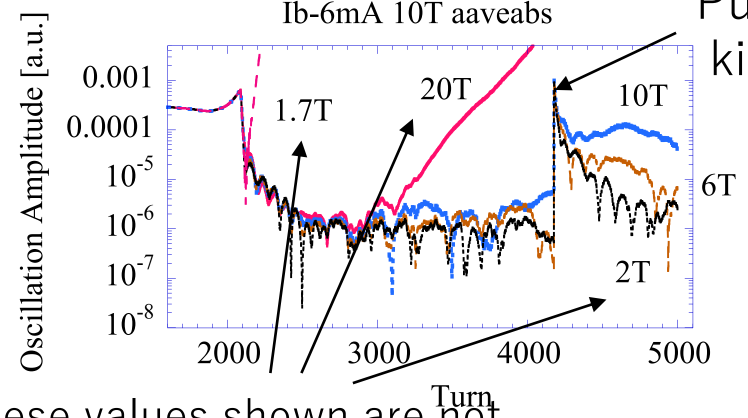


Phase between **CM** and **Pitch** Oscillations



(Pitch -> Pitch Kick) + **CM Feedback** (τ_{CM} = 10T)

Log scale

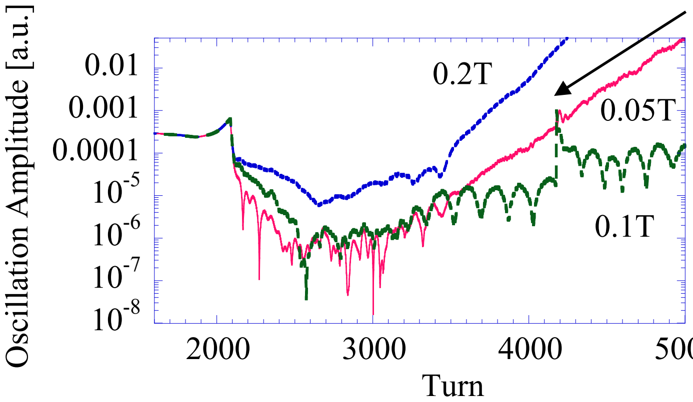


Pulsed kick

These values shown are not
expected damping time
(just gain parameters)

(CM position -> Pitch Kick)
+ **CM Feedback** (τ_{FB} = 10T)

Log scale



Pulsed kick

FIR phase is not optimized

Code : T. Nakamura, Workshop SAD2006, KEK (2006) ; http://acc-physics.kek.jp/sad/SAD2006/Doc/Slide/Nakamura.pdf

Summary

* Pitch / Yaw monitor for pico second bunch
is under development

* Beam test shows “plausible” result
but We need to confirm more…

* Resolution ??

* Pitch/Yaw correction kickers are proposed
but Strength is depends on Resolution of Monitor

* May be used to observe dynamics of single-bunch instabilities
in time domain / realtime