Adaptive Feedforward Control of Closed Orbit Distortion Caused by Fast Helicity-Switching Undulators

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OUTLINE

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Introduction

- **Storage-ring-based light sources**

  Now essential platforms for photon sciences, including industrial purposes.

  Next-generation light sources:

  → Developments in progress around the world

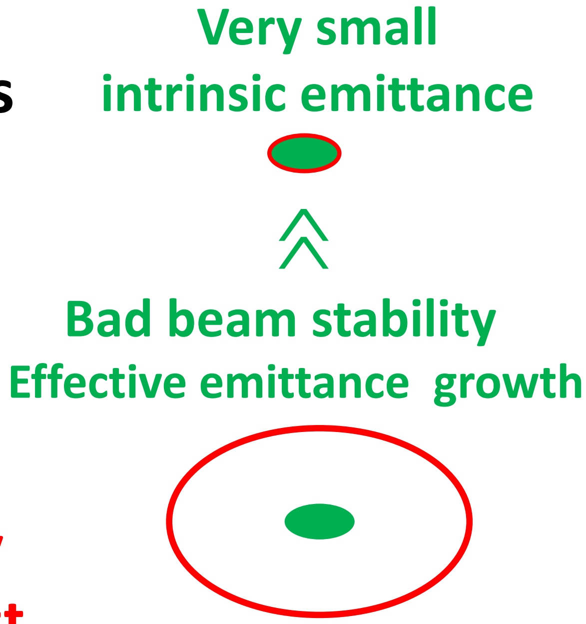
- **Important figures of merit for light source users**

  Brightness of light, Transverse coherence

High beam stability

→ To achieve the inherent light source performance, the pointing stability should be significantly smaller than the electron beam size.

The 4-th generation light source rings will essentially demand ultimate orbit stabilization. One of the most important issue is how to suppress orbit disturbances in a ring.



Very small intrinsic emittance

Bad beam stability

Effective emittance growth

➢ Error sources causing beam orbit disturbances in a storage ring

- Mechanical motions of magnets or vacuum chambers
  due to ground motion, cooling water, and so on.

- Electro-magnetic noises of magnet power supplies or RF sources

- Insertion devices (IDs)
  - Magnet pole gap or phase motions
  - Polarization switching kickers

➢ How to cure the orbit disturbances ?

- Feedback control
- Feedforward control
- Removal of error source itself

➢ For the case that error sources are unknown

- Global orbit feedback is effective

  Slow COD correction: 0 Hz ~ 1 Hz (typ.)

  Fast COD correction : 1 Hz ~ 1 kHz (typ.)

➢ For the case that error sources are known

- Remove the error sources

  An ideal solution, but may not be feasible for all error sources.

- Feedforward correction

  Feedforward counter kicks are located near the error source without removing the error source itself.

  e.g. ID gap motion, Fast switching undulator

- **Adaptive Feedforward Control (AFC)**

  If the error source conditions is slowly changing,
  Dynamically update the feedforward tables to meet the changes.

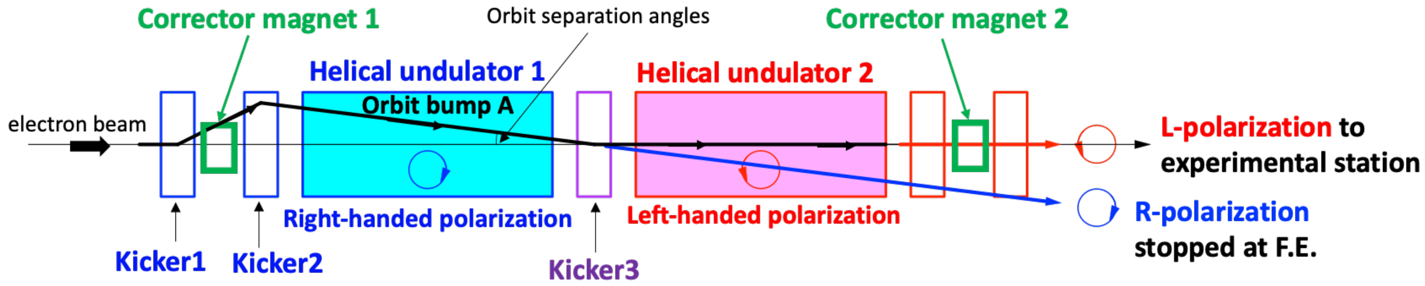
Helicity-switching undulators (ID23, ID25) of SPring-8

- Twin Helical Undulator system (THU)

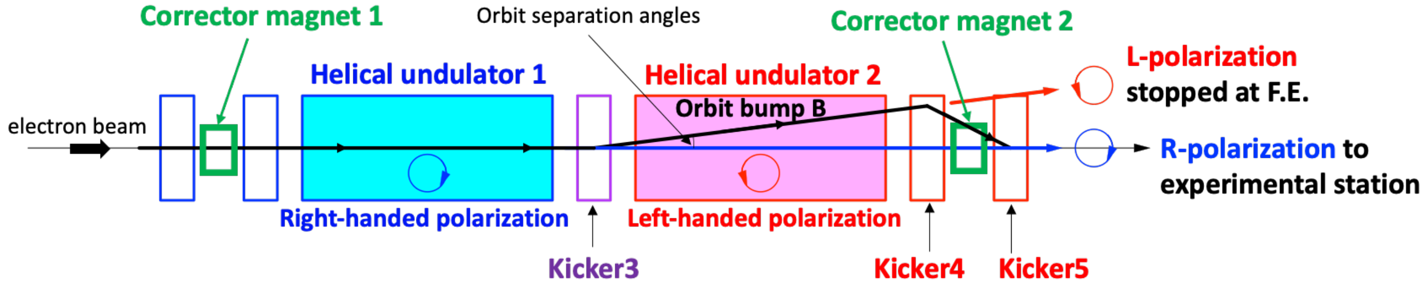
    Right- and left-handed polarizations from the undulators placed in tandem.
- Both polarizations are alternately switched by dynamical horizontal orbit bumps A and B.

    Repetition frequency of the switching : 1 Hz or 0.1 Hz

When switching to the orbit bump A, L-polarization light to experimental station.



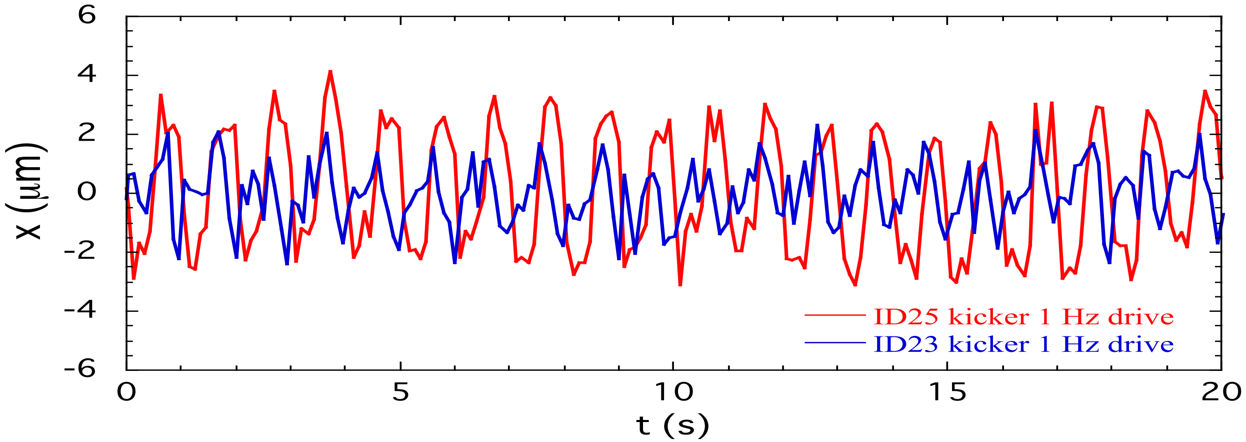
When switching to the orbit bump B, R-polarization light to experimental station.



However, the feedforward correction accuracy gradually degraded with time (typically a few weeks). → Deterioration rate is slow.

Periodic orbit variation (typically several microns) synchronized with the kicker excitation was observed, including fast frequency of several tens of Hz.

→ Detrimental to user experiments



- The cause of the deterioration remains unclear.
- The feedforward tables used to be updated a few times a year during accelerator beam tuning time, not be done timely during user time.
- **This led to the need for a new correction system (AFC).**

Adaptive Feedforward Control (AFC)

Our goal for orbit stabilization is to keep the COD fluctuation below 1 μm (RMS) even during the helicity switching.

➢ Key points of the AFC

1) Automatic table updating without stopping the helicity switching.
2) High-precision and efficient extraction of the only error kicks coming from the switching undulators.
3) Even if simultaneous switching of the two THUs, ID23 and ID25, well-resolving each counter kick.
4) Resistant to orbit perturbations due to error sources other than the THUs.

➢ Correction scheme

Characteristics of the COD variations due to the switching kicker

- Periodic variation with the switching repetition frequency of 1 Hz or 0.1 Hz.
- Containing fast components up to several tens of Hz.
  But, sufficiently slow compared with radiation damping time of ms-order.
- Superposition of instantaneous CODs caused by time-dependent multiple error kicks.

Time-dependent orbit displacements at BPMs

$$x_{BPM,i}(t) = \sum_{j=1}^{n} R_{ij}\theta_{error,j}(t)$$

$\theta_{error,\,j}$: Error kicks (j = 1, 2, , , n)
$x_{BPM,\,i}$: Beam displacement at BPMs (i = 1, 2, , , m)

Response matrix elements between the error sources and BPMs

$$R_{ij} \equiv \frac{\sqrt{\beta_i\beta_j}}{2\sin(\pi\nu)}\cos\left(\pi\nu - \left|\mu_i - \mu_j\right|\right)$$

β : betatron function at BPMs, error kicks
ν : betatron tune
$\mu_i - \mu_j$: betatron phase advance between BPMs and error kicks

Fast feedforward correctors placed near the error sources

$$-x_{BPM,i}(t) \sim \sum_{j=1}^{n} R_{ij}\theta_{corr,j}(t)$$

Number of BPMs (m) ≧ Number of correctors (n)

The counter kicks $\theta_{corr,\,j}$ at the correctors are solved with **SVD method.**

In case of SPring-8,

- 2 correctors for each switching undulator (ID23 or ID25)
- 4 BPMs to detect the horizontal COD perturbations

The four horizontal counter kicks have to be well-resolved, even while ID23 and ID25 are switching at the same frequency.

→ The placement (selection) of the BPMs and their noise reduction are important.

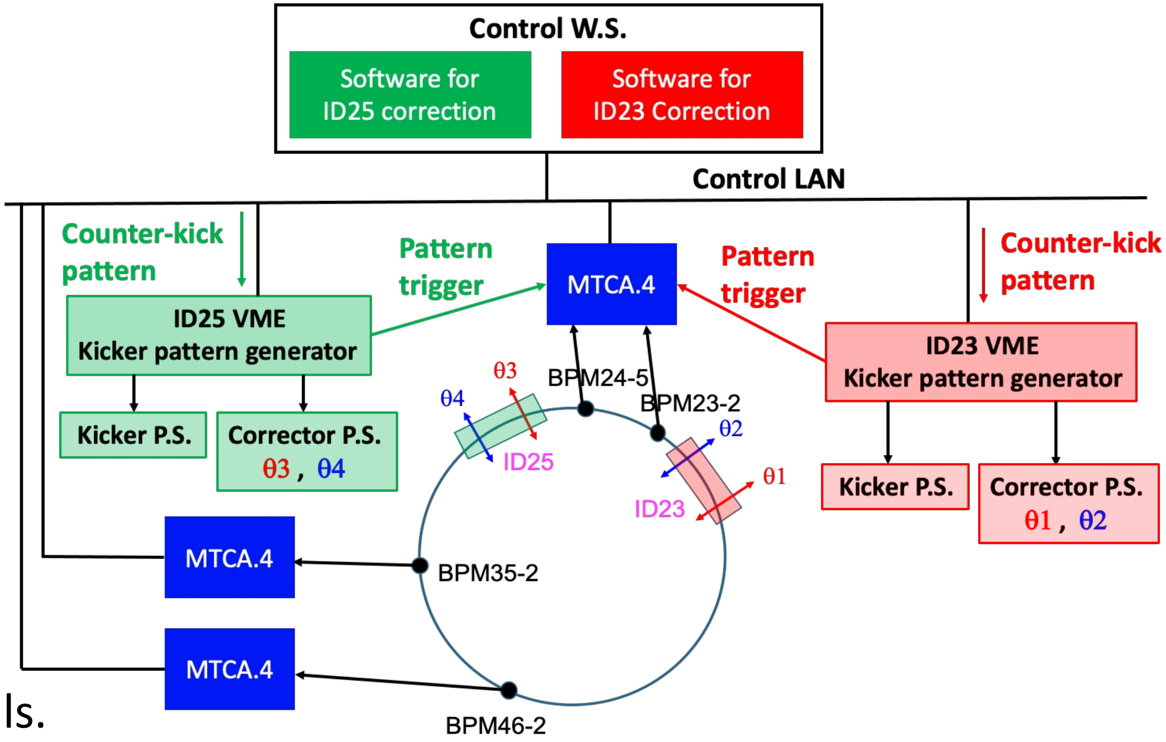
Measured 4-by-4 horizontal response matrix

R_{ij} (m/rad)	ID23 Upstream (θ_1)	ID23 Downstream (θ_2)	ID25 Upstream (θ_3)	ID25 Downstream (θ_4)
BPM23-2 (x_1)	**+26.4**	**+25.6**	-3.07	+1.05
BPM24-5 (x_2)	+0.623	-3.29	**+25.6**	**+25.8**
BPM35-2 (x_3)	-2.08	+1.66	**-22.8**	**-20.2**
BPM46-2 (x_4)	**-18.2**	**-20.9**	+6.69	+2.71

Selected 4-BPMs sensitive to horizontal kicks at the THUs.

BPM23-2 and 46-2 sensitive to kicks at ID23
BPM24-5 and 35-2 sensitive to kicks at ID25

➢ System Overview



Fast feedforward correctors:

- Air core coils at both ends of each of the two THUs.

Fast BPMs :

- MTCA.4 based readout circuit with 10 kHz sampling rate (FA mode)

VME system:

- Generate the kicker and corrector patterns along with the trigger signals.

Synchronization of the BPMs with kicker driving:

- Two kicker trigger signals are fed to a MTCA.4 digitizer board.
- Synchronization by marking with their common time-stamps shared on the control network.

New correction patterns:

- Adding counter patterns obtained from the BPM data to the previous pattern.

➢ Counter kick calculation, Experimental verifications

To achieve orbit correction accuracy of less than 1 μm (rms),
Counter-kick errors of the fast correctors need to be within 0.05 μrad (rms).

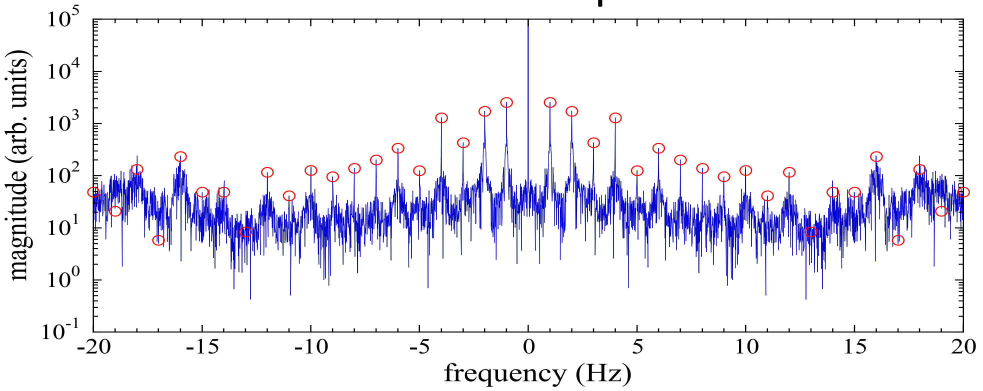
Keys of BPM data processing:

- **Random noise reduction to secure sub-micron resolution**
- **Filtering to eliminate contamination due to error kicks other than THUs**

Low-noise extraction of the periodic COD variation

1. Data accumulation for several tens of periods
2. Folding process in the frequency domain
   - Pick up peaks at the repetition frequency and its harmonics in the FFT spectrum
3. Transform to time domain pattern by an inverse FFT using the only picked-up peaks

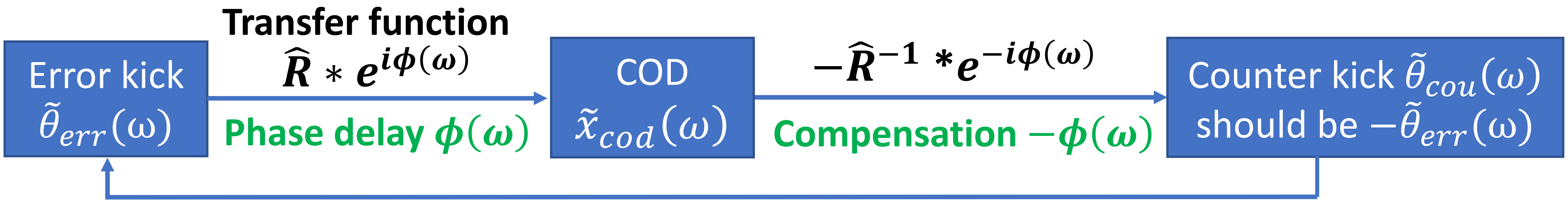
FFT spectrum of a raw BPM data for 60 periods on 1 Hz switching



Compensation for time response of the AFC system

To accurately counteract error sources, it is important to compensate the time response (Phase delay) of the AFC correction loop itself.

< Correction loop in the frequency domain >



Error kick $\tilde{\theta}_{err}(\omega)$

Transfer function $\boldsymbol{\hat{R} * e^{i\phi(\omega)}}$

Phase delay $\boldsymbol{\phi(\omega)}$

COD $\tilde{x}_{cod}(\omega)$

$\boldsymbol{-\hat{R}^{-1} * e^{-i\phi(\omega)}}$

Compensation $\boldsymbol{-\phi(\omega)}$

Counter kick $\tilde{\theta}_{cou}(\omega)$ should be $-\tilde{\theta}_{err}(\omega)$

If the phase delay compensation is not adequate, the error kick are not reliably counteracted. In the worst case, it even builds up !!

Phase delay measurement of the AFC system and its compensation

1. Step response measurement of the BPMs by exciting the correctors with a step function.
2. By analyzing the step response in the frequency domain, the phase delay $\phi(\omega)$ obtained.
3. Compensate the phase delay in advance, on the filtering process of the BPM data in the frequency domain.

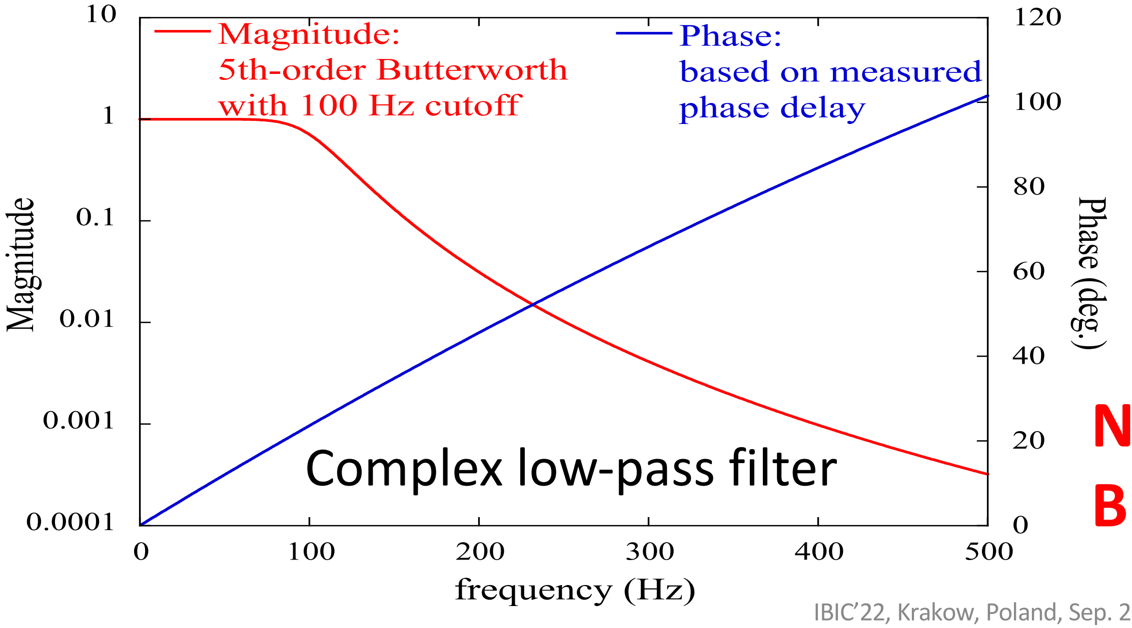
Complex low-pass filtering for the FFT spectrum of BPM data

1. Filter phase function to compensate the time response of AFC system

- An opposite sign of the measured phase delay

2. Filter magnitude to cut-off high frequency noise

- 5th-order Butterworth filter with 100 Hz cutoff for 1 Hz switching
- For 0.1 Hz switching, 30 Hz cutoff



Noise level of the processed BPM data reaches 0.2 μm (rms).

• Case of ID23 and ID25 simultaneously switching

Solving the counter kicks with SVD method

Singular values and RMS CODs of each mode in a random kick of 0.1 μrad (rms) at each corrector

Mode #	Singular Values	COD (μm) Kick at ID23-U	COD (μm) Kick at ID23-D	COD (μm) Kick at ID25-U	COD (μm) Kick at ID25-D
1	50.4	0.94	1.2	3.9	1.3
2	43.7	1.3	1.2	0.84	1.0
3	1.89	0.05	0.04	0.05	0.06
4	1.22	0.03	0.04	0.03	0.02

Modes #1 and #2 are main components, apparently need to be corrected.
Modes #3 and #4 have significantly smaller contributions.

Corrected modes		Counter kick errors from the BPM noise
Only main modes (#1 and #2)	:	Inappropriate solution → NG
All four modes (#1 to #4)	:	0.1 μrad (rms) → NG
Three modes (#1 to #3)	**:**	**0.05 μrad (rms) → OK**

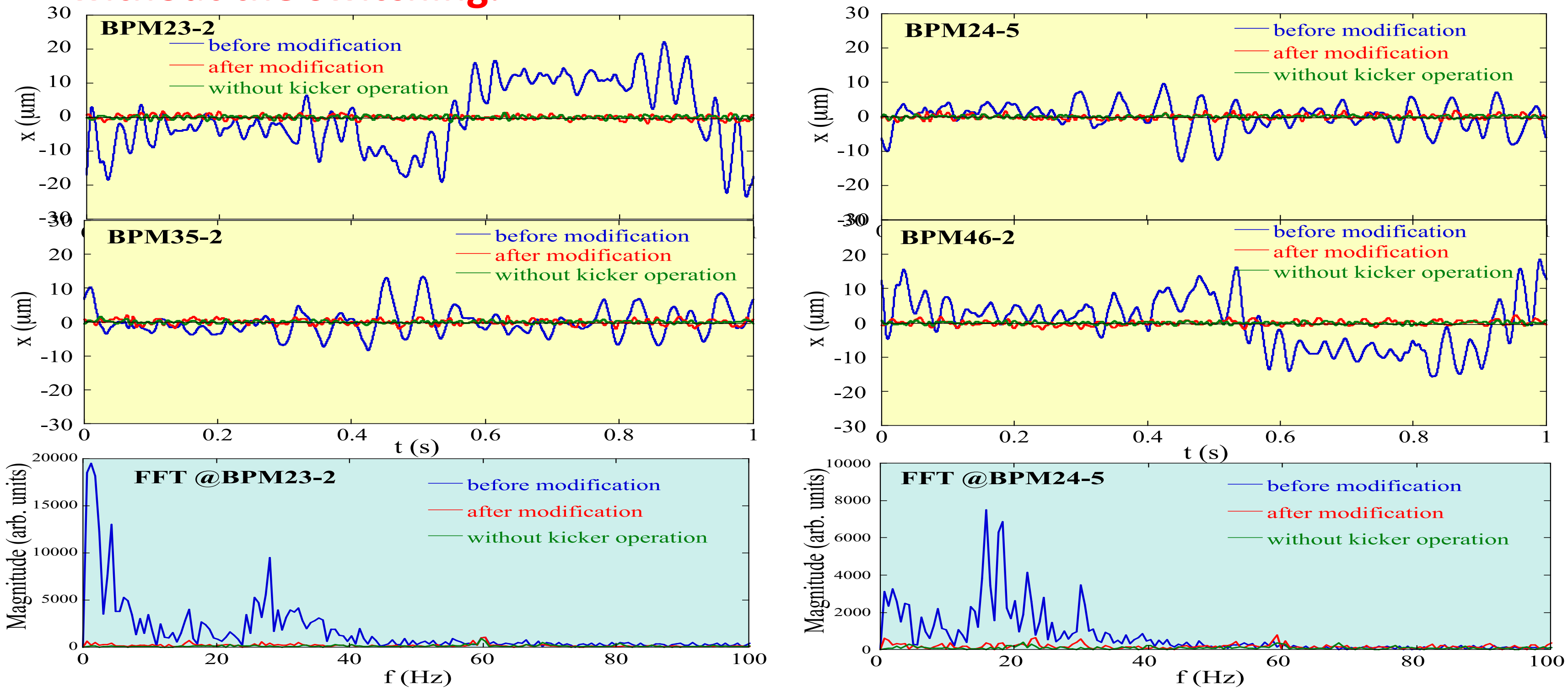
The 4-mode case dose not satisfy the target counter kick accuracy.

Adopt the counter kick calculation using the 3 modes, discarding mode #4.

Experimental verification of simultaneous 1 Hz switching of ID23 and ID25

Example of horizontal orbit fluctuation observed at the 4-BPMs

- Before applying the AFC, Orbit displacement : 20 ~ 40 μm (p.p)
  Frequency range : several tens of Hz
- **After applying the AFC, the orbit fluctuation is drastically damped to the same level without the switching.**



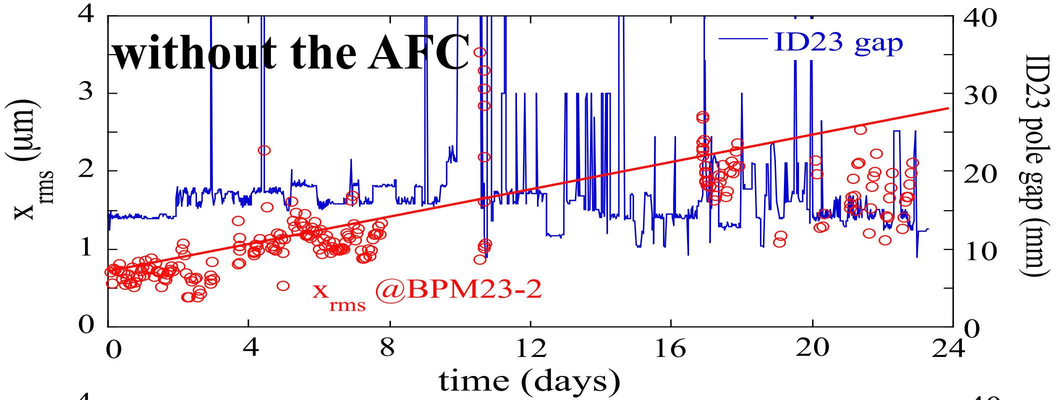
• Long-term performance

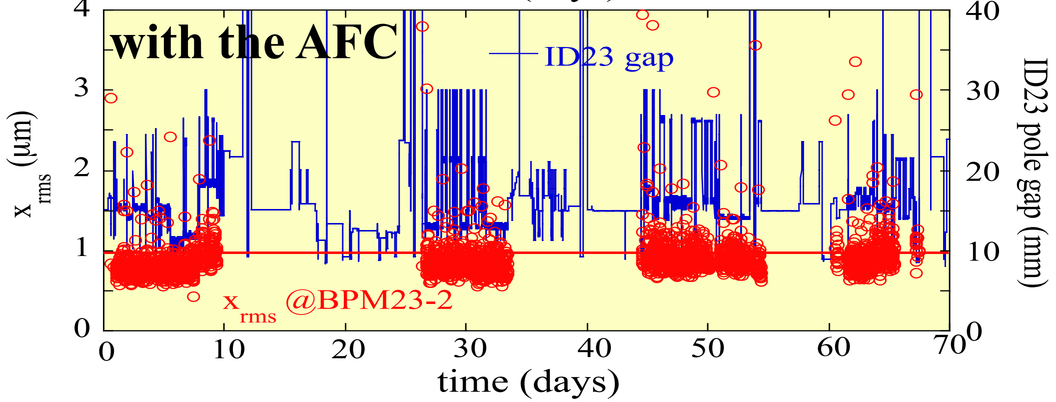
Example of ID23 1Hz solo switching during user time operation

RMS of horizontal orbit fluctuation observed at BPM23-2 sensitive to ID23 switching

Without the AFC : Gradually growth at a rate of typically 80 nm/day

With the continuous AFC : **Successfully suppressed within 1 μm RMS over the long term**





Why did not choose fast global orbit feedback (FOFB)

➢ Potential risk of FOFB

FOFB is based on global correction scheme for fast orbit variations.

Characteristics of global correction

- No need to identify the error sources.
- However, the correction accuracy is limited by the number and placement of BPMs and correctors.
- **Potential risk of unwanted orbit distortions around the error sources.**
- Because the correctors are not always placed near the error sources.

Simulation assuming the SPring-8 storage ring

Corrector number dependence of global correction accuracy

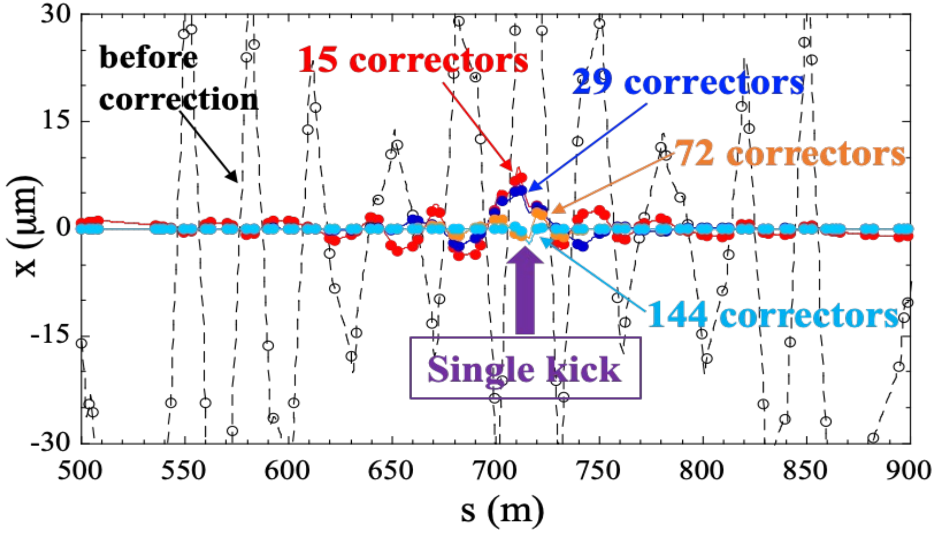
Assumed simulation condition

Error source : Horizontal single kick of +1 μrad at s=716.05 m @around ID25 center

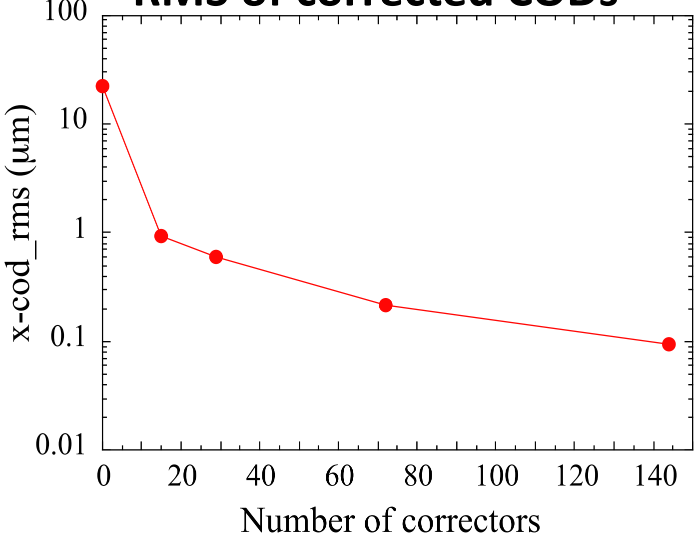
Number of correctors : 15, 29, 72, 144 correctors with equal spacing

Number of BPMs : 286 BPMs (all BPMs of the ring)

Corrected CODs



RMS of corrected CODs



Small number of correctors results in unwanted local orbit bump around the error kick.

Only the case of 144 correctors shows that such the local bump does not almost appear.

Conclusion

➢ A new COD correction technique with the **A**daptive **F**eedforward **C**ontrol

- The development and verification have been successfully done at SPring-8.

- The AFC works well for suppressing fast periodic orbit fluctuations during operation of helicity-switching undulators with kickers.

- It keeps the COD fluctuation suppressed with sub-micron order for long times.

➢ Toward ultimate photon beam stability for next-generation light sources

- Relying solely on **Global Correction Scheme**, including FOFB, is not sufficient.

- When the error source is known, for example, such as an insertion device, a **Source Suppression Scheme** such as the AFC can be very effective.

- Both schemes in a complementary relationship are indispensable to achieve the ultimate pointing stability of photon beam.

Thank you for your attention