Beam instability and cure

放射光源において

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若手の会

Beam instability at SPring-8

Beam instability
- Beam parameter change
- Excitation of betatron and synchrotron motions
- Limit on beam current

Beam instability at SPring-8

Multi-bunch instability betatron motion

* Limit on average beam current
* Narrow gap undulator (small pipe)
* Low frequency Cu …

Single-bunch instability (mode coupled instability)

* Limit on bunch current
* Betatron motion unstable
* Geometric or resistive wall etc. high frequency range.

Microwave instability

* Energy spread increase (Threshold current)

Increase bunch current

Beam heating on pipe (Gate valve and bellows)

Bunch length increase

Betatron frequency decrease

Instability suppression by feedback

Multi-bunch instability

Almost suppression

Single-bunch instability

Chromaticity = 1 (< 3) for wide dynamic aperture

In-vacuum IDs **Open**

3.5 mA/bunch => 14 mA/bunch

Feedback **OFF** **ON**

~ simulation result

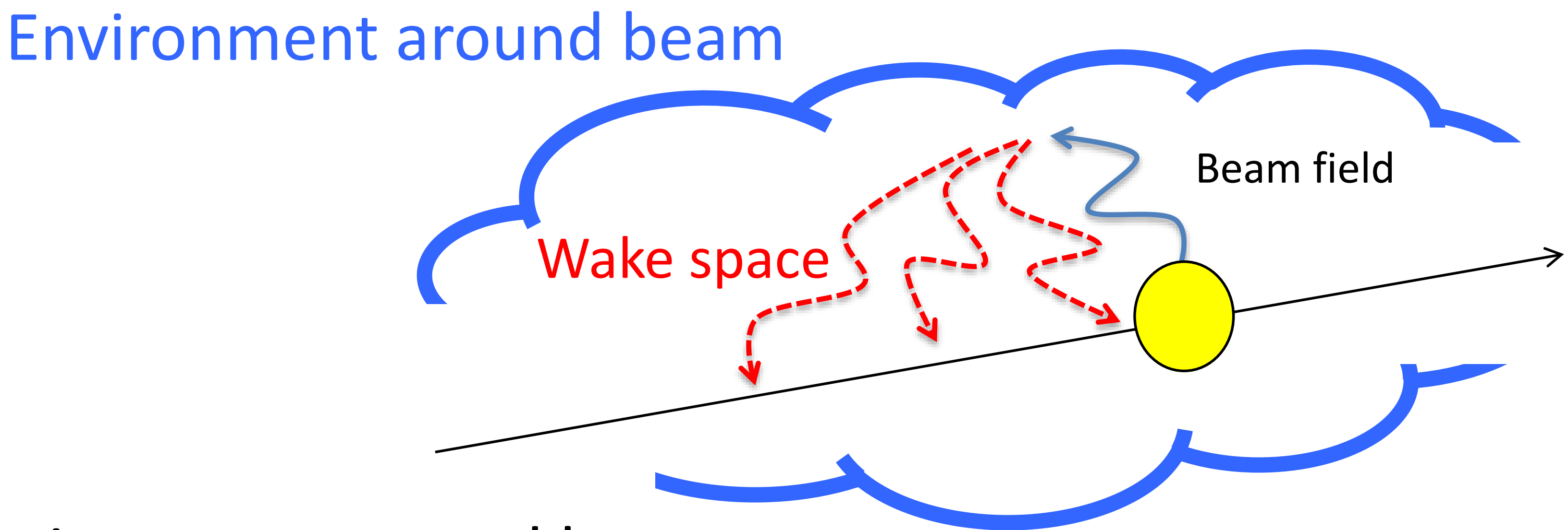
In-vacuum IDs **Close** **(**Partly ~ user operation**)**

2.5 mA/bunch => 6 mA/bunch

Feedback **OFF** **ON**

5 mA/bunch for User operation

Beam instability occur in wakefield space



Environment around beam

Beam pipe shape change

Taper, Bellows, Cavity, Kicker, Furrow, etc.

Resistive on pipe

Residual current => magnetic field => Kick generation

Ion(- charge beam)、electron (+ charge beam)

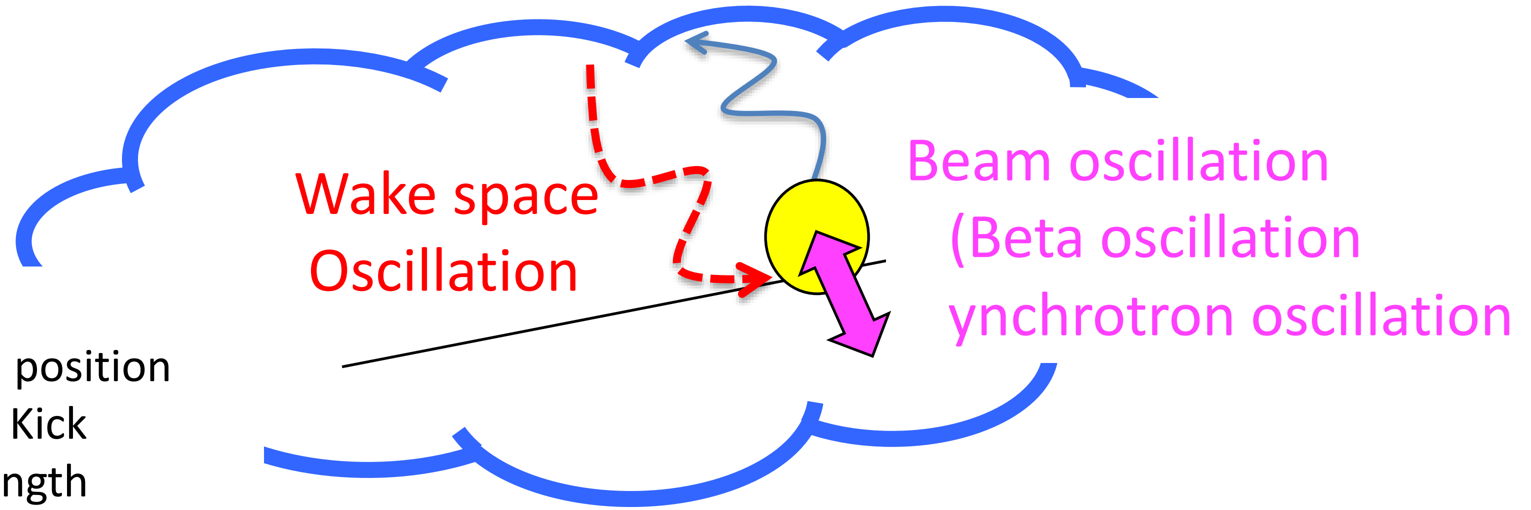
Interaction of ion or electron according to beam charge.

Synchrotron radiation

Radiation longer than bunch => .....

Beam instability

No instability in wake space



Along beam position
Wakefield = Kick
Change strength

Beam vibration x

=> Wake field vibration Wake = kx

=> Beam vibration increase a kick W(t) x

$$\frac{d^2x}{dt^2} + \omega_0^2 x = f$$

Equilibrium motion

$$\frac{d^2x}{dt^2} + \omega_0^2 x = fx$$

Change in frequency

$$\frac{d^2x}{dt^2} + \omega_0^2 x = W(t')x(t-t')$$

Positive feedback: Growth /decay

Beam instability

Beam vibration

Betatron oscillation

Synchrotron oscillation

Feedback loop

=> Wake fields where beam also oscillate

=> Bounce off the beam and kick

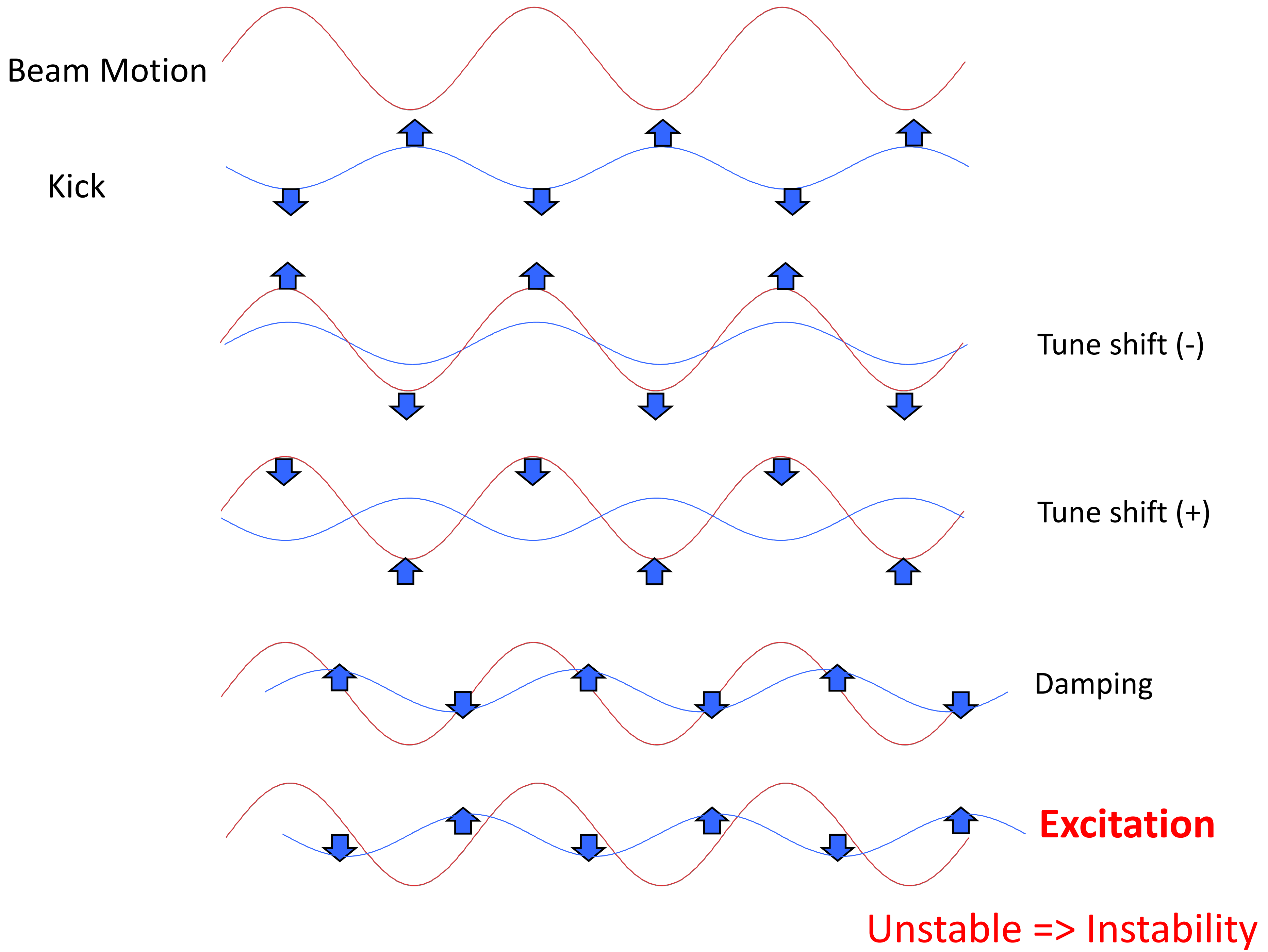
Positive feedback : Vibration、Wake grows

Negative feedback： Vibration, Wake decay

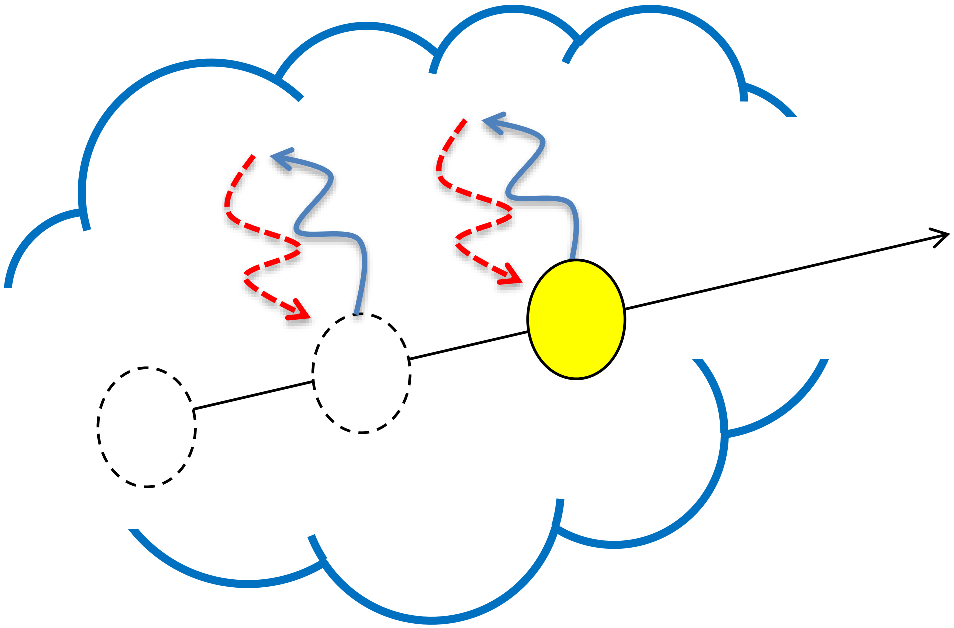
Wake to generate positive and negative loops

May occur at the same time and fight each other

=> You should strengthen the wake to generate negative


Beam Motion
Kick
Tune shift (-)
Tune shift (+)
Damping
Excitation
Unstable => Instability

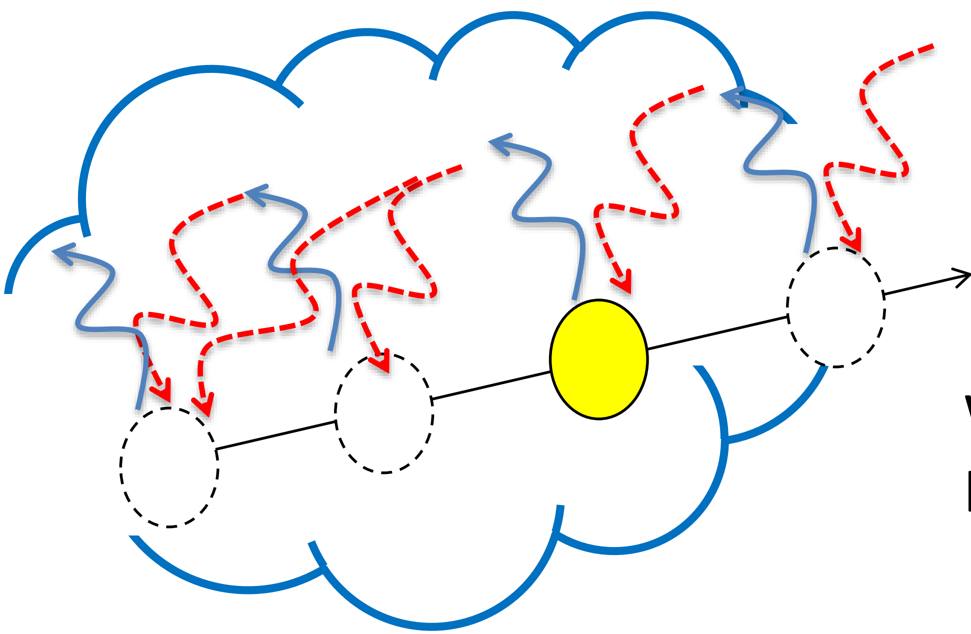
Beam instability : 2 way



Single bunch instability

High bunch current

Wake where the bunch occurred、
Kick itself

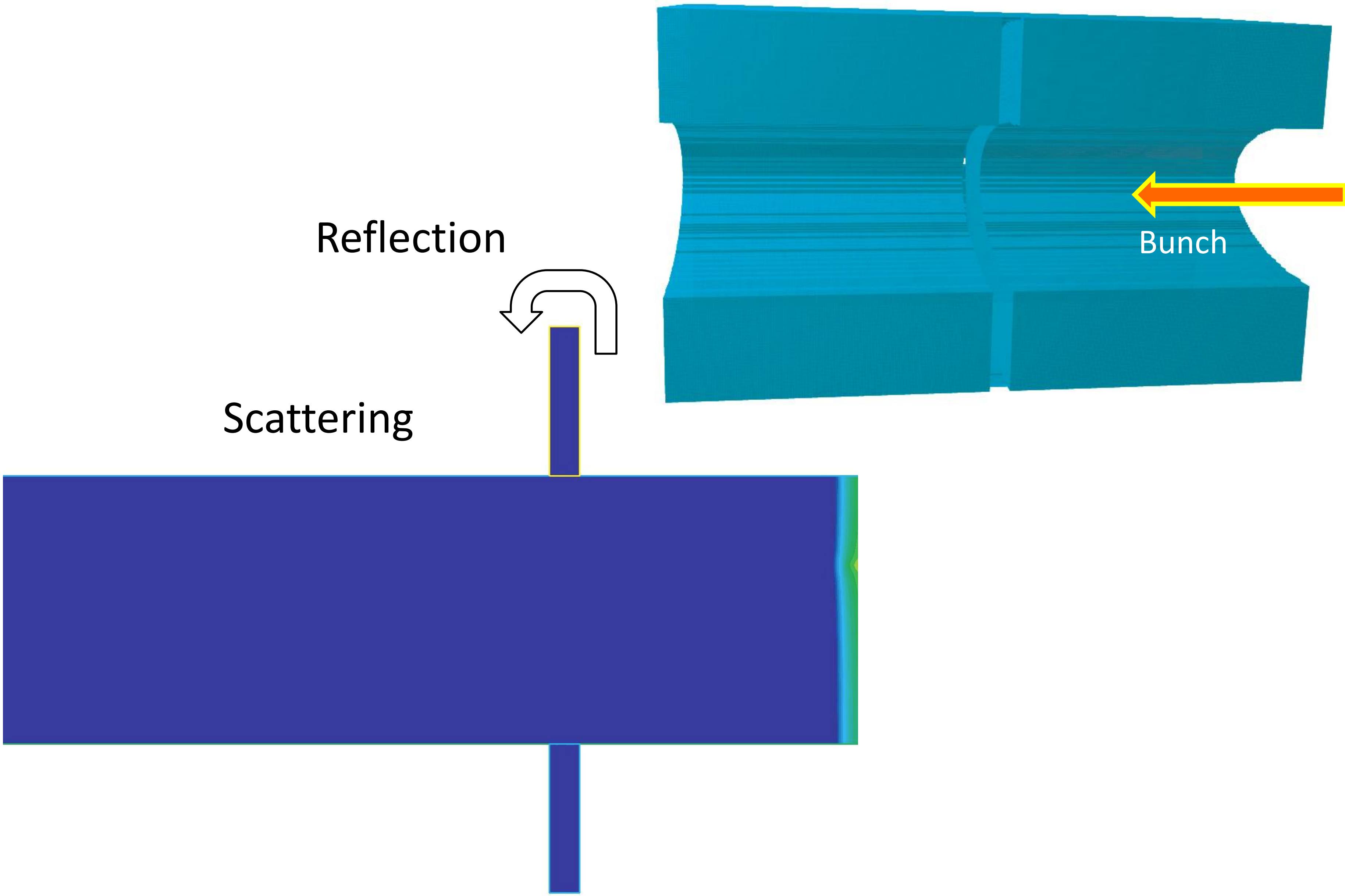


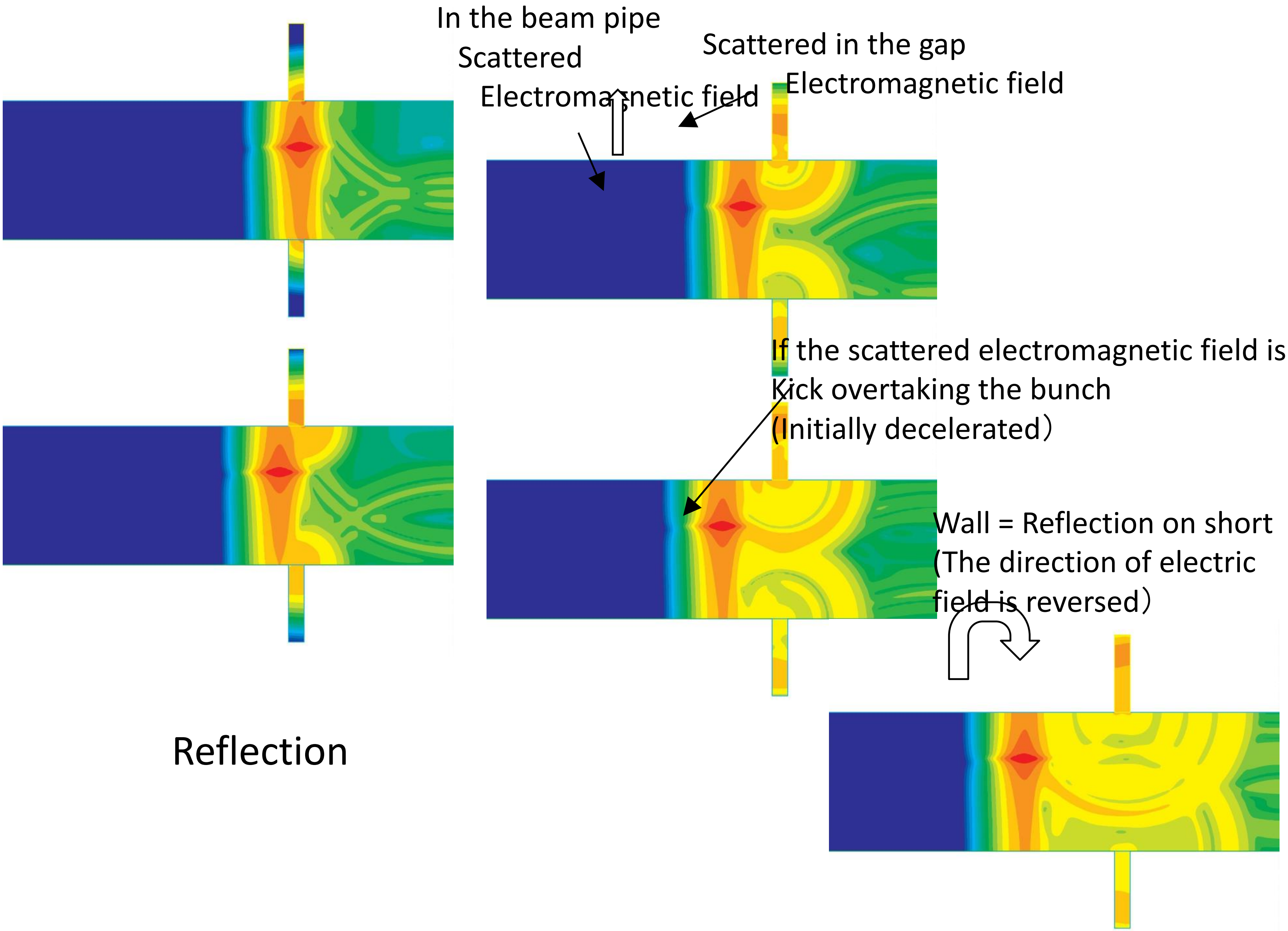
Multi bunch instabililty

High average current

Wake where the bunch occurred、
Kick the following bunch

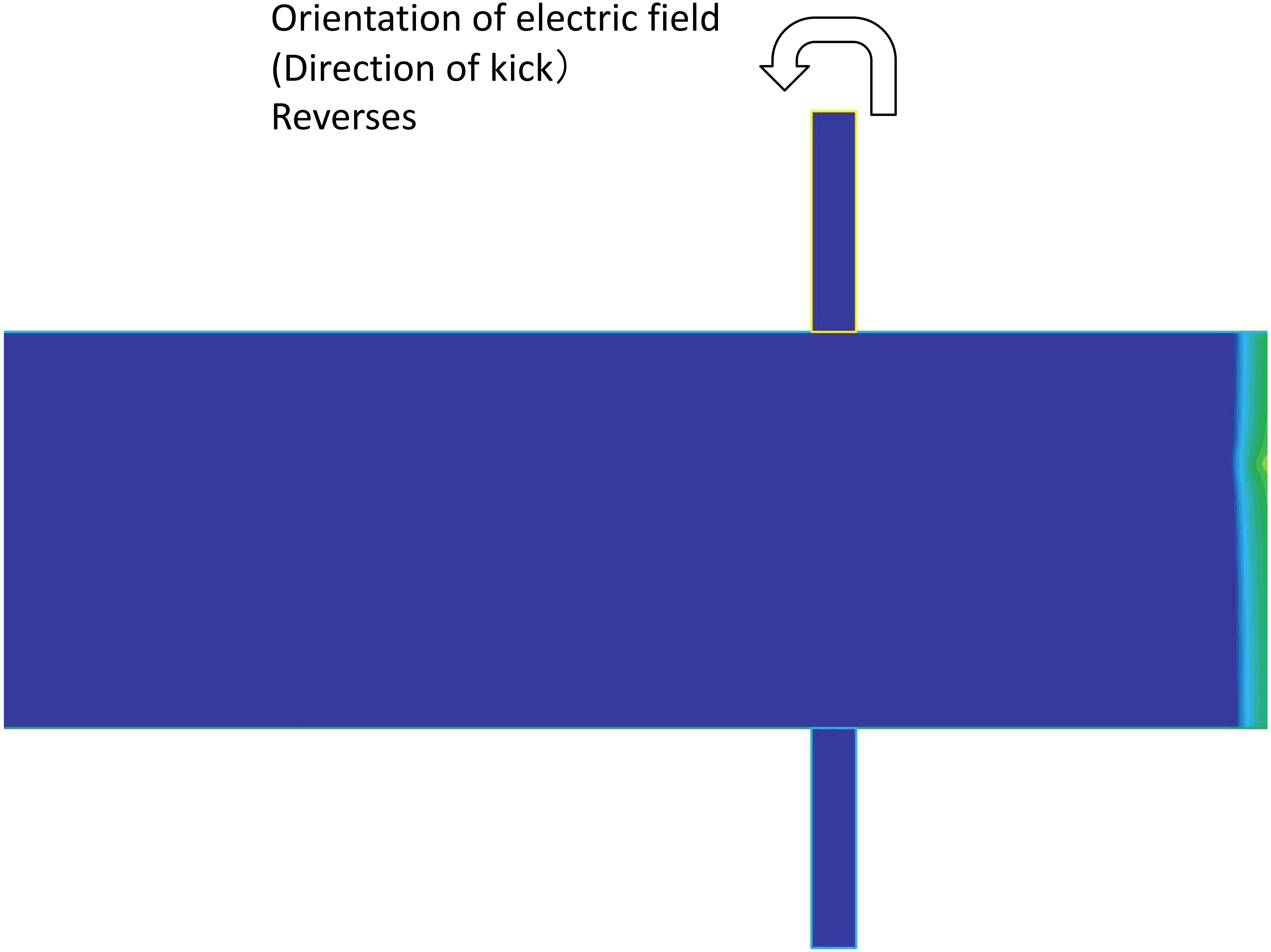
Wakefield occurrence

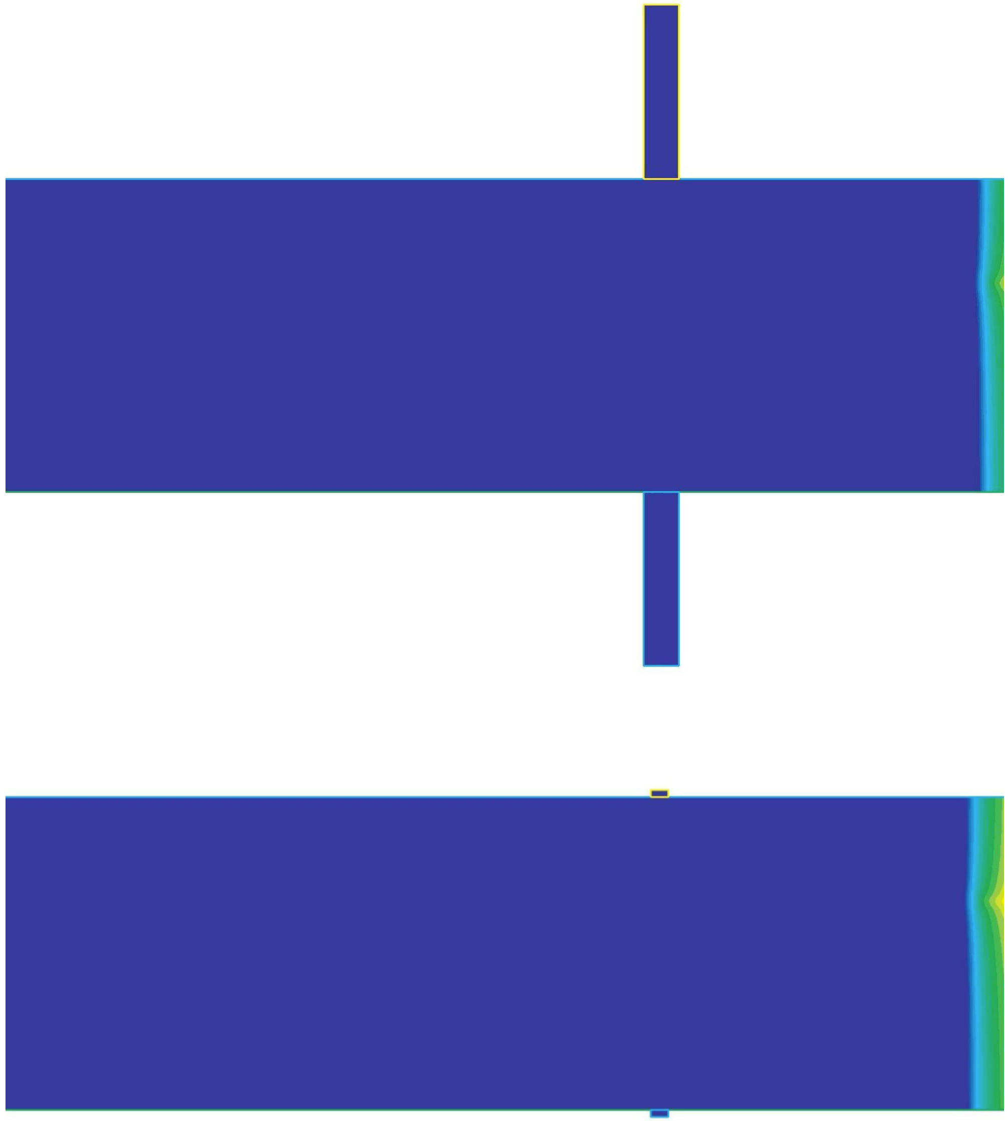



In the beam pipe
Scattered
Electromagnetic field
Scattered in the gap
Electromagnetic field
If the scattered electromagnetic field is
Kick overtaking the bunch
(Initially decelerated)
Wall = Reflection on short
(The direction of electric
field is reversed)

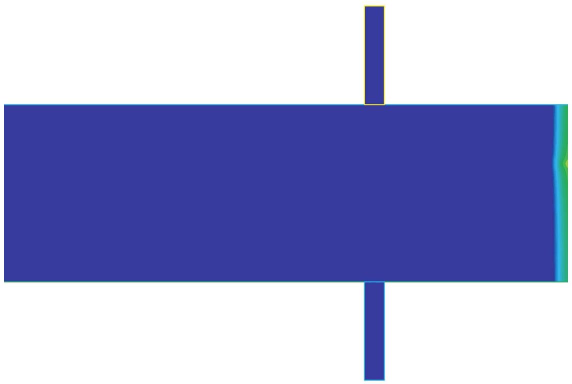
Reflection

Wall = Short circuit
Orientation of electric field
(Direction of kick)
Reverses





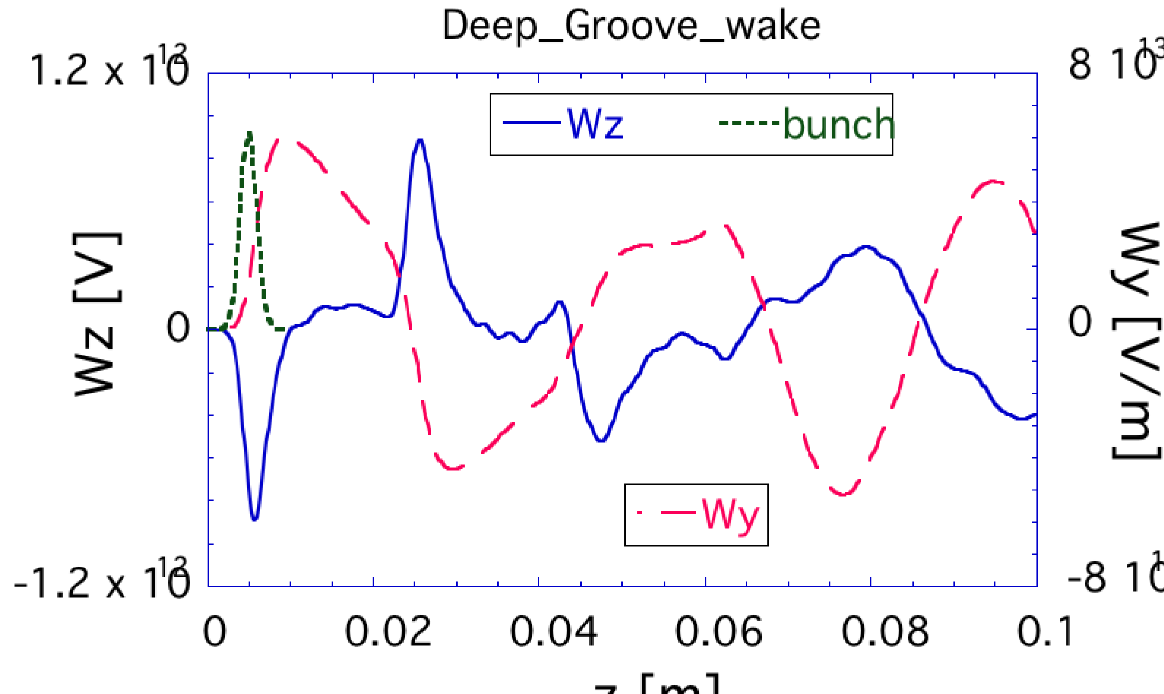
Kick by wake-by field (Wake potential)

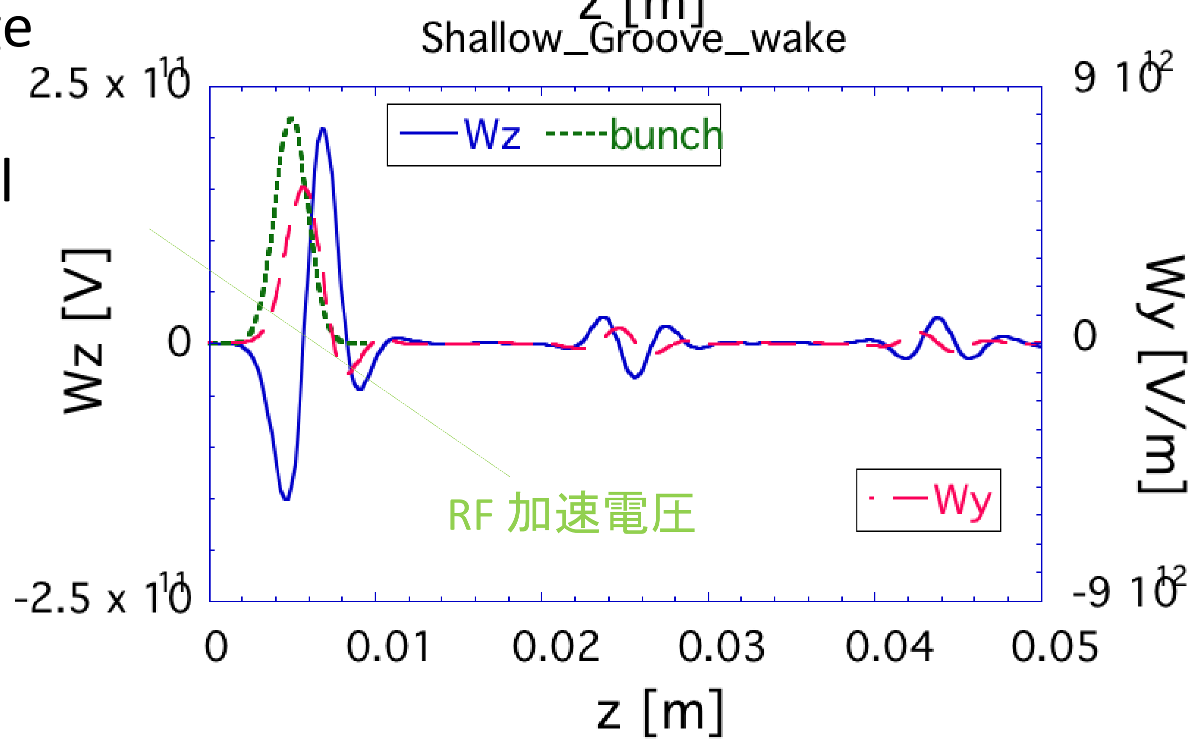


Wz : longitudinal

Wy : Horizontal: Kick voltage

Wy x Generate a wake
  Proportional to the lateral position of the beam

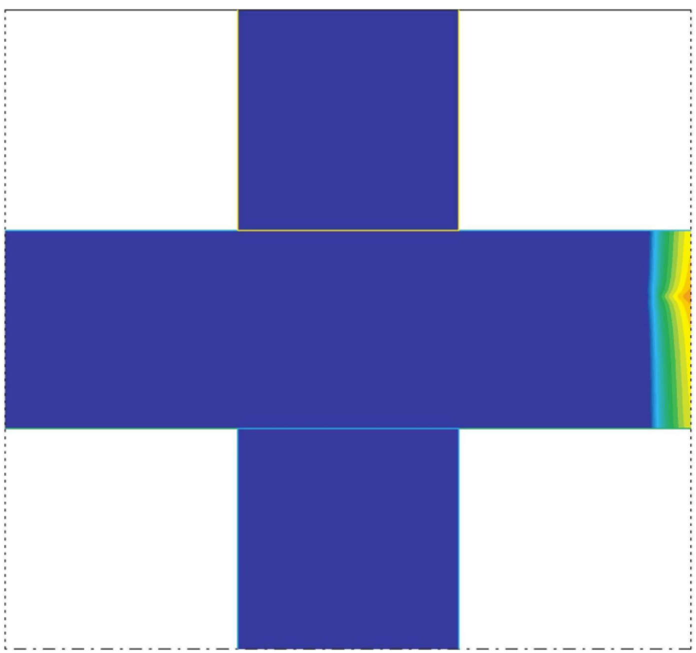


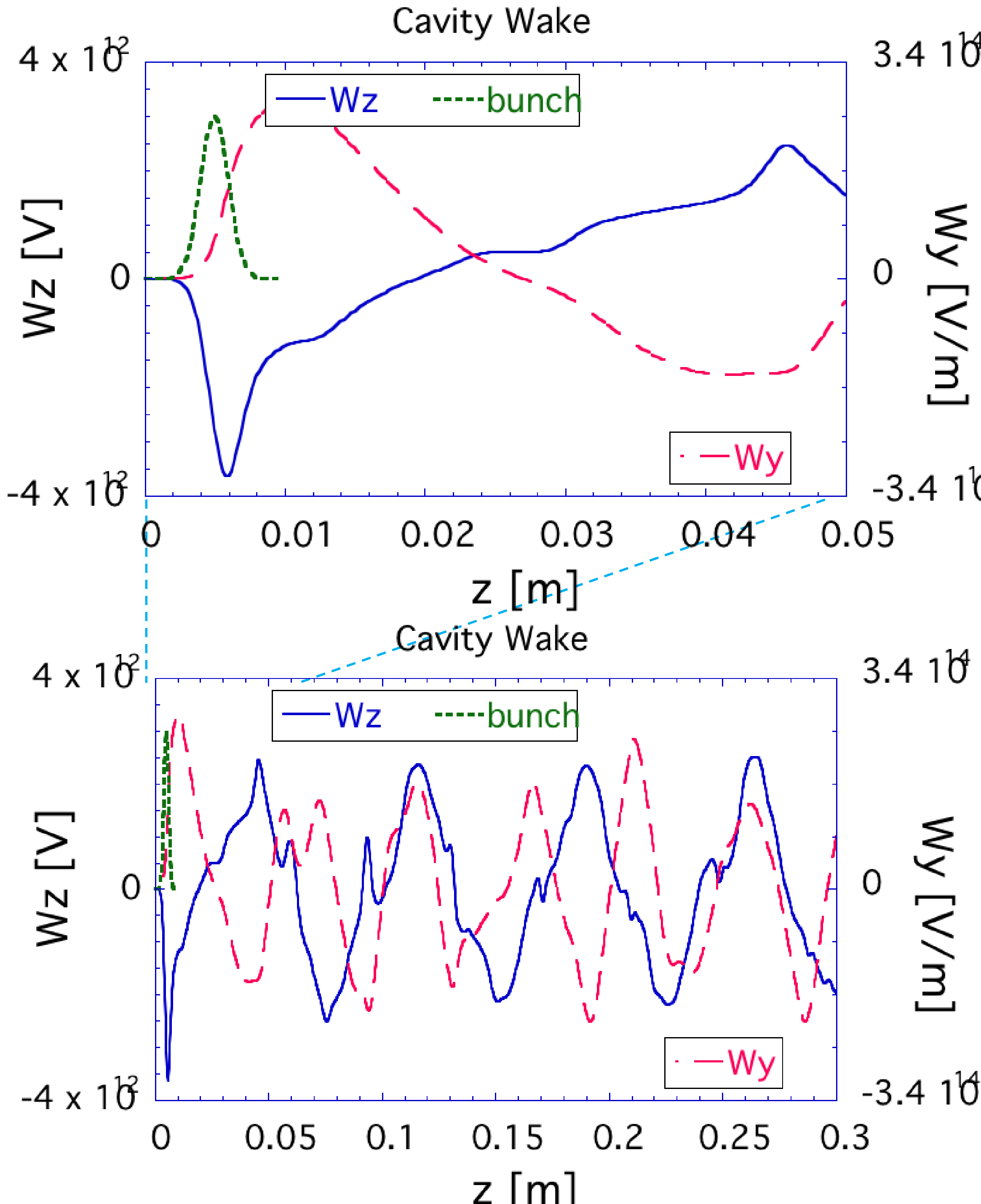


Cavity

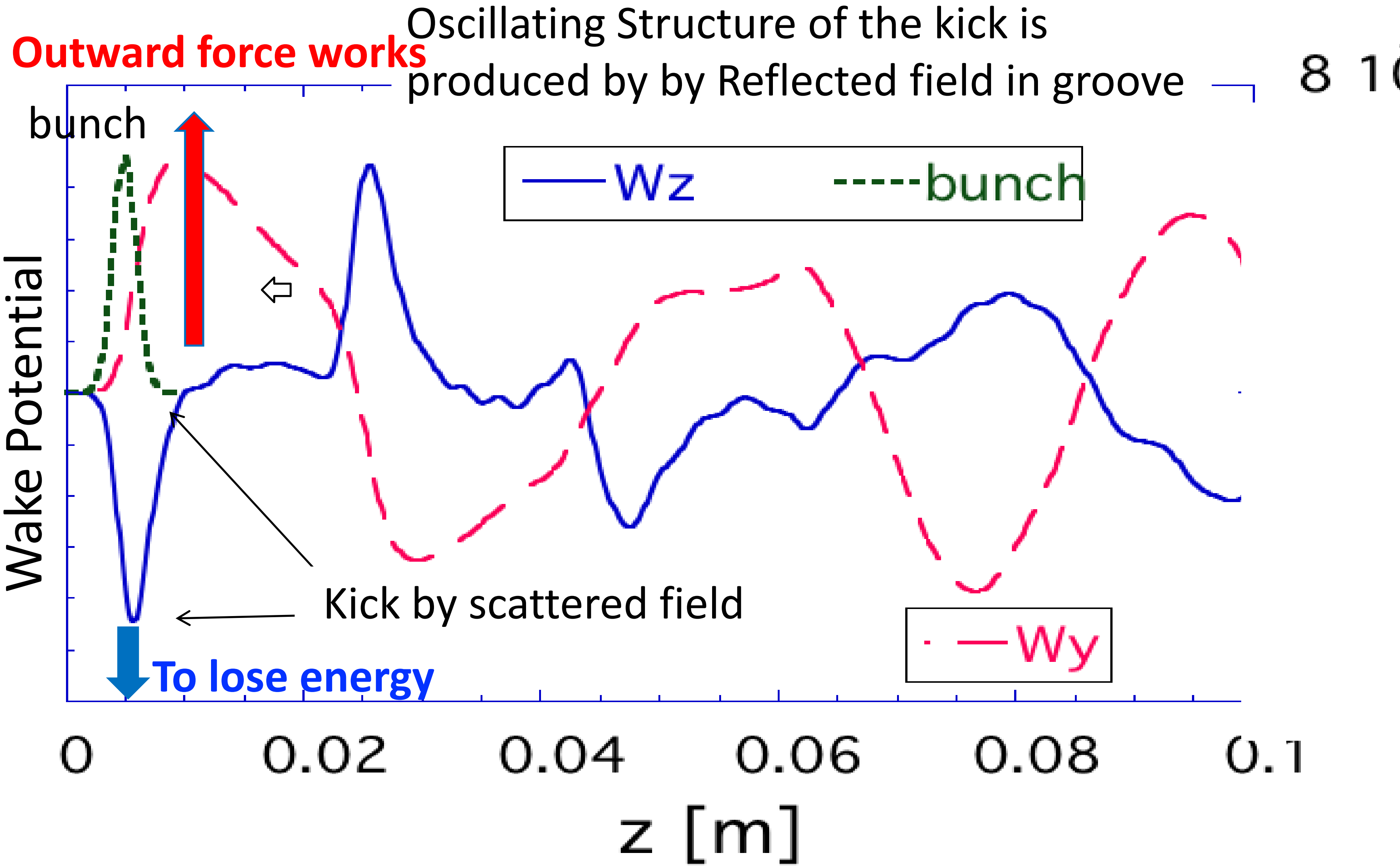
Gap length > Beam pipe

Wake field, beam pipe
Form a cavity mode past it



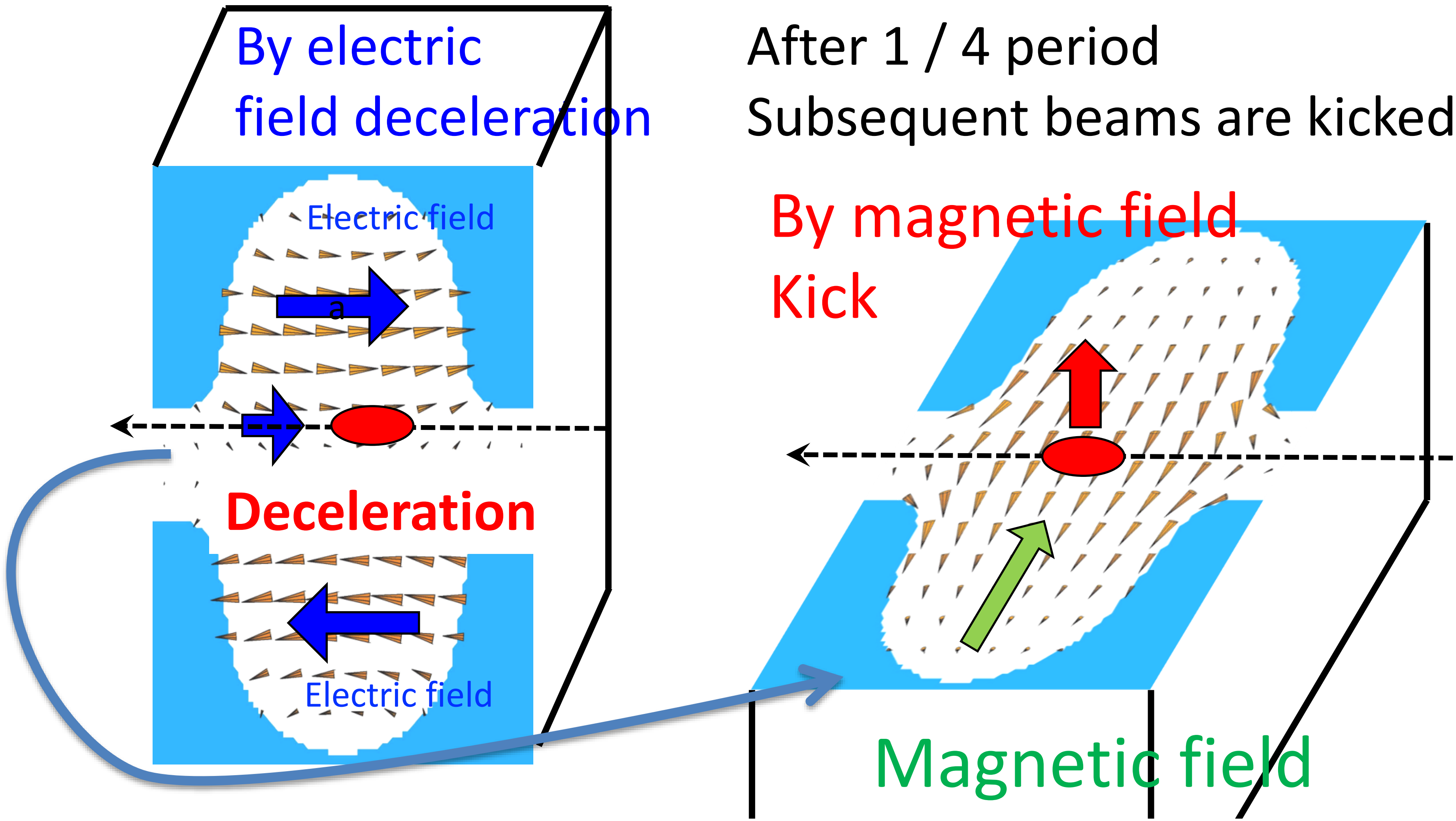


Kick by wake field



z = -(s – ct) : coordinate running with beam

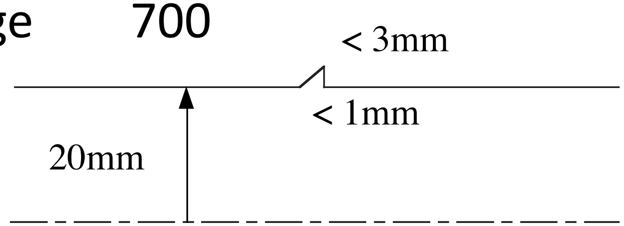
Cavity case (TM110 higher order mode)



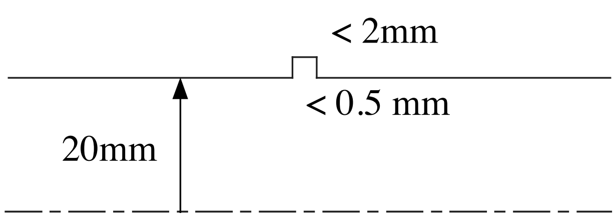
The beam deviated from the center is decelerated
Convert kinetic energy to electromagnetic field energy

Beam pipe structure

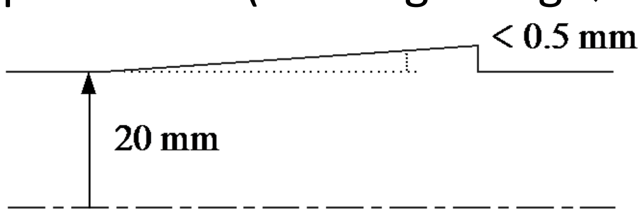
Flange 700



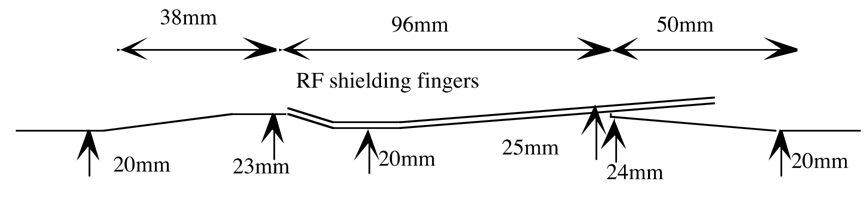
Welding 2000



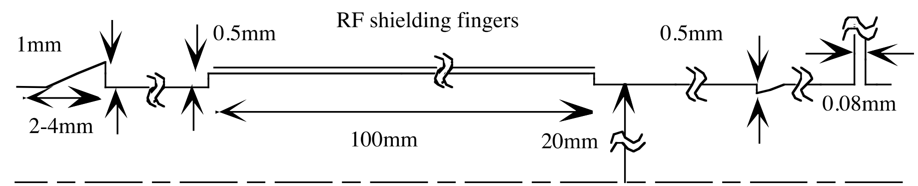
Displacement (welding・flange） 2700



Bellows 400



valve 400

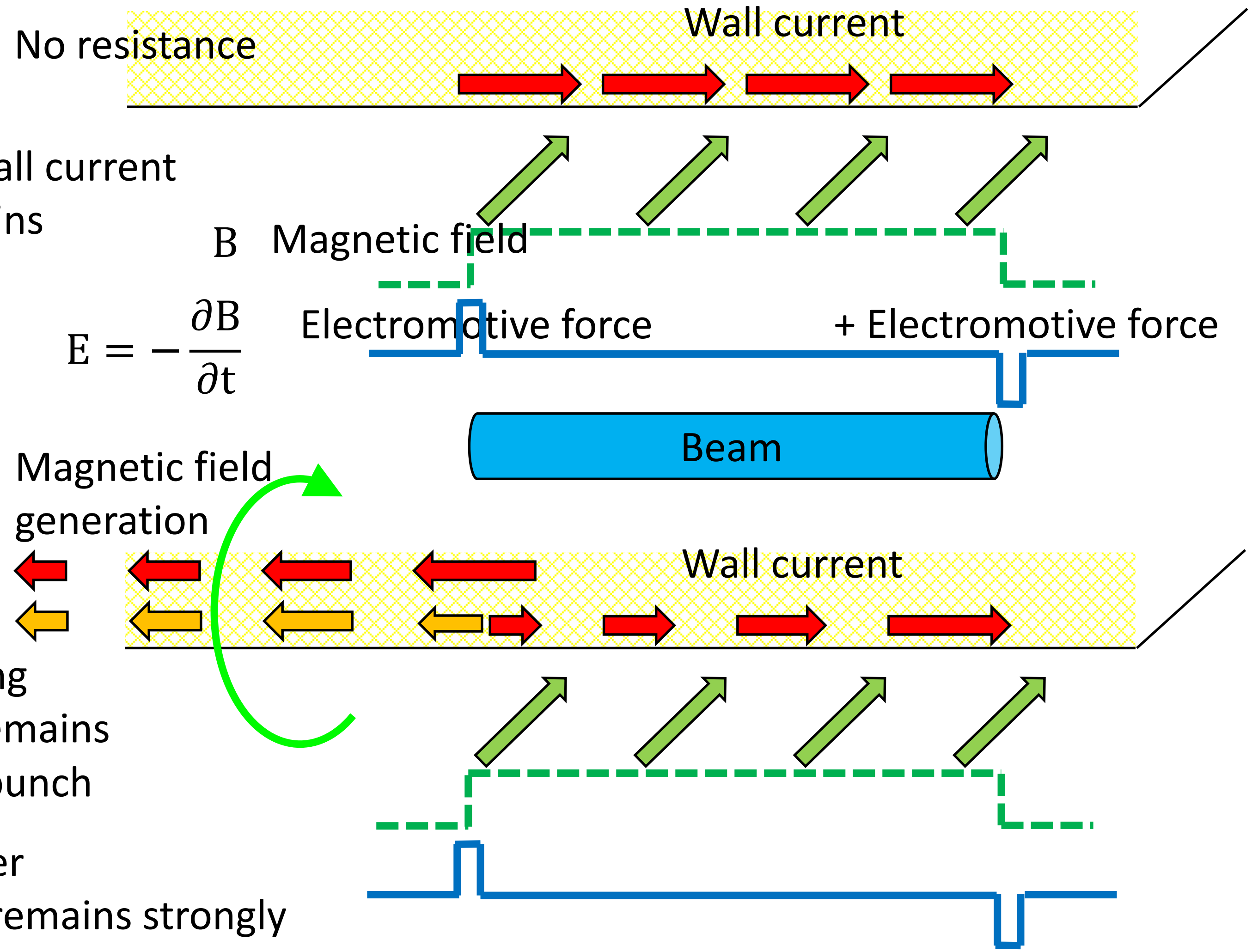


1-2mm There is a large amount of steps

Resistive-wall Wake (Impedance)

Even on a flat wall、Resistance of the wall、wake field occur

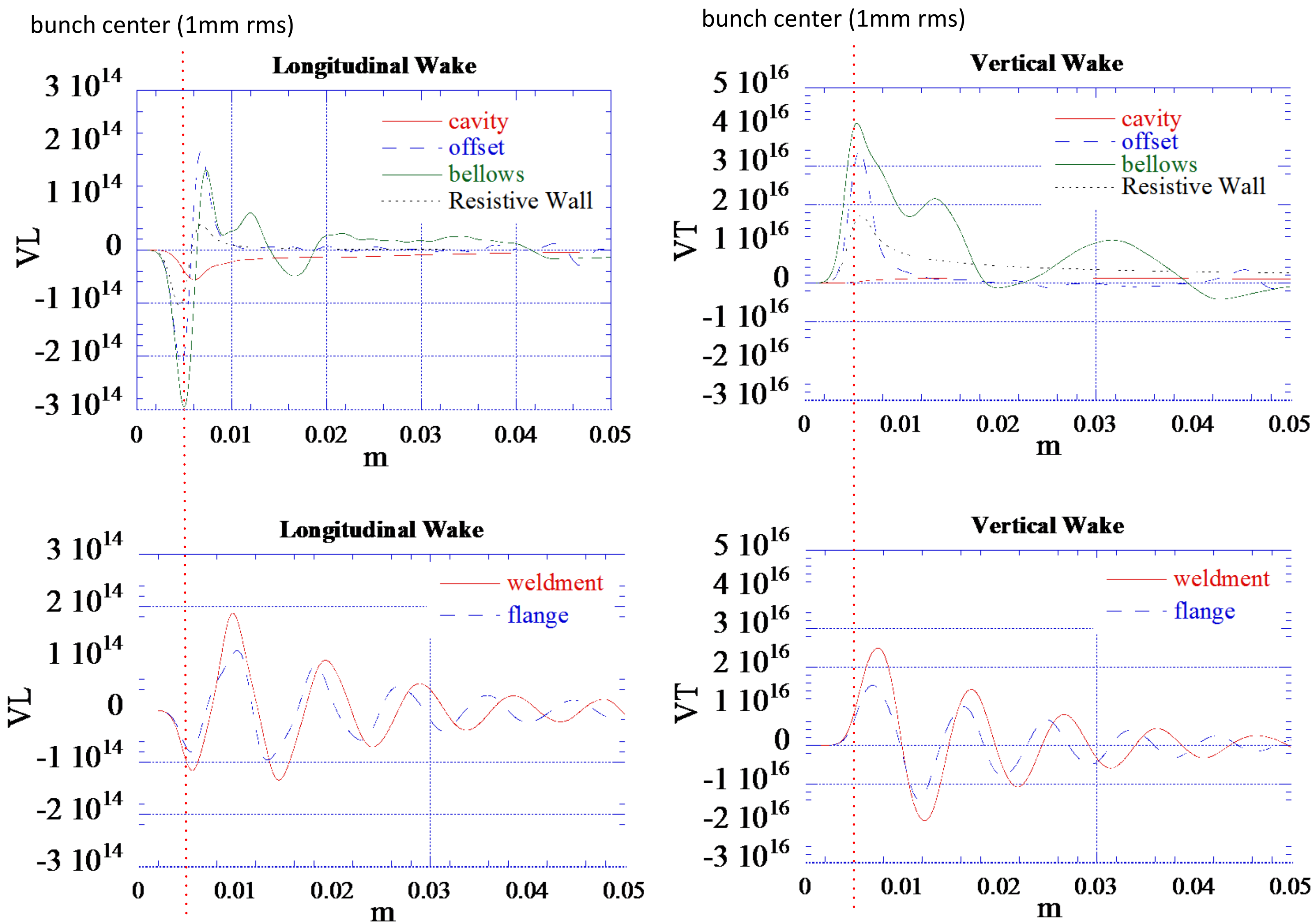
Low frequency
Horizontal kick is
Large
The strength of wake is
$1/gap^3$、
With undulator etc.
To occur strongly



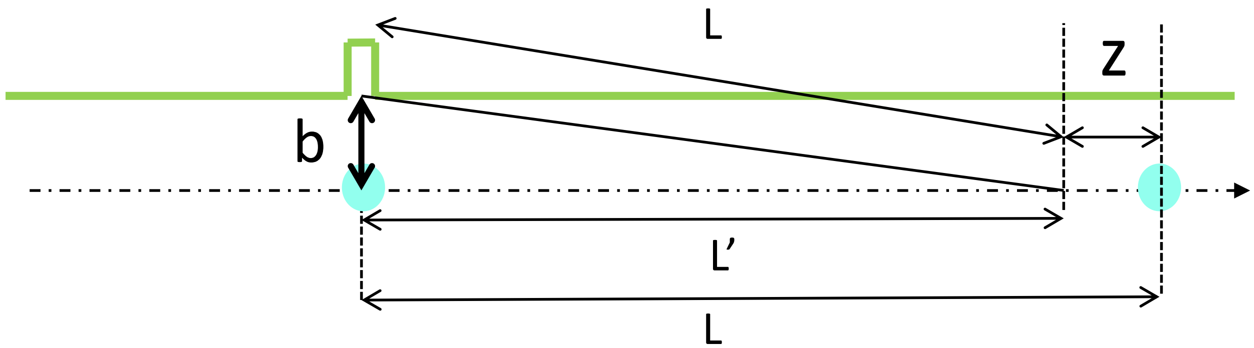
Wall current remains long
= Magnetic field: kick remains
Kick the following bunch

Beam shifts up from center
= The upper wall current remains strongly
= The magnetic field by the wall current on the beam axis is stronger from the upper side
= Kicking in the wall direction osscurs

Wake Potential of Components (SPring-8)



Catch Up of Wake



$$L' = \sqrt{L^2 - b^2} = L\sqrt{1 - \left(\frac{b}{L}\right)^2} \sim L\left(1 - \frac{1}{2}\left(\frac{b}{L}\right)^2\right) = L - \frac{b^2}{2L}$$

$$z = L - L' = \frac{b^2}{2L} \qquad L = \frac{b^2}{2z}$$

If the accelerator is shorter than this
Wake does not affect bunch

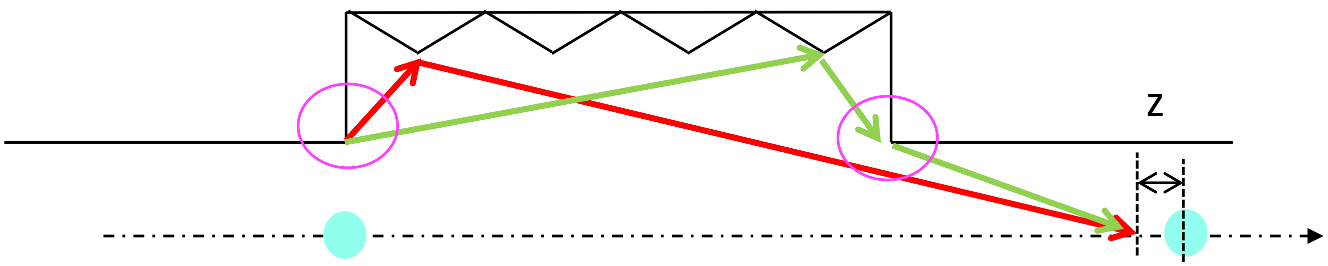
Storage Rings	XFEL Linac		
b = 20mm	b = 3mm (Undulator gap)		b = 10mm
z = 1mm (3ps)	z = 30um (100fs)	....	z = 0.01um
L= 0.2m	L= 0.3 m		L= 5000m > Accelerator length

(Beam bends)

In case of extremely short bunch, it is not affected by wake
Kinetic energy of electrons is not lost. No kick

Catch Up of Wake

In the case of short bunch, shingle pass、
The structure withdrawn to a certain extent can be neglected
（I can not catch up with the bunch anyway）



However、○the wake field generated at the corner, surrounded by circles affects the beam。

Like a storage ring
When the bunch is long (the spread due to diffraction is large）、
By making it a taper instead of a corner, the electromagnetic field spreading by diffraction is smoothly connected to the wall. It is possible to relieve the occurrence of a wakefield、

When the bunch is short, the electromagnetic field is peeled off immediately from the taper, and even if it is tapered, it can not be relaxed much。

Impact of Wake field

Stationary (mostly at high bunch current)

Energy kick (vertical direction)

- Energy loss => EM field、wall resistance loss
  - Acceleration voltage required
  - Beam pipe heat generation
- Deformation of acceleration potential
  - Increase of bunch length (normal）
  - Shortening of bunch length（$\alpha < 0$)

Horizontal kick (horizontal, vertical direction)

- Current dependence tune
- Current dependence COD

Impact of Wake field

Transient

Longitudinal

- Excitation of synchrotron oscillation
  - Multi-bunch instability (Bunches joined together）
    - Wake with long time constant : RF HOM
- Microwave instability
  - Density modulation inside the bunch occurs
    - => Enhanced energy spread
      - => Further increase in bunch length
  - Generation of coherent synchrotron radiation (sub THz ~ THz)
    - Burstly
  - Short wake : Small groove of beam pipe etc.

Impact of Wake field

Transient

Transverse direction

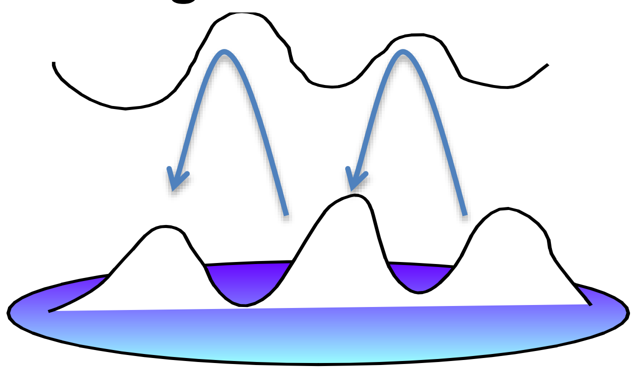
- Excitation of betatron oscillation
  - Multi bunch instability
    - Wake with long time constant
      - Wall resistance wake、RF HOM
  - Single bunch instability
    - Vibration of the head of the bunch
      - => Wake field vibrates
        - => Exciting the buttocks of the bunch
    - Centroid vibration、Internal vibration

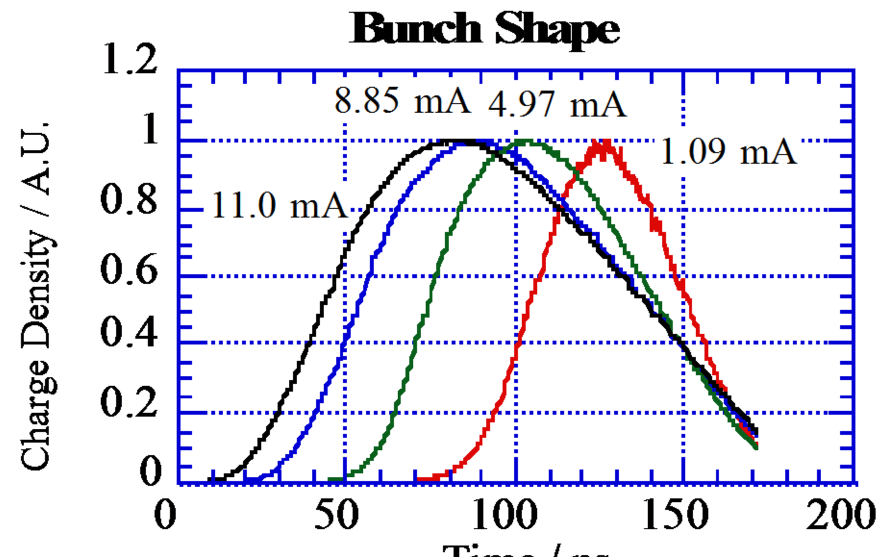
中村 http://www.jssrr.jp/journal/pdf/17/p161.pdf

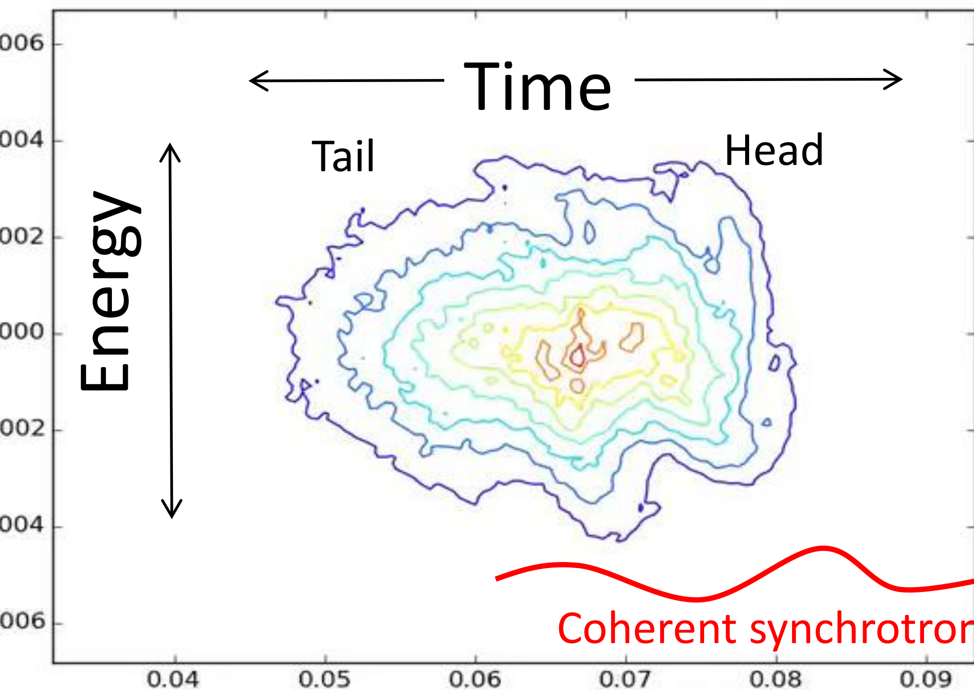
Microwave instability

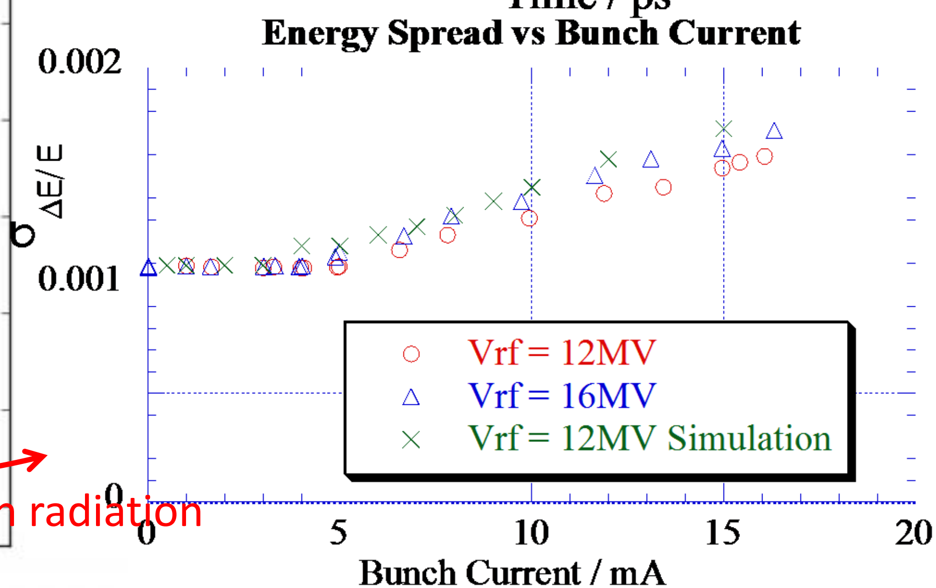
Energy spread increase

Small irregularities









Coherent synchrotron radiation

T. Nakamura, et. al, http://www.pasj.jp/web_publish/pasj6/papers/wpbta05.pdf

Transverse single bunch instability

Vibration of the head of the bunch

=> Oscillating wake field is generated

=> Excite vibrations by kicking the tail of the bunch

=> By synchrotron oscillation

Head and tail position reversed

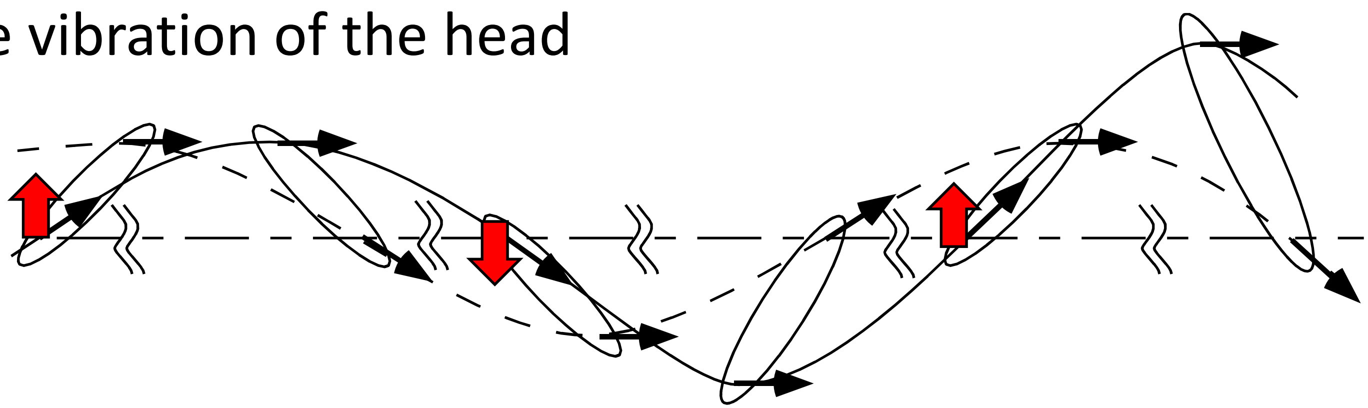
=> By the vibration the head was giving to the tail

The head itself gets kicked

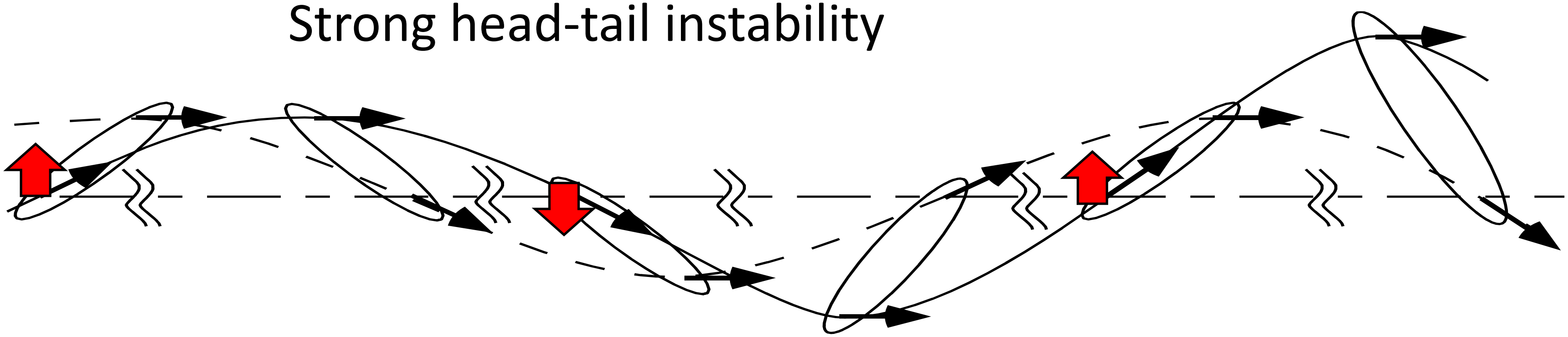
=> Loop occurs

However, the kick of the wake is proportional to the position of the head of the bunch

=> The vibration of the tail of the bunch is 90 degrees behind the vibration of the head



Strong head-tail instability



Phases of vibration/kick

With synchrotron vibration
Head and tail are swapped

Head osci		**0 deg**	**0 deg**	**-90 deg**
⇩	0 deg	⇩	⇩	⇩
Tail kick		0 deg	0 deg	-90 deg
⇩	-90 deg	⇩	⇩	⇩
Exci. Vib of the tail		**-90 deg**	**-90 deg**	**-180 deg**
Tail vibration		-	**-90 deg**	**0 deg**

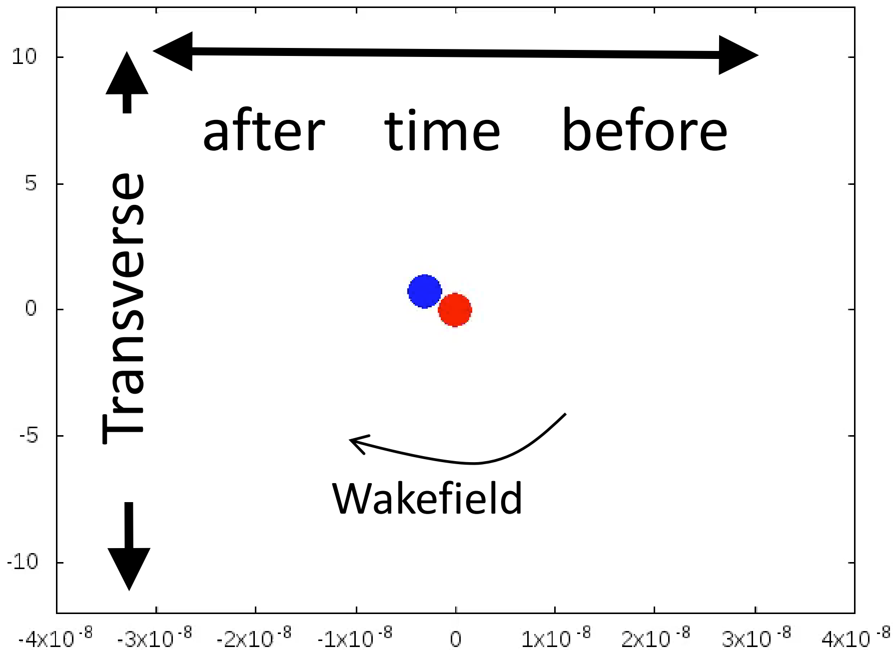
互いに打ち消す方向

Phase difference -180deg

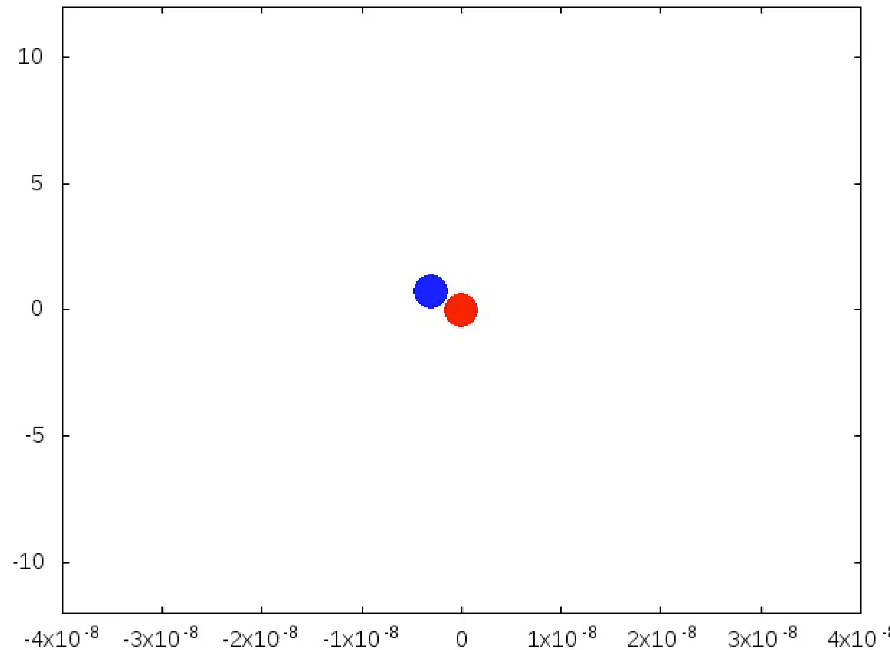
Strong head-tail instability

2 particle model

Less threshold current



Higher threshold current



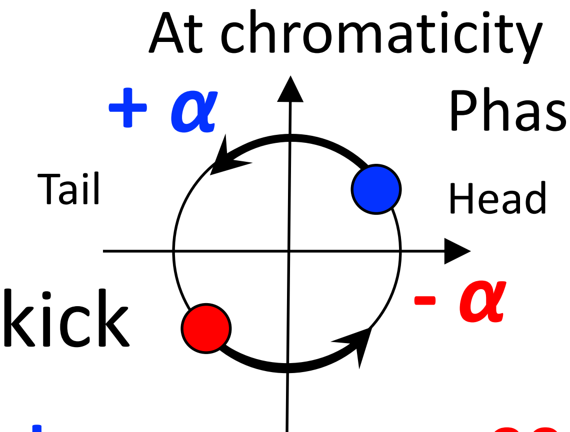
Vibration of tail particle
Stimulated and stable

After the vibration of the tail particle is canceled because the kick by the wake field is large、It is excited more than the same amplitude as the head

There is a threshold current in the mode coupling instability, and it becomes unstable beyond than

Head-tail instability

Chromaticity != 0



Phases of vibration and kick

Head vib		0 deg	0 deg	-90 deg - α
	0 deg			
Tail kick		0 deg	0 deg	-90 deg - α
	-90 deg			
Tail vibration exci		-90 deg	-90 deg	-180 deg - α
Tail vibration		-	-90 deg	0 deg + α

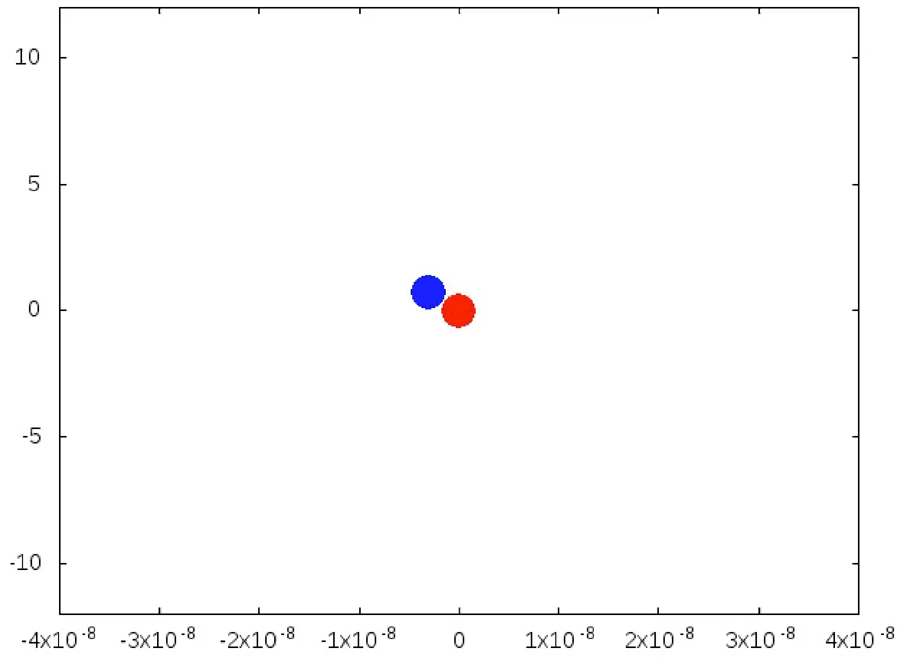
位相差 -180deg - 2 α

Due to the phase shift, the cancellation is misaligned and to the attenuation / excitation

Head-tail Instability

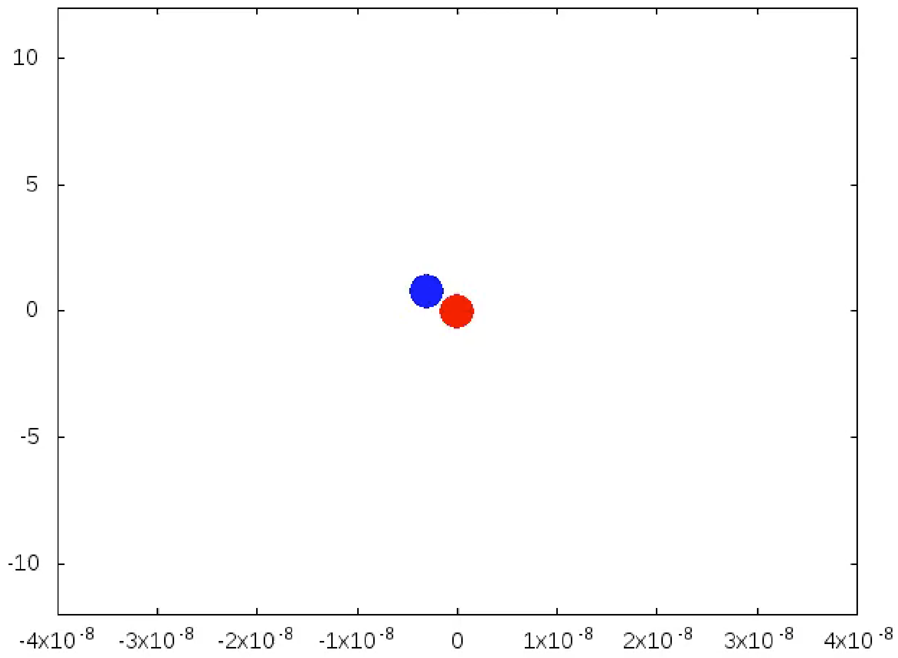
2 particle model

Chromaticity > 0



Relative vibration is excited

Chromaticity < 0



Center of motion excitation

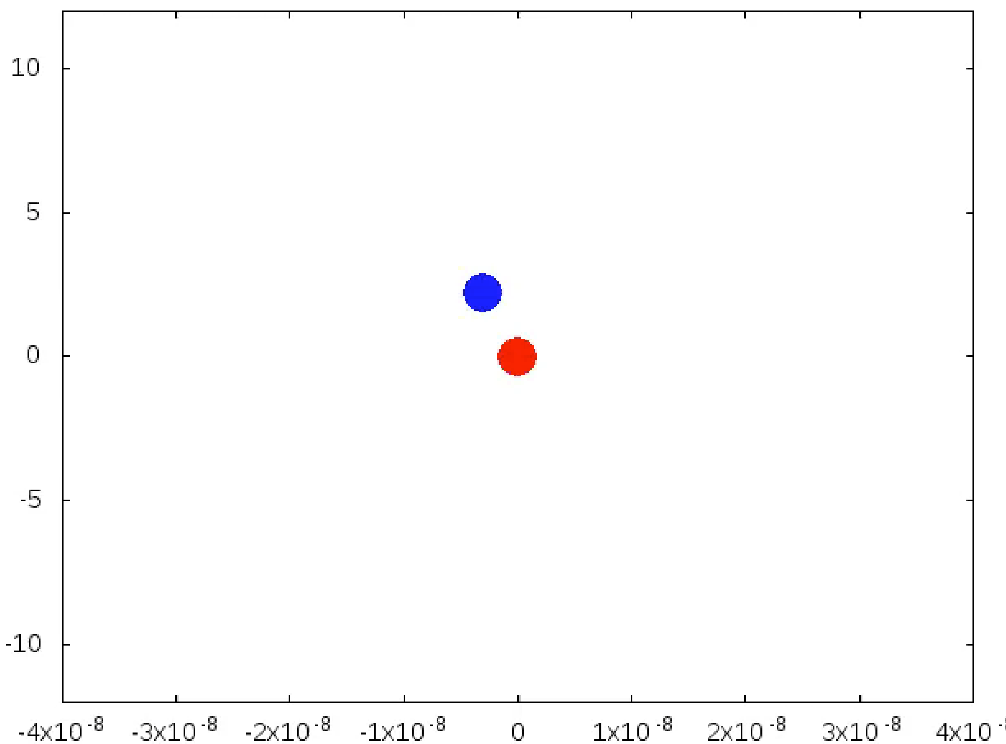
（positive alpha case。
In case of negative alpha, it is reversed due to phase differnece）

Head-tail instability

Polarity of chromaticity (positive alpha case）

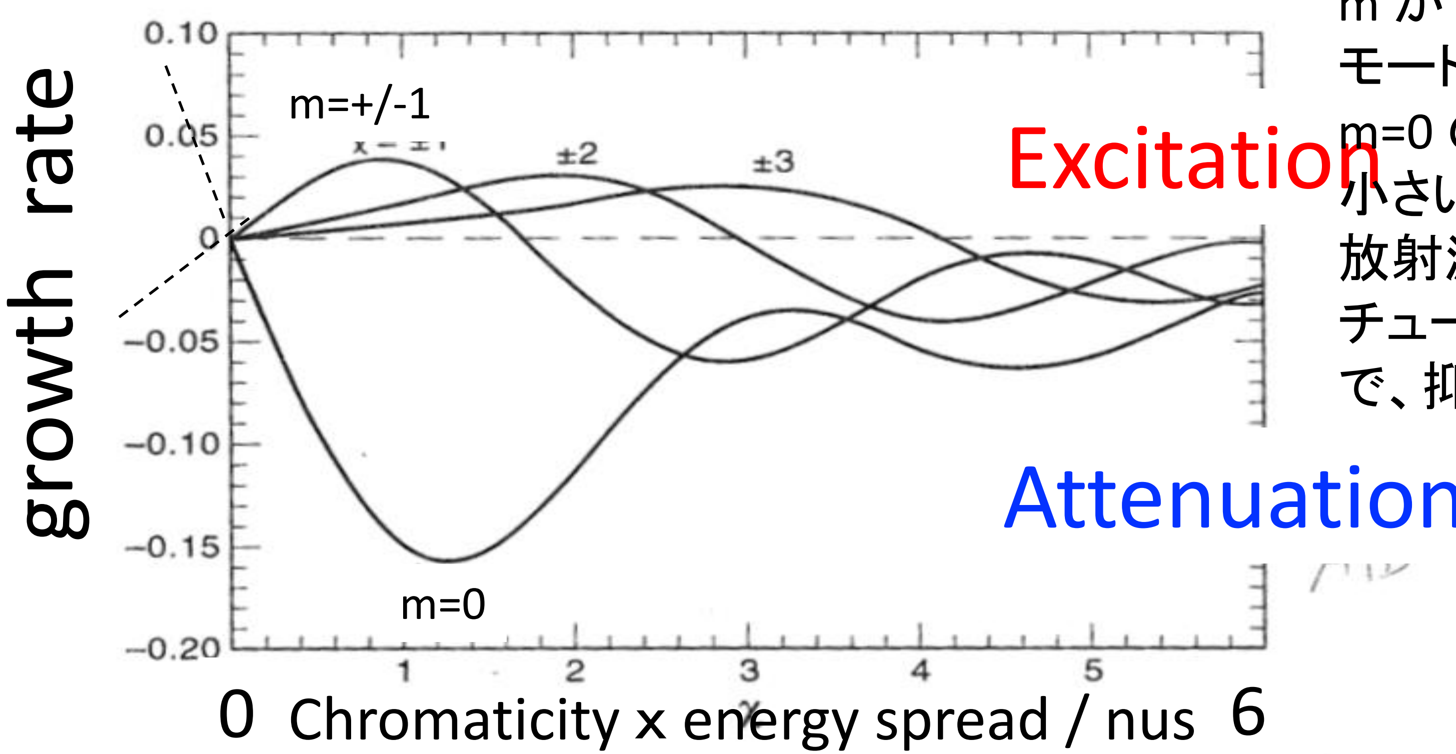
Positive	centroid damping	Relative vibration is unstable
Negative	centroid unstable	Relative vibration is dampling

Attenuation of centroid vibration (Head-tail attenuation) with positive chromaticity



Calculation results in a certain distribution(Air-bug model)

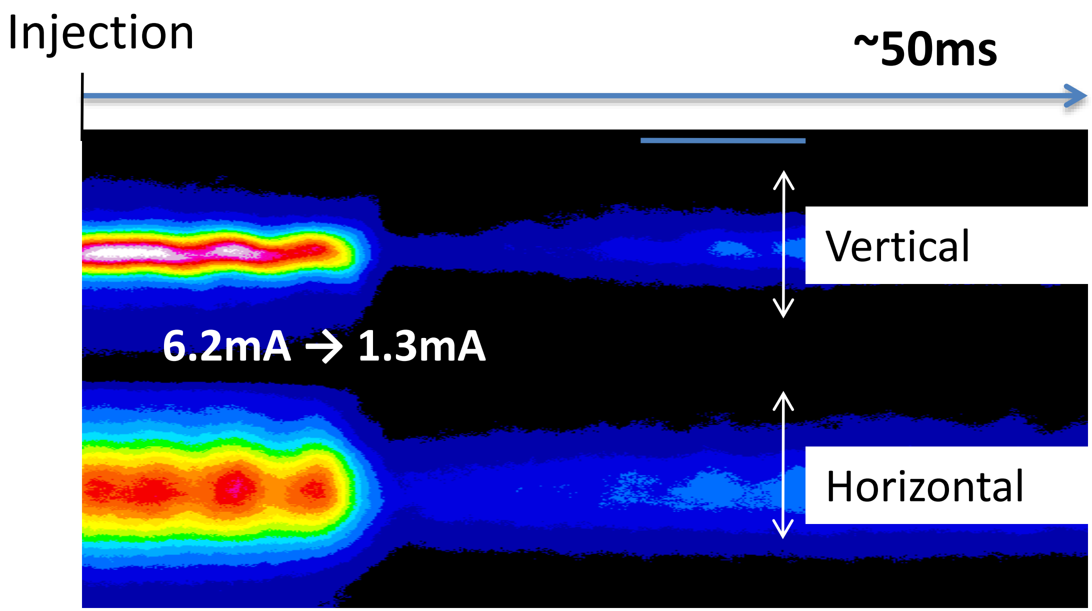
Chromaticity polarity	(Positive alpha） centroid (m=0)	relative (m=+/-1)
+	attenu	excit
-	excit	attenu



m が 0でない
モードの成長率は
m=0 のモードより
小さい
放射減衰や
チューン広がりなど
で、抑制

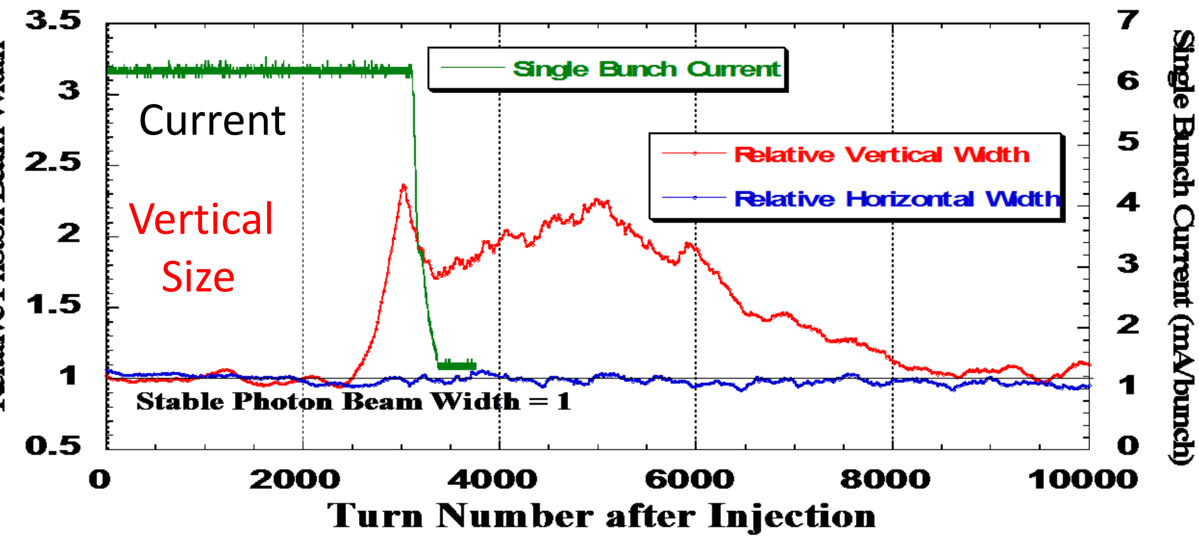
From A. Chao’s text book http://www.slac.stanford.edu/~achao/wileybook.html

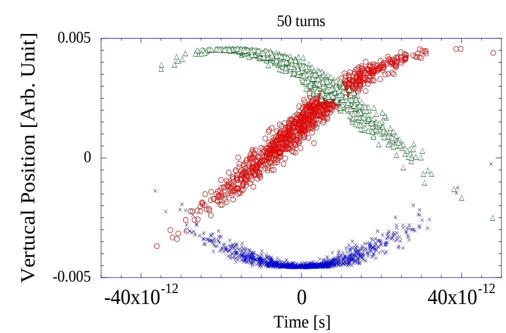
Vertical Beam Size Growth by ID radiation profile monitor



courtesy of M. Masaki, JASRI

Feedback suppresses only
CM motion
chromaticity
mixing of CM motion
and head-tail motion
Indirect suppression of
head-tail motion ??

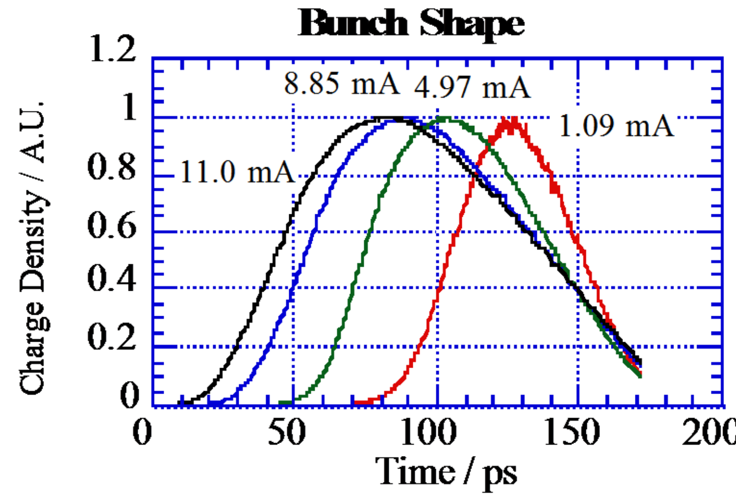


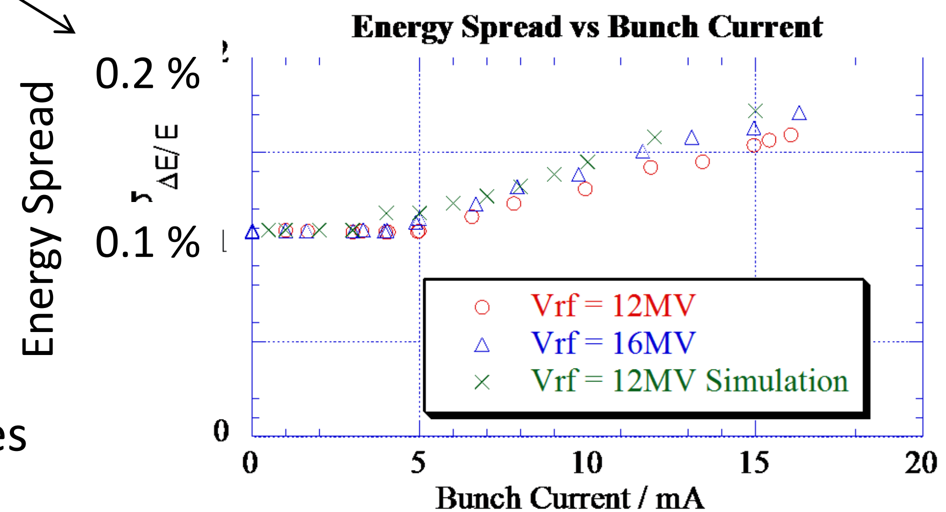


Instabilities observed in SPring-8

Longitudinal

- Heating of components
  - Gate vale finger, Kicker electrode,
- Bunch lengthening by Potential well distortion
- Energy Spread increase by microwave instability
- Multi-bunch Instability by RF cavity
  - observed at 6 GeV (not 8 GeV)





Transverse

- Multi-bunch Instability
  - by RF cavities
  - by Resistive-wall of Insertion devices
    - Vertical and Horizontal
- Single bunch Instability (Mode coupling Instability)
  - Vertical and Horizontal
    - Unstable at > 2mA/bunch for vertical
  - driven by beam pipe components (steps, grooves, tapers, .. .)
    - Resistive-wall of Insertion devices

Reduction of Wake

Reduction of wake for Single-bunch Instabilities

step < 0.5mm, gap < 0.5mm, depth of groove < 1-2mm
weldment , flanges, Shielded Bellows,

Taper angle 5deg
RF cavities, Insertion Devices,

Reduction of wake for Multi-bunch Instabilities

Scatter higher mode frequency
by Careful cavity shape tuning
Cu Sheet on Insertion device surface
Shield of permanent magnets (high resistivity)

Suppression of beam instability

Feedback

Head-tail attenuation

Set chromaticity to plus some large value

For strong attenuation, a big chromaticity

Stable region (dynamic aperture) is narrowed by strong sextupole

Reduced injection efficiency、short lifetime

(lower energy aperture)

Tune spread introduction

Instability is caused by the coherent motion of the particles of the beam

You should break coherence

For each particle, if the frequency is shifted, the phase of particle vibration is

The average of the positions of the particles = “centroid motion” become 0。 ➔ Damping of centroid (Landau dampling?)

Suppression of beam instability

* Beam broaden in the tune

- Make bunch spread
  Both single bunch and multi bunch suppressed
    Generation of amplitude dependence tune at 8 pole
      => stable region reduction
    At large amplitude tune shift is too large to fit into stable region
- Change the tune for each bunch
  Suppression of multi bunch
    Horizontal : Change the strength of quadrupole at the T
      KEK PF perform
    Vertical : Gap is added to the beam and the RF acceleration voltage
      Bring modulation during one ring of the ring
      => Synchrotron frequency is different for each bunch
      ESRF
- Chromaticity
  Instantaneously, there is an effect, but after one cycle of synchrotron T
  The tune shift returns to 0, and the particles cooperate again with each

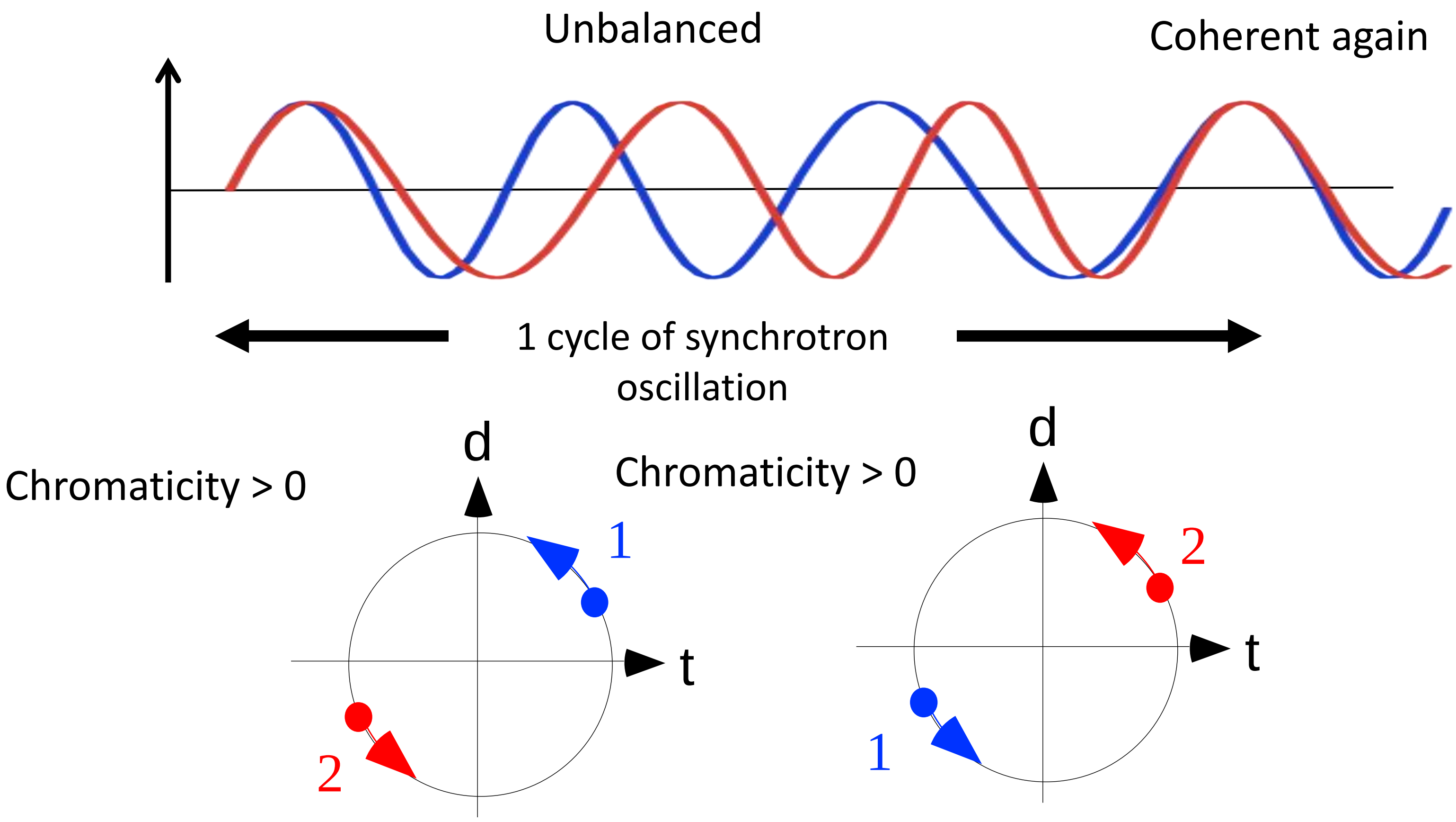
Suppression of beam instability

- Chromaticity

There is an effect, but after one cycle of synchrotron T

Tune shift returns to 0, and the particles cooperate again with each oth

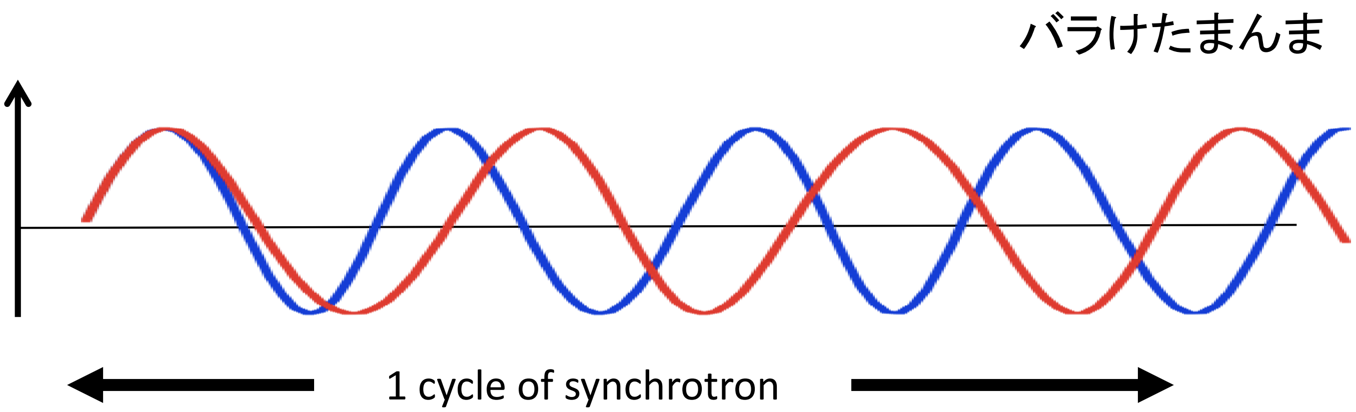
Tune spread effect is small

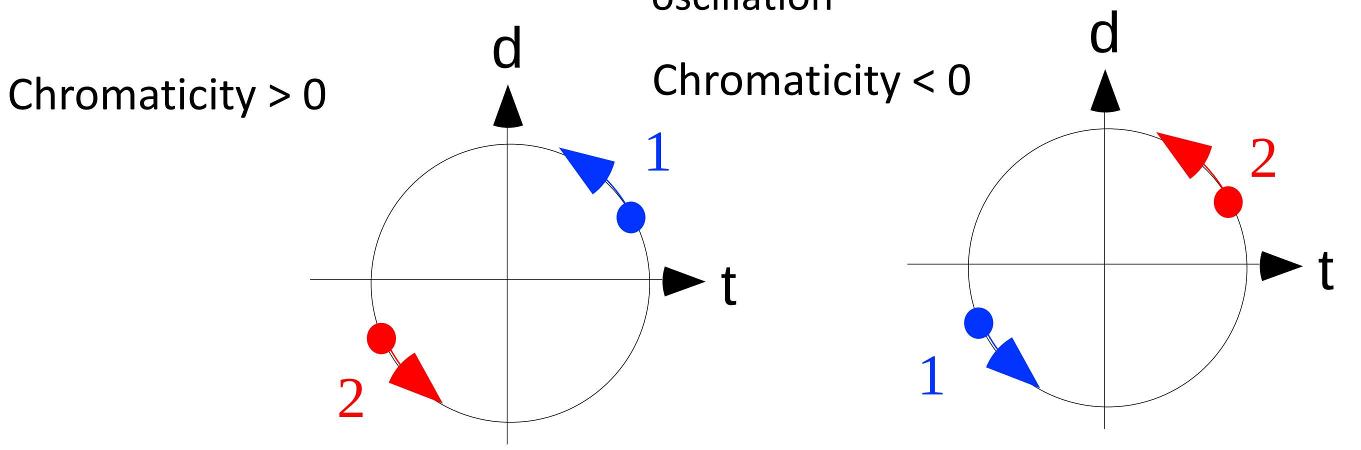


Suppression of beam instability

AC Chromaticity

Modulate chromaticity with the cycle of synchrotron T





T. Nakamura, http://accelconf.web.cern.ch/AccelConf/p95/ARTICLES/WAC/WAC14.pdf

クロマティシティ変調

シンクロトロン周波数での
クロマティシティの変調

＋

エネルギー広がり

↓

横方向チューンの広がり

$$\xi(t) = \xi_0 + \xi_1 \cos \omega_s t$$

$$\frac{\Delta E}{E} = \delta(t) = \hat{\delta} \cos(\omega_s t + \phi)$$

$$\nu(t) = \xi(t)\delta(t) = (\xi_0 + \xi_1 \cos \omega_s t)\hat{\delta} \cos(\omega_s t + \phi)$$

$$\bar{\nu} = \overline{\xi_1 \hat{\delta} \cos \omega_s t \cos(\omega_s t + \phi)} = \frac{1}{2}\xi_1 \hat{\delta} \cos \phi = \frac{1}{2}\xi_1 \delta(0)$$

エネルギーの初期値とおなじ分布
（ガウス分布）

$$\sigma_\nu = \frac{1}{2}\xi_1 \sigma_\delta$$

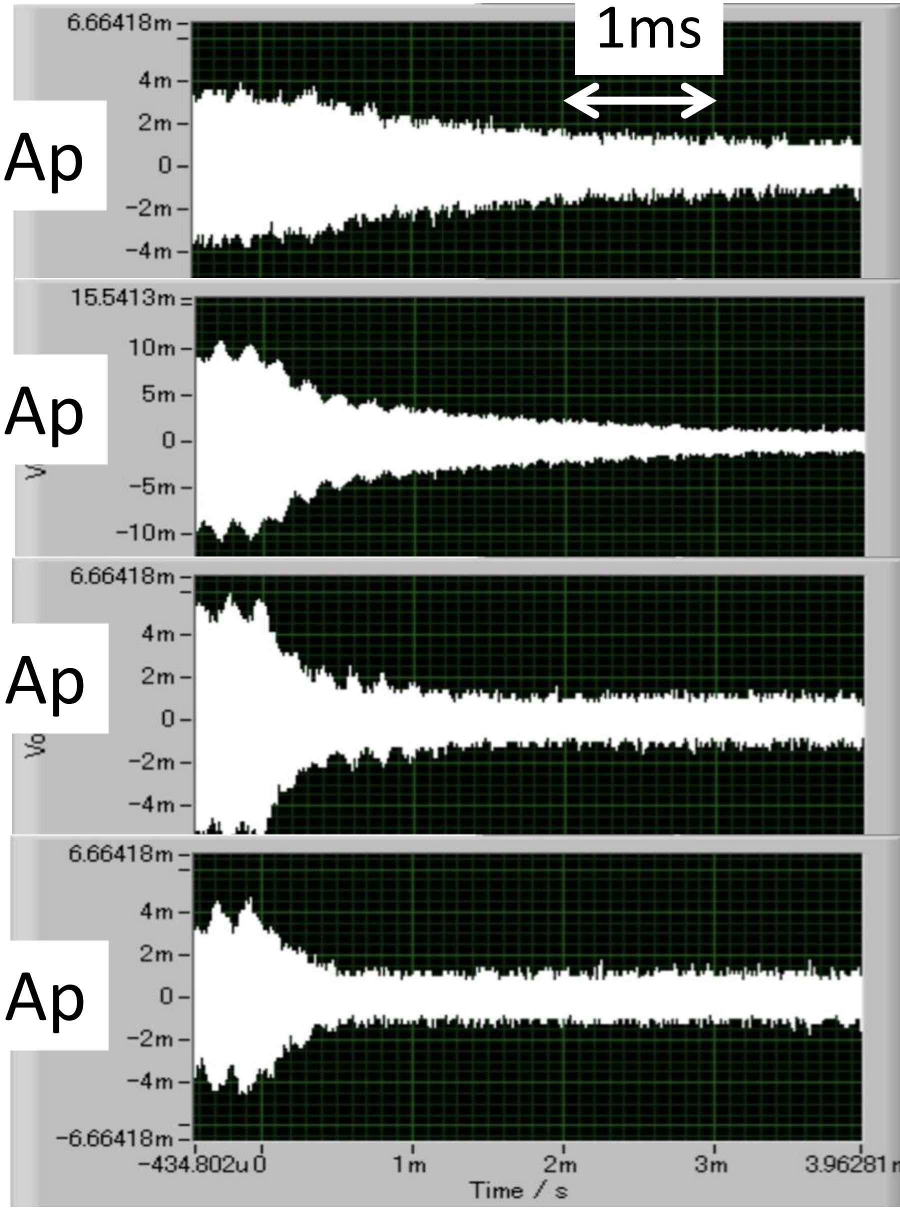
We tried　　　Decay time meas.

AC 6 poles

New SUBARU installed

Excitation beam oscillation

Vibration attenuation after forced off



中村　剛、大熊　春夫、熊谷　教孝、
大島　隆、武部　英樹、松井　佐久夫
JASRI
安東　愛之助、庄司　善彦、橋本　智、
服部　正
兵庫県立大学
熊谷　桂子
理化学研究所

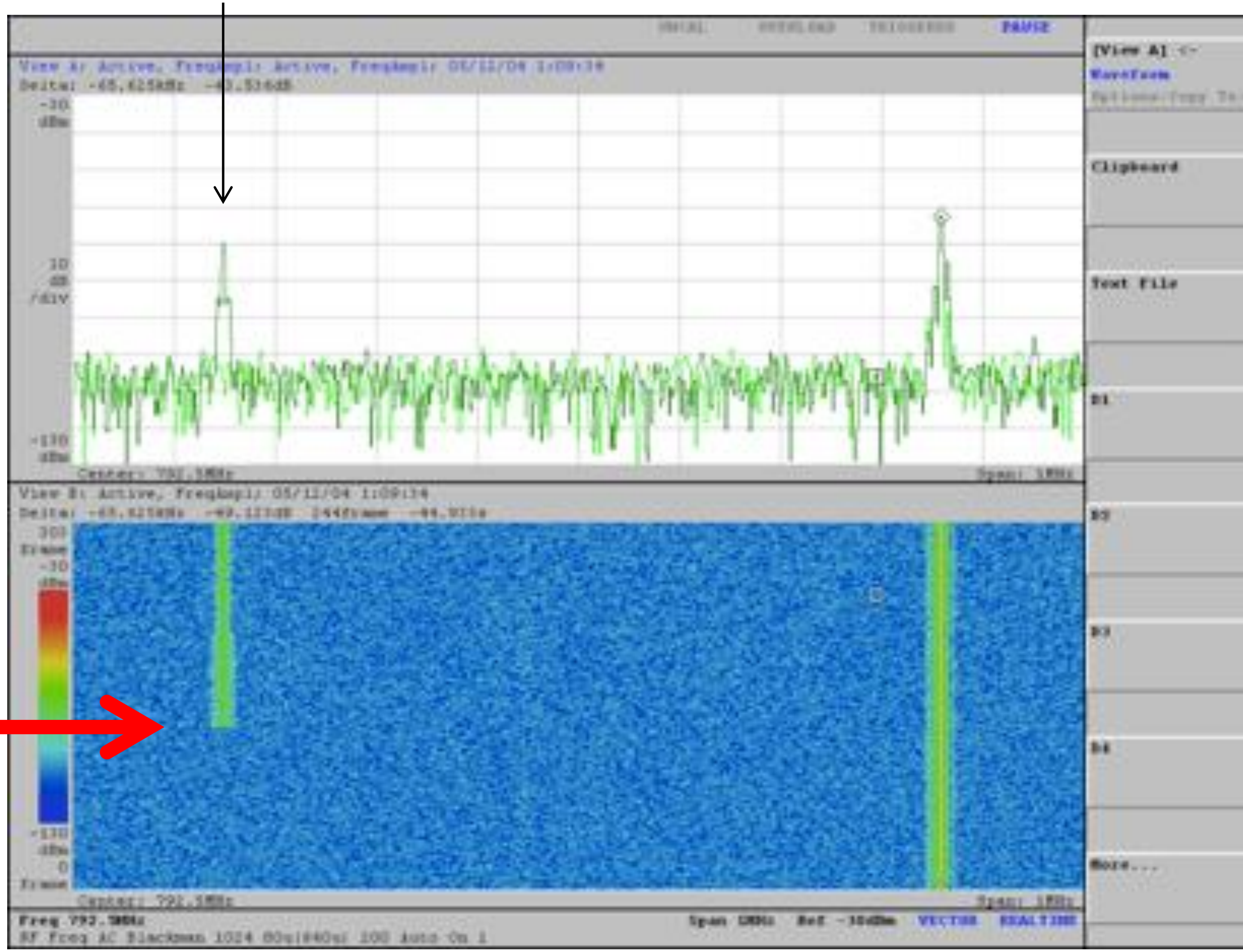
http://www.pasj.jp/web_publish/pasj3_lam31/Proceedings/T/TO08.pdf

Multi-bunch instability suppressio

Multi-bunch instability due to RF HOM

Horizontal

Real time spectrometer



AC hexapole
187Ap

Chromaticity can not be strong

Injection loss increases

Lifetime shortened

Frequency of injection increases

During injection (Top-up injection) user uses

It is not good from radiation safety

=> Feedback (bunch by bunch)

Feedback by analog circuit

DSP、digital feedback and custom LSI is practical. but

Adjustment is serious

Insufficient performance

It costs too much money

FPGA is cheap, fast and high performance => useable …

Mr. Kazuo Kobayashi right beside was a digital element design

T.Nakamura, K. Kobahashi, et al., https://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT068.PDF

=> KEK-PF, HLS, TLS, SSRF, PLS, PLS-II, SOLEIL, Aichi-SR, and several proton/ion rings

FPGA

Field Programmable Gate Array

= On-site changeable logic circuit

Logic circuit = Hardware

CPU + Software

High speed processing

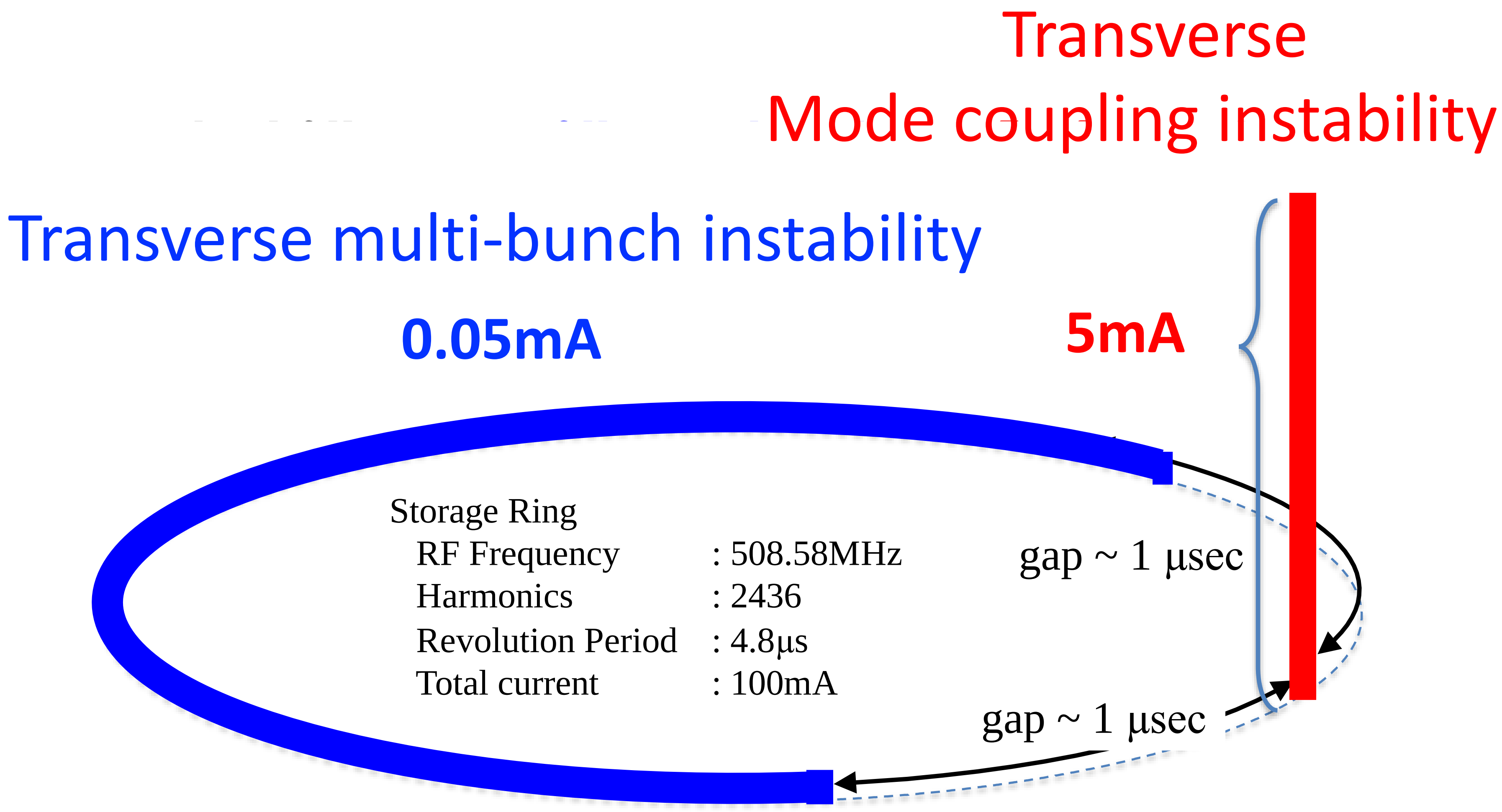
Parallel processing : Independent processing for each bunch

Parallelize signal lines and circuits by the number of processes

Complex processing difficult : FIR filter easy

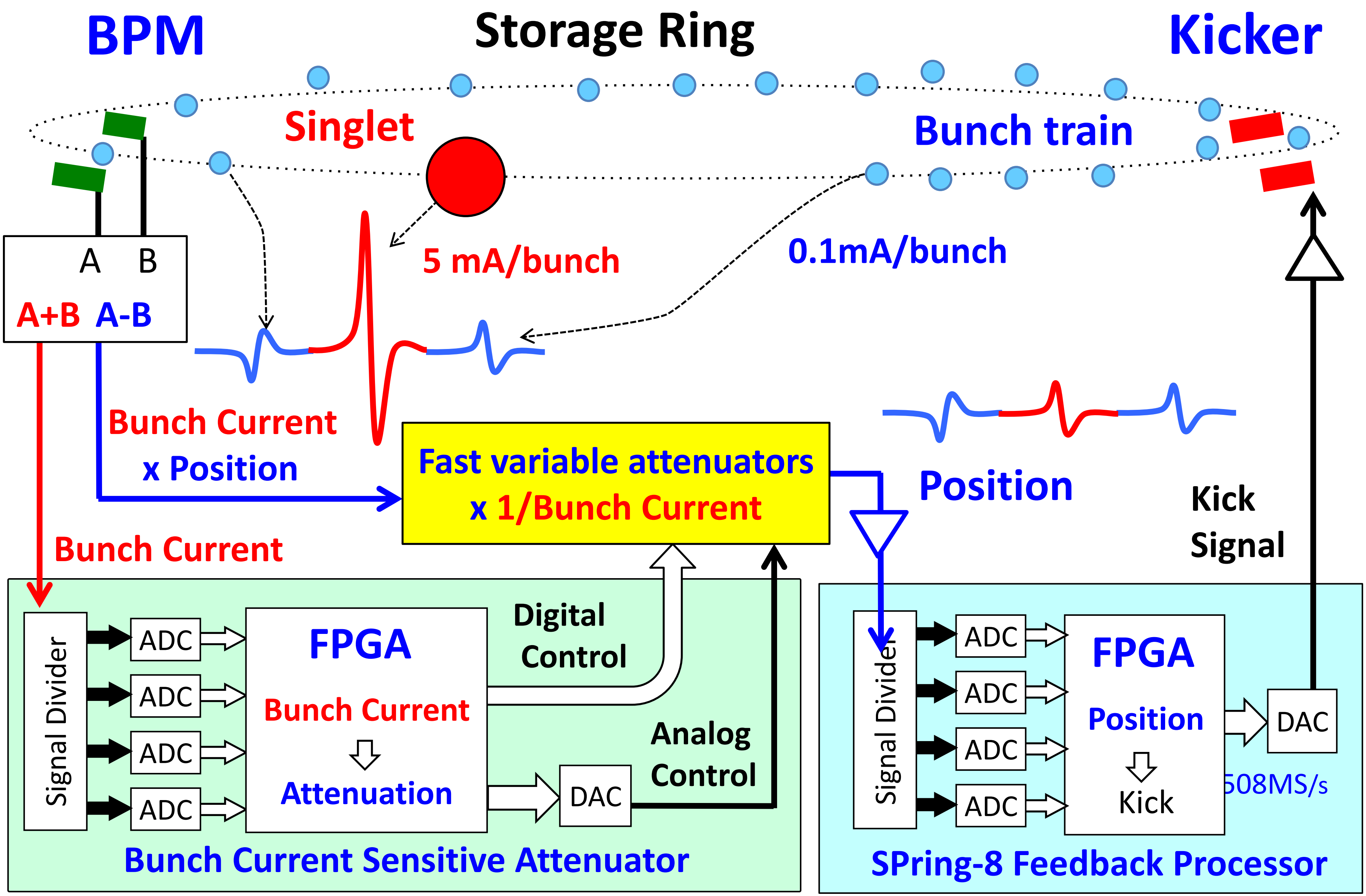
Some FPGAs have built-in CPU

Storage ring: Bunch current largely different



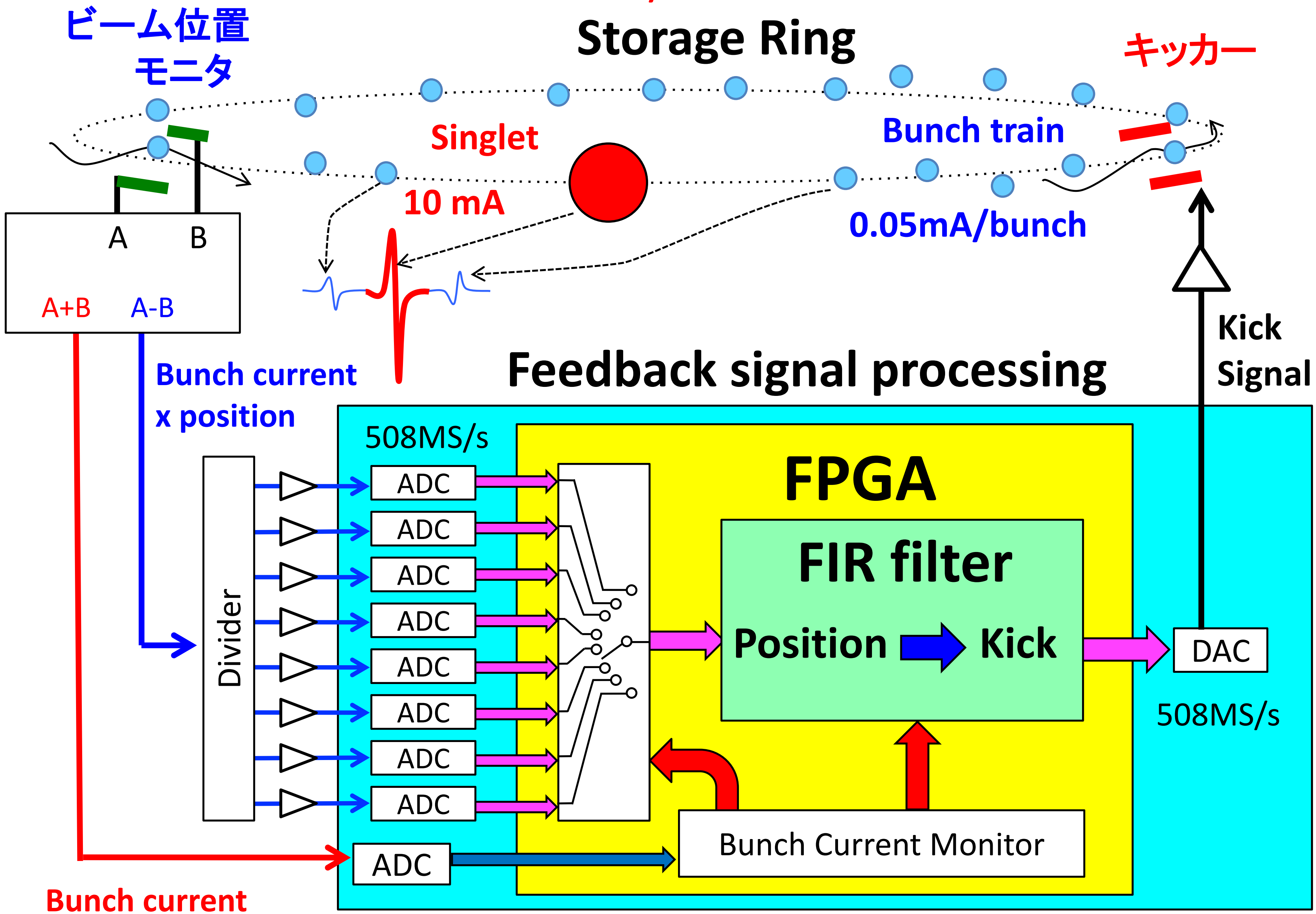
It is necessary to simultaneously suppress two instabilities

Bunch by bunch feedback unit last year

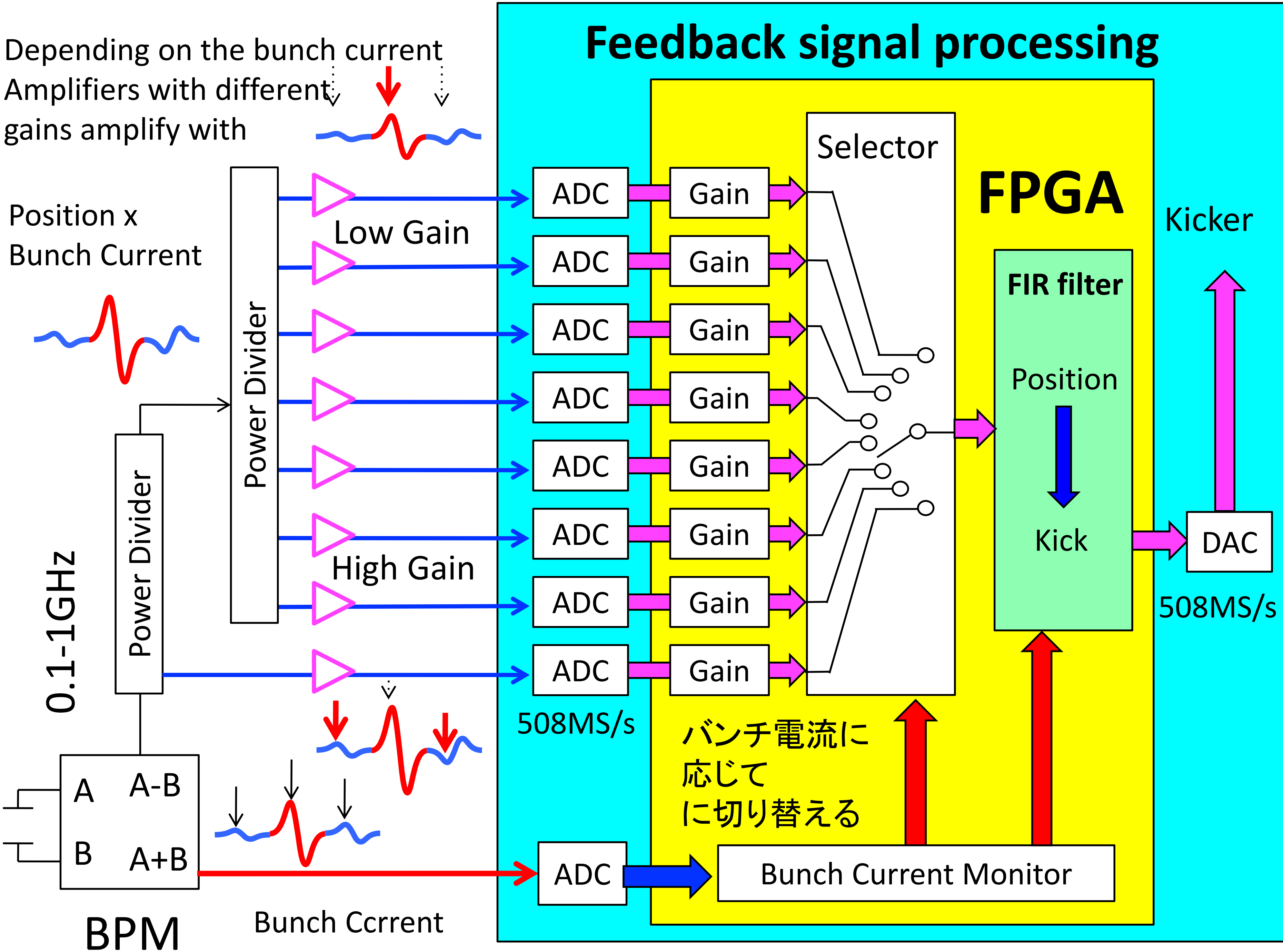


K. Kobayashi, T. Nakamura, http://accelconf.web.cern.ch/AccelConf/icalepcs2009/papers/thb006.pdf

Current bunch by bunch feedback

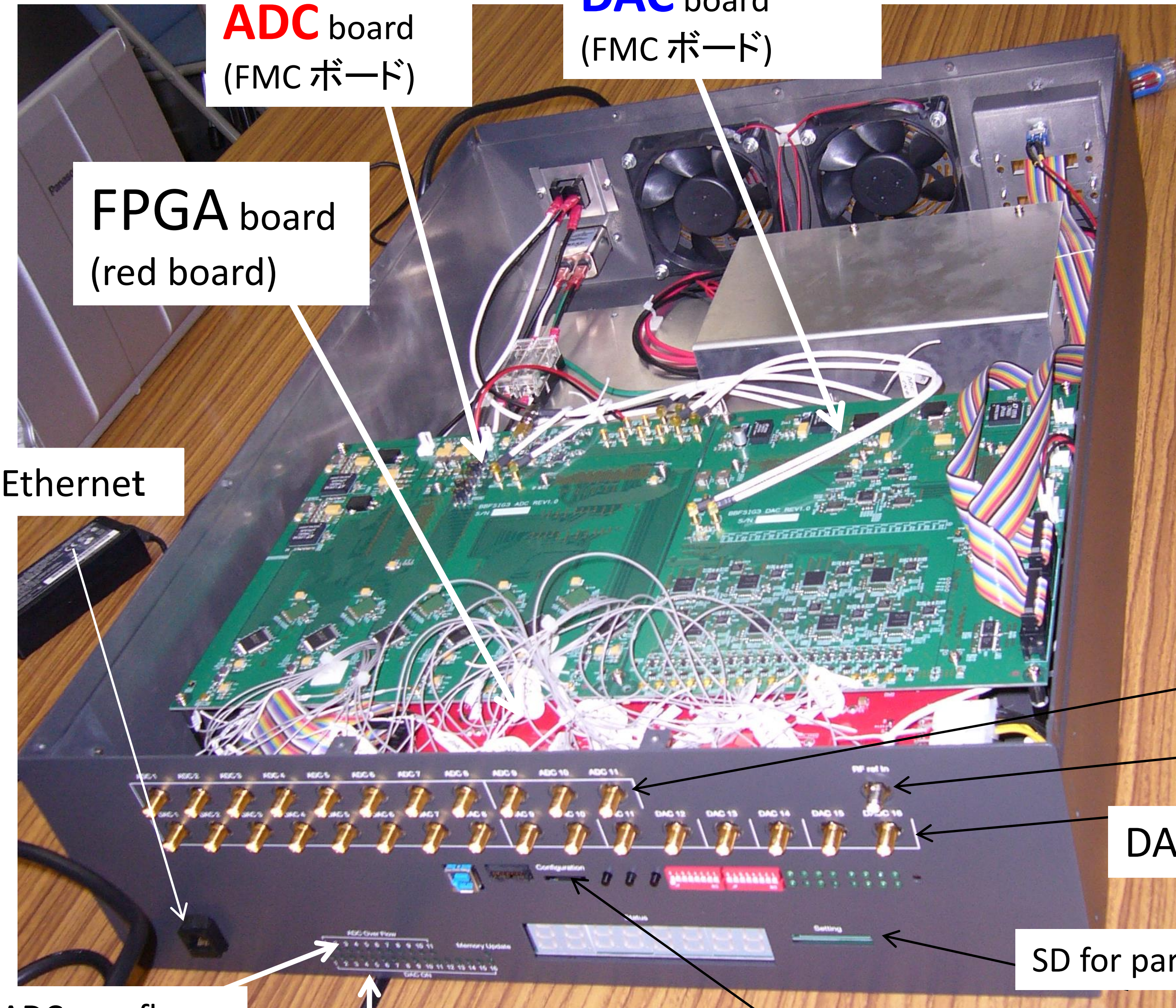


K. Kobayashi, et. al, http://www.pasj.jp/web_publish/pasj2015/proceedings/PDF/WEOL/WEOL03_oral.pdf


Feedback signal processing
Depending on the bunch current
Amplifiers with different
gains amplify with
Position x
Bunch Current
Power Divider
Low Gain
High Gain
0.1-1GHz
Power Divider
ADC
Gain
Selector
FPGA
FIR filter
Position
Kick
Kicker
DAC
508MS/s
508MS/s
バンチ電流に
応じて
に切り替える
A
B
A-B
A+B
BPM
Bunch Ccrrent
ADC
Bunch Current Monitor

Processing deivce

(upside down)



Signal Processing by FIR filter in FPGA

Number of Taps

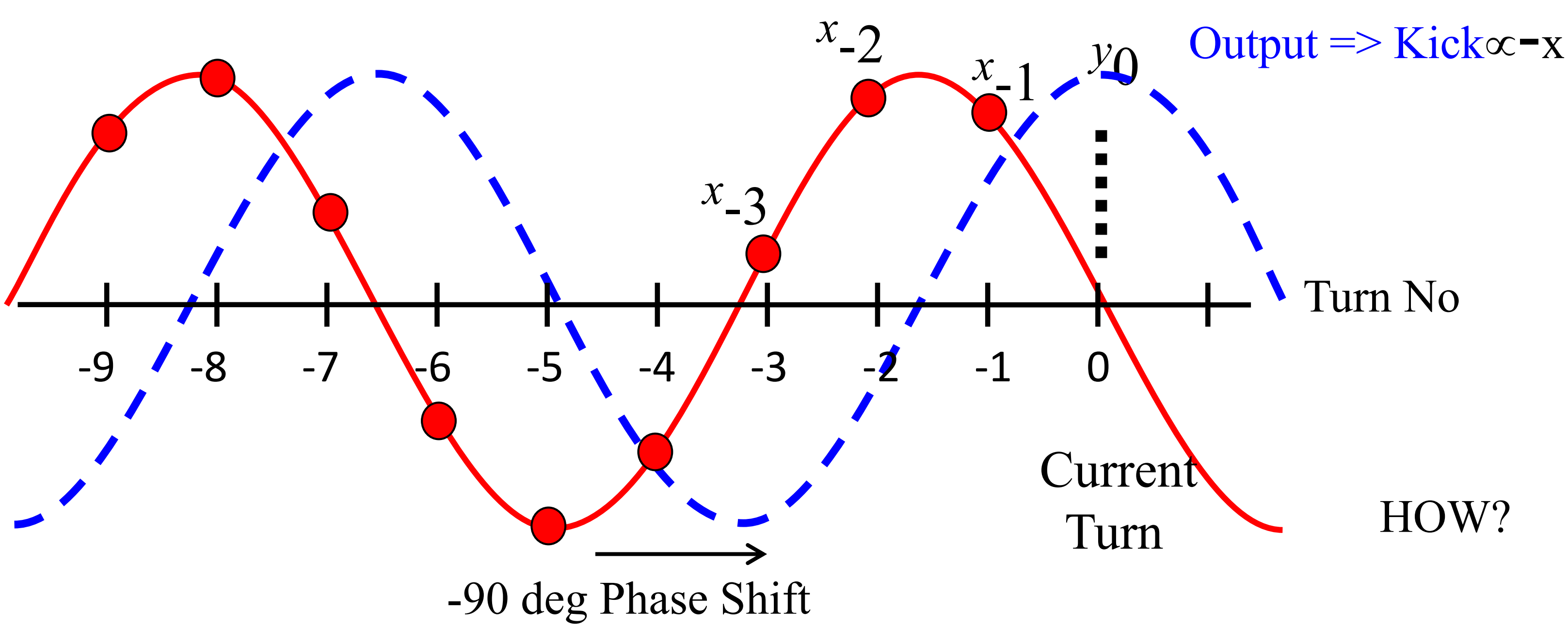
FIR filter

$$y_n = \sum_{k=1}^{N} a_k x_{n-k}$$

Kick

Bunch Position History

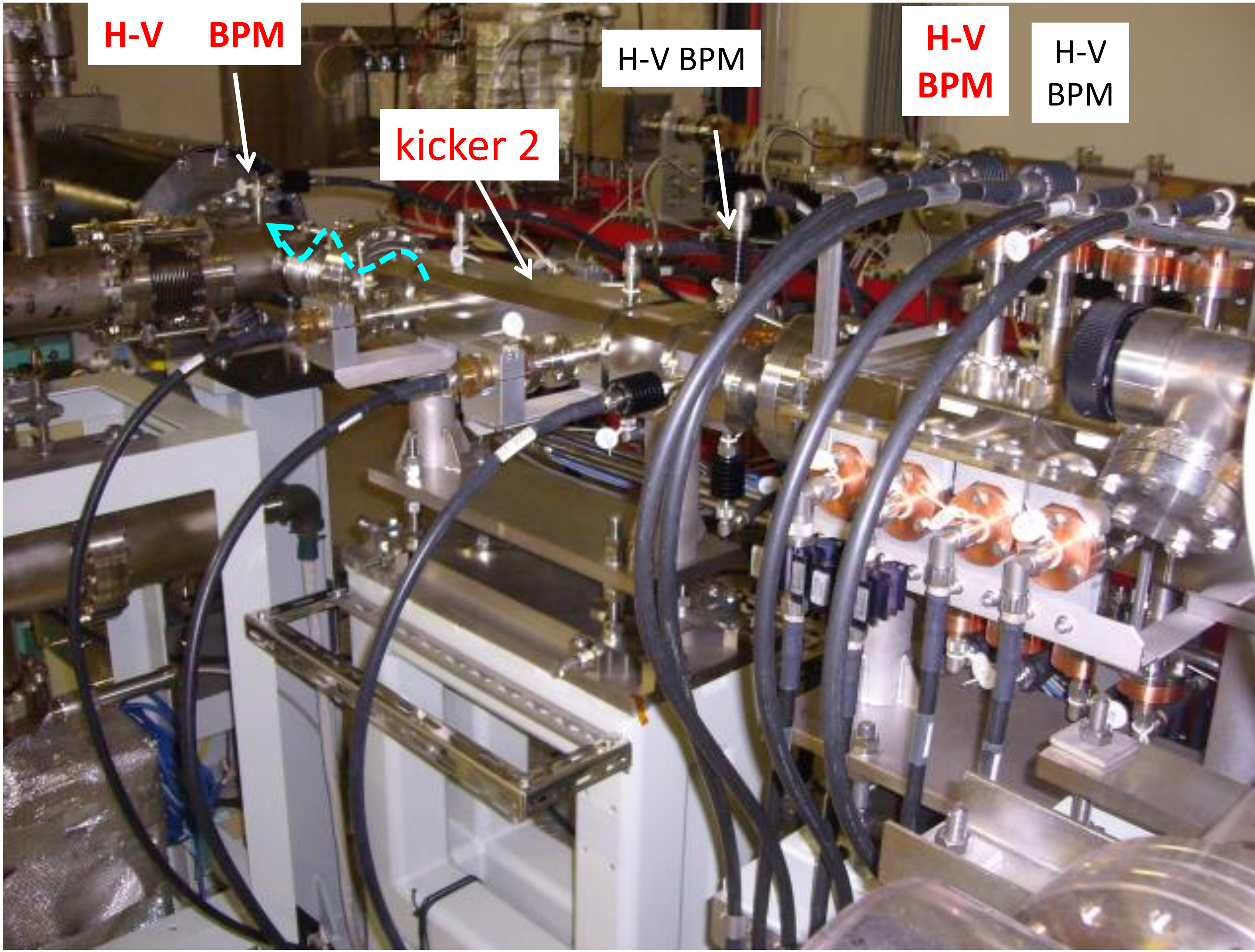
Bunch Position = Input

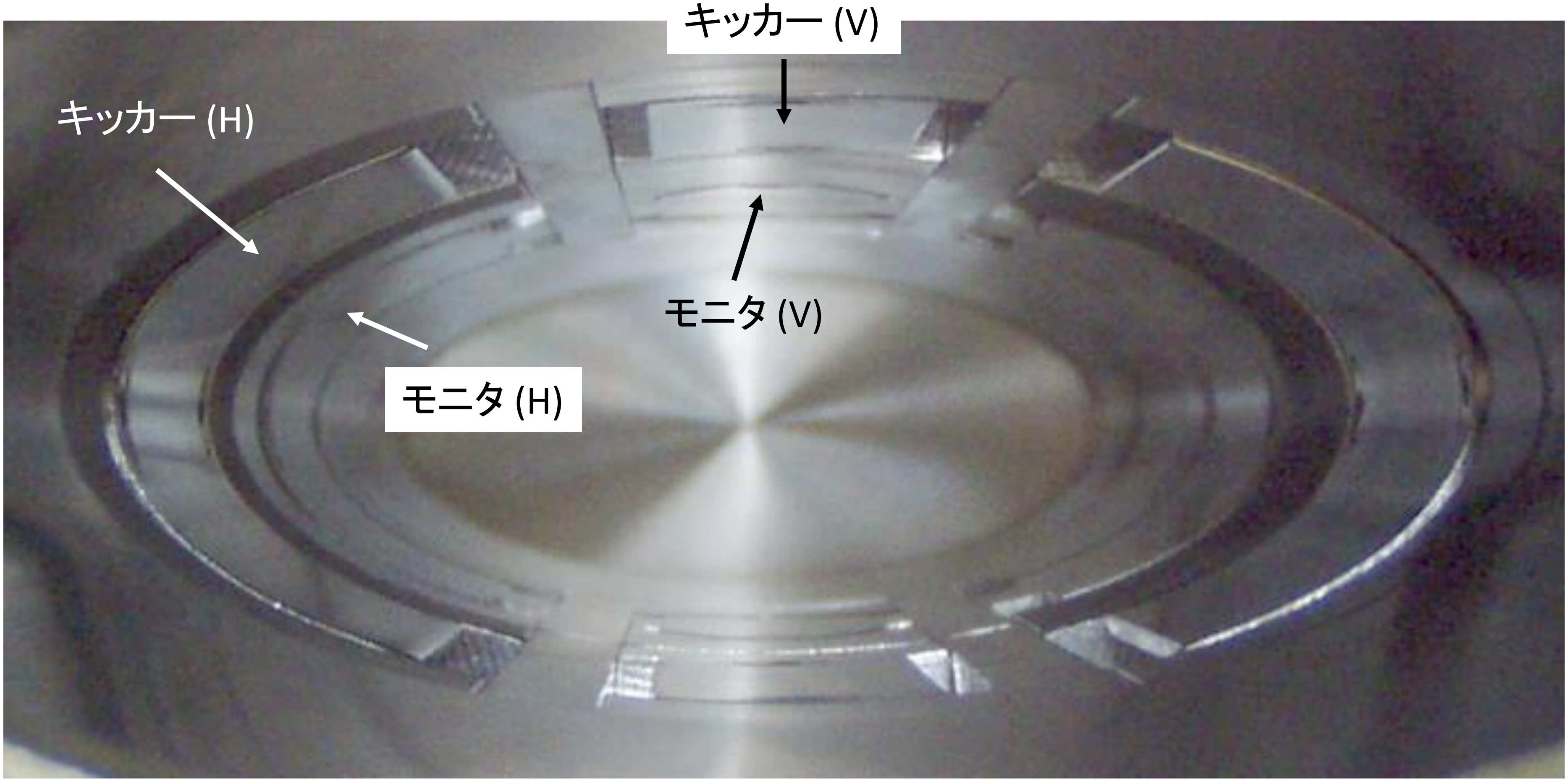


Developed calculation method of coefficient a_k (Noise reduction with many inputs)

T.Nakamura, K. Kobahashi, et. al, https://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT068.PDF

Horizontal bunch by bunch BPM kicker

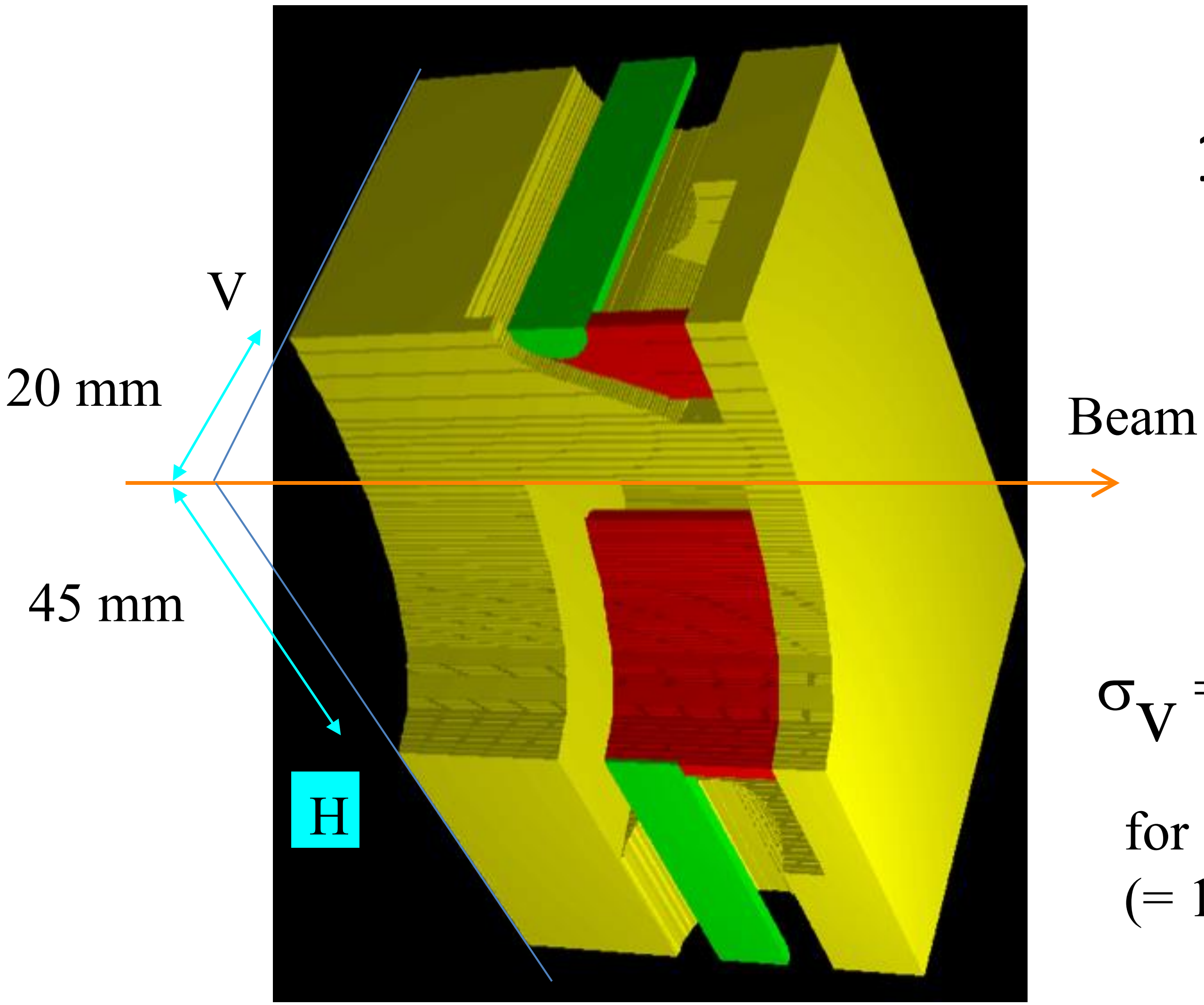




T. Nakamura, https://accelconf.web.cern.ch/accelconf/d05/PAPERS/POW027.PDF

High Resolution BPM by Shorted Stripline Structure

ビーム位置モニタ (BPM) のノイズがフィードバックを通してビームを揺する
=> 高分解能の BPM によりノイズを減少



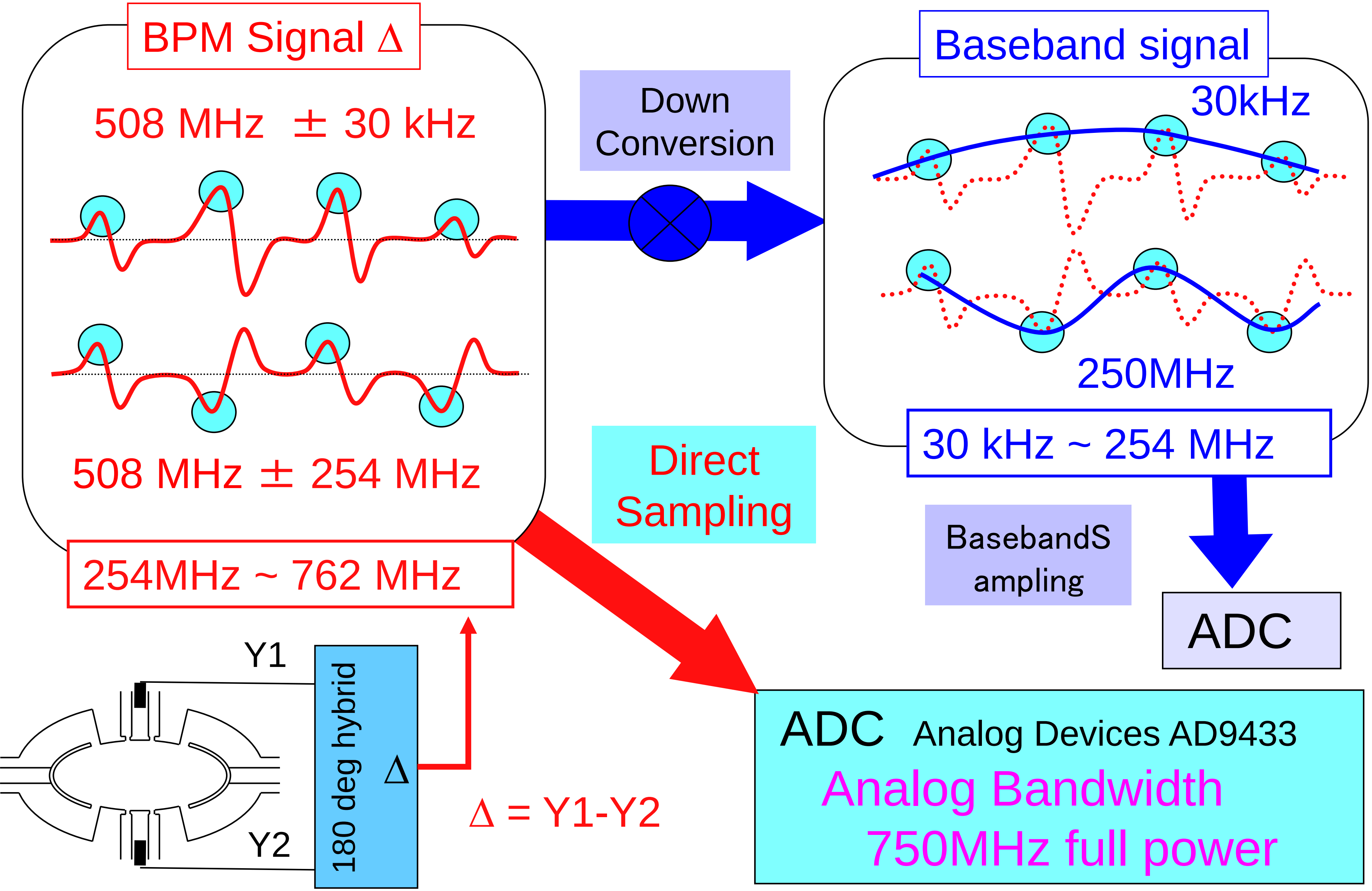
1 / 4

$\sigma_V = 5\mu m$

for 0.2nC bunch
(= 100mA x 2ns)

T. Nakamura, https://accelconf.web.cern.ch/accelconf/d05/PAPERS/POW027.PDF
T. Nakamura, http://acc-web.spring8.or.jp/%7Enakamura/papers/Nanobeam05/proc-WG3b-12.pdf

RF Direct Sampling

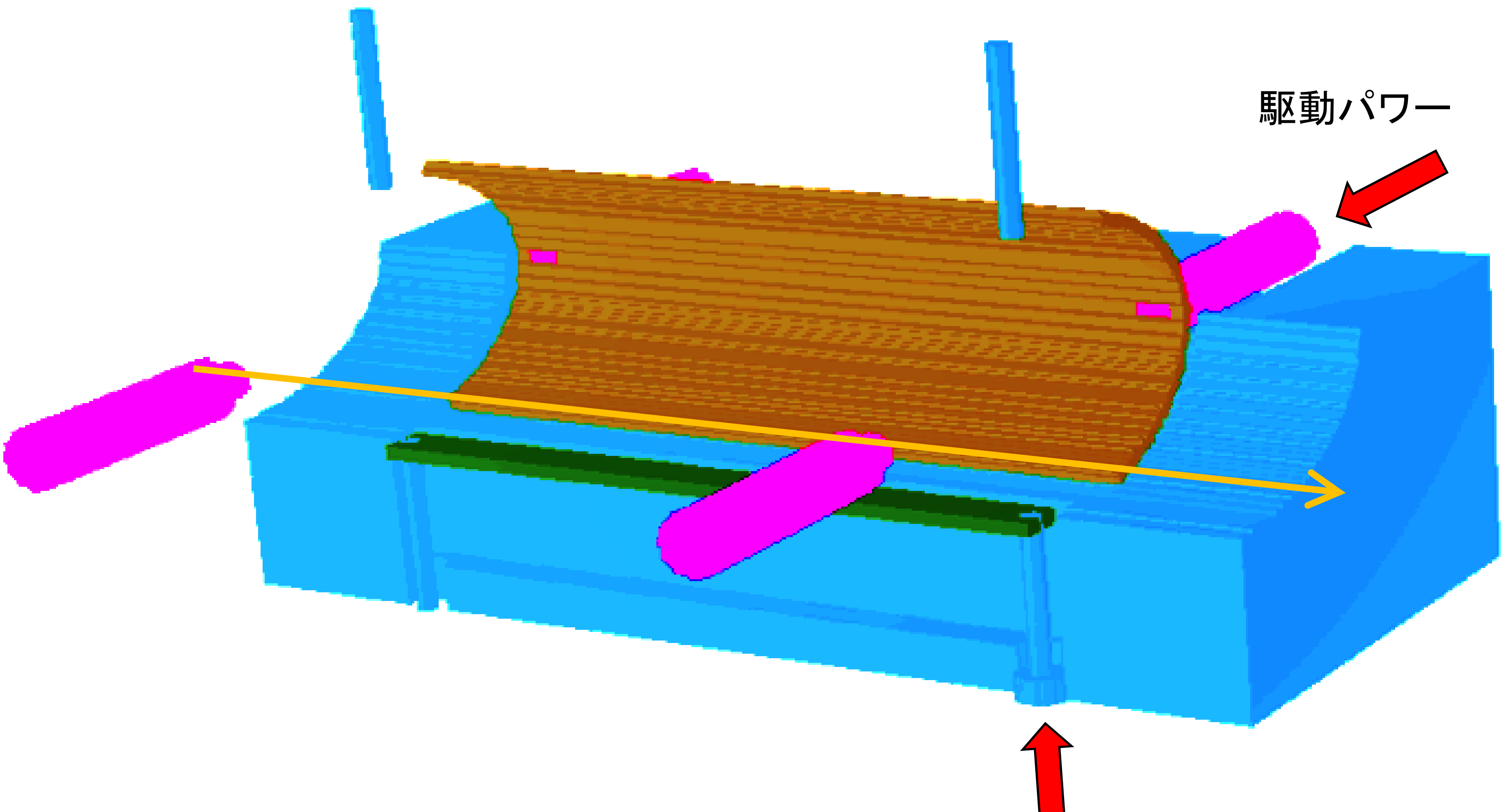


T. Nakamura, et. al, https://accelconf.web.cern.ch/accelconf/e08/papers/thpc128.pdf

ストリップラインキッカー (TEMモード)

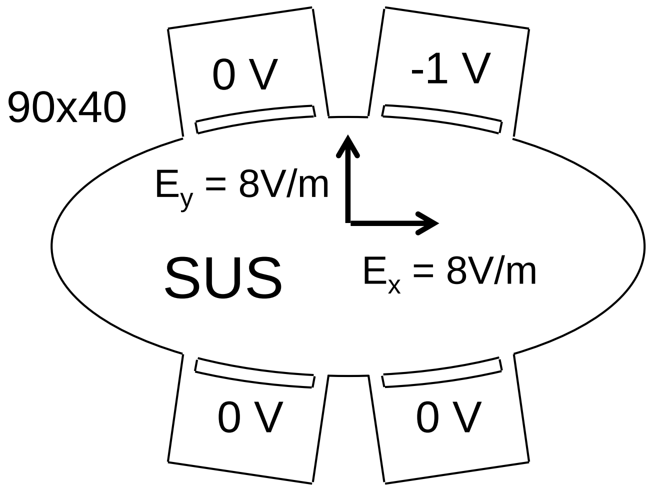
バンチ間隔 (2ns)で、バンチを個別にキックすることが可能

時定数 2ns (30cm長)　　磁石は使えない: 時定数 数十ns

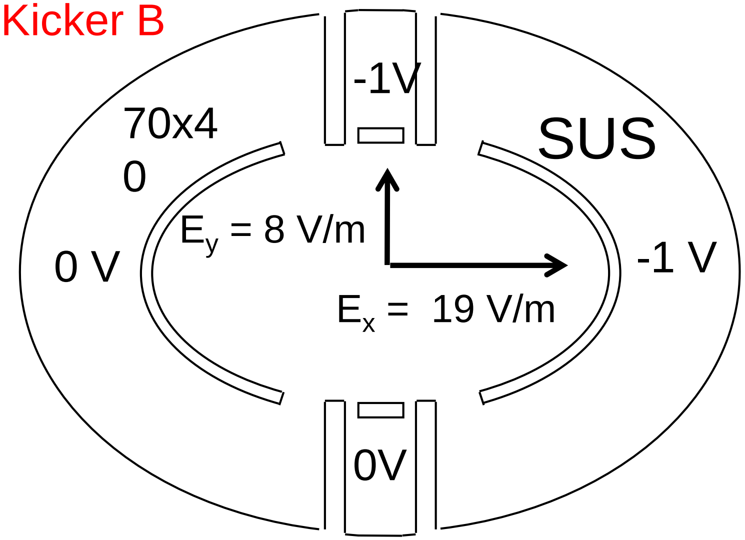


Stripline Kickers in SPring-8

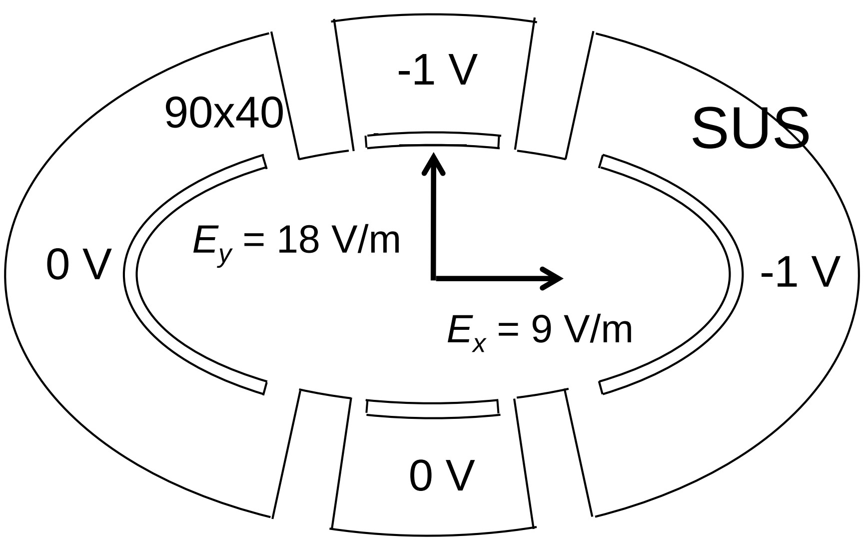
Diagonal Kicker



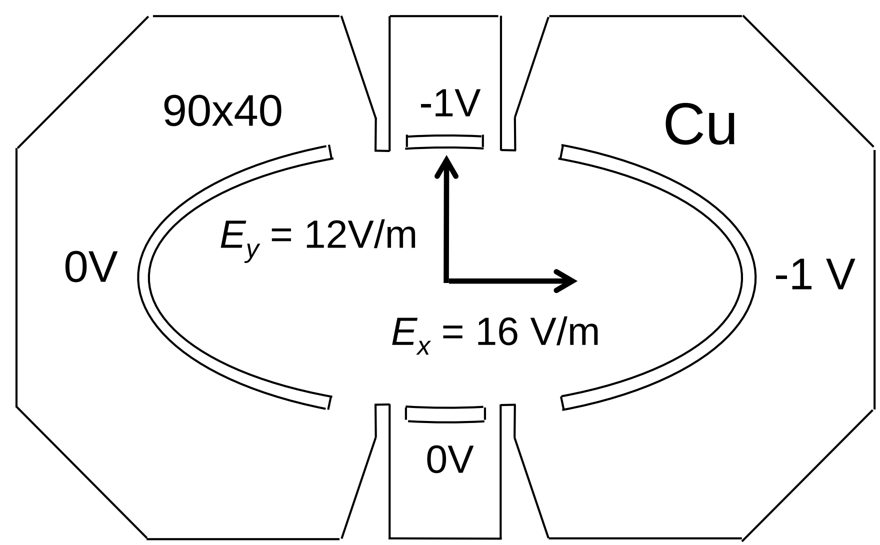
Orthogonal Kicker B



Orthogonal Kicker A



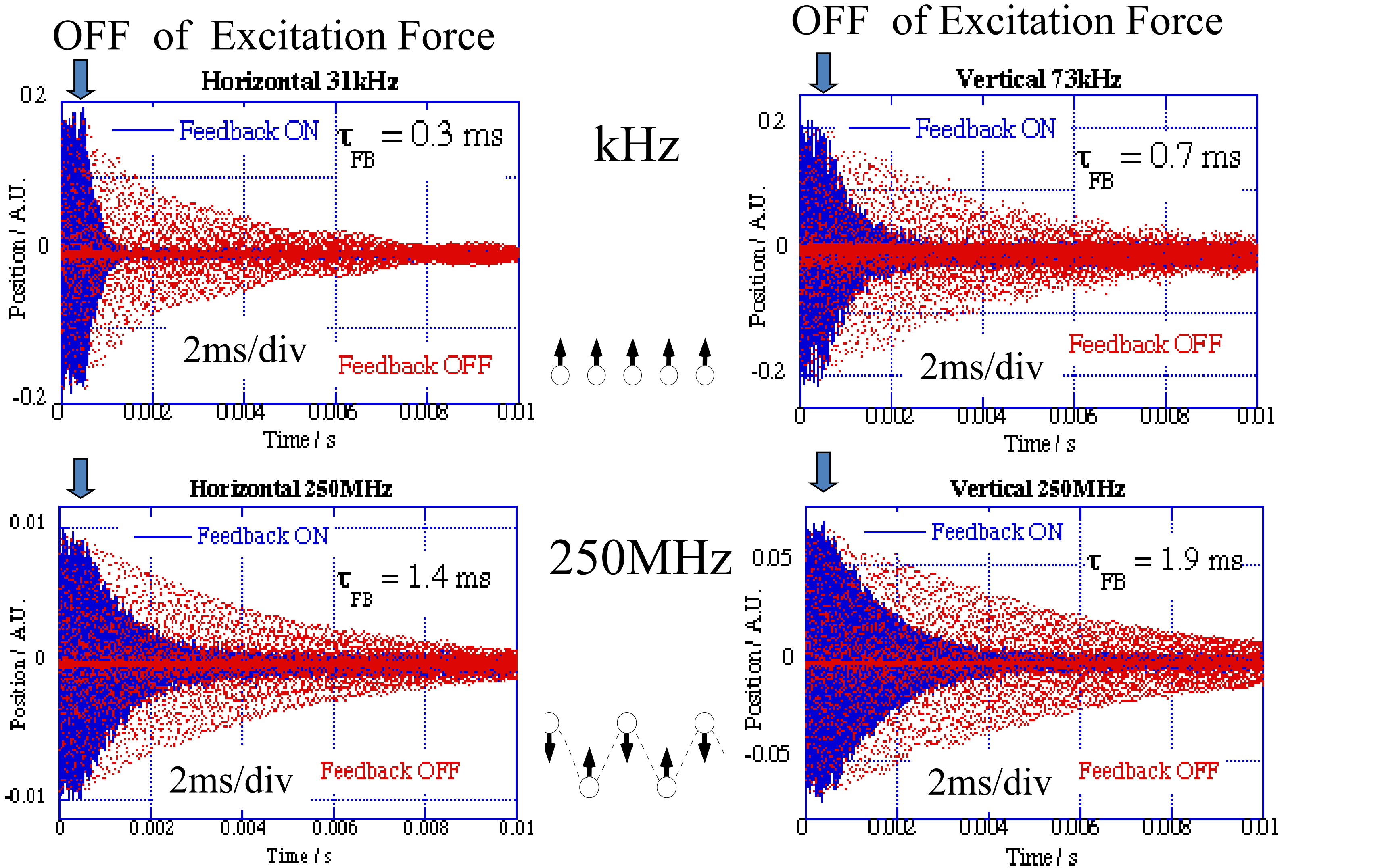
Orthogonal Kicker C



Damping Time Measurement

400 bunch 0.05 mA /bunch

Horizontal Vertical

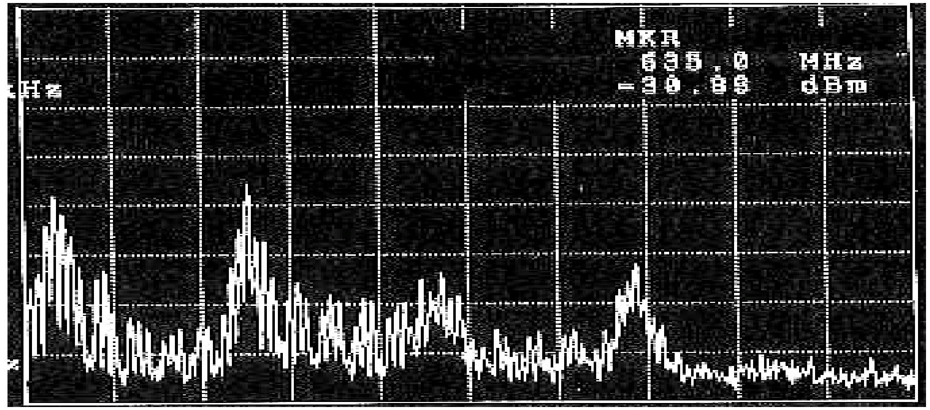


T.Nakamura, K. Kobahashi, et. al, https://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT068.PDF

Beam Test : Horizontal Coupled-Bunch Instability by Cavity HOM

Beam spectrum of horizontal motion

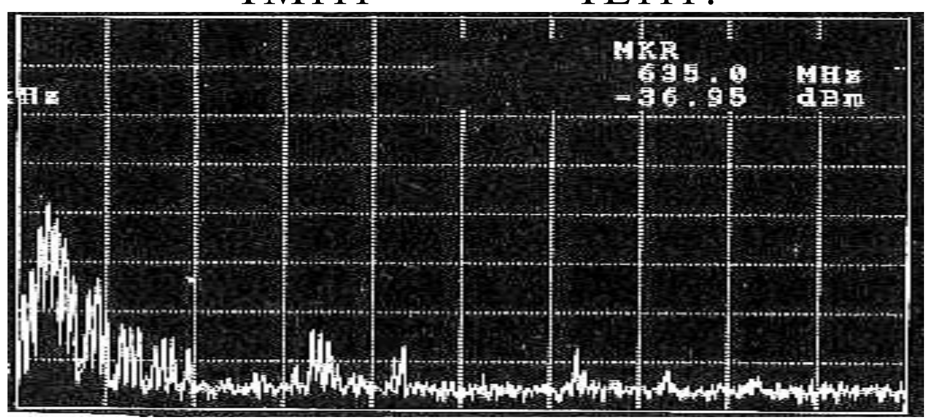
Feedback OFF



0MHz 60MHz 170MHz 260MHz

TM111 TE111?

Feedback ON



residual revolution signal by non-uniformness of filling

T.Nakamura, K. Kobahashi, et. al, https://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT068.PDF

Suppression of Single-bunch instability by Feedback

mode-coupling (fast head-tail) for V (and H : weak)

Chromaticity = 1 (< 3) for wide dynamic aperture

In-vacuum IDs **Open**

3.5 mA/bunch => 14 mA/bunch

Feedback **OFF** **ON**

~ simulation result

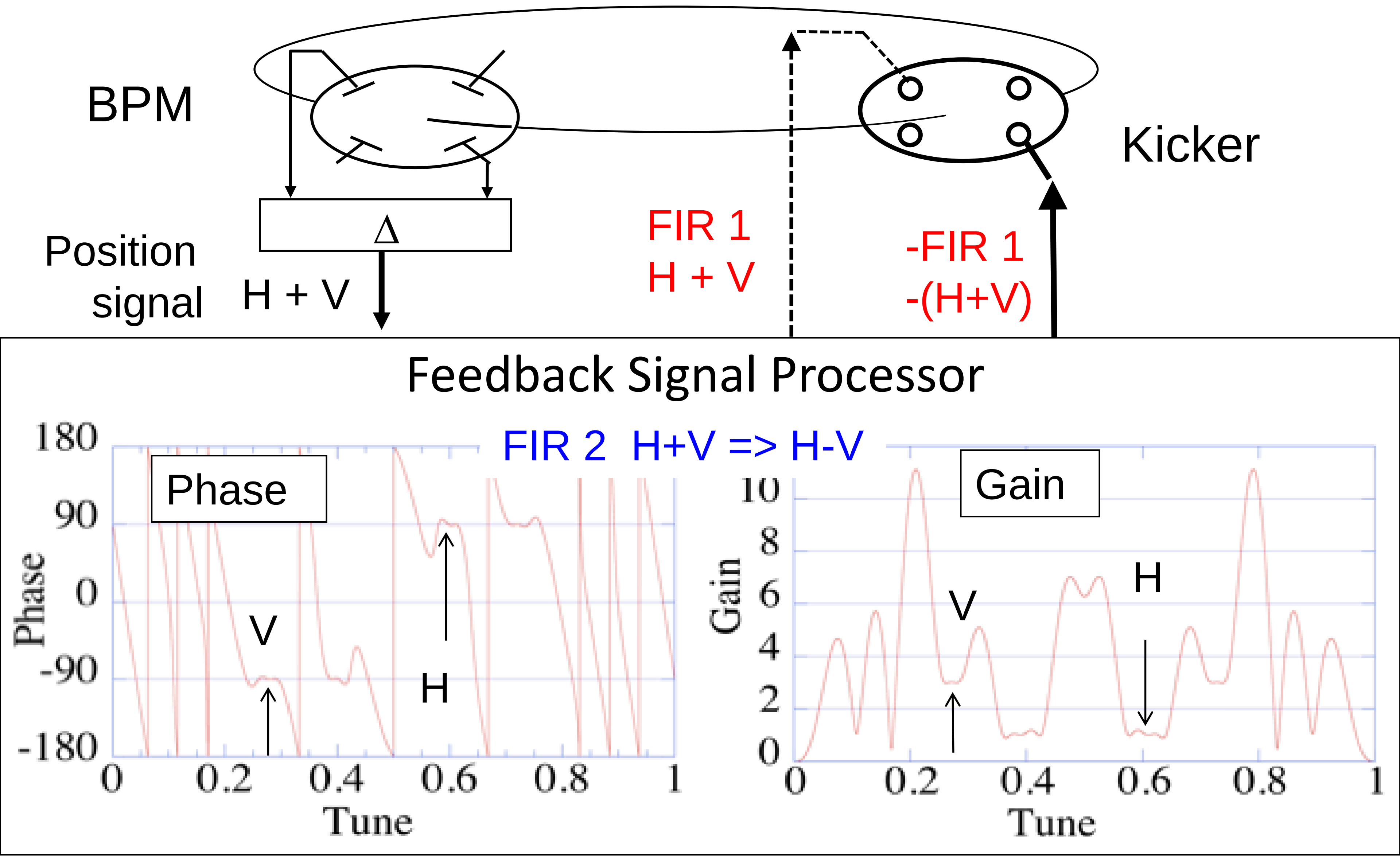
In-vacuum IDs **Close** **(**Partly ~ user operation**)**

2.5 mA/bunch => 6 mA/bunch

Feedback **OFF** **ON**

5 mA/bunch for User operation

Single-Loop Two-Dimensional Transverse Feedback



T. Nakamura, et. al, http://accelconf.web.cern.ch/accelconf/e06/papers/thpch092.pdf

縦方向

Longitudinal Instability Driven by Cavity HOM (TM011)

8 GeV: stable ~ 100mA, 6 GeV: ~ 90 mA, 4 GeV : ~ 20mA

New Shape Energy Kicker

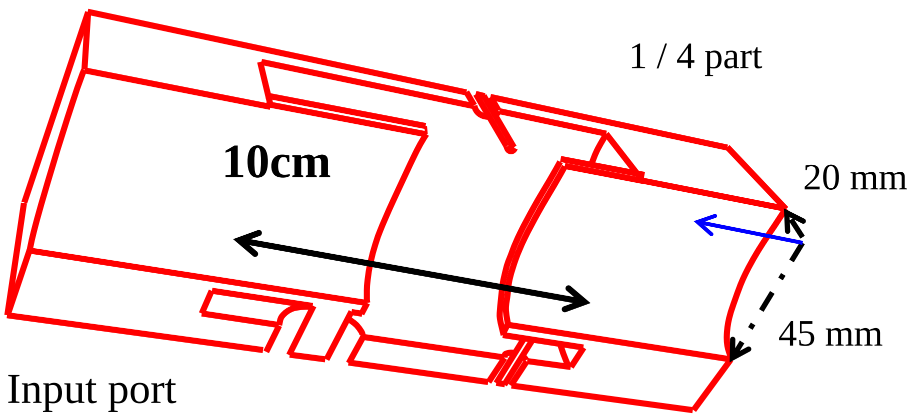
High Shunt Impedance / m

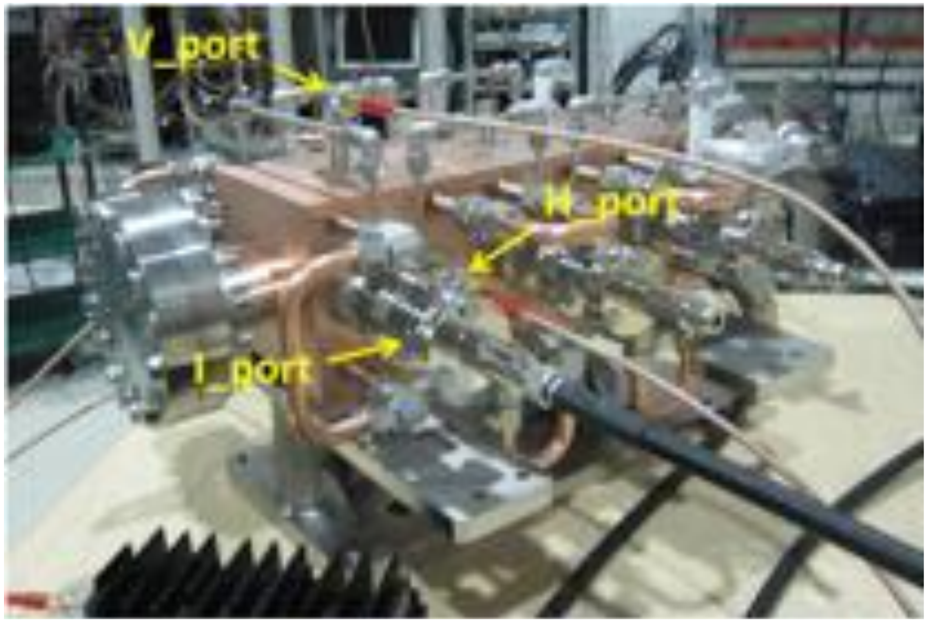
x3 of over damped cavity

Higher Frequency

Eliminate QPSK modulator

at cavity drive stage



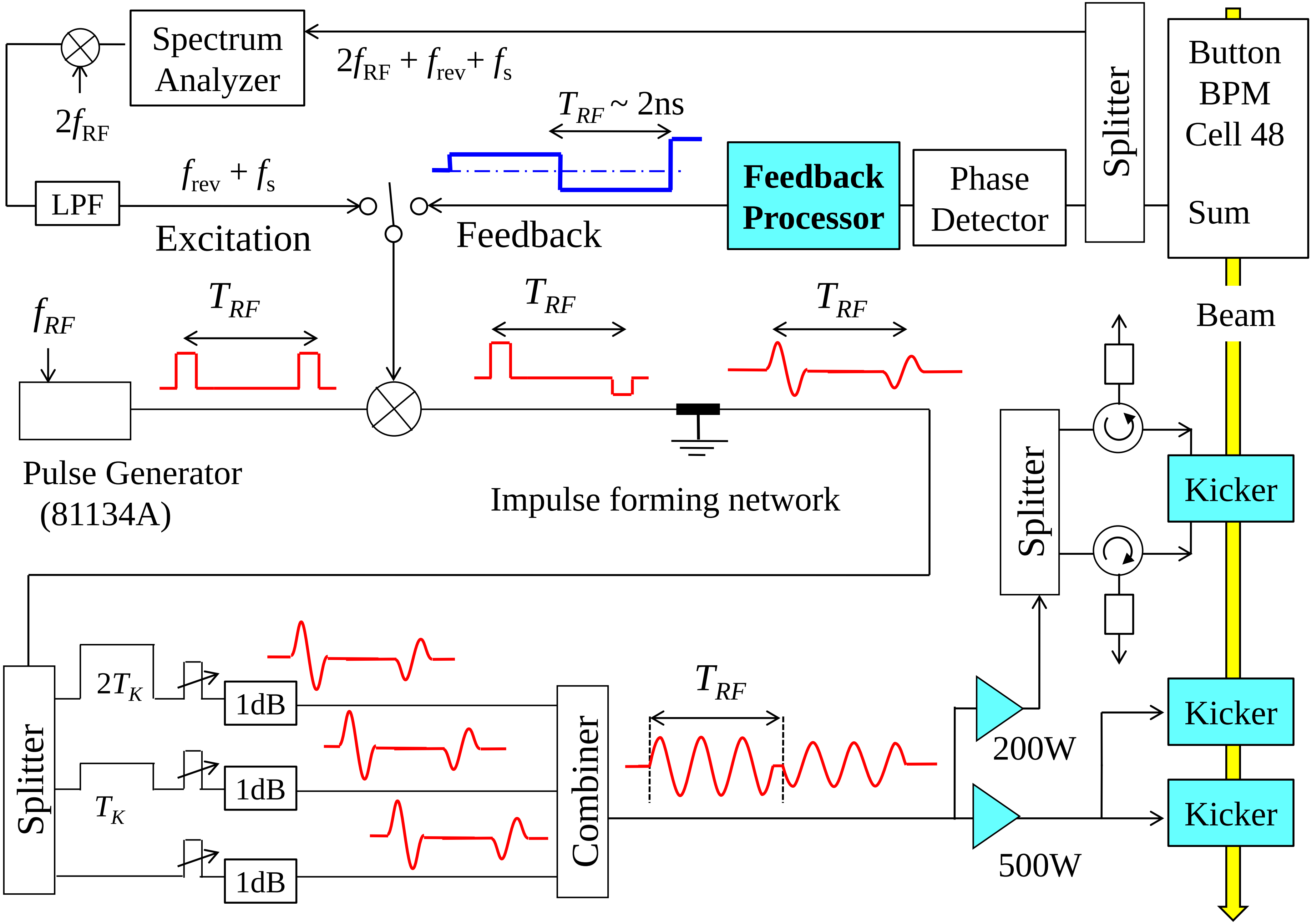


3 cavities / unit

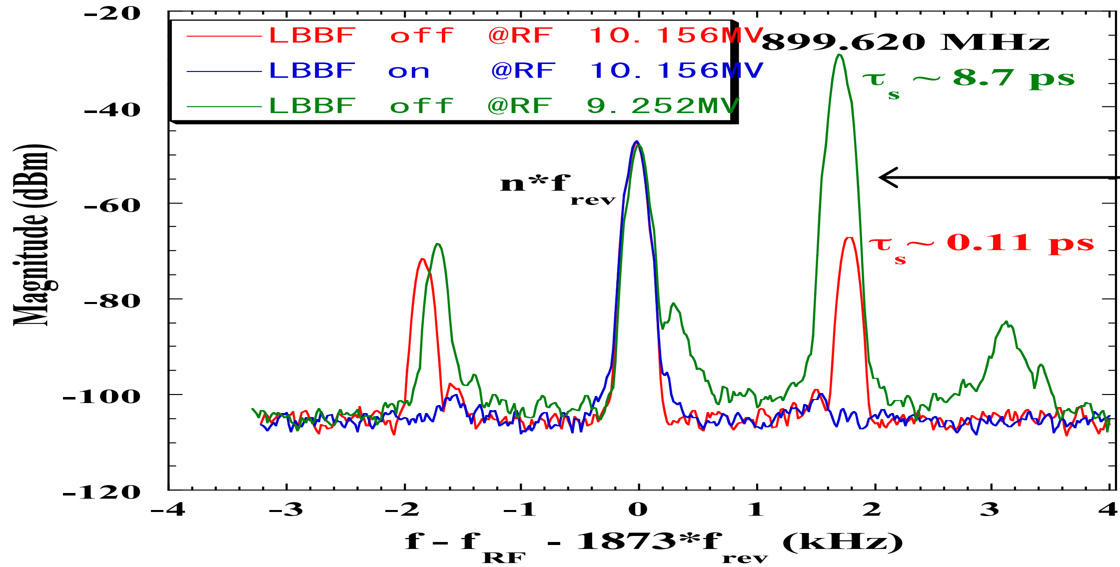
T. Nakamura, http://accelconf.web.cern.ch/AccelConf/IPAC2011/papers/mopo007.pdf

M. Masaki, et. al, http://accelconf.web.cern.ch/AccelConf/ibic2013/papers/tupc18.pdf

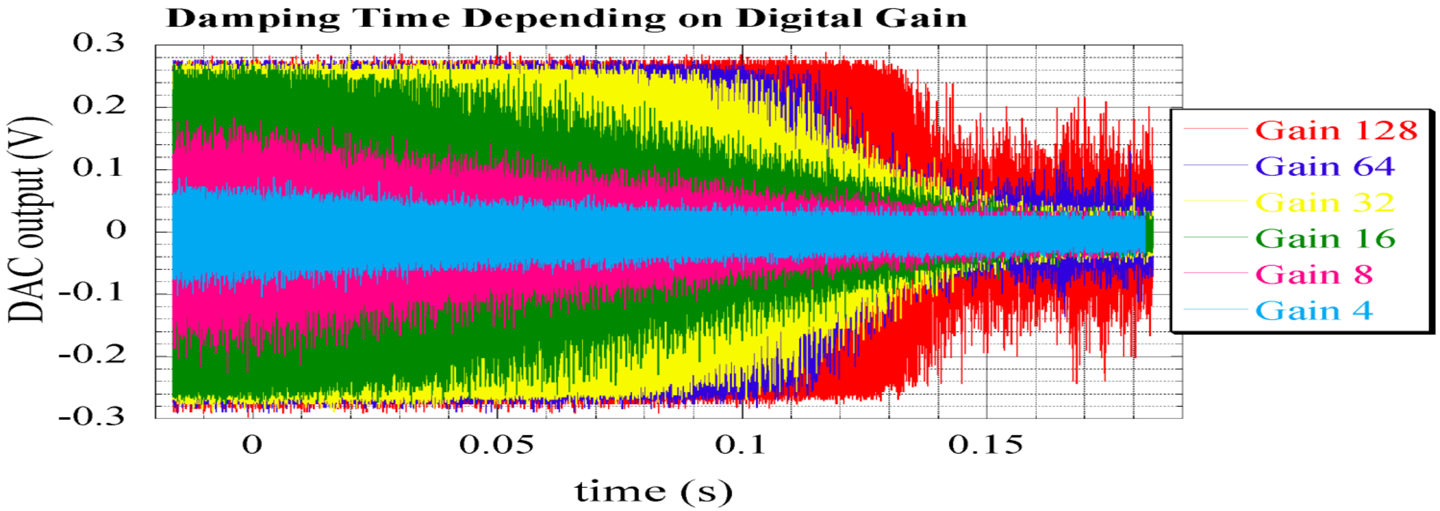
簡単な駆動回路　13/4 f_{RF} (Passive, No QPSK)



Suppression of instability driven by cavity at 6GeV



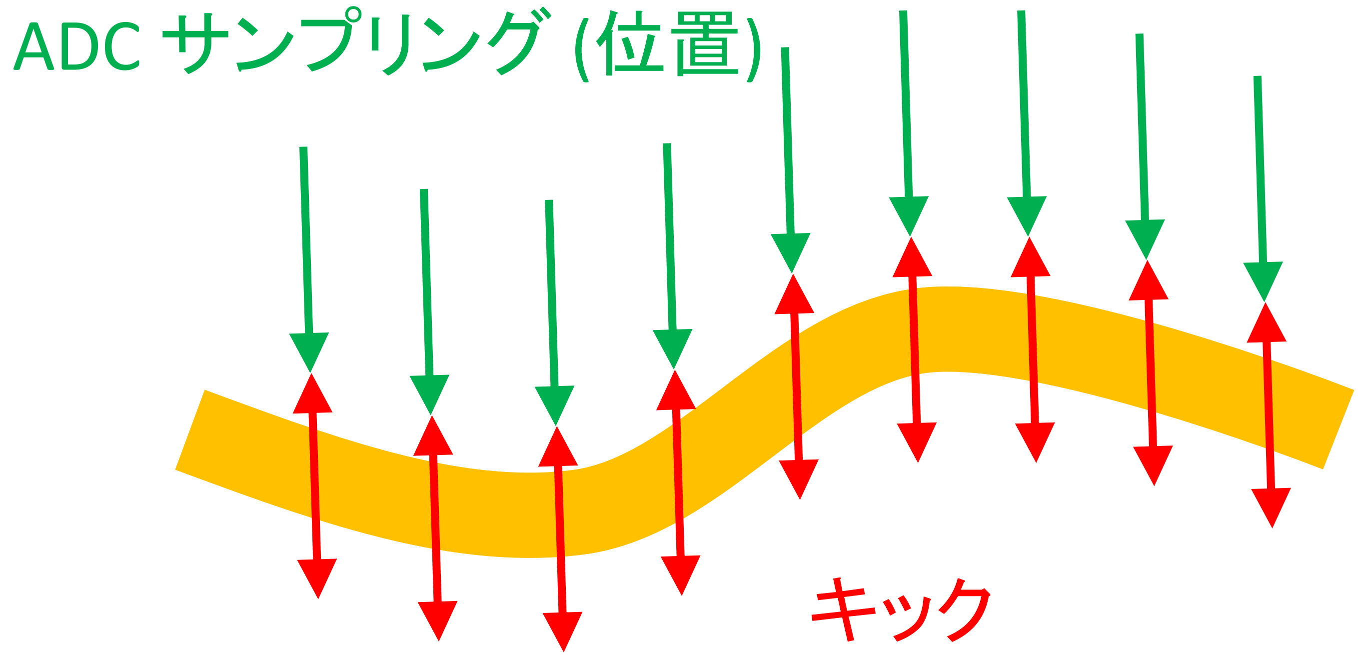
Longitudinal Multi-bunch Beam Instability Peak



M. Masaki, et. al, http://www.pasj.jp/web_publish/pasj2015/proceedings/PDF/WEP0/WEP088.pdf

長いバンチの横方向フィードバック

イオンのリング
- バンチ長さ ~ 100ns は、電子リングの 数千倍
- 2ns のサンプリング => 50回
- バンチの部分毎にフィードバック
  - KEK PS での head-tail 不安定性を抑制



DCビームの不安定性抑制

イオンのリング
- 部分毎にフィードバック
  - S-LSR (京大)
  - HIMAC (放医研)のイオンビーム
    - 電子冷却されたビームの不安定性を抑制
      - 強度を一桁向上

DCビーム : RF がない!
- 周回の同期が取れない
- but 、10ターンぐらいなら

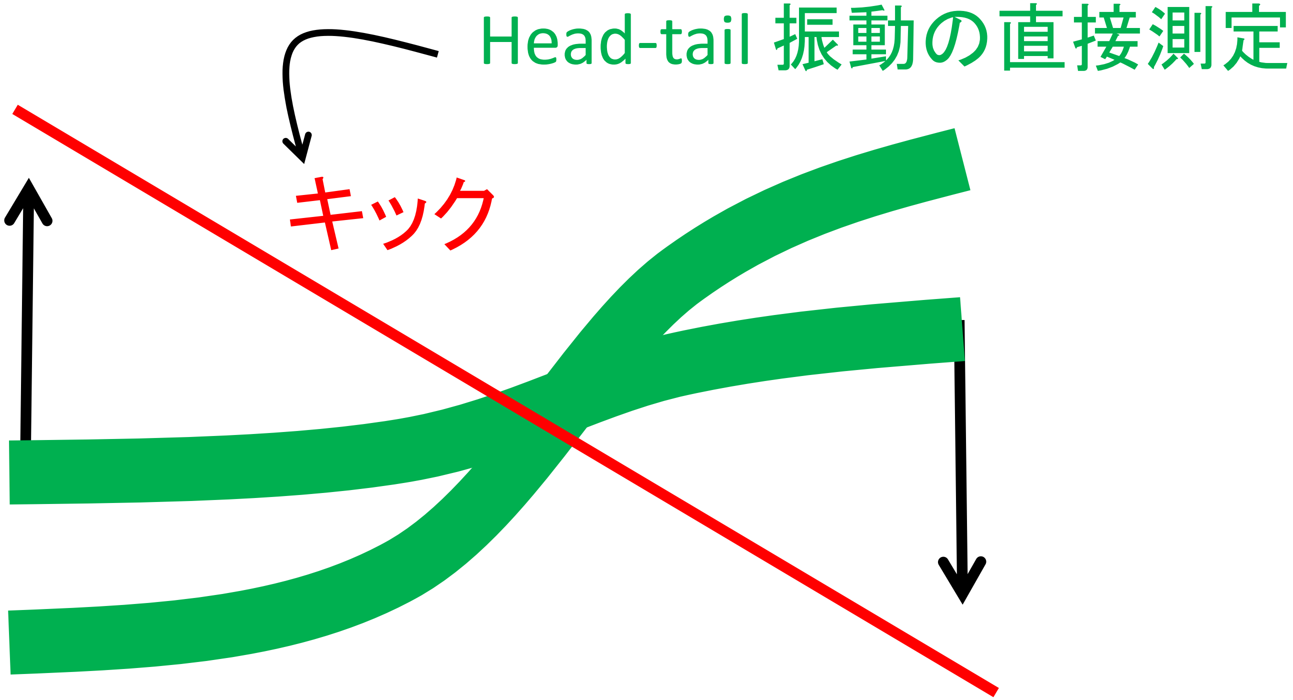
同期が少しずれていても
サンプリング間隔に比べて
ズレは小さい！

非同期クロックを
用いた
フィードバック

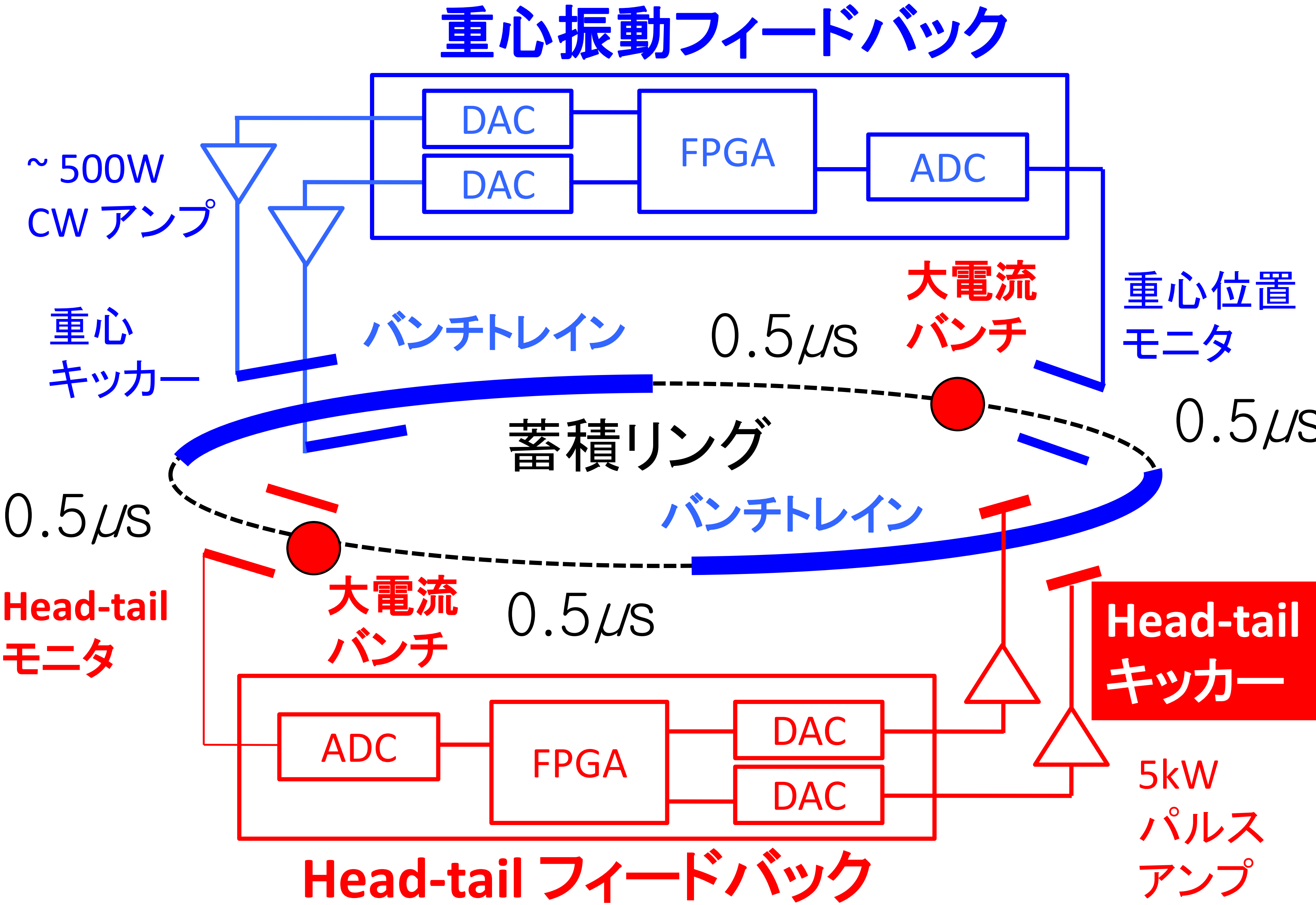
リングとの同期は無し！

Head-tail フィードバック (まだ)

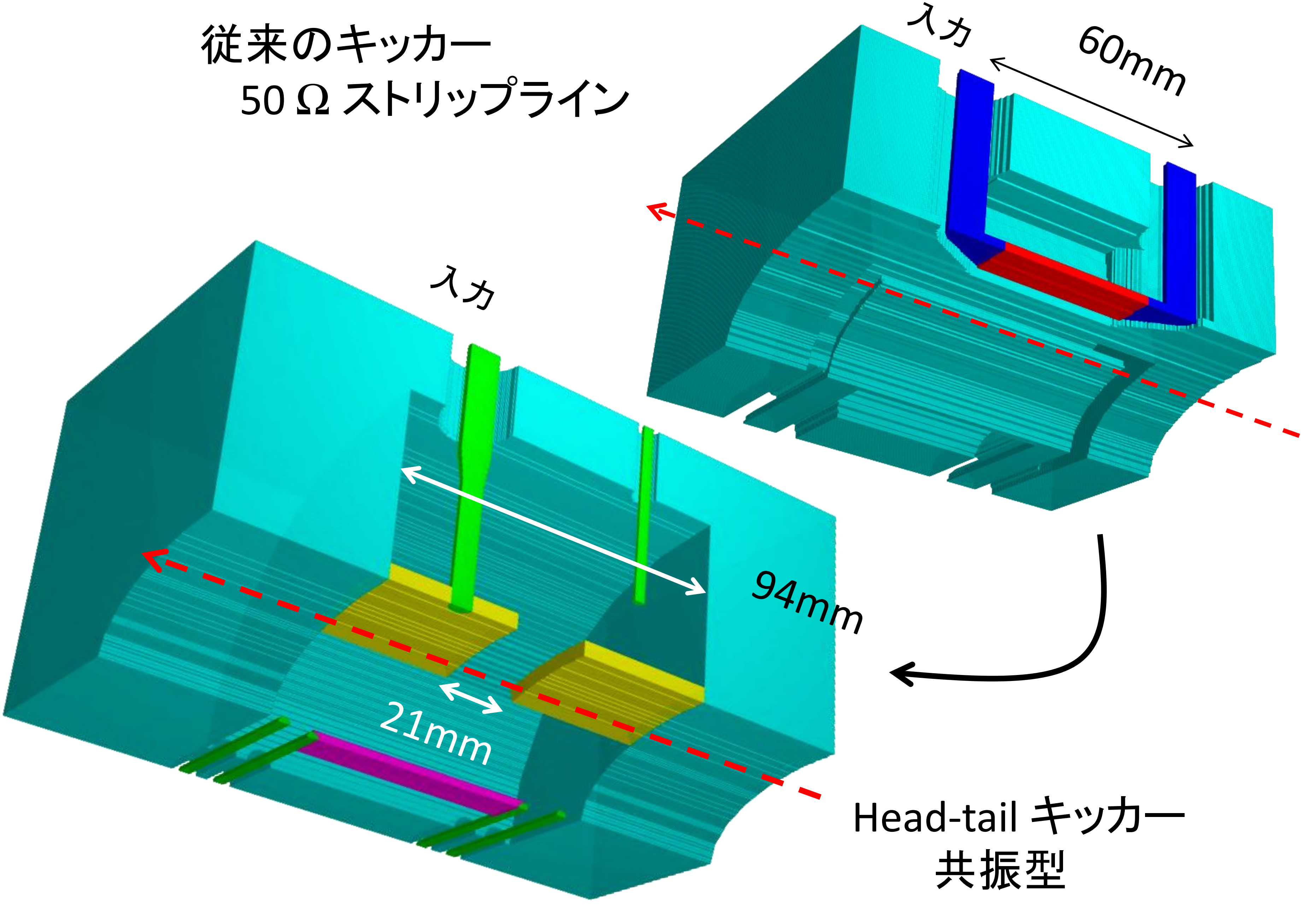
重心振動の抑制によるモード結合不安定性は
フィードバックの強さが原理的限界にぶち当たる



バンチを、時間変化が大きいキック力で
キックし、バンチの内部振動を抑制



重心振動フィードバック
~ 500W
CW アンプ
DAC
DAC
FPGA
ADC
重心
キッカー
バンチトレイン
0.5μs
大電流
バンチ
重心位置
モニタ
0.5μs
蓄積リング
0.5μs
バンチトレイン
Head-tail
モニタ
大電流
バンチ
0.5μs
Head-tail
キッカー
ADC
FPGA
DAC
DAC
5kW
パルス
アンプ
Head-tail フィードバック



T. Nakamura, 日本物理学会第 70 回年次大会(2015 年)概要集

Simulation

Home made code (SISR)

- Wake potential
  - Geometrical wake : Simulation by MAFIA
    - bellows, weldments, flanges, RF cavities, tapers, BPMs, offset
  - Resistive-wall wake : Theoretical Wake
  - CSR not included
    - Microwave instability Threshold :
      - ~ 3mA/bunch for
        - CSR (theory)
        - Simulation based on Geometrical Wake
        - Observation

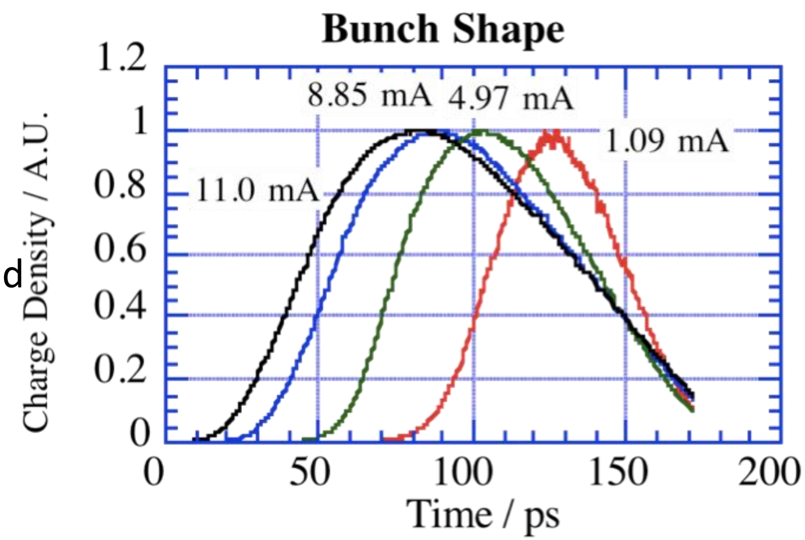
T. Nakamura, http://accelconf.web.cern.ch/accelconf/e96/PAPERS/WEPG/WEP104G.PDF

T. Nakamura, http://acc-physics.kek.jp/SAD/SAD2006/Doc/Slide/Nakamura.pdf

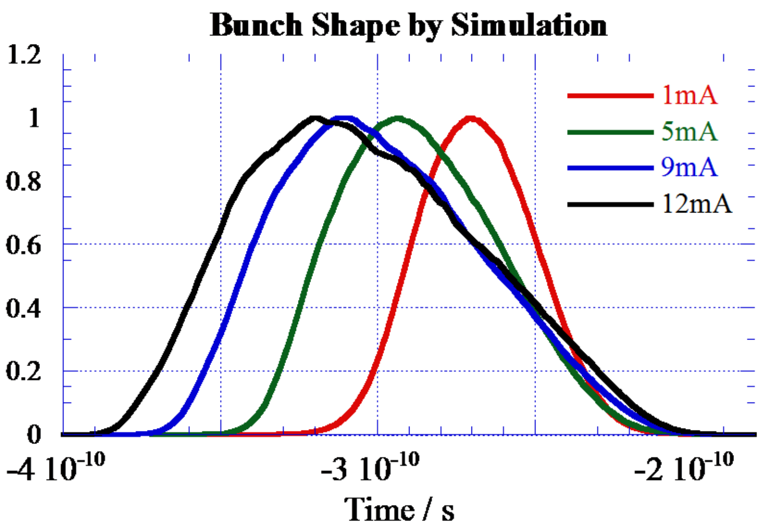
Comparison with Experiment

Longitudinal

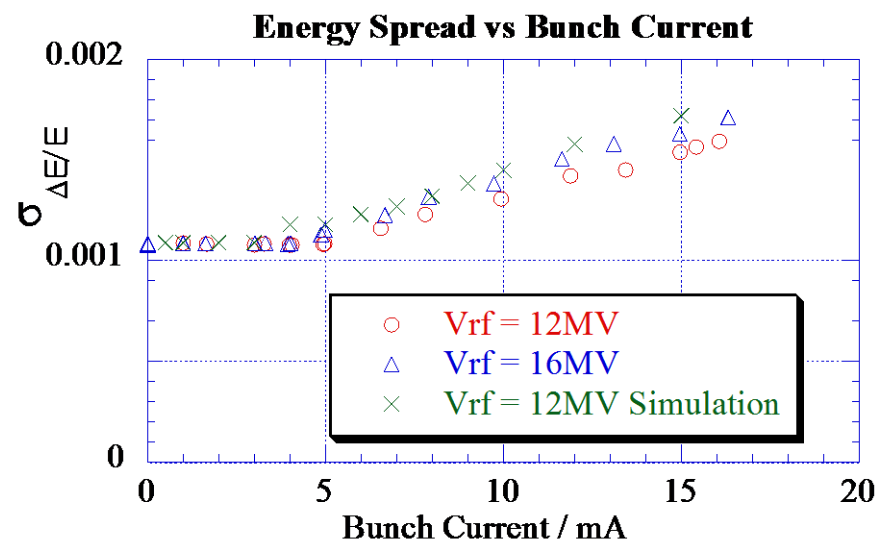
Measured



Simulation



Energy Spread



additional
Inductive wake ~ 40nH
is required for bunch length

Comparison with Experiment

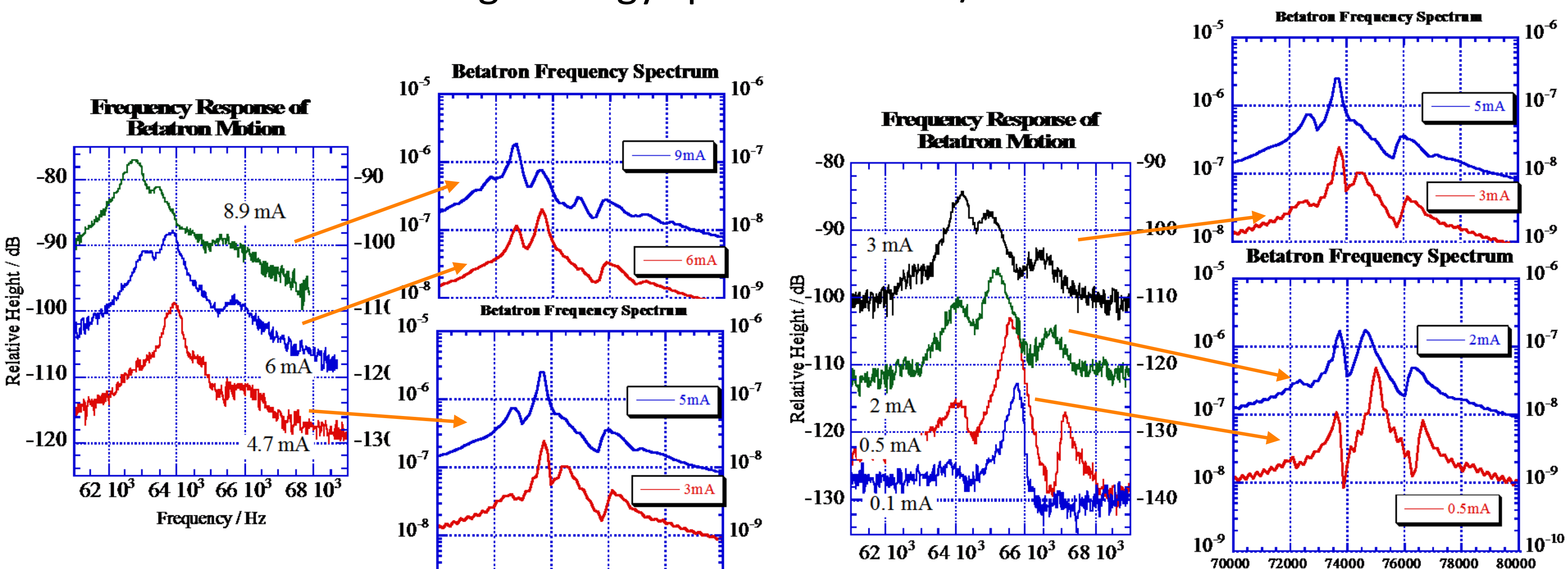
Vertical Single-Bunch Instabilities

Simulation based on Calculated Wake Function

-4.3 0.5mA/bunch (m=0 head-tail)

0.24 3.5-4mA/bunch (mode-coupling) 4 > 16mA/bunch

1.5 times large energy spread at 10mA/bunch



Measured

Simulation

Measured

Simulation