Transverse and Longitudinal Bunch-By-Bunch Feedback for Storage Rings

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IPAC’18 Vancouver, April 29 to May 4, 2018

Outline

Topics are Focused on feedback for Electron Rings
(For Hardon Rings, a report later in this session)

FIR filter Coefficients Calculation Method

Front-End with RF Direct Sampling

Transverse Feedback for Hybrid Filling

Instability of Feedback at High Gain

Instability Free Feedback with Beam Position data at Multiple Locations

Single-Loop Two Dimensional Transverse Feedback

Two Tunes Control of Longitudinal Feedback

for Dipole and Quadrupole Oscillation (DΦFNE)

Space Saving High Efficiency Longitudinal Kicker

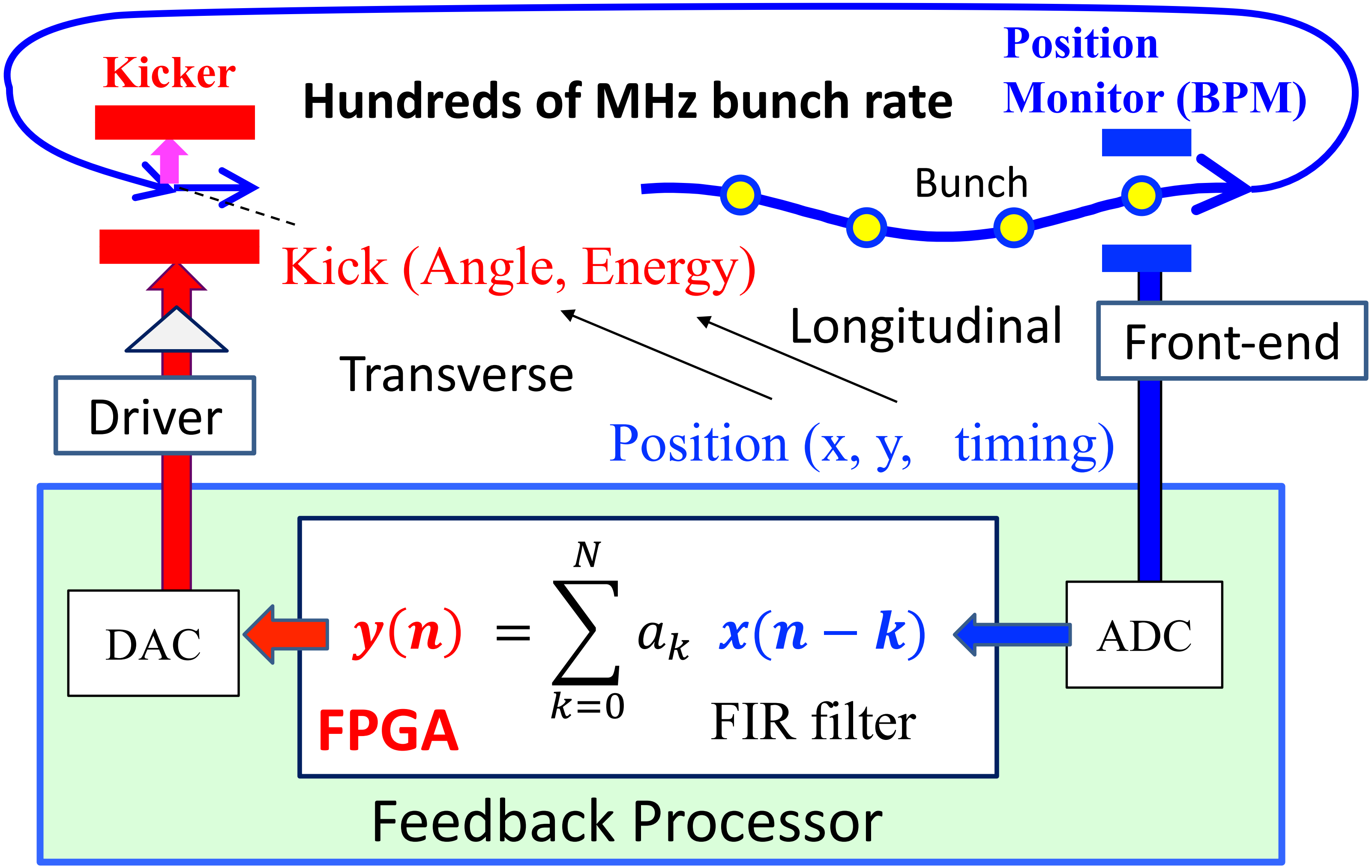
beam excitation by BPM Noise and High Resolution BPM

Transverse and Longitudinal Digital Feedback

Devices for Damping of Betatron or Synchrotron Oscillations

for Suppression of beam instabilities

Fast damping of excited oscillation (mostly at injection)



FPGA

DSP (PEP-II, Elettra/SLS, ..)
Custom LSI (KEK)

⇩

FPGA (Field Programmable Gate Array)
- Hardware
  - Very Fast for simple processes
- Field Programmable
  - we can easily change its logic

- Reduction of Cost, Size
- Simple architecture

Examples of FPGA based Digital Feedback Processors

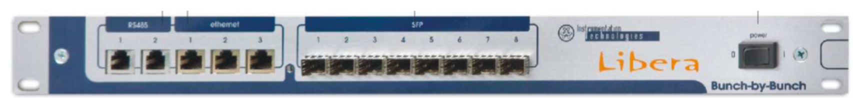
Old **SPring-8**
Feedback Processor*
(First FPGA Based Processor
~500MS/s ?)

Photon Factory, New SUBARU, Aichi-SR ,TLS, HLS, SSRF, SOLEIL, PLS, PLS-II,
KEK-PS (proton, intra-bunch), S-LSR(coasting ion), HIMAC(electron beam cooled ion)

iGp12, Dimtel, Inc.

(based on SLAC / KEK / INFN-LNF design collaboration)
ALS, DAΦNE, Indus-2, SPEAR3, ANKA DELTA, LNLS, SuperKEKB, PEPC-II, Duke SR-FEL, MLS, TLS, BESSY II, ELSA, NSLS-II, TPS, CesrTA, HLS, Phton Factory, J-PARC, ..

LIBERA Bunch-by-bunch,
i-tech

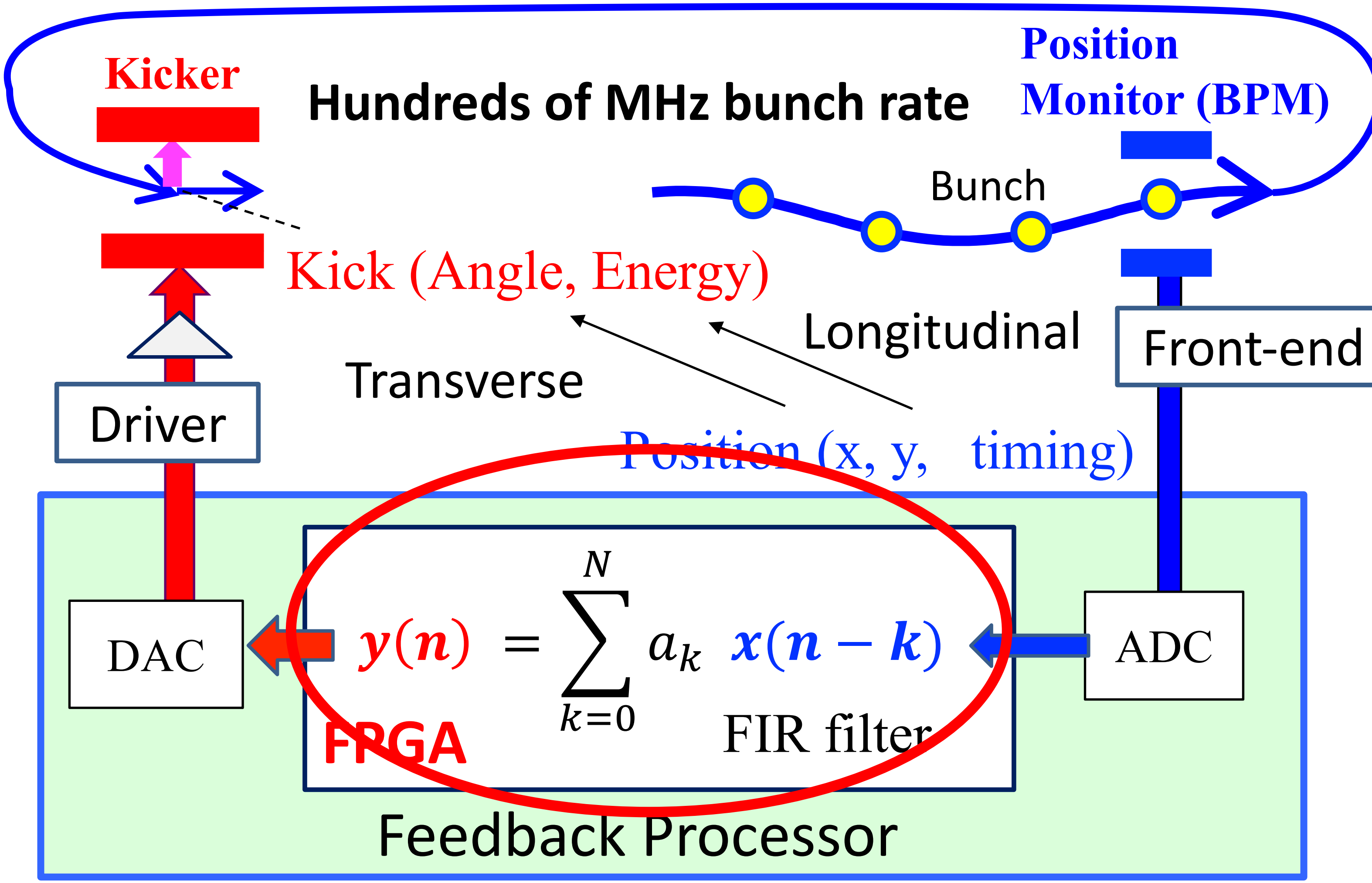


ESRF, ASP, ALBA, ANKA, CLS, **Diamond**, LNLS, NSRRC

* T. Nakamura, K. Kobayashi, et al., EPAC'04, ICALEPSC'05 (First FPGA based for hundreds MS/s)

FIR Filter

Devices for Damping of Betatron or Synchrotron Oscillations
for Suppression of beam instabilities
Fast damping of excited oscillation (mostly at injection)



T. Nakamura, K. Kobayashi, et al., EPAC'04, ICALEPSC'05 (First FPGA based for hundreds MS/s)

Function of FIR filter

Feedback Kick

$$y(n) = \sum_{k=0}^{N} a_k \; x(n-k)$$

Coefficients

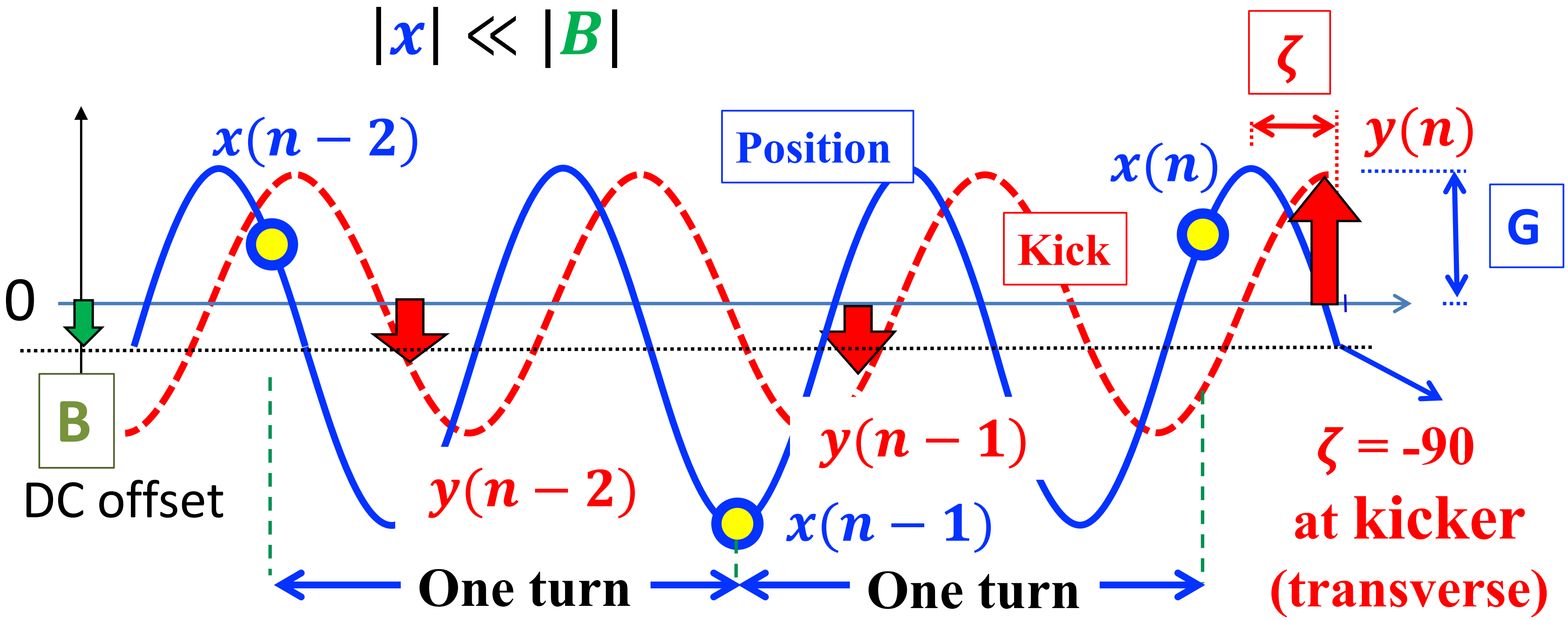
History of turn-by-turn **Position data ((N+1) data)**

Function of FIR filter

* Beam position = Sinusoidal <= Phase Shift ζ and Gain **G**

* Removal of DC offset **B** (closed orbit, BPM signal unbalance,)

$$|x| \ll |B|$$



Frequency (Tune) Response of FIR filter

"Add <u>Phase Shift</u> ζ and <u>Gain</u> **G** , Remove <u>DC offset</u> **B**"

$$x(k) = \tilde{\boldsymbol{x}} \exp(-ik(2\pi \boldsymbol{\nu_i})) + \mathbf{B}$$

$$y(k) = \boldsymbol{G}(\boldsymbol{\nu_i}) e^{i\boldsymbol{\zeta}(\boldsymbol{\nu})} \tilde{\boldsymbol{x}} \exp(-ik(2\pi \boldsymbol{\nu_i}))$$

$$\boldsymbol{y}(\boldsymbol{n}) = \sum_{p=0}^{N} a_k \, \boldsymbol{x}(\boldsymbol{n} - \boldsymbol{k})$$

2 constraints

$$\boldsymbol{G}(\boldsymbol{\nu_i}) e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i})} = \sum_{k=0}^{N} a_k \exp(-ik(2\pi \boldsymbol{\nu_i}))$$

1 constraints

$$\mathbf{0} = \sum_{k=0}^{N} a_k$$

Frequency Domain Condition for FIR filter

Constraints on Coefficients of FIR filter

Setting Phase and Gain

$$\boldsymbol{G}(\boldsymbol{\nu_i})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i})} = \sum_{k=0}^{N} a_k \exp(-ik(2\pi\boldsymbol{\nu_i}))$$

at Target tunes : $\boldsymbol{\nu_i} = 0, \nu_1, \nu_2, \dots, \nu_M$ (1+M tunes)

constraints on coefficients a_k

2M (for $\boldsymbol{\nu_i} \neq 0$) + 1 (for $\boldsymbol{\nu_i} = 0$)

⇩

We have 2M+1 coefficients (only)

⇔ We have more turn-by-turn data if 2M+1 < N+1

We need at least one oscillation data to get good response of FIR filter

Frequency Domain Condition for FIR filter

Constraints on Coefficients of FIR filter

Setting Phase and Gain

$$G(\nu_i)e^{i\zeta(\nu_i)} = \sum_{k=0}^{N} a_k \exp(-ik(2\pi\nu_i))$$

Minimization of

$$P = \int_0^1 |G(\nu)|^2 d\nu = 2\pi \sum_{k=0}^{N} |a_k|^2$$

* Minimization of Noise Power passing though FIR filter
* Reduction of gain not at $\nu = \nu_i$

Minimization : No limit for the number of coefficients up to N+1 (the number of position data)

Example

5 Constraints : Target tune **0.15** with **flat response**

$$G(0) = 0$$

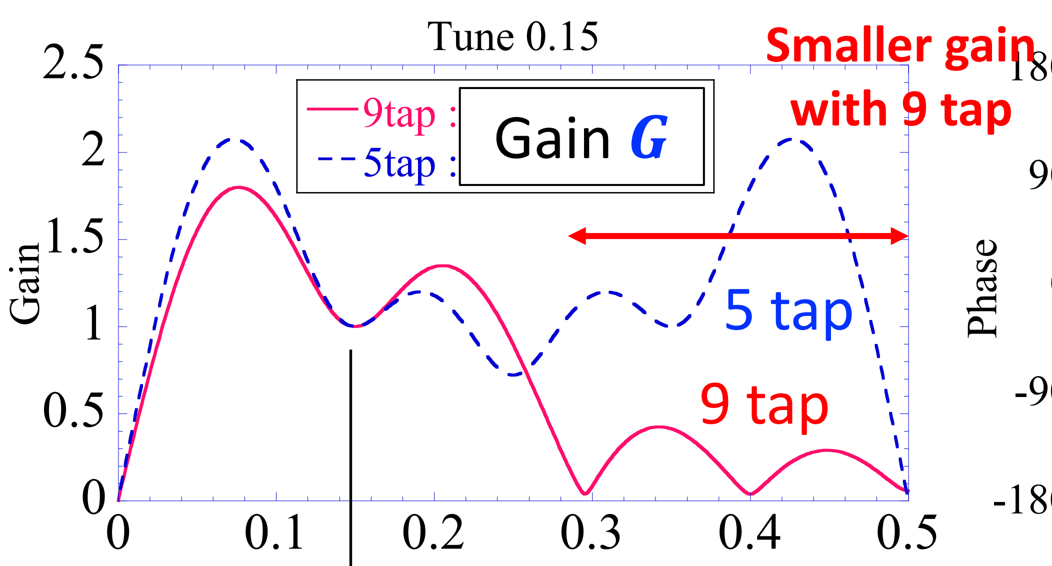
$$G(0.15 - 0.01) = G(0.15 + 0.01) = 1$$

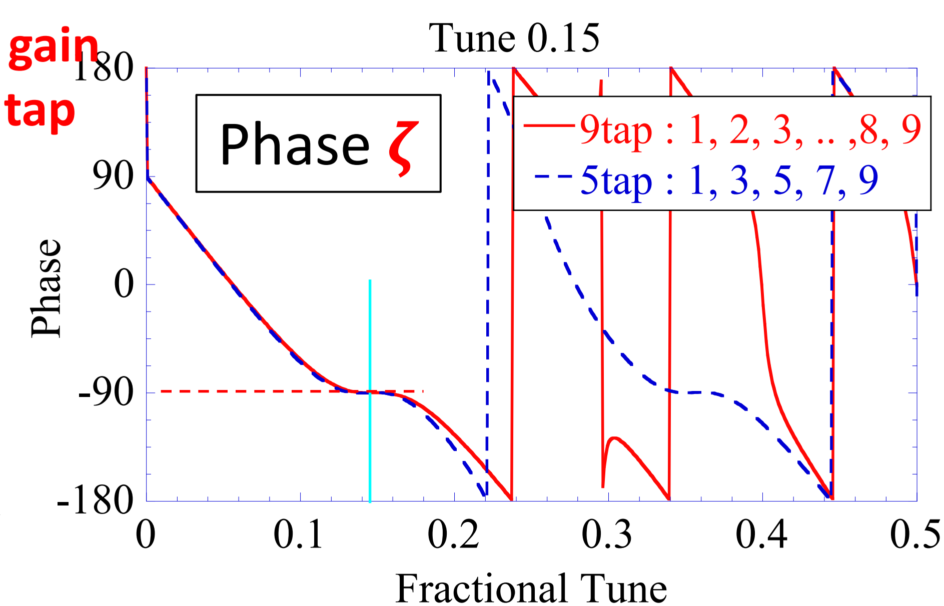
$$\zeta(0.15 - 0.01) = \zeta(0.15 + 0.01) = -90\ \mathrm{deg}$$

position data

5 tap : **-1, -3, -5, -7, -9** turns

9 tap : **-1, -2, -3, -4, -5, -6, -7, -8, -9** turns





$G(0) = 0$

$G(0.15 - 0.01) = G(0.15 + 0.01) = 1$

$\zeta(0.15 - 0.01) = \zeta(0.15 + 0.01) = -90$

Least Square Fitting (TDLSF method) for Coefficients

$$x[n] = A\cos(2\pi\nu_0 n + \psi) + \mathrm{B}$$

Least Square Fitting

$$= \boldsymbol{p_0} + \boldsymbol{p_1}\cos 2\pi\nu_0 n + \boldsymbol{p_2}\sin 2\pi\nu_0 n \Rightarrow \boldsymbol{p_m} \text{ to } \boldsymbol{x_k}$$

$$\boldsymbol{p_m} = \sum_{k=0}^{N} C_{m,k}\boldsymbol{x_{-k}}$$

Measured position

$$y[0] = \boldsymbol{G}A\cos(\psi + \boldsymbol{\zeta})$$

$$\phi_0 = 0$$

$$y[0] = \boldsymbol{p}_1\boldsymbol{G}\cos\boldsymbol{\zeta} + \boldsymbol{p}_2\boldsymbol{G}\sin\boldsymbol{\zeta} = \sum_{k=0}^{N}\left(C_{1,k}\boldsymbol{G}\cos\boldsymbol{\zeta} + C_{2,k}\boldsymbol{G}\sin\boldsymbol{\zeta}\right)\boldsymbol{x_{-k}}$$

$$a_k = C_{1,k}\boldsymbol{G}\cos\boldsymbol{\zeta} + C_{2,k}\boldsymbol{G}\sin\boldsymbol{\zeta}$$

$$\boldsymbol{y}[0] = \sum_{k=0}^{N} a_k\boldsymbol{x_{-k}}$$

We have a_k , k = 0, 1, 2, ... , N

Extension to multiple tunes is easy

T. Nakamura, et al. EPAC’04

TDLSF is equivalent to Frequency Domain with Constraints on Coefficients of FIR filter

Setting Phase and Gain

$$\boldsymbol{G}(\boldsymbol{\nu_i})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i})} = \sum_{k=0}^{N} a_k \exp(-ik(2\pi\boldsymbol{\nu_i}))$$

Minimization of

$$\boldsymbol{P} = \int_0^1 |\boldsymbol{G}(\boldsymbol{\nu})|^2 d\nu = 2\pi \sum_{k=0}^{N} |a_k|^2$$

* Minimization of Noise Power passing though FIR filter
* Reduction of gain not at $\boldsymbol{\nu} = \boldsymbol{\nu_i}$

Minimization : No limit for the number of coefficients up to N+1 (the number of position data)

Constraints on Coefficients of FIR filter

Setting Phase and Gain

$$\boldsymbol{G}(\boldsymbol{\nu_i})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i})} = \sum_{k=0}^{N} a_k \exp(-ik(2\pi\boldsymbol{\nu_i}))$$

$$\frac{\boldsymbol{\partial}}{\boldsymbol{\partial\nu}}\left(\boldsymbol{G}(\boldsymbol{\nu})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu})}\right)\Big|_{\boldsymbol{\nu}=\boldsymbol{\nu_i}} = -2\pi\mathrm{i}\sum_{k=0}^{N} a_k k \exp(-ik(2\pi\nu_i)) = 0$$

Flat response at $\boldsymbol{\nu} \sim \boldsymbol{\nu_i}$

Minimization of

$$\boldsymbol{P} = \int_0^1 |\boldsymbol{G}(\boldsymbol{\nu})|^2 d\nu = 2\pi\sum_{k=0}^{N} |a_k|^2$$

Frequency Domain Condition for FIR filter

TDLSF is Equivalent to Following Frequency Domain condition

Gain, Phase and "Flat response" : Equivalent to

$$\boldsymbol{G}(\boldsymbol{\nu_i})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i})} = \boldsymbol{G}(\boldsymbol{\nu_i} \pm \Delta)e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i} \pm \Delta)}$$

$$= \sum_{k=0}^{N} a_k \exp(-ik(2\pi(\boldsymbol{\nu_i} \pm \Delta)))$$

$$\boldsymbol{G}(\boldsymbol{\Delta})e^{i\boldsymbol{\zeta}(\boldsymbol{\Delta})} = \boldsymbol{0}$$

with setting $\Delta \ll 1$

Minimization of $\boldsymbol{P} = \int_0^1 |\boldsymbol{G}(\boldsymbol{\nu})|^2 d\nu = 2\pi \sum_{k=0}^{N} |a_k|^2$

Least Square Fitting (TDLSF method) for Coefficients : 1st order

$$x[n] = A\cos((1+\Delta)\phi_n + \psi) + \mathrm{B}$$

$$\phi_n = 2\pi\nu_0 n$$

$$\rightarrow \boldsymbol{p_0} + \boldsymbol{p_1}\cos\phi_n + \boldsymbol{p_2}\sin\phi_n + (\boldsymbol{p}_3\phi_n\cos\phi_n + \boldsymbol{p}_4\phi_n\sin\phi_n)$$

for $|\Delta| \ll 1$ $\qquad \sim O(\Delta)$

Linear for $\boldsymbol{p_m}$

Least Square Fitting

$\boldsymbol{p_m}$ to $\boldsymbol{x_k}$ turn-by-turn Positions

$$\boldsymbol{p_m} = \sum_{k=0}^{N} C_{m,k}\boldsymbol{x_{-k}}$$

$$y[0] = \boldsymbol{G}A\cos((1+\Delta)\phi_0 + \psi + \boldsymbol{\zeta}) = \boldsymbol{G}A\cos(\psi + \boldsymbol{\zeta})$$

$$\phi_0 = 0$$

$$y[0] = \boldsymbol{p}_1\boldsymbol{G}\cos\boldsymbol{\zeta} + \boldsymbol{p}_2\boldsymbol{G}\sin\boldsymbol{\zeta} = \sum_{k=0}^{N}(C_{1,k}\boldsymbol{G}\cos\boldsymbol{\zeta} + C_{2,k}\boldsymbol{G}\sin\boldsymbol{\zeta})\boldsymbol{x_{-k}}$$

$$a_k = C_{1,k}\boldsymbol{G}\cos\boldsymbol{\zeta} + C_{2,k}\boldsymbol{G}\sin\boldsymbol{\zeta}$$

We have a_k , k = 0, 1, 2, ... , N

$$\boldsymbol{y}[0] = \sum_{k=0}^{N} a_k\boldsymbol{x_{-k}}$$

Extension to multiple tunes is easy

T. Nakamura, et al. EPAC'04

TDLSF and Frequency Domain : 1st order

TDLSF (1storder) : Equivalent to

Setting Phase and Gain

$\boldsymbol{p_1} \cos\phi_n + \boldsymbol{p_2} \sin\phi_n$

$$\boldsymbol{G}(\boldsymbol{\nu_i})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu_i})} = \sum_{k=0}^{N} a_k \exp(-ik(2\pi\boldsymbol{\nu_i}))$$

$(\boldsymbol{p_3}\phi_n \cos\phi_n + \boldsymbol{p_4}\phi_n \sin\phi_n)$

$$\left.\frac{\partial}{\partial \boldsymbol{\nu}}\left(\boldsymbol{G}(\boldsymbol{\nu})e^{i\boldsymbol{\zeta}(\boldsymbol{\nu})}\right)\right|_{\boldsymbol{\nu}=\boldsymbol{\nu_i}} = -2\pi \mathrm{i} \sum_{k=0}^{N} a_k k \exp(-ik(2\pi\nu_i)) = 0$$

Flat response at $\boldsymbol{\nu} \sim \boldsymbol{\nu_i}$

Minimization of

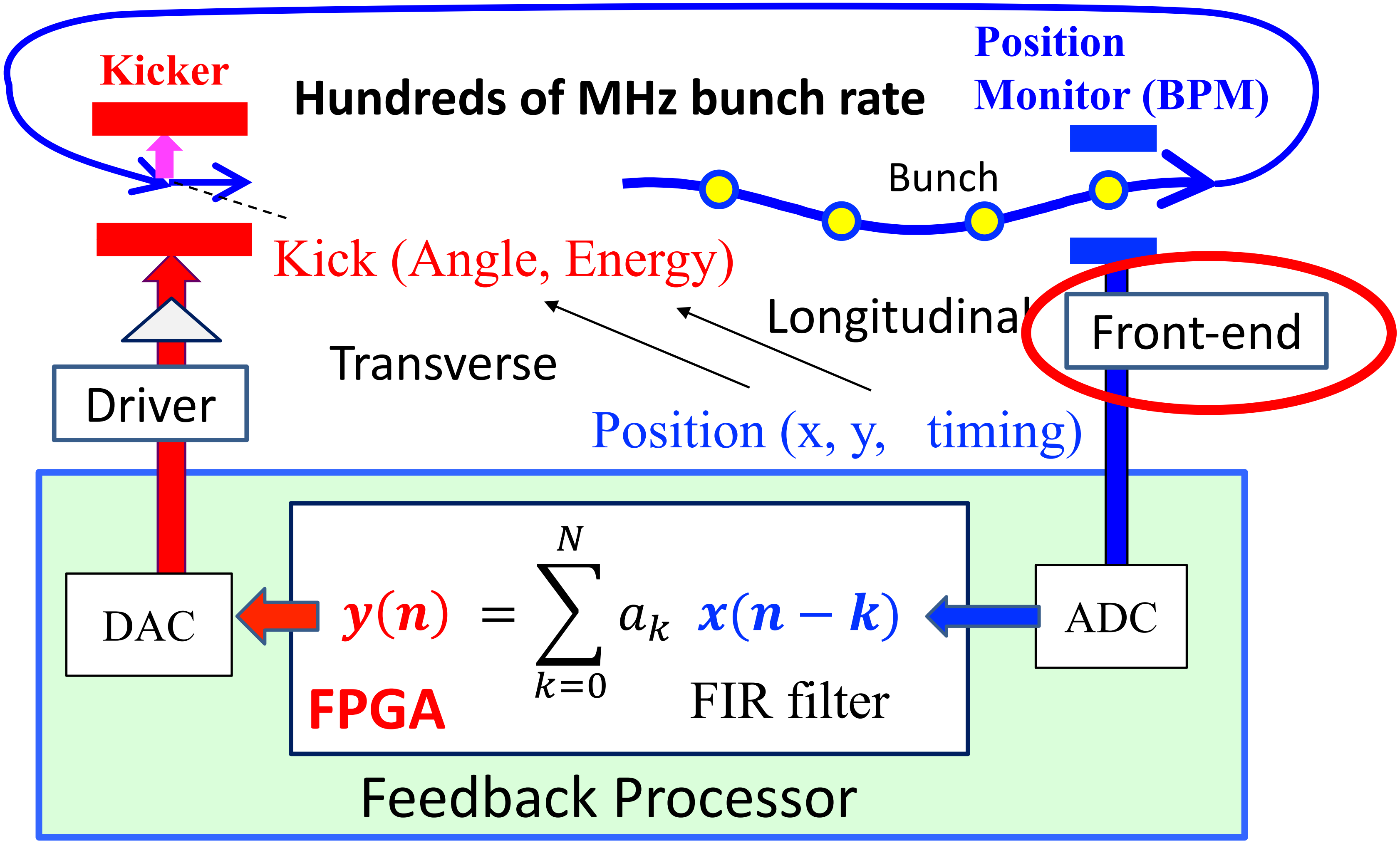
$$\boldsymbol{P} = \int_0^1 |\boldsymbol{G}(\boldsymbol{\nu})|^2 d\nu = 2\pi \sum_{k=0}^{N} |a_k|^2$$

Font-End

Devices for Damping of Betatron or Synchrotron Oscillations

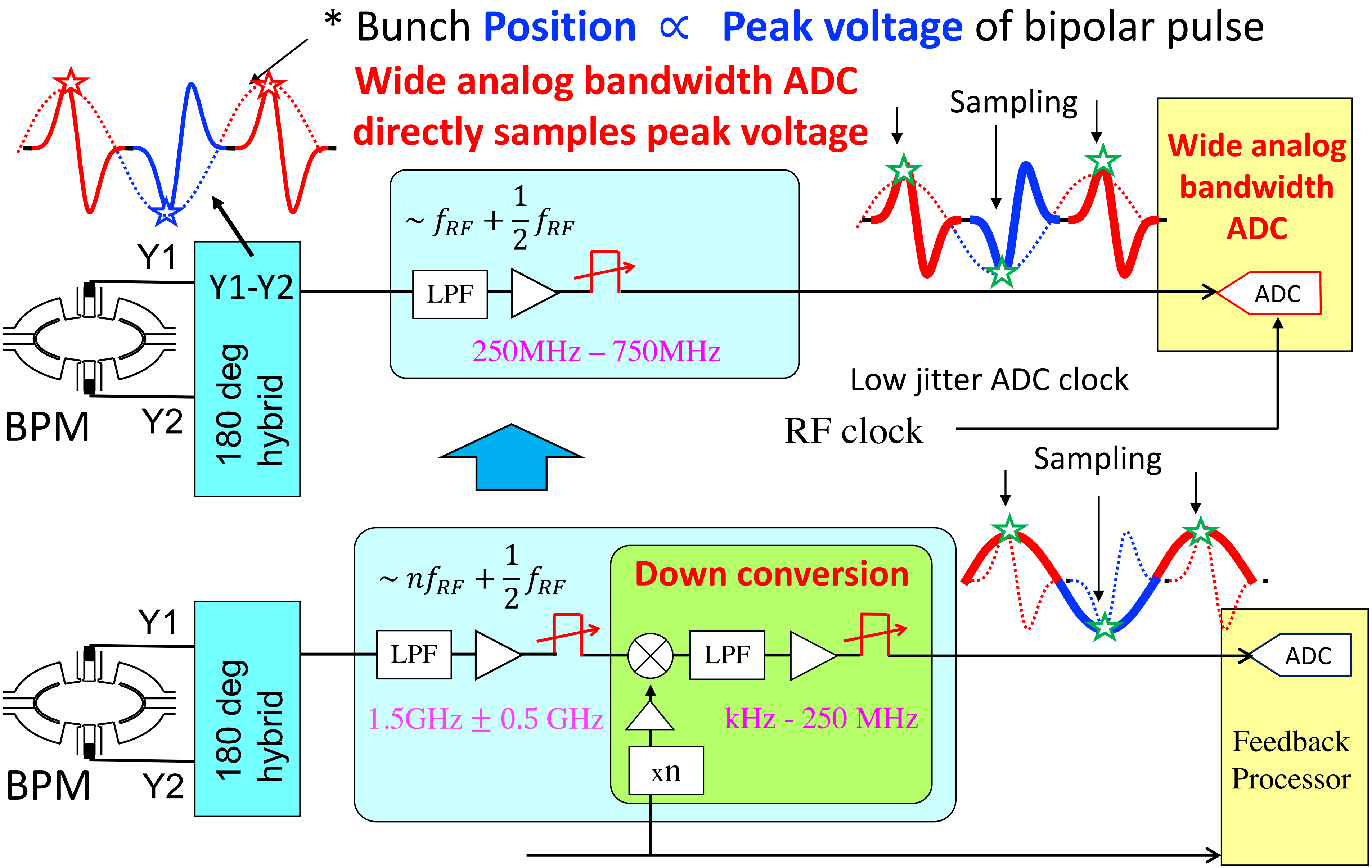
for Suppression of beam instabilities

Fast damping of excited oscillation (mostly at injection)



T. Nakamura, K. Kobayashi, et al., EPAC'04, ICALEPSC'05 (First FPGA based for hundreds MS/s)

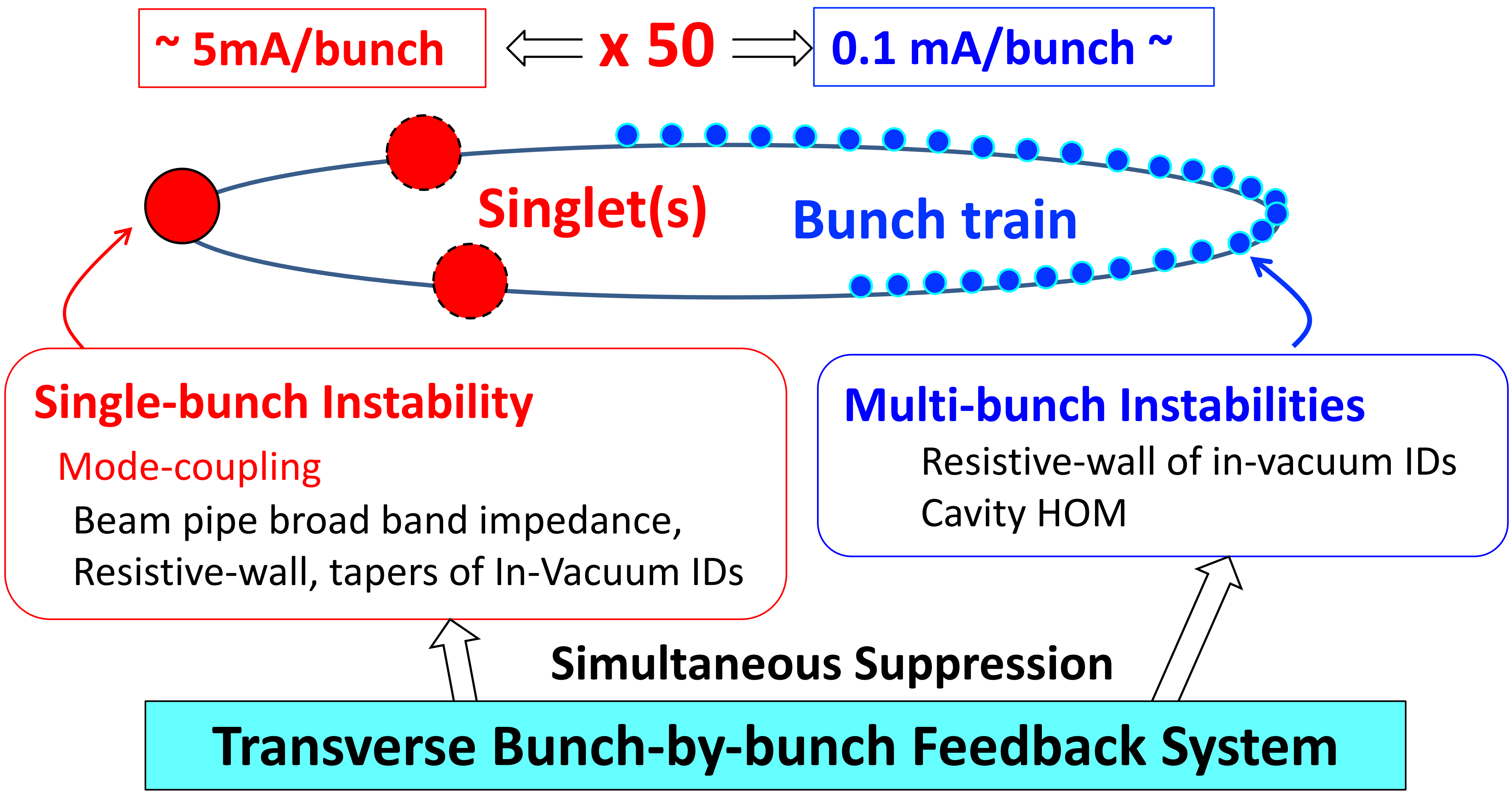
Front-End with Direct Sampling for Transverse Feedback



T. Nakamura, K. Kobayashi, Z. Zhou, EPAC'04

Transverse Feedback for Hybrid Filling

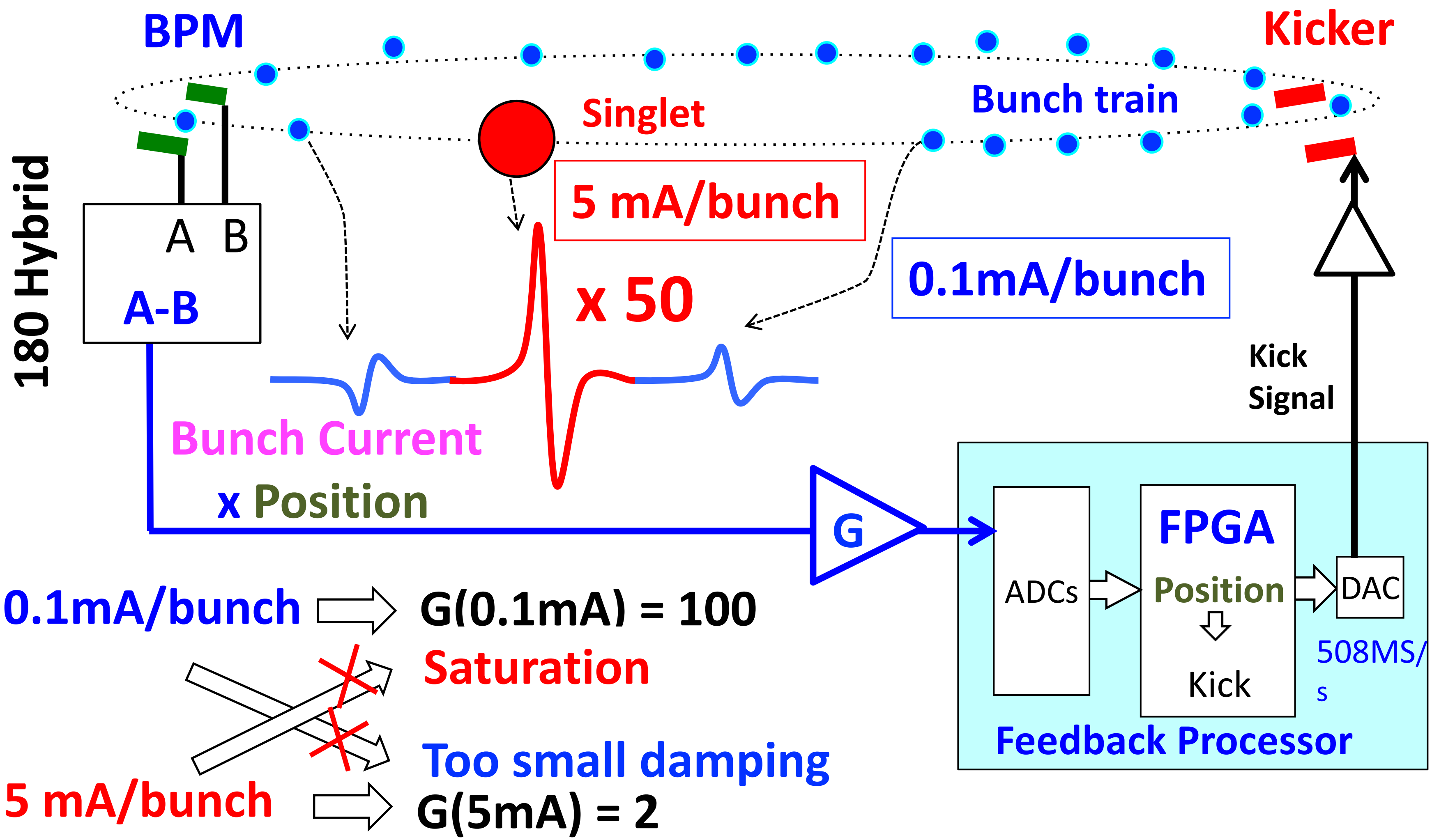
High Bunch Current Singlet Bunch(es) + **Low** Bunch Current Trains
Requested by Synchrotron Radiation Users



1 x **5mA/bunch** + **1/3** fill, 5 x **3mA/bunch** + **1/7** fill, … for SPring-8

Front-End : Saturation with Singlets OR Too Low Gain for Train

Simple Front-end cannot Handle Both bunch current

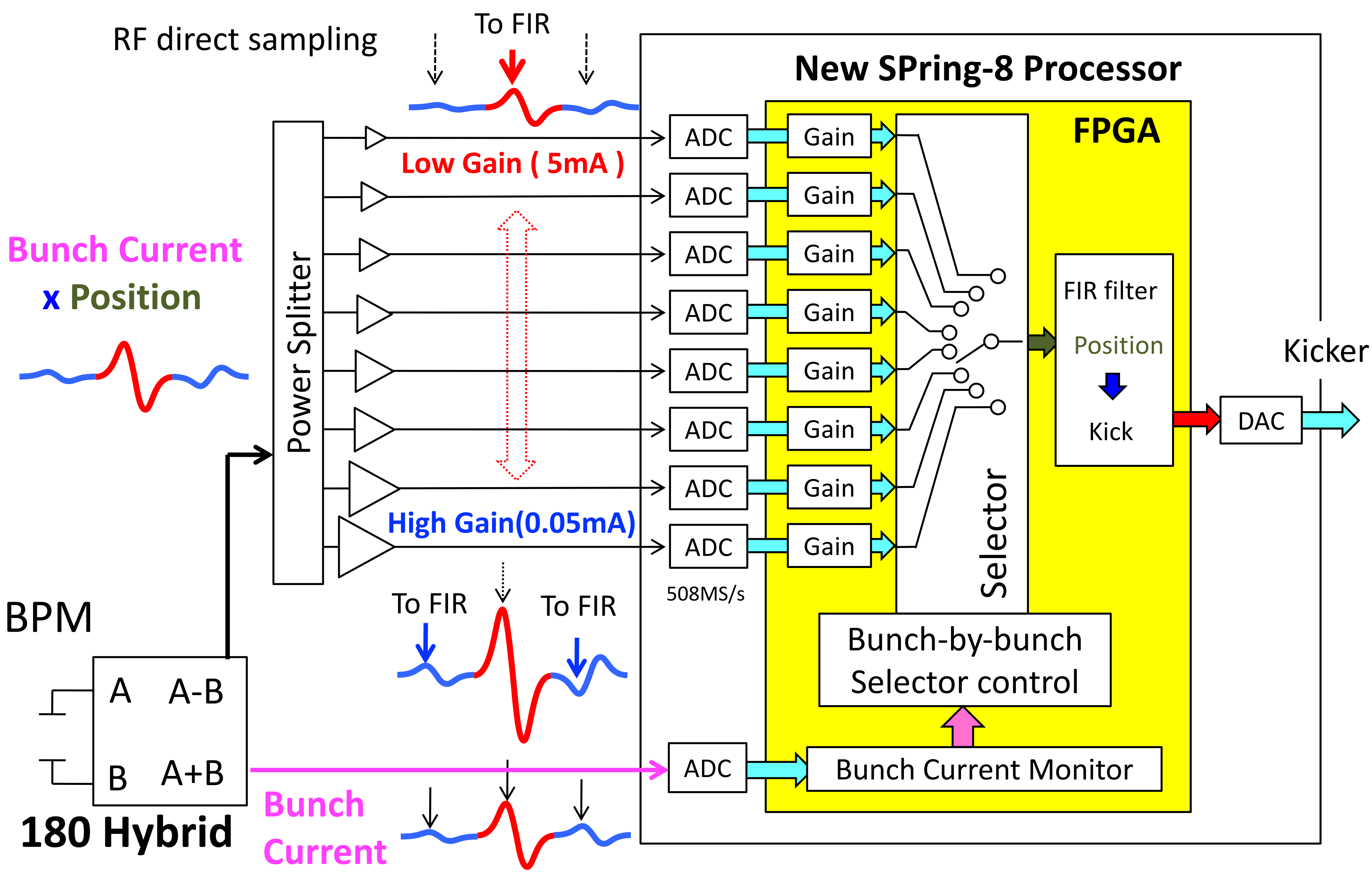


"Fast automatic bunch-by-bunch Attenuator" is one solution

K. Kobayashi, T. Nakamura, ICALEPCS'09 (for SPring-8)

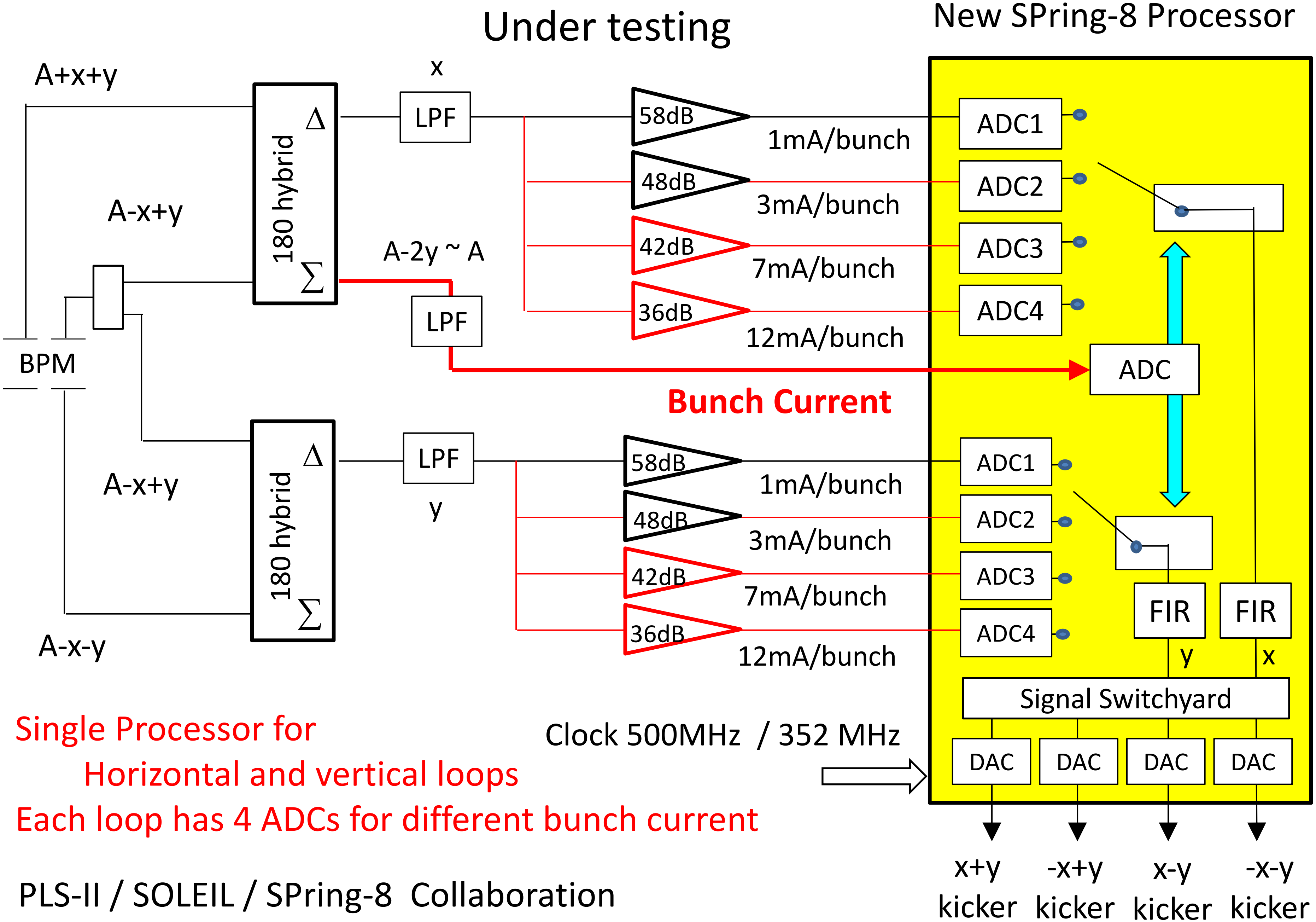
New SPring-8 Feedback Processor for Hybrid Filling

Select ADC with "good" signal level Front-end based on measured bunch current



K. Kobayashi, T. Nakamura, et al. Part. Acc. Soc. Japan (2015) In operation at SPring-8

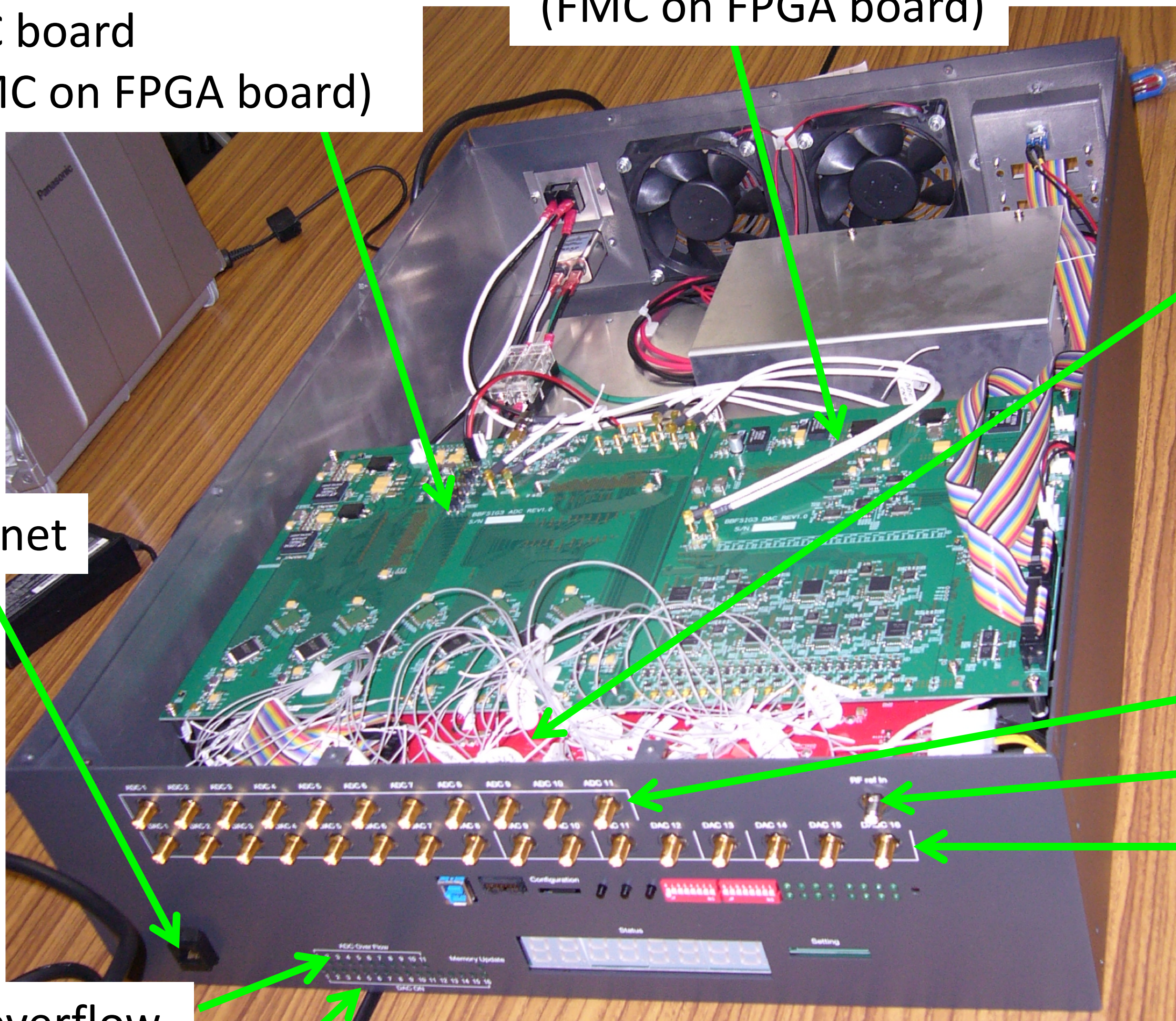
For Hybrid Filling for PLS-II and SOLEIL : H and V in one processor



Single Processor for
Horizontal and vertical loops
Each loop has 4 ADCs for different bunch current

PLS-II / SOLEIL / SPring-8 Collaboration

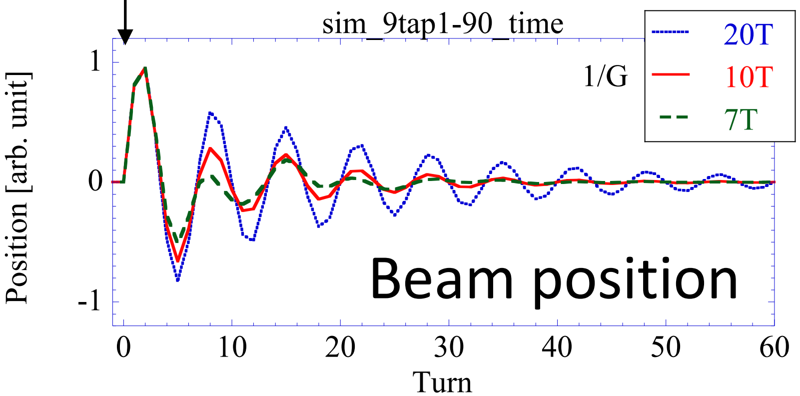
New SPring-8 Signal Processor (upside down)



Instability of Feedback at High Gain

At High Gain, feedback system drives beam oscillation

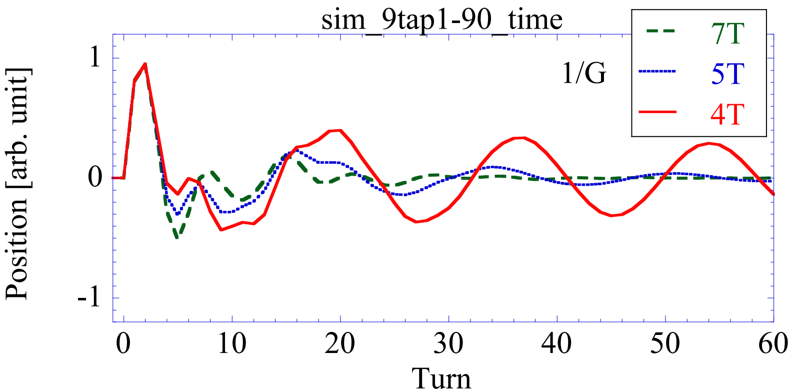
Kick

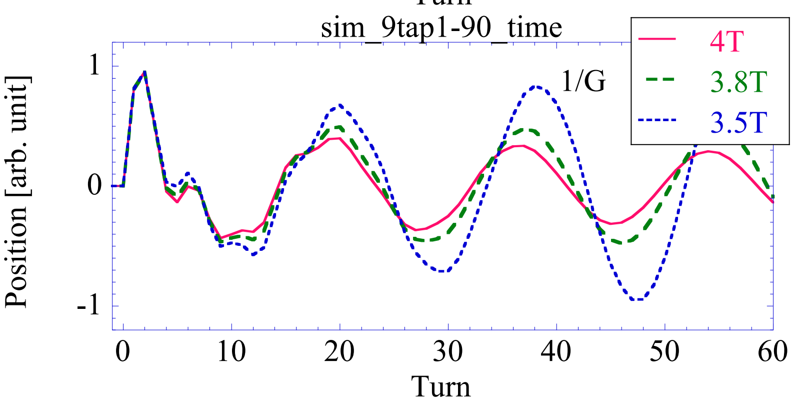


nT <= Gain corresponding to Damping time n turns

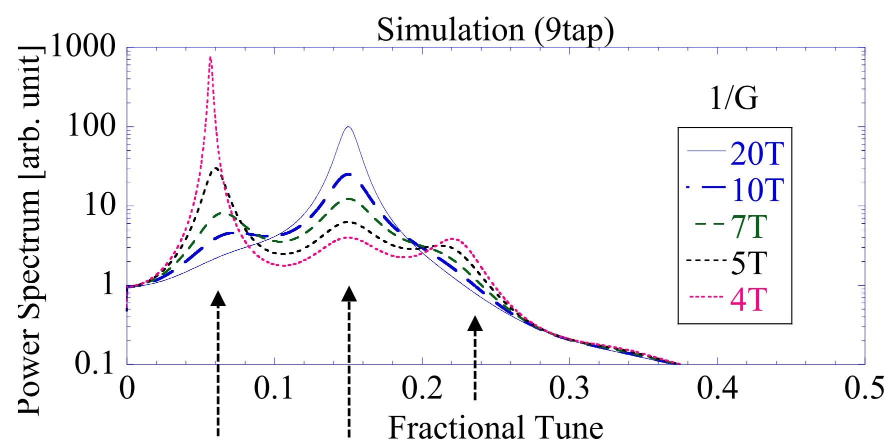
Higher Gain

Beam is unstable at High gain with Different tune from original





Fourier Trans.



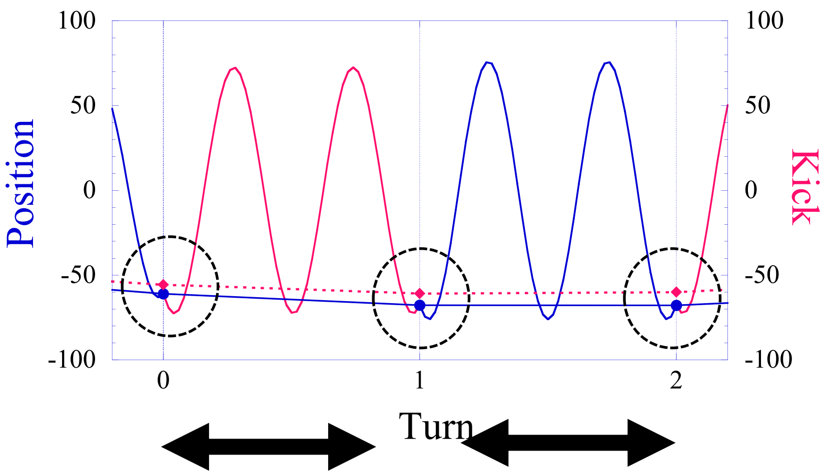
Excited	Original	Excited
0.05	0.15	0.23

1/Threshold Gain = 3.8 turns

Tune Shift by Feedback at High Gain

High Gain Feedback Drives Tune to Unstable Region

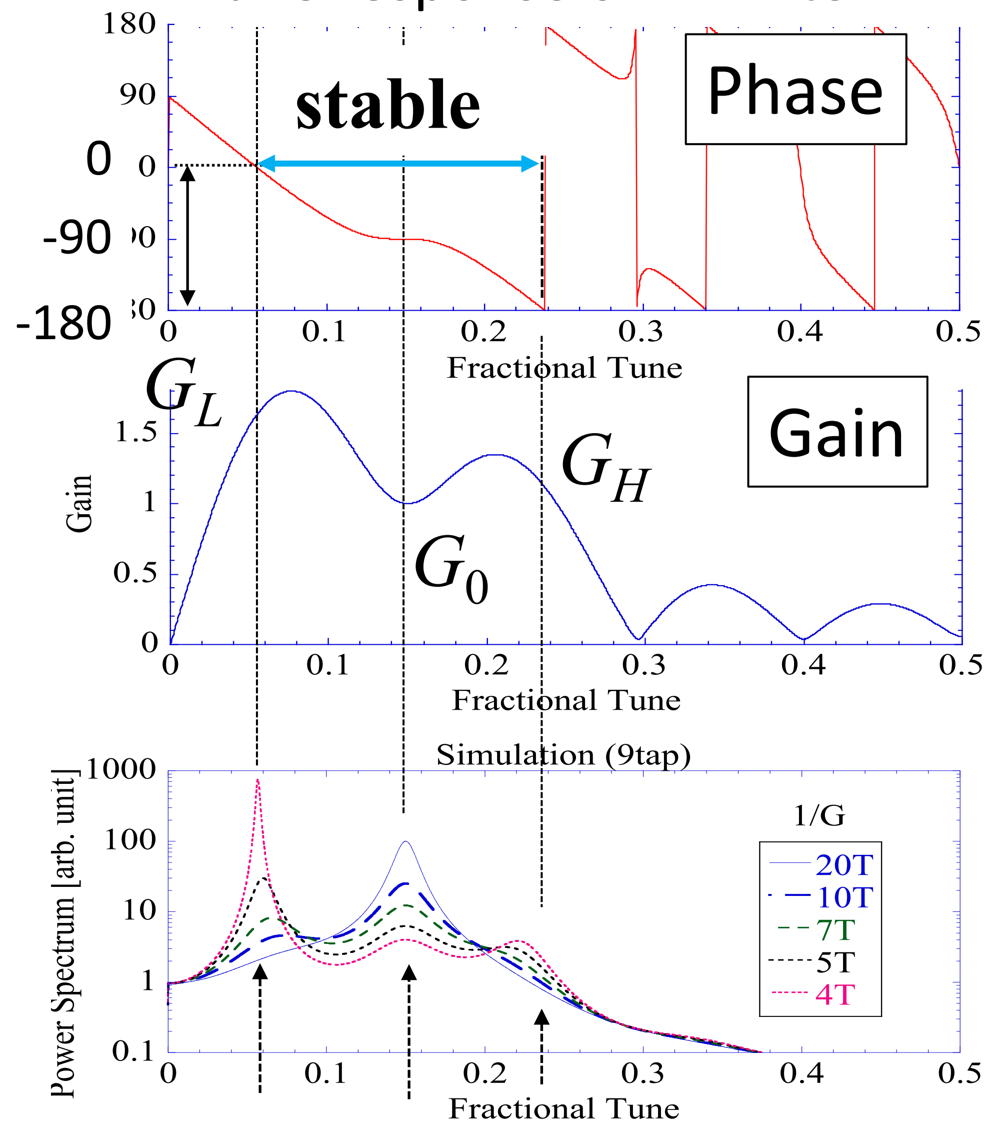
1/G = 2.8 T < 3.8 T (threshold)



1 turn 1 turn

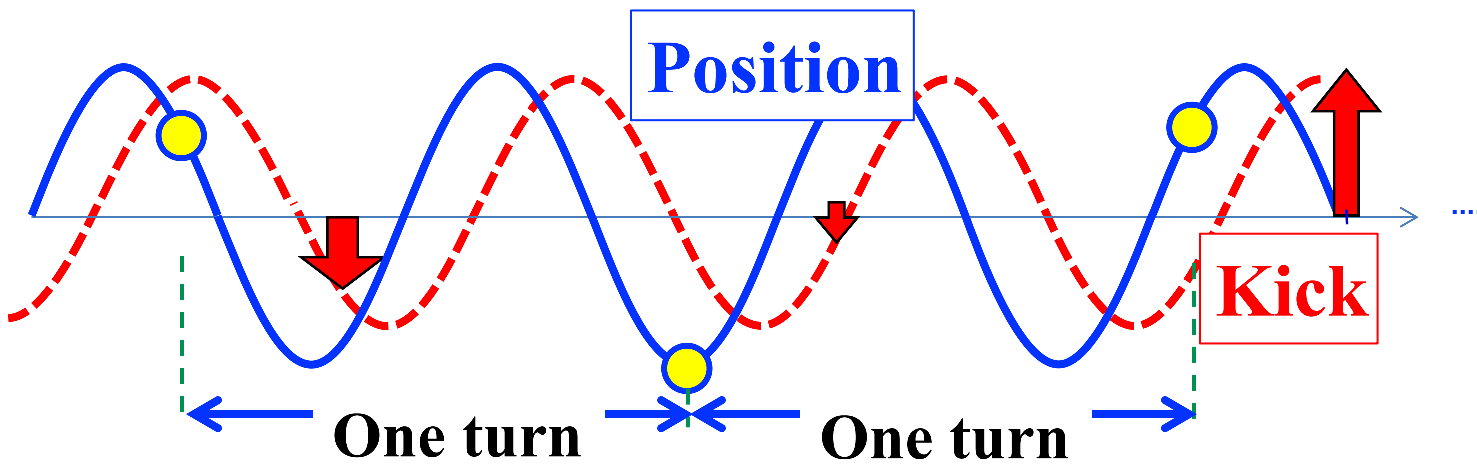
Feedback is Defocusing kick gain G_L is strong enough to shift tune from 0.15 -> 0.05

Tune response of FIR filter



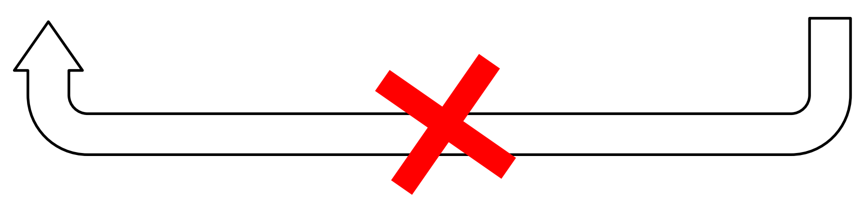
Excited 0.05 original 0.15 Excited 0.23

Instability of Feedback Driven by Closed Loop : Position - Kick



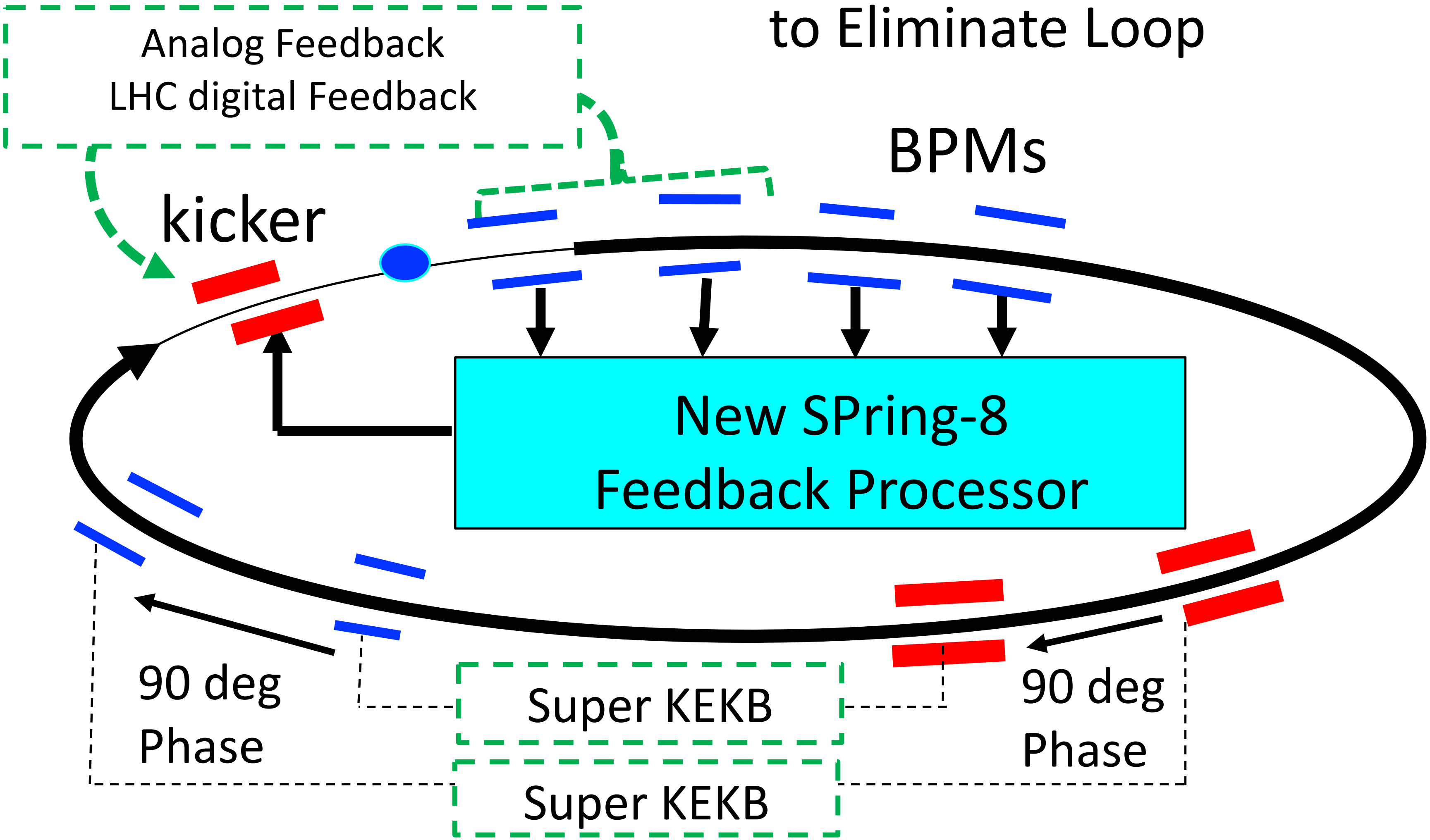
Turn-by-turn position data ⇨ Kick

Position data at multiple Locations at one previous turn ⇨ Kick



Digital Feedback with Position Data at Multiple Locations (BPMs)

kick is calculated with beam **Positions at Multiple Locations** to Eliminate Loop



For LHC with Two BPM : P. Baudrenghien, et al. EPAC'08

T. Nakamura, TWIICE 2014 (SOLEIL), Phys. Soc. of Japan(2016), Part. Acc. Soc. of Japan(2017)

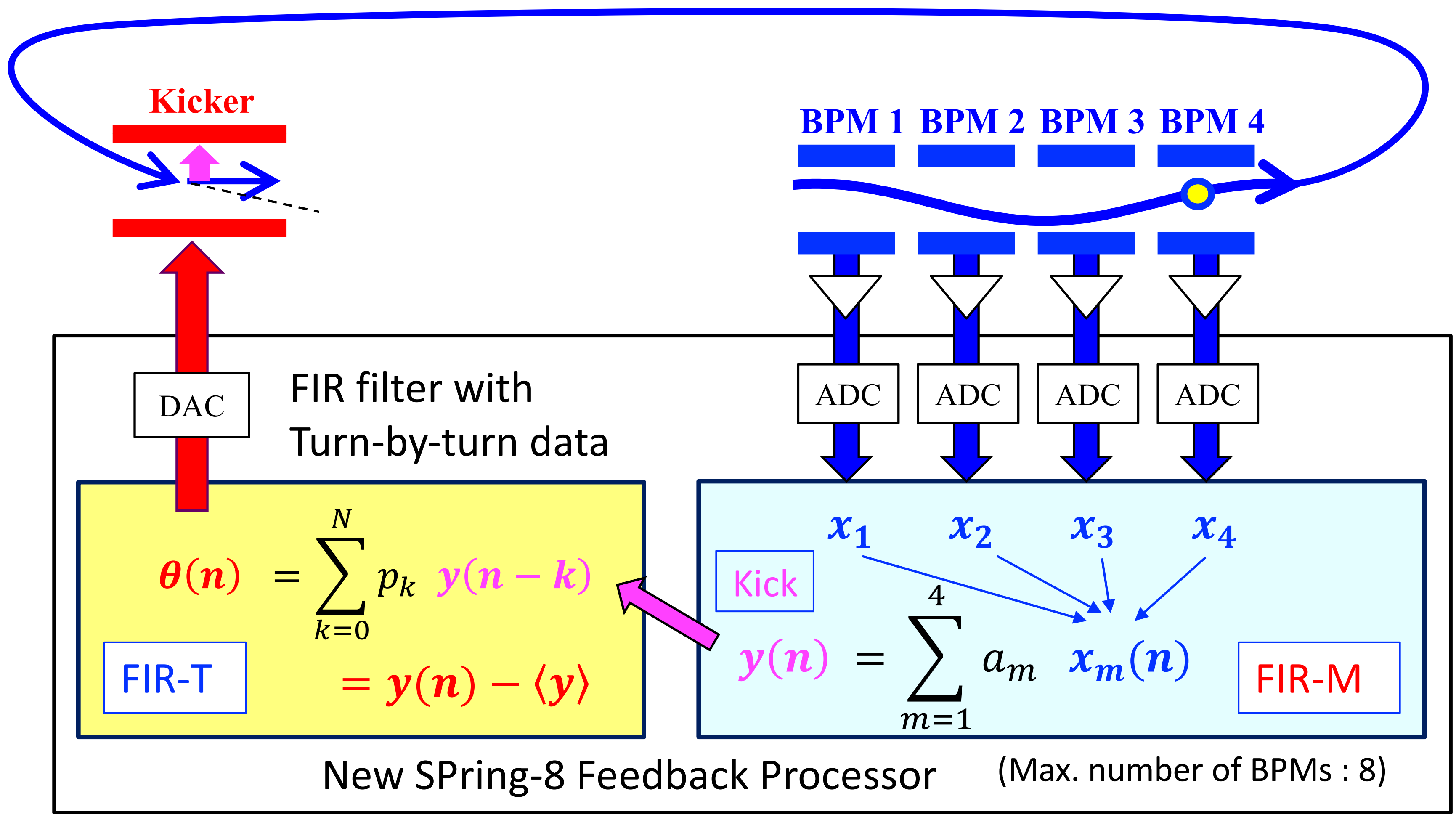
Digital Feedback with Position Data at Multiple Locations (BPMs)

FIR-M for **Kick from beam positions at multiple locations**

4 BPM -> DC offset subtraction is possible for **Ideal case (static)**

FIR-T for **Subtraction of DC offset**

Produced by drift of **Closed orbit**, **Amplifier gain**, **ADC gain and timing**



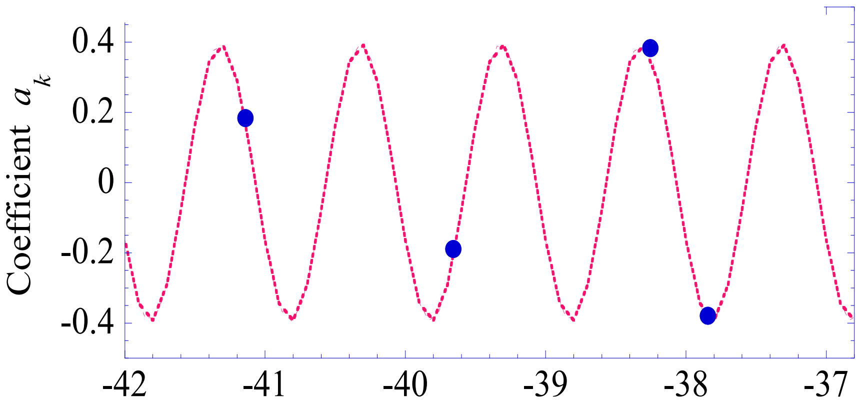
Digital Feedback with Position Data at Multiple Locations (BPMs)

FIR-M

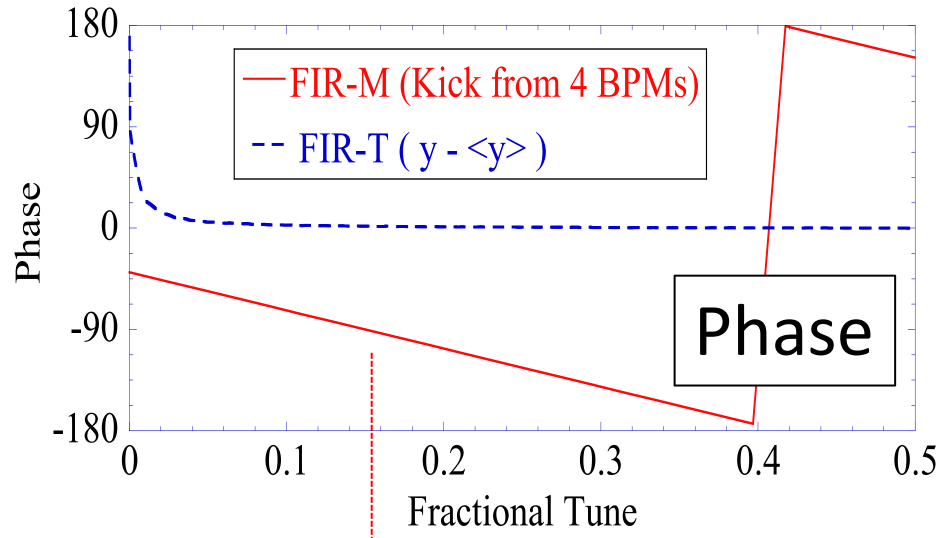
$$y(n) = \sum_{m=1}^{4} a_m \, x_m(n)$$

FIR filter response

Coefficients of and Phase of **4 BPMs**



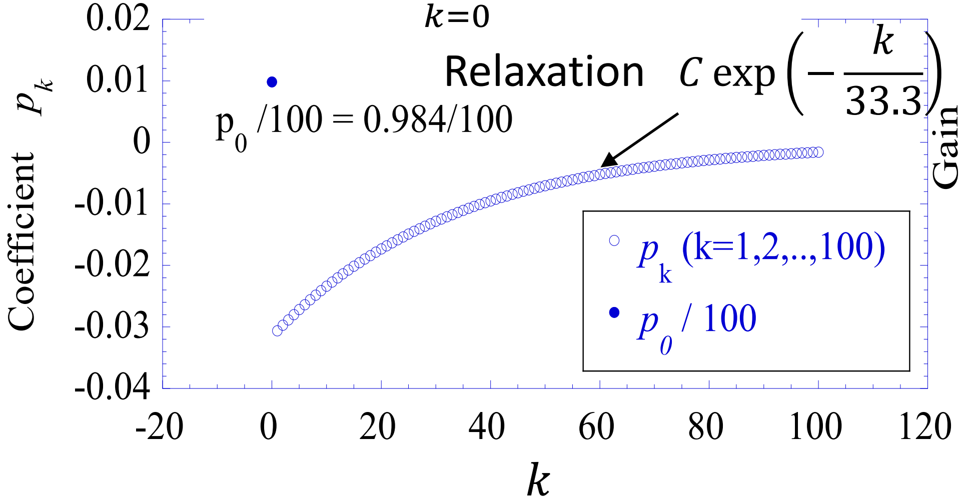
Phase Shift / (2π) at BPM from Kicker

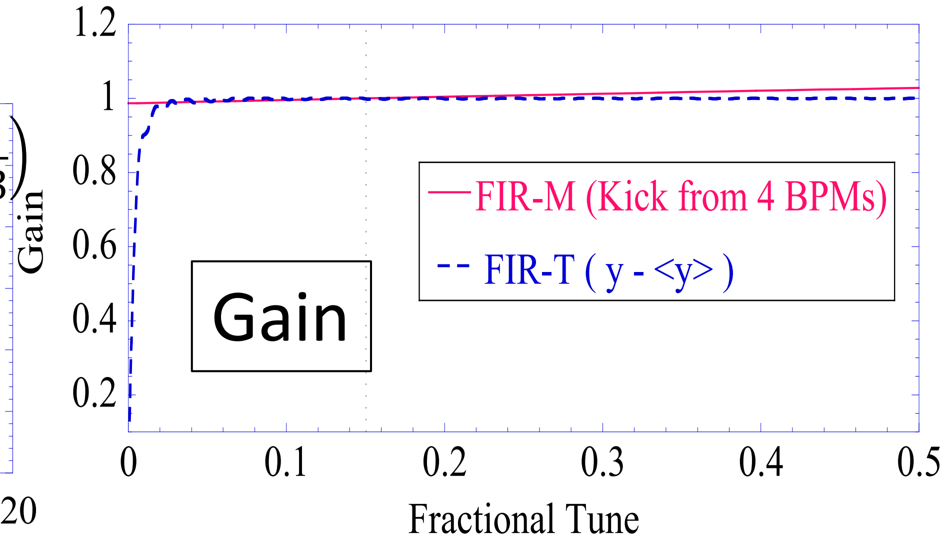


Tune should be FIXED even at High Gain

FIR-T

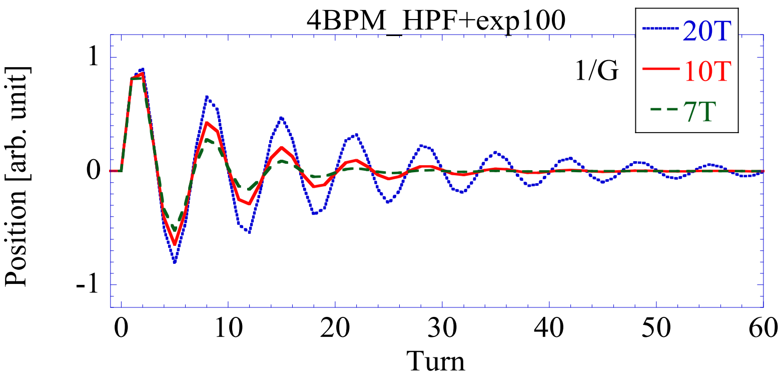
$$\theta(n) = \sum_{k=0}^{100} p_k \, y(n-k)$$

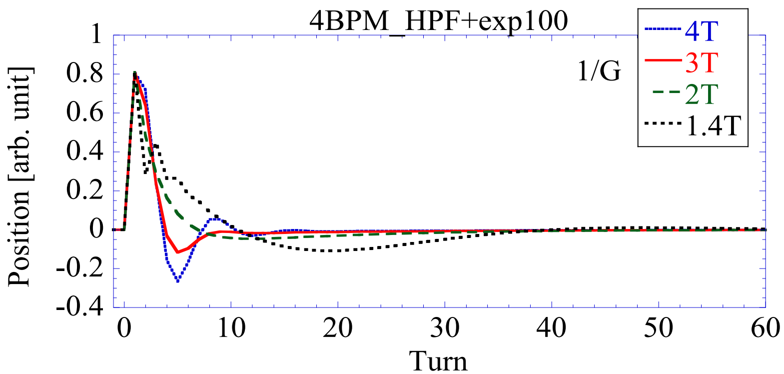




Simulation Results : Feedback with Position Data at Multiple Locations

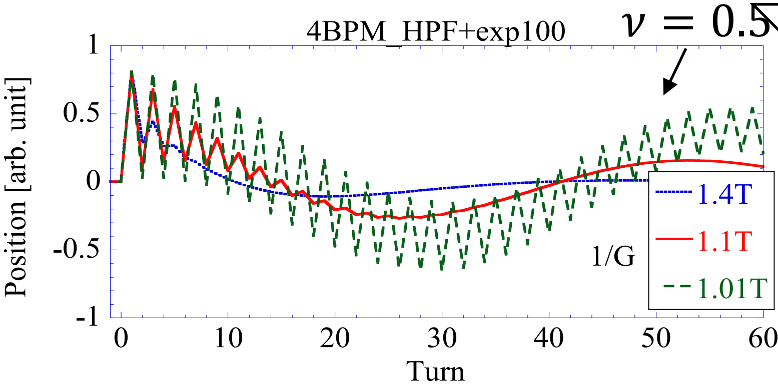
Damping time up to ~ 1.1 turns
No growth



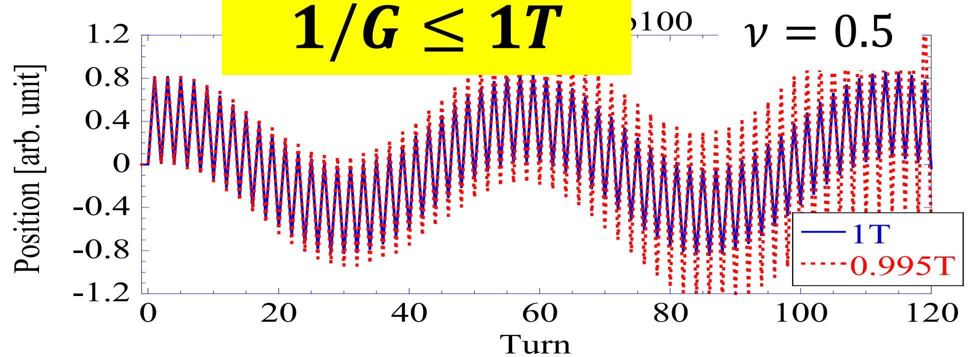


Increase of Gain

$\nu = 0.5$

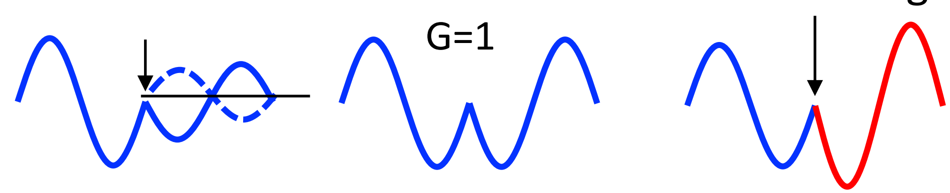


$1/G \leq 1T$ $\nu = 0.5$



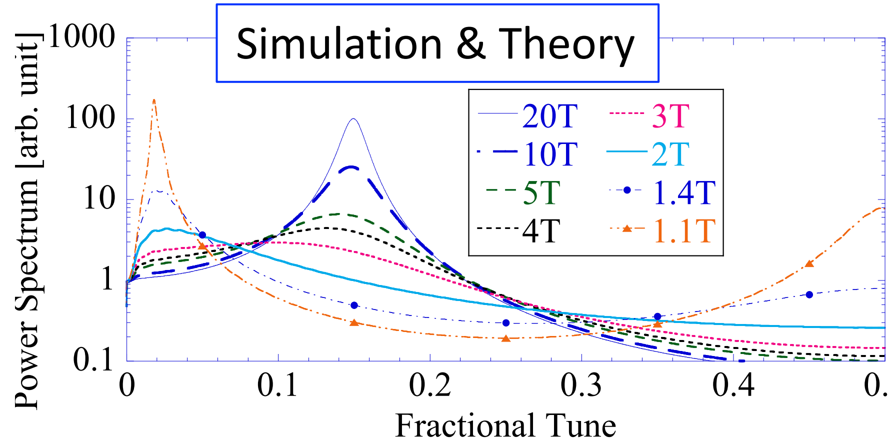
Beam is unstable for > G=1T
even with ideal feedback : **kick = - 2 G x angle**

kick < -2 x angle | kick = -2 x angle | kick > -2 x angle



stable | critical | unstable

Simulation & Theory

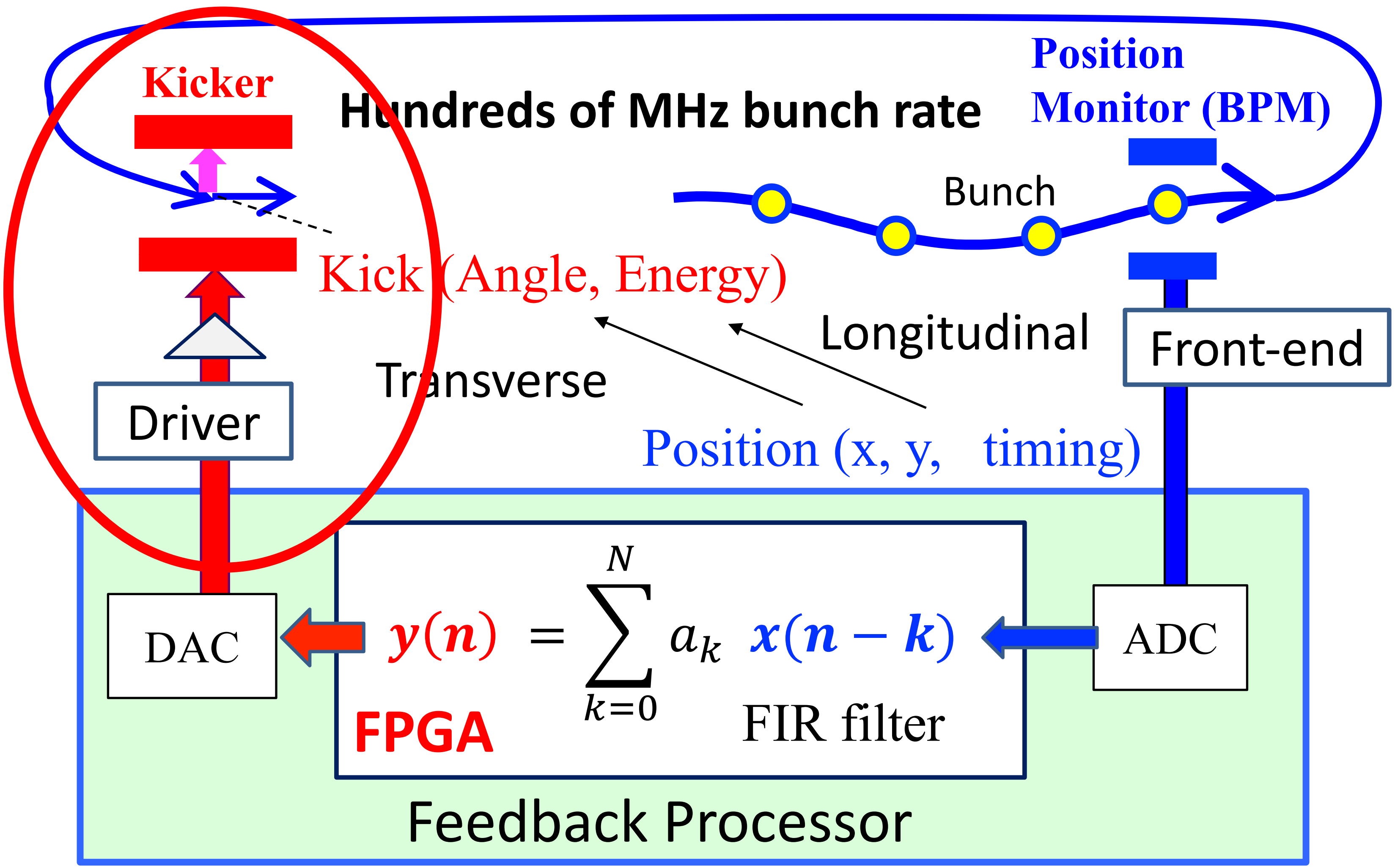


Kicker

Devices for Damping of Betatron or Synchrotron Oscillations

for Suppression of beam instabilities

Fast damping of excited oscillation (mostly at injection)



T. Nakamura, K. Kobayashi, et al., EPAC'04, ICALEPSC'05 (First FPGA based for hundreds MS/s)

SPring-8 Longitudinal Kicker

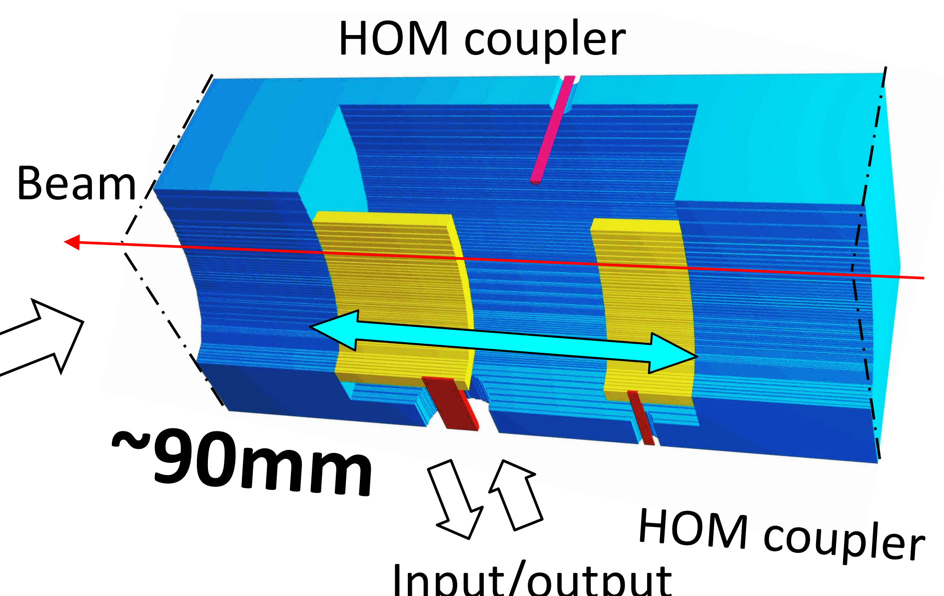
SPring-8 Storage ring (at 6 GeV operation)

* Large Revolution Period (5us) and High Energy (6GeV)
  => **Large** kick
* Limited space for kickers
  => **Short** kicker
* Higher frequency
  3 + 1/4 period / bunch spacing @500MHz is preferable
  => Simple drive circuit without QPSK modulator

High Shunt Impedance
Short Kicker

1/4 part

Beam pipe shape is Preserved
no taper transition is necessary



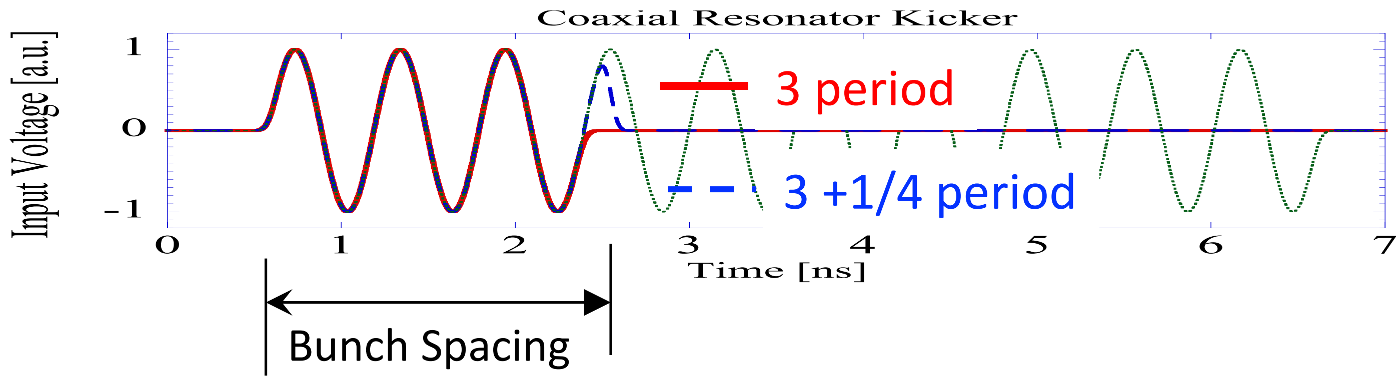
T. Nakamura, IPAC'11 (proposal, test model). Masaki, et al. IBIC'16 (feedback test at SPring-8)

SPring-8 Longitudinal Kicker

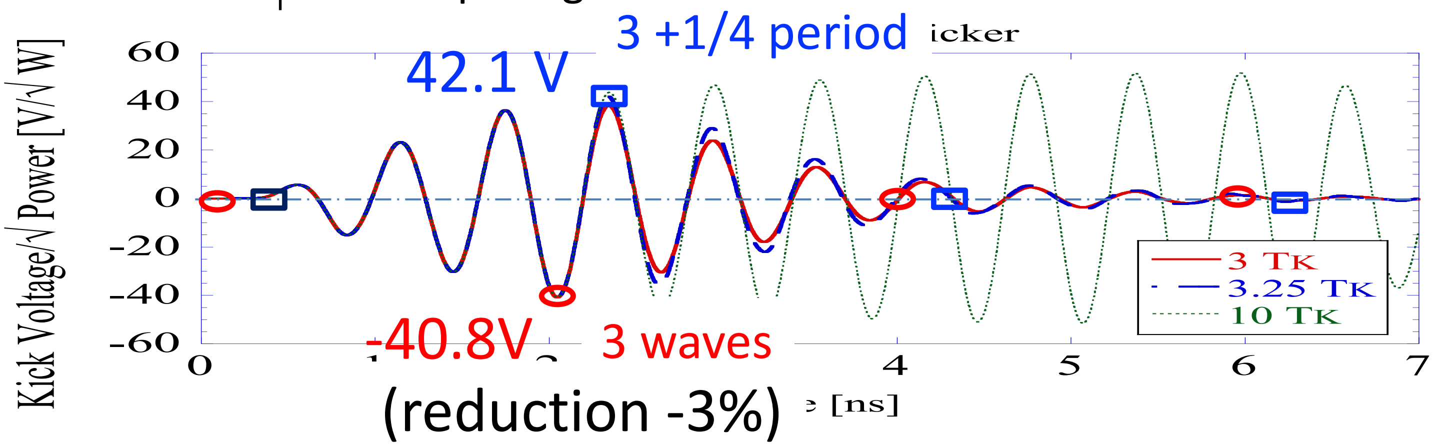
3 + 1/4 period / bunch spacing @500MHz is preferable

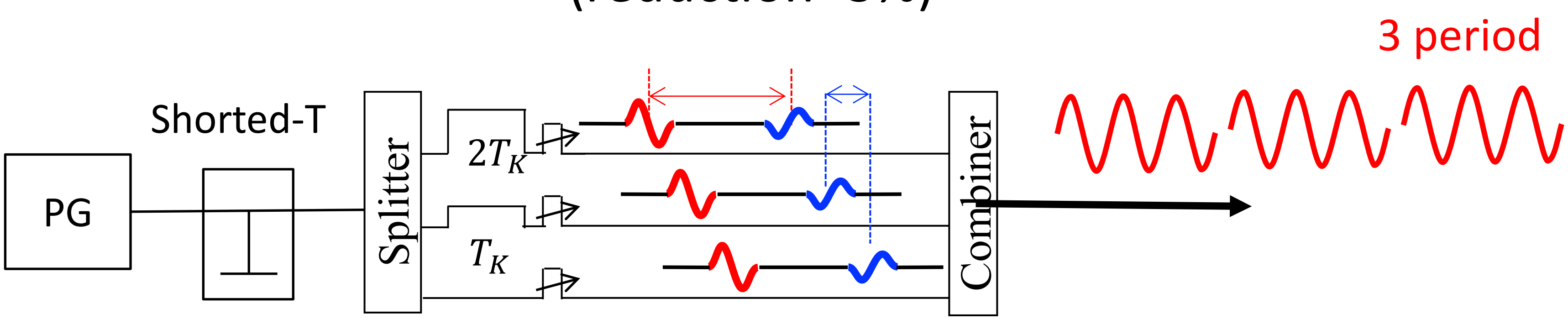
=> Simple drive circuit without QPSK modulator

Kicker Drive Signal



Kicker Voltage





Longitudinal Kicker (Comparison)

Standard Kicker widely used

SPring-8 Type Kicker

1.6 GHz : 3 + 1/4 period / bunch

3 period drive : 3% loss

No QPSK modulator

↔

DAΦNE type Overdamped Cavity

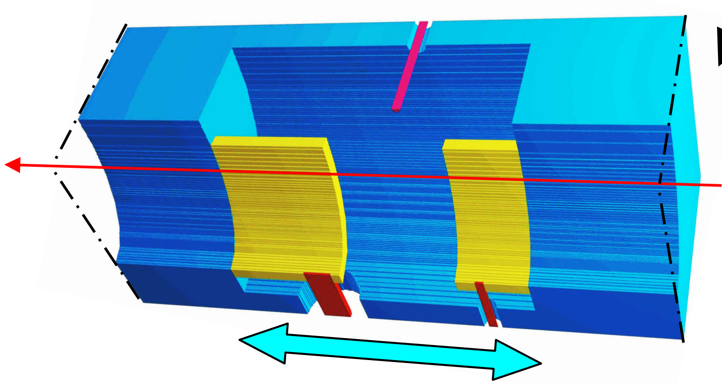
1.4 GHz :

2 + 3/4 period / bunch

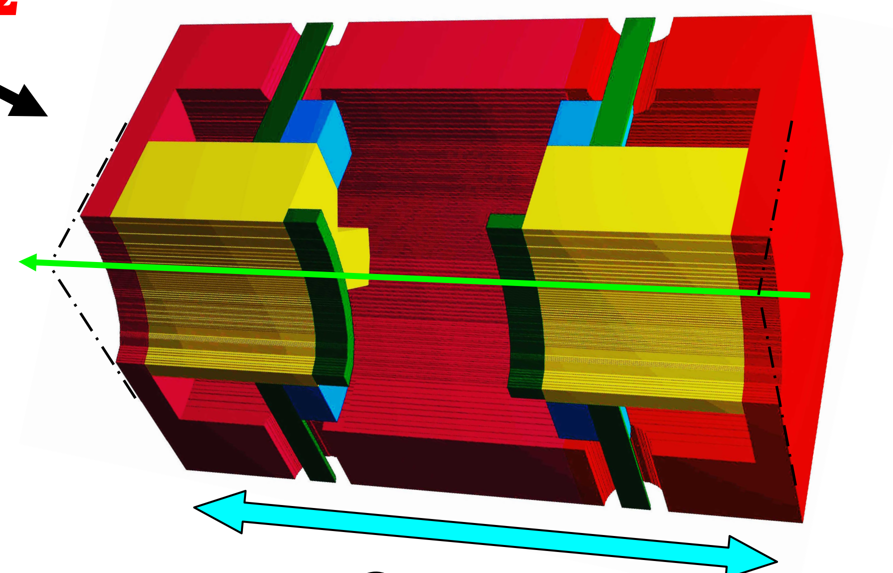
needs **QPSK modulator**

(2 period drive : 20 % loss)

Shunt Impedance ~ 1.3 – 1.4 kΩ



~90mm



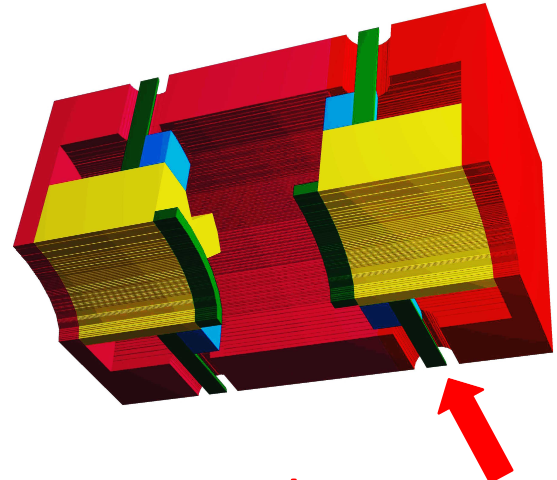
~ 200 mm

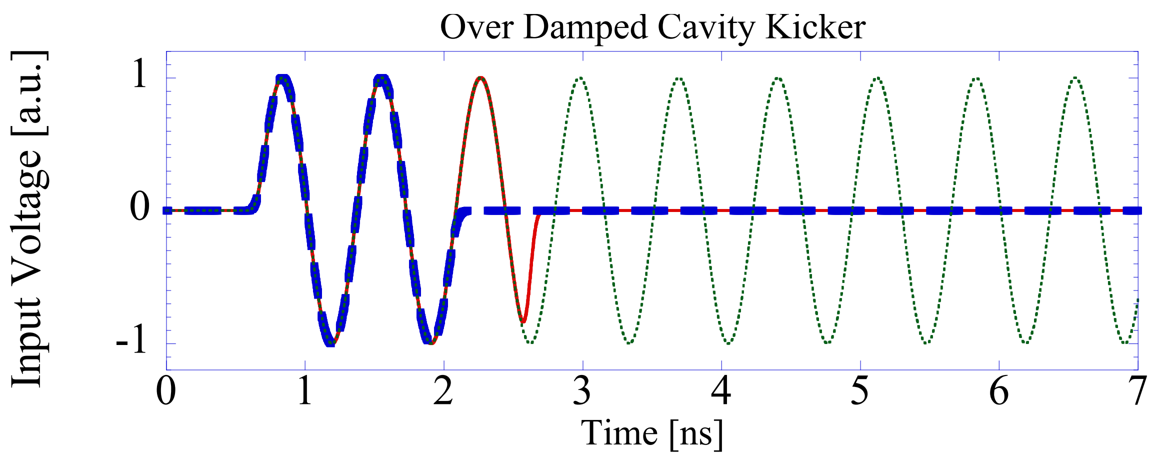
f_{RF} ~ 500MHz region

BESSYII/SLS/Elettra/TLS kicker shape

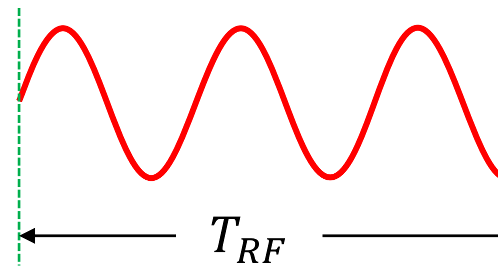
Drive Signal for Overdamped cavity (DAFNE type kicker)

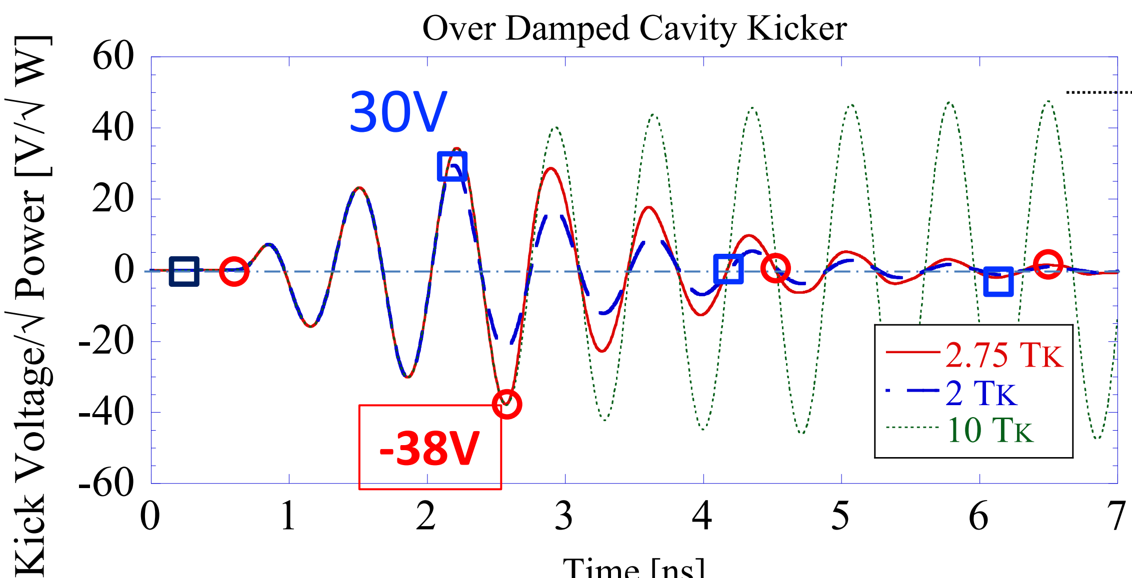
fK ~ 1.4 GHz = > **2 + 3/4** period / bunch (500MHz)





2 + 3/4 waves





48V

Rsh = 1.14 k Ohm

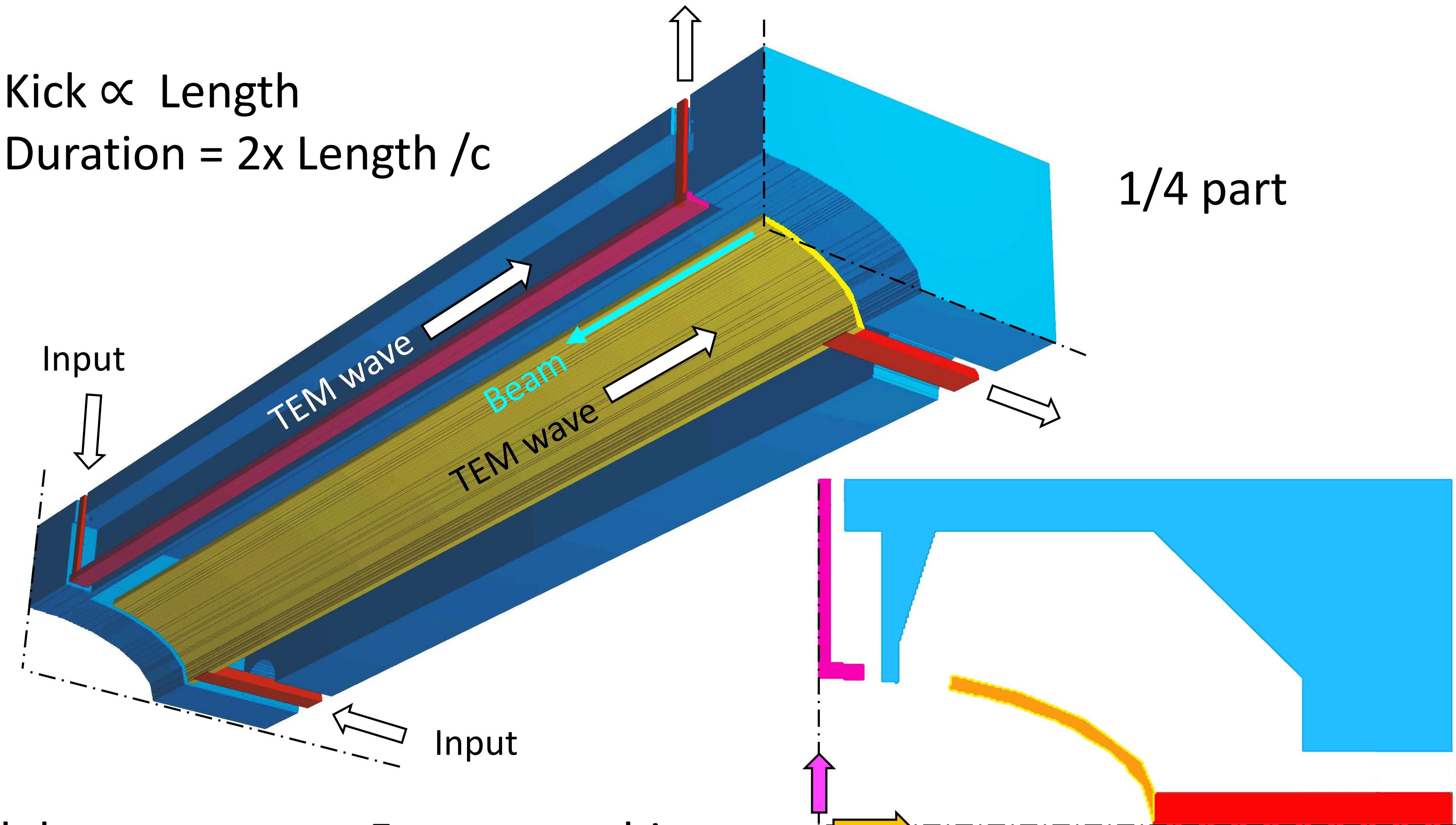
$$\frac{V_K(2\ \text{wave})}{V_K\ (2+3/4\ \text{wave})} \sim 80\%$$

Example of Transverse Kicker : Stripline type

Length : half of bunch spacing
30 cm for 500MHz

Example of Orthogonal Kicker
with Electrodes for H and for V

* Kick ∝ Length
* Duration = 2x Length /c



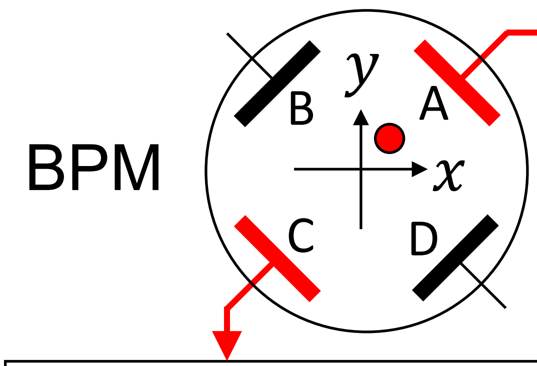
High beam power at Factory machines :
kicker for high current beam is under development (Tobiyama, KEK)

Single-Loop Two-Dimensional Transverse Feedback

One Position Signal, **One** Processor, for **Horizontal and Vertical feedback**

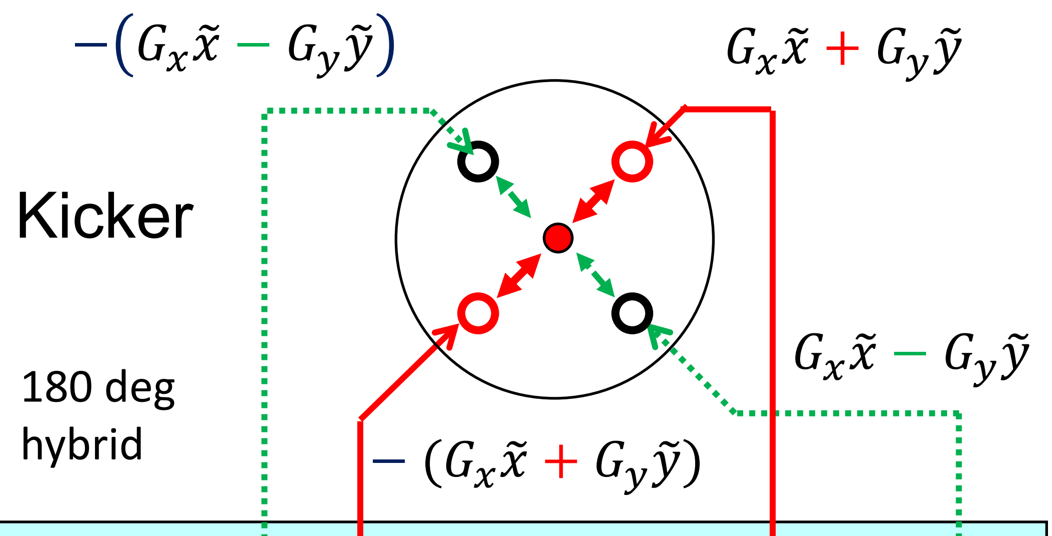
* Less components, cost and tuning points

* No special devices are needed (but SPring-8 Processor for all kick electrodes)



$$\Delta = V_A - V_C = \boldsymbol{k}\left(\tilde{x}(\nu_x) + \tilde{y}(\nu_y)\right)$$

180 deg hybrid



$\tilde{x}(\nu_x) + \tilde{y}(\nu_y)$

$$\tilde{x}(\nu_x) = \hat{x}\, e^{i2\pi\nu_x k}$$

$$\tilde{y}(\nu_y) = \hat{y}\, e^{i2\pi\nu_y k}$$

FIR filter

$G_x e^{i\zeta_x}\,\tilde{x}(\nu_x) + G_y e^{i\zeta_y}\tilde{y}(\nu_y)$

− FIR 1 $\tilde{x} + \tilde{y} \rightarrow G_x\tilde{x} + G_y\tilde{y}$ +

− FIR 2 $\tilde{x} + \tilde{y} \rightarrow G_x\tilde{x} - G_y\tilde{y}$ +

SPring-8 Processor

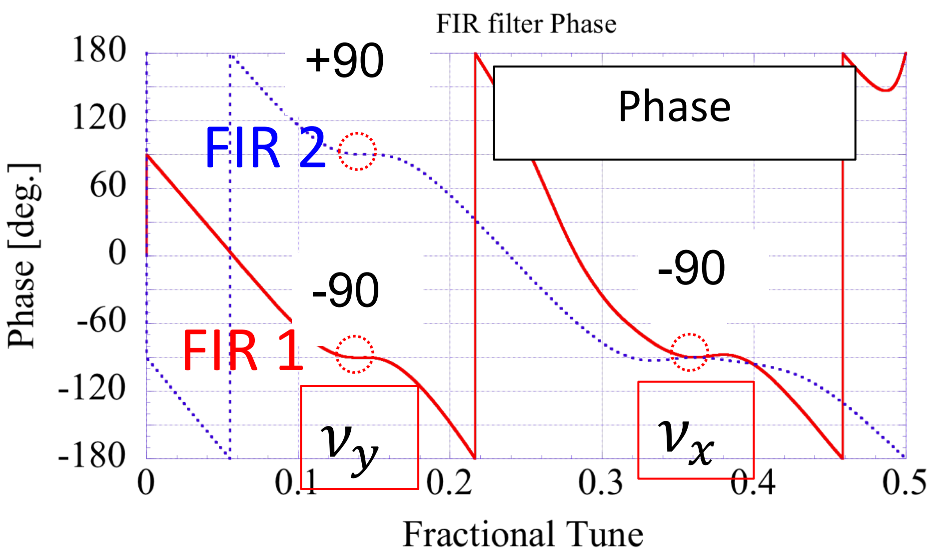
T. Nakamura, et al, EPAC06, "Single-loop Two-Dimensional Transverse Feedback for Photon Factory"

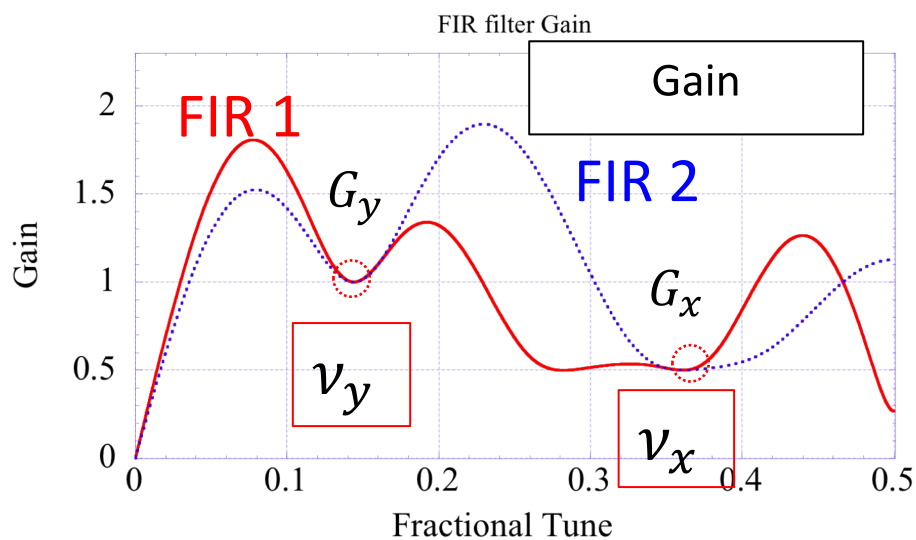
PF, TLS, SOLEIL for their early stage, PLS-II in operation

PLS-II Two-Dimensional Feedback

FIR 1 $\quad \tilde{x} + \tilde{y} \rightarrow G_x\tilde{x} + G_y\tilde{y}$

FIR 2 $\quad \tilde{x} + \tilde{y} \rightarrow G_x\tilde{x} - G_y\tilde{y}$





Adjust gain for required damping / acceptance
with beta function at BPM and Kicker

E.-H. Lee, et al., Review of Scientific Instruments **85**, 125102 (2014)

Two Tune Drive in Longitudinal Feedback

DAΦNE

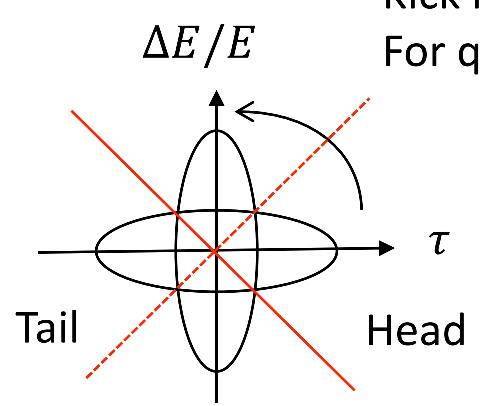
Longitudinal

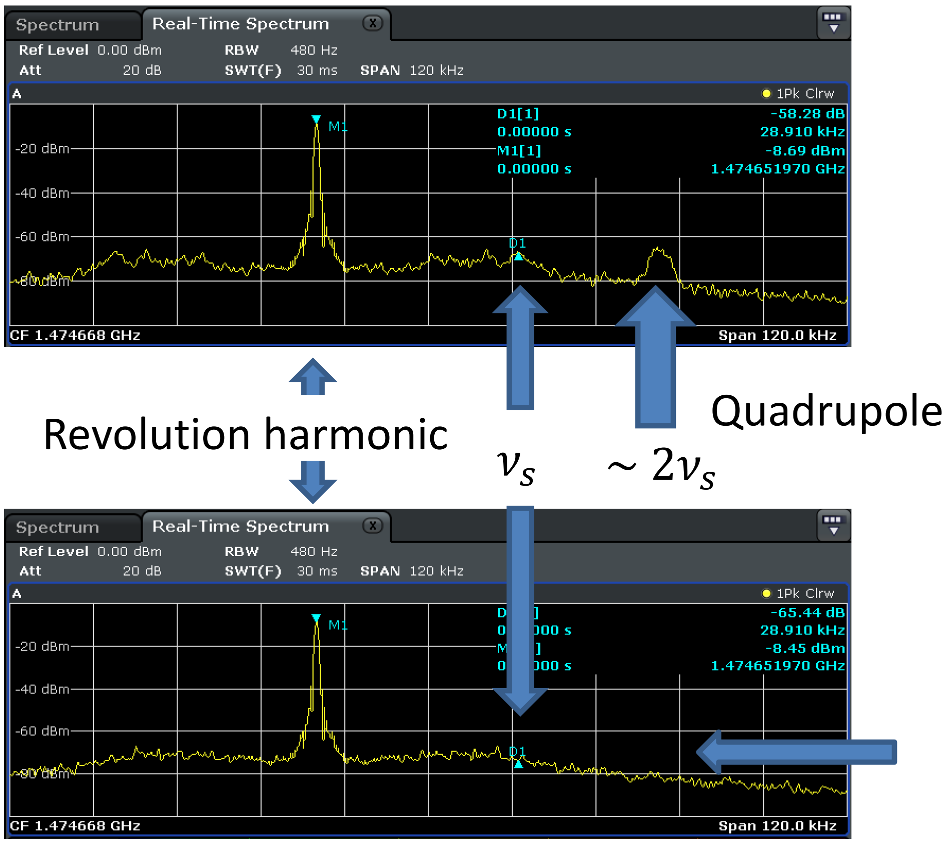
Dipole Oscillation ν_s

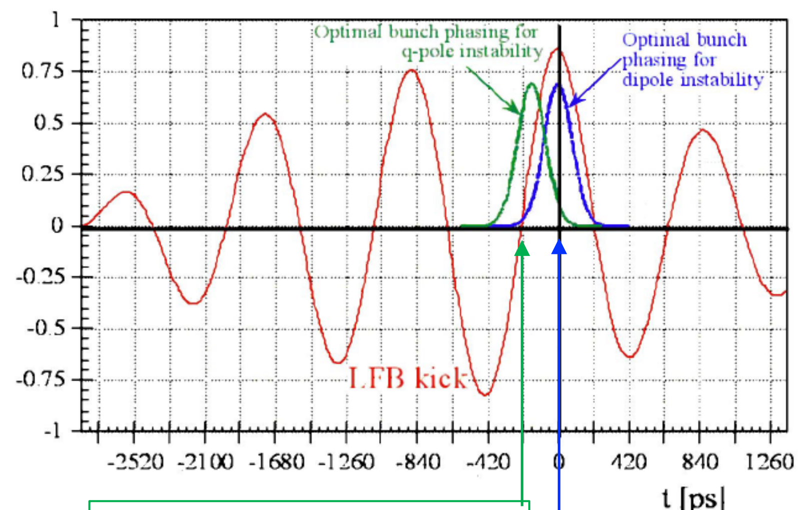
Quadrupole Oscillation $\sim 2\ \nu_s$

FIR filter optimized for two tunes & Kick timing shift

Kick required
For quadrupole







For Quadrupole Kick

For Dipole kick

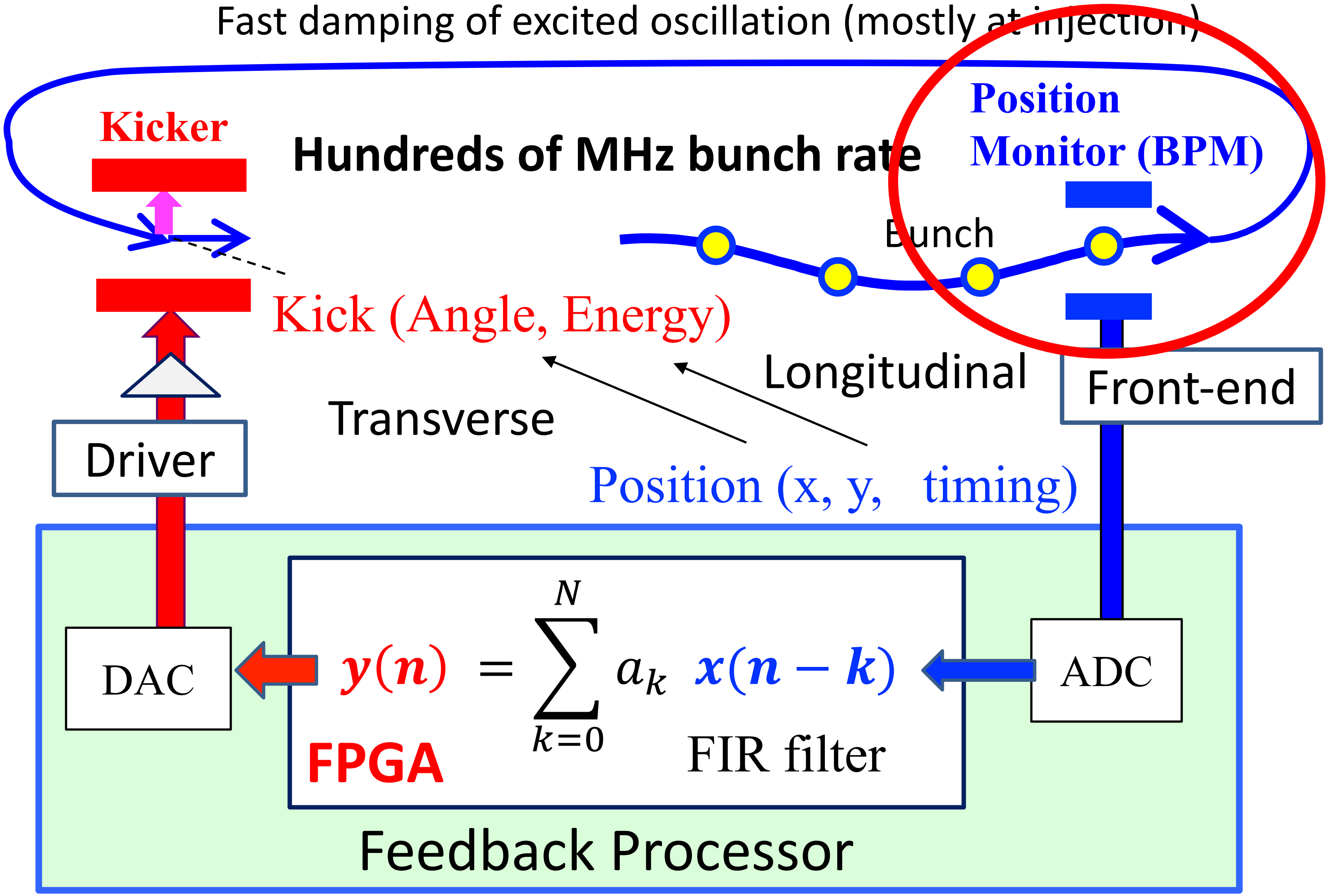
A.Drago, et al. , PRST-AB, 6, 052801-1-11, 2003.

Transverse and Longitudinal Digital Feedback

Devices for Damping of Betatron or Synchrotron Oscillations

for Suppression of beam instabilities

Fast damping of excited oscillation (mostly at injection)



T. Nakamura, K. Kobayashi, et al., EPAC'04, ICALEPSC'05 (First FPGA based for hundreds MS/s)

Increase of beam size by BPM noise

BPM random noise → Transverse Feedback → Effective beam size at BPM by noise kick

Resolution σ_{BPM}

$$\sigma_x = \frac{\sqrt{\tau_{total} T_0}}{\tau_{FB}} \sigma_{BPM} \sim \sqrt{\frac{T_0}{\tau_{FB}}} \sigma_{BPM}$$

$$\tau_{FB} = 0.5\mathrm{ms} = 100 T_0$$

$\sigma_x = \frac{1}{10} \sigma_{BPM}$ << Vertical Beam size ~ 5 μm

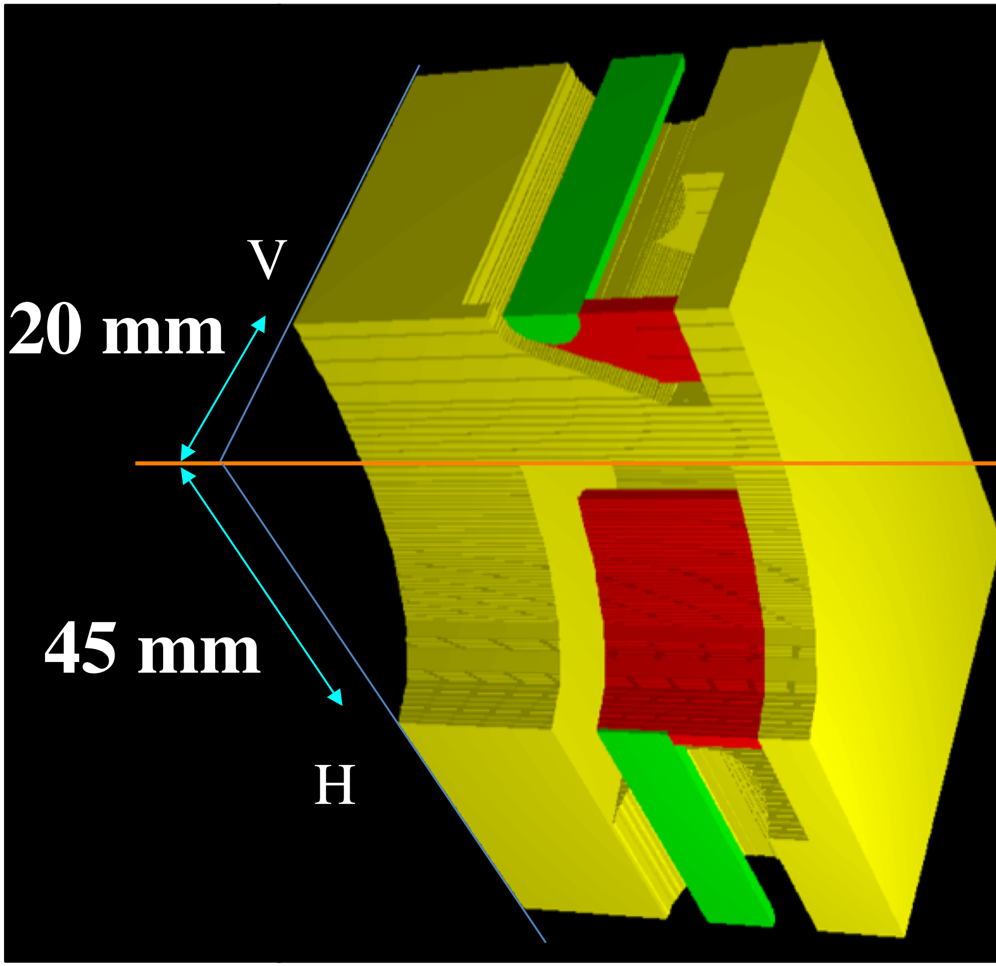
$$\sigma_{BPM} \sim 5\ \mu m$$

for one passage of bunch

T> Nakamura, NANOBEAM 2005, http://acc-web.spring8.or.jp/~nakamura

High Resolution BPM by Shorted Stripline Structure

1/4 of structure



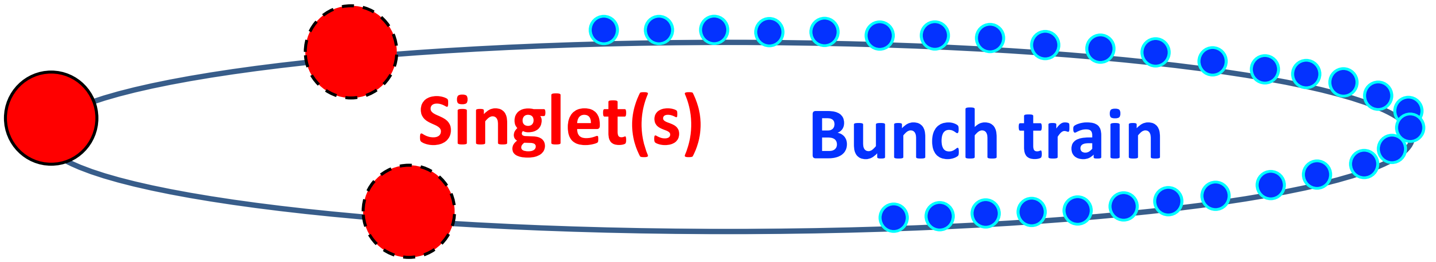
Beam axis

$\sigma_V = 5\mu m$

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

T. Nakamura, DIPAC05,

Hybrid Filling



Bunch Timing Spread at Hybrid Filling (Localized Filling)

Localized Filling (1/3 fill, 1/14 fill, …)
at Large Ring (5us revolution) Beam time structure ~ a few us

Normal RF Acceleration Cavities Filling time ~ a few us

⇩

Beam Loading by Localized Filling Modulates
Voltage and Phase of Cavity Voltage

⇩

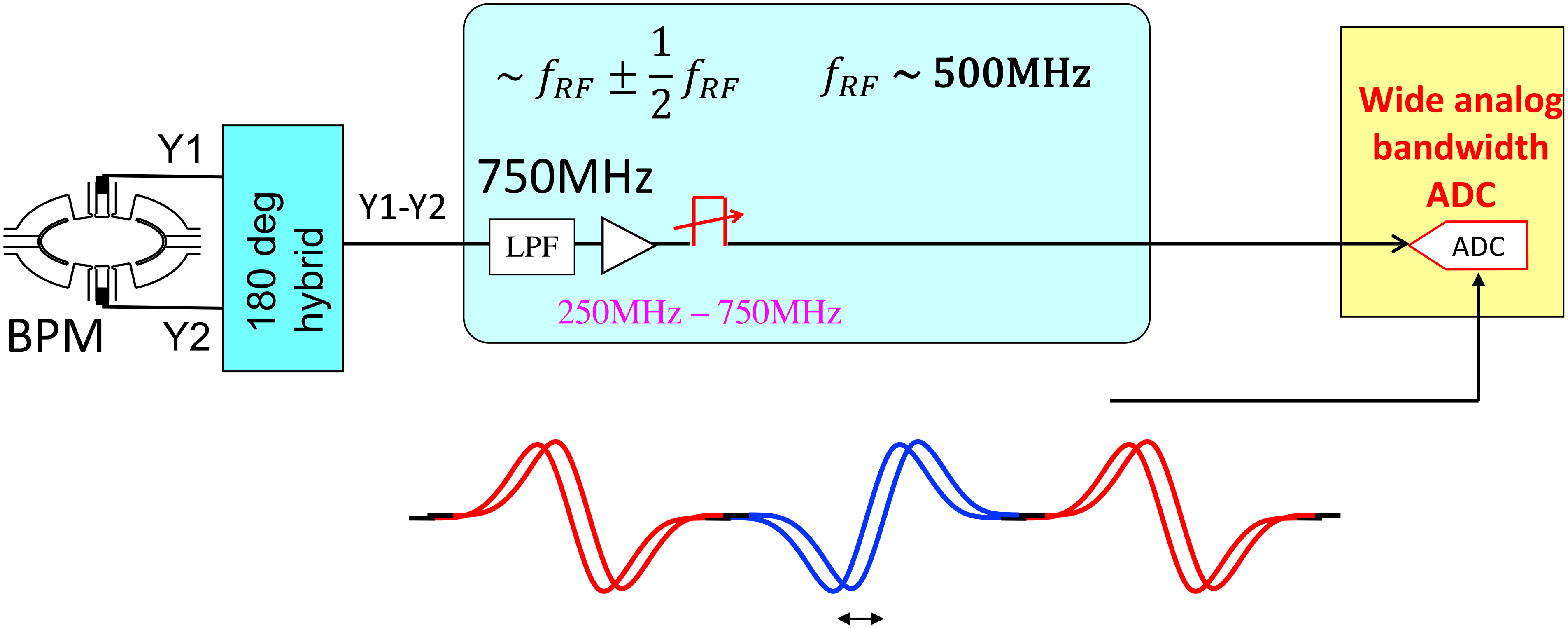
Timing Spread of Bunches
~ 100ps (SPring-8 case)

We choose Lowest Carrier frequency for BPM

$n \times f_{RF} = f_{RF}\ (n=1) \sim 500\text{MHz}$

for wider acceptance for timing

Low Carrier Frequency in Front-End



100ps spread (not jitter) is not big problem for 250-750MHz

Acknowledgement

D. Teytelman (Dimtel), M. Tobiyama (KEK), T. Obina (KEK), A. Drago (INFN),
for their offering the information of their interesting work.
S. Rajesh (SOLEIL), R. Nagaoka(SOLEIL), Lee Jaeyu (PAL/PLS-II), Shin Seunghwan (PAL/PLS-II), Kim Dotae (PAL/PLS-II) for offering the information and for the collaboration for beam study and development of new feedback processor.
Colleagues at SPring-8 : K. Koayashi, T. Fujita, M. Masaki, H. Dewa, S. Sasaki, H. Ohkuma, N. Kumagai, M. Shoji, M. Ohishi, K. Tamura,
and
all feedback people for their exploring the interesting world

Many Reports from the world are presented in IPAC18. Don't miss.

Special thanks to

K. Kobayashi (JASRI), for his technical work for hardware development and FPGA programming
Tokyo Electron Device LTD, for their help for development of feedback processors

Information related to this talk is in http://acc-web.spring8.or.jp/~nakamura