The fast kicker correction system for transparent top-up injection at SPring-8

SPring-8/**JA**pan **S**ynchrotron Radiation **R**esearch **I**nstitute (JASRI)
Light Source Division,
Accelerator Group, Magnet team
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Outline

- Introduction of SPring-8 bump system and its history
- Motivation to introduce the FCK system
- Fast correction kicker system (FCK)
  - System Development History
  - Performance
- Suppression of residual oscillation by FCK
  - Beam oscillation results
  - Efficiency for light axis stability
- Current status and remaining issues
- Summary

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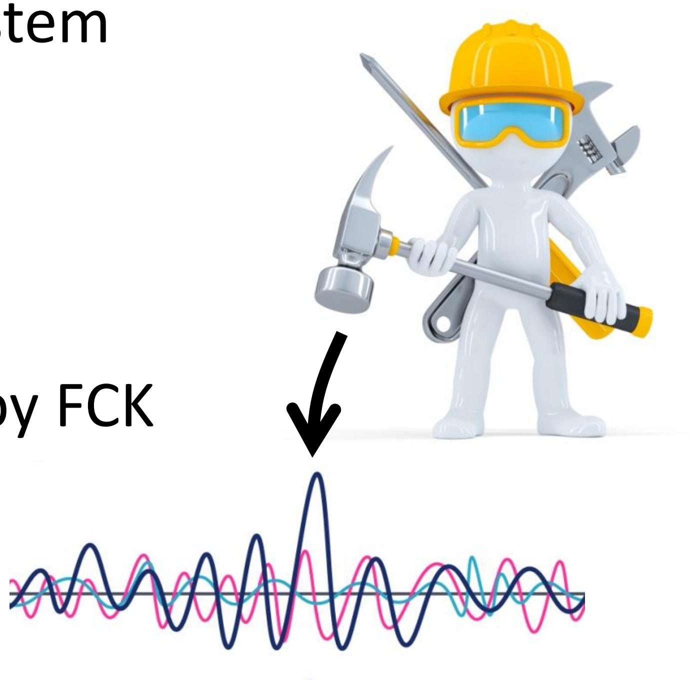

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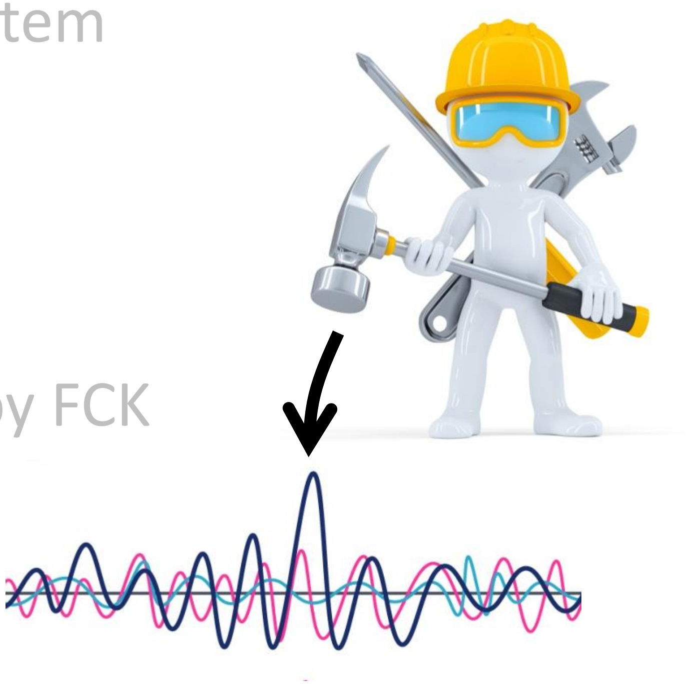
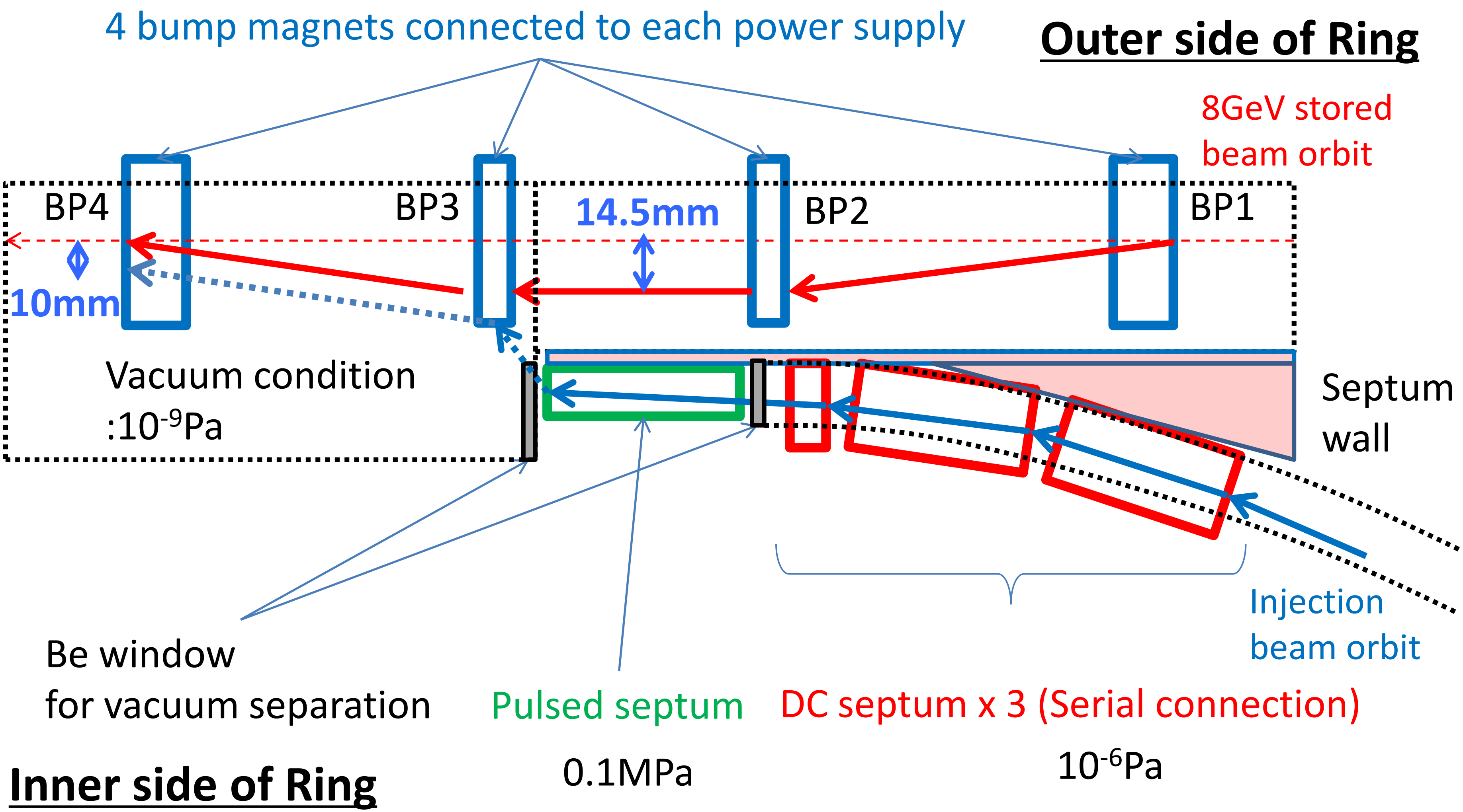


Top-view of beam injection system in SPring-8

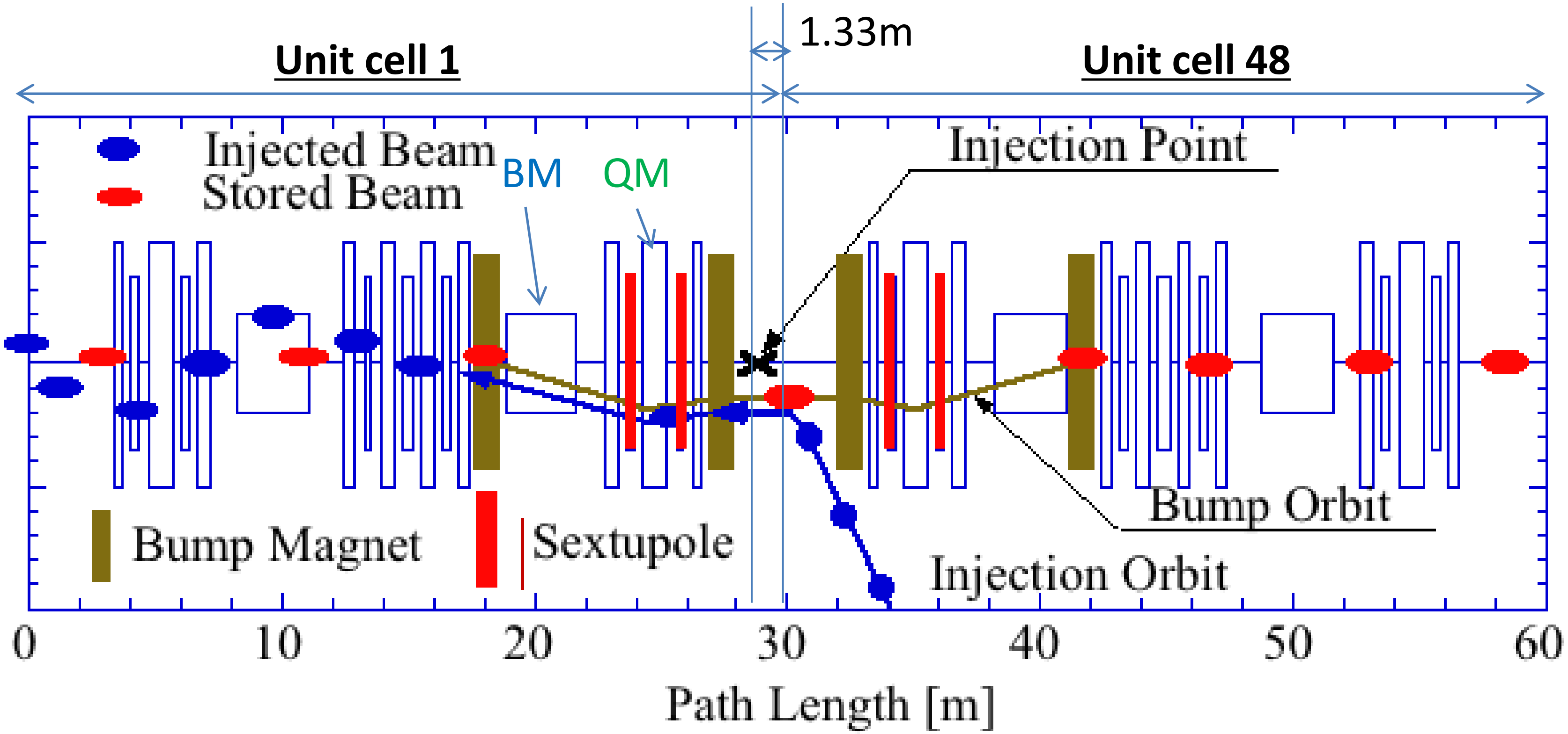


Injection magnet parameters

Magnet	Length (m)	Gap (mm)	Coil turn #	Rated Curr. (ope.)	Field (T)	Ope. Kick angle (mrad)
DC septum 5,6	1.09	17	8	2460A/40V (2209A)	1.29	46.35
DC septum 7	0.50	15	4	2460A/40V (2209A)	0.73	12.03
Pulsed septum(*)	1.20	8	1 turn/6.2μH	4.0kA/4.5kV/45μs (2.2kV)	0.59	23.40
Bump1,4(*)	0.32	56	1 turn/5.5μH	6.2kA/26kV/8.4μs (14.7, 14.1kV)	0.202	2.17(BP1) 2.24(BP4)
Bump2,3(*)	0.17	56	1 turn/4.0μH	5.6kA/15kV/8.4μs (10.5,7.5kV)	0.112	0.86(BP2) 0.60(BP3)

*Pulsed current shapes are half-sine wave function, βx=5.1m @ bump magnets

Overview of 4 bump magnets arrangement



- 4 bump magnets are arranged in normal straight section, the total distance of 24 m.
- Irregularly, to keep the high symmetry structure of the ring optics, non-linear optical magnets of sextupole exists between the bump orbit.
- Ring optics, for example, COD, betatron-tune, dynamic-aperture have an effect to the closing condition of bump orbit.

Historical improvement before top-up operation

- Top-up operation in SPring-8 started in 2004.
- Before top-up operation, the sources of stored beam oscillation were improved. The major sources were estimated as followings at that time.
- **95% of stored beam oscillation amplitude was caused by bump effect.**

Horizontal

Dominant source

- ☐ The **non-similarity** of 4 bumps shape around the bump standing and falling point.
- ☐ The **non-linearity effect** by S-magnets between the bump magnets.
- ☐ The leakage fields from septum magnets, charging current of bump PS, eddy current induced at the vacuum chamber.

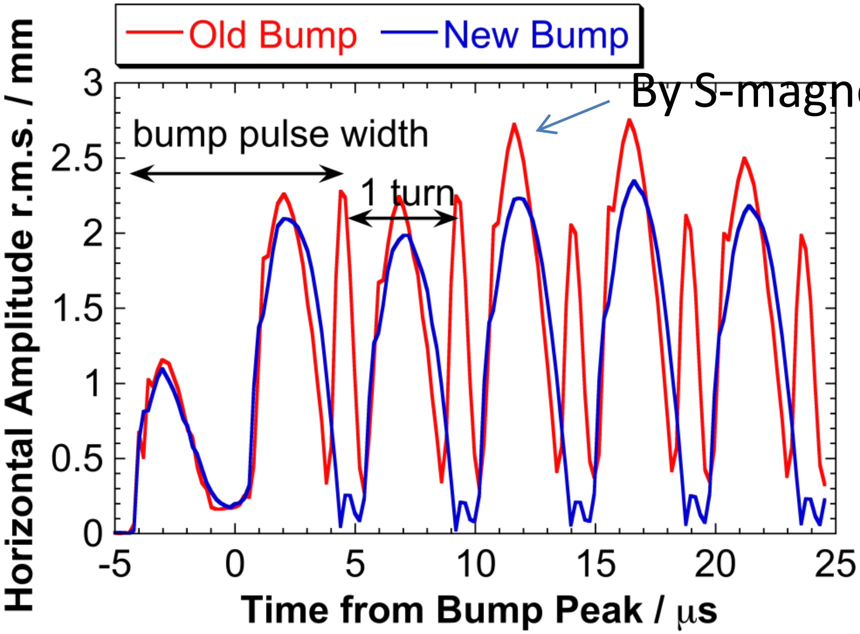
Vertical

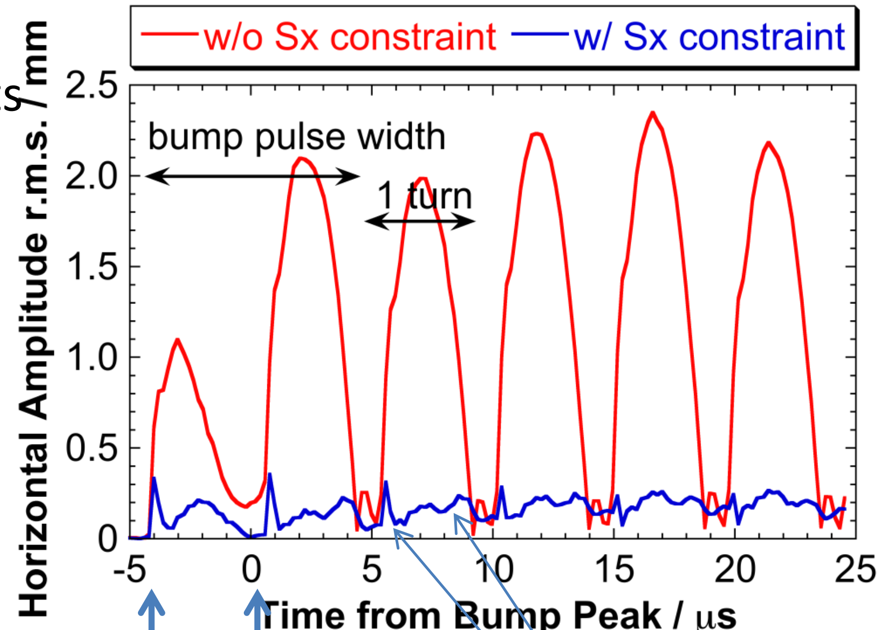
- ☐ The bump magnets tilt.
- ☐ The beam tilt by coupling effect by the magnet field errors along the storage ring. The horizontal kick couples the vertical kick.

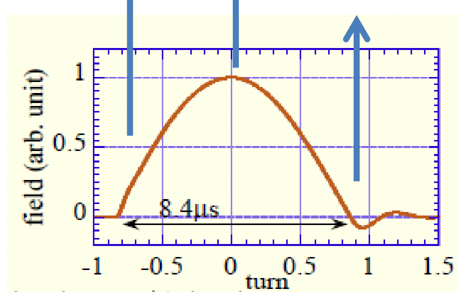
Oscillation reduction after improvement

T. Ohshima, et al., proc. of EPAC'04, Lucerne, Switzerland,(2004), p. 414

W/ bump magnet improvement (involve DC Septum improvements) → **W/ bump magnet improvement +Sx-magnet strength ratio optimization**





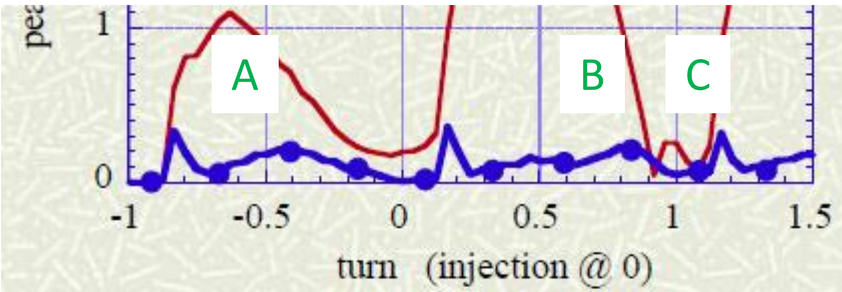


Residual oscillation of 0.3 mm (r.m.s.) in average.

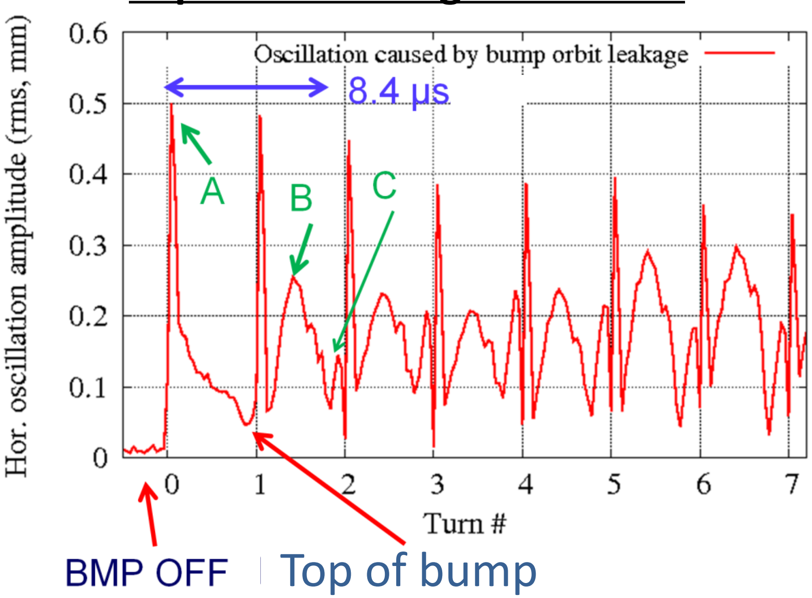
- Oscillation amplitude changes in 2004
  - •Bump : 2.4mm→0.3mm -87% red.
  - •Sx-magnet:2mm→0.2mm -90% red.

Still remaining residual oscillation

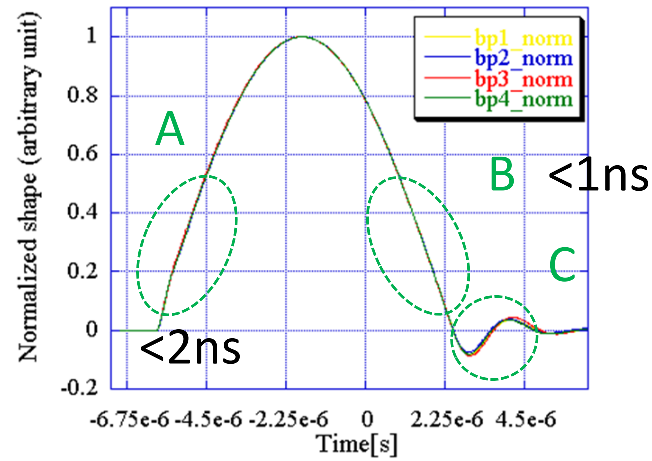
After many improvements in 2004



Expanded the figure in 2008



Residual oscillation is caused by non-similarity of field shape in each part



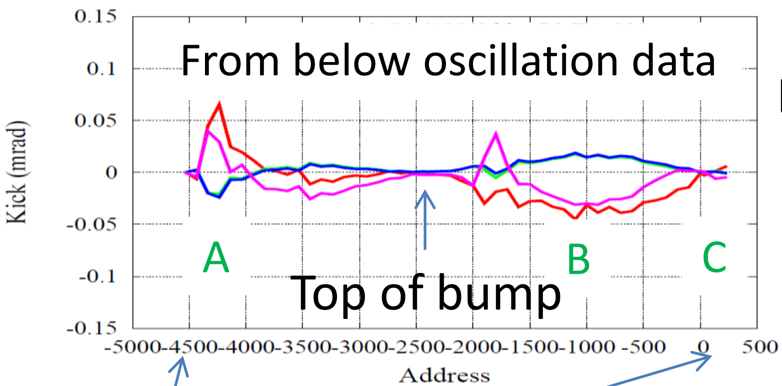
The pulse width were adjusted within 2ns.

But… The small difference are remaining.

Part of shape	Oscil. Amp.	Error kick
A	0.5mm	0.075 mrad
B	0.25 mm	0.05 mrad
C	0.15 mm	0.025 mrad

Still remaining residual oscillation

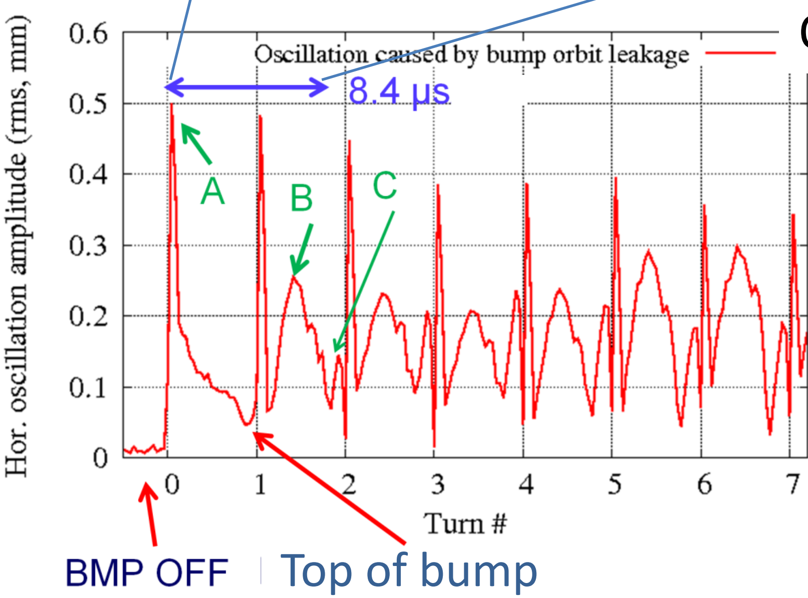
Calculated error kick angle of bumps



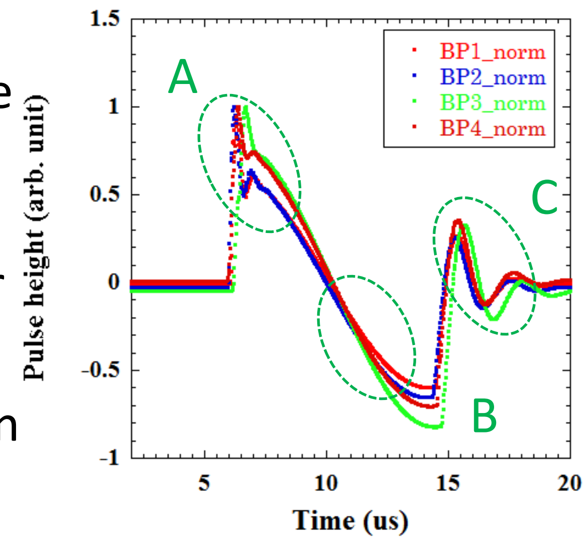
Difference

Kick Error

Oscillation



Field differential shape measured by pick-up coil



Actually, there are small differences in magnetic field. These differences cause errors.

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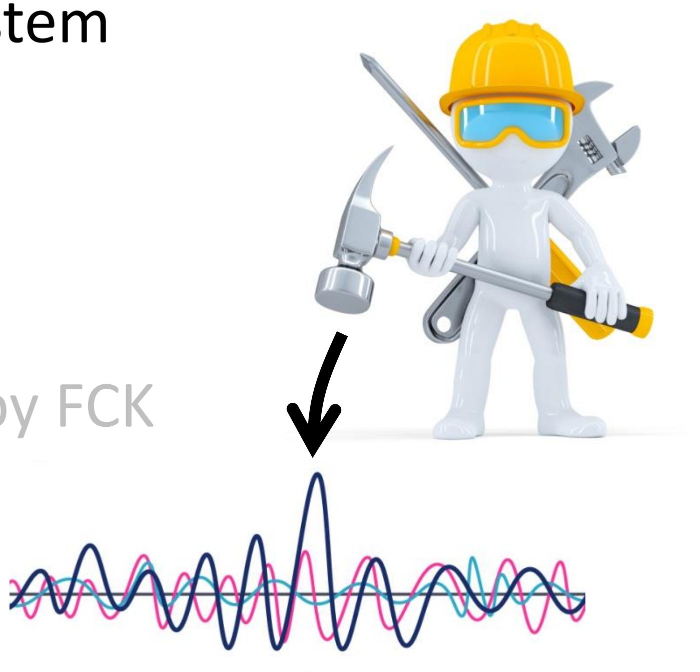
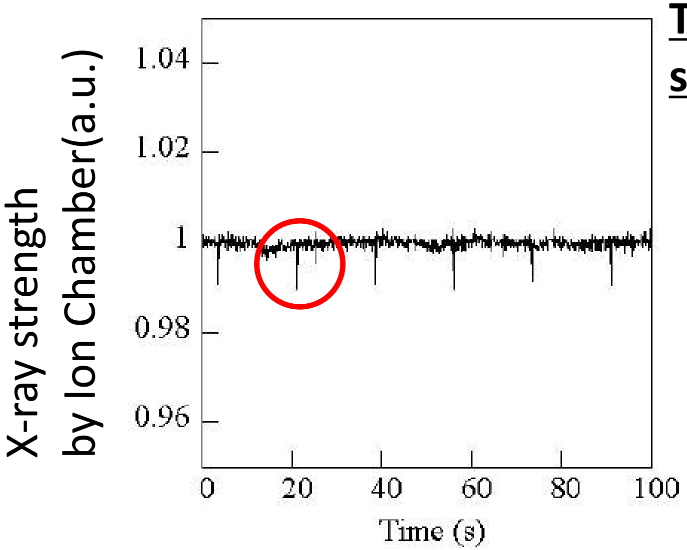


Impacts to user experiments by residual oscillation

- **Time-integrated experiment**. Need mask for oscillation dumping time (~10ms).
- **XPC and µSAXS experiment**. Need X-ray axis stability. Aiming stability is <0.2% ~ stored beam current stability of 0.1%.
- **High current single bunch filling**. Take care of filling location of high current single bunch as the bunch has no large oscillation amplitude.

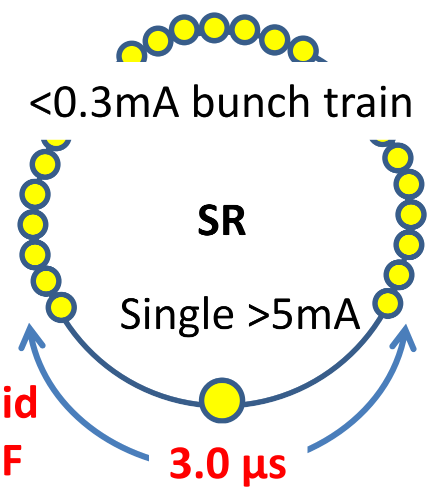


Time dependency of X-ray strength @ BL03

X-ray strength changing at top-up injection(1%)

Hybrid filling mode with high current single bunch

Need a large space to avoid the oscillation part for BBF



To-do list to aim at more reduction

- Reducing the residual oscillation by precise bump parameter tuning
  - More precise pulse width adjustment for 4 bumps. **Adjusted within 2ns and 1ns in rising and falling part respectively.**
  - 4 bumps power supply system. 4 knobs of kick angle x 4 knobs of kick fire timing.
  - Precise tuning of kick angle and kick timing to reduce the error kick and oscillation amplitude. **Tuned with 0.01 mrad and 10ns precision.**

- We had done all efforts for bump. But, we couldn't achieve enough.
- **We decided to introduce the feed-forward Fast Correction (or Counter) Kickers as a final solution**.
  - Applying each FCK to each oscillation part
  - Applying precise FCK tuning of kick timing and kick angle

FCK's complementary works to BBF

- **FCK system was expected the complementary work to the bunch-by-bunch feedback (BBF) system.**
- BBF system needs a feed-back time to give kicks (~40 turns).
- It is difficult simultaneously to suppress both the high current bunch oscillation with large amplitude and low current bunch oscillation by BBF system at that time. For example, high current > 5mA and large oscillation >0.3mm.
- Thus, it is most helpful for FCK system to suppress the large oscillation as fast as possible.
- Feed-forward scheme of FCK is good solution to the reduction of known oscillation source.

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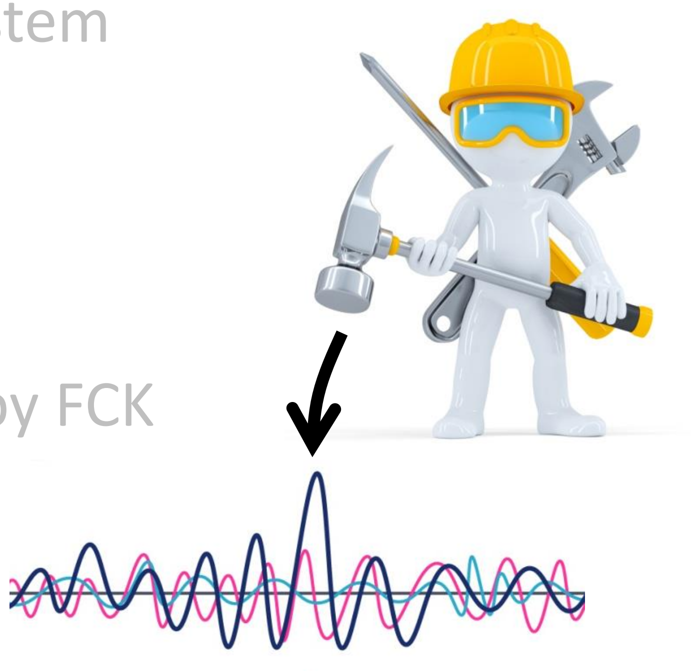
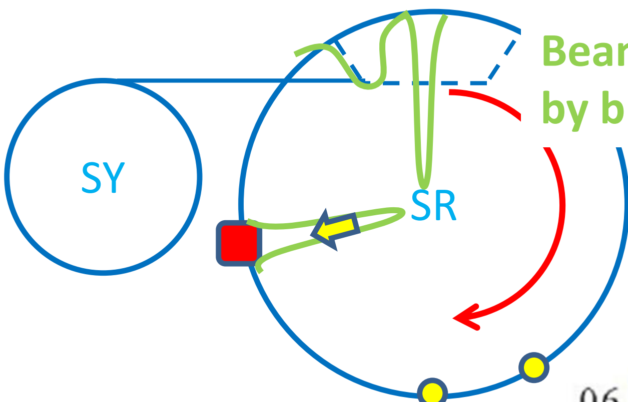


Fast Correction (or Counter) Kicker (FCK) system

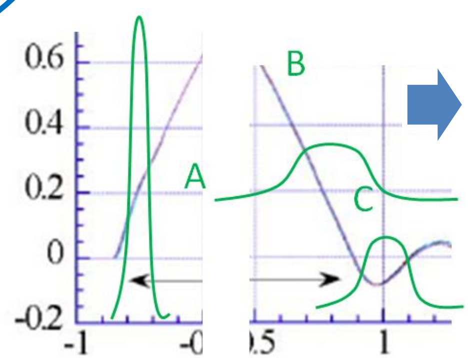
- Bump height and fire timing adjustment of 4 bumps are controlled within 0.01mrad and within 10 ns corresponding to kick angle of 0.01 mrad.
- However, error kicks are not reduced in the bump orbit. Further enhancing the similarity of magnetic field shapes of 4 bumps is difficult.

FCK system was introduced as final suppression way



Beam oscillation occurred by bump error kick

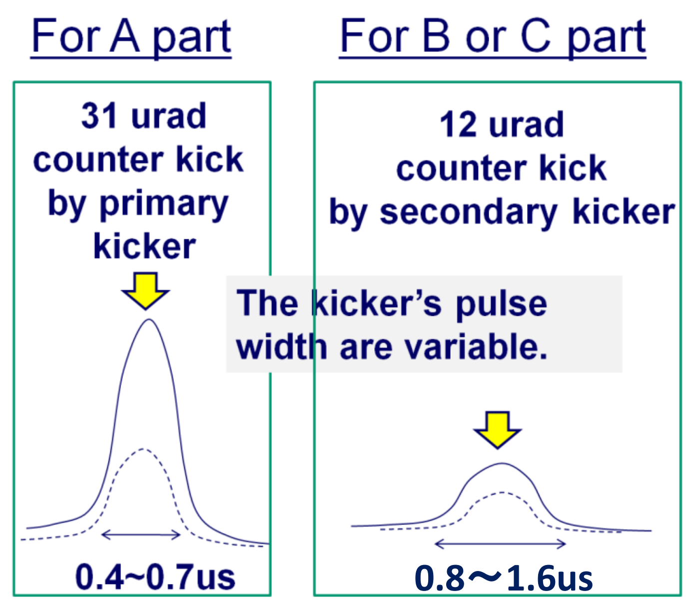
Expected the oscillation shape



FCK put at max. hor. β place.

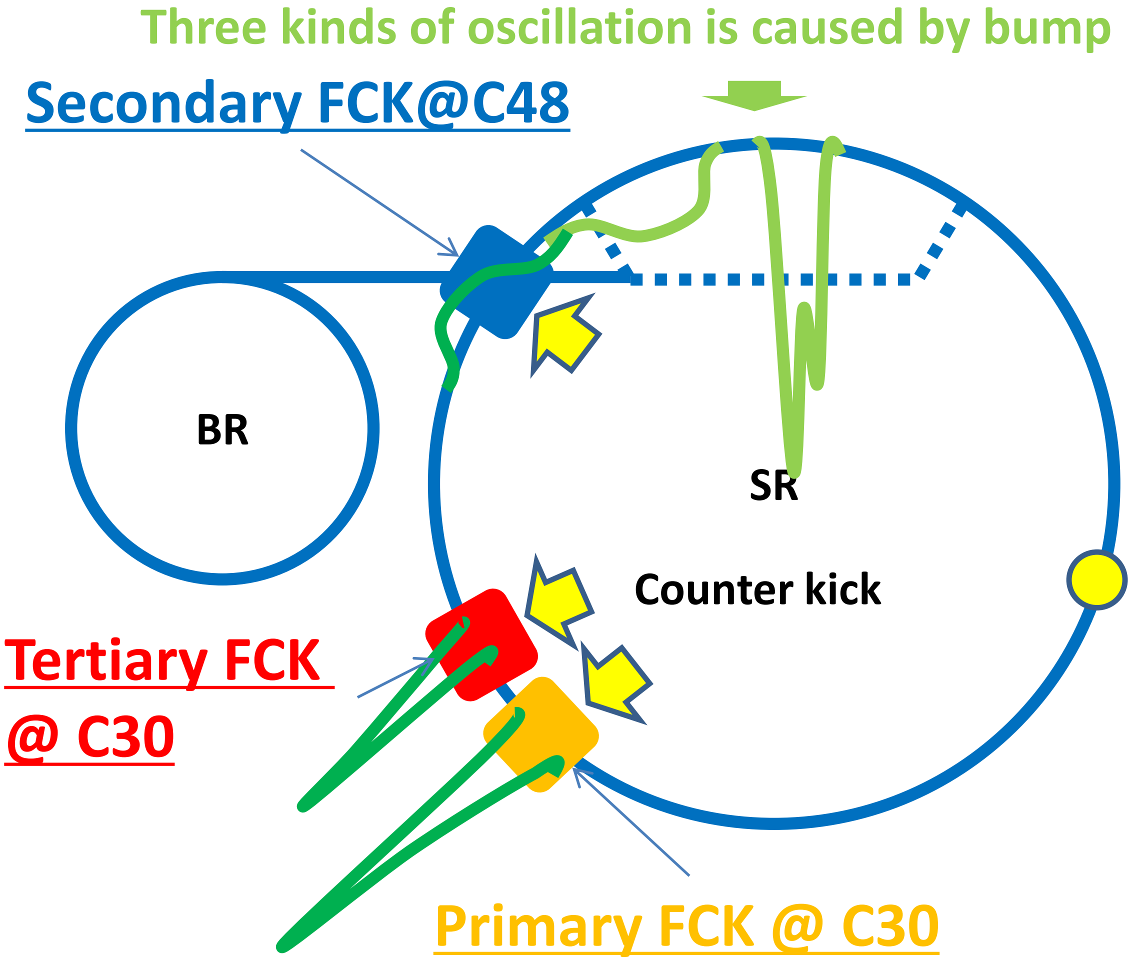
Horizontal tune is νx=40.15, correction can be done within 7 turns.

Solution: giving counter kicks



Installation history and current FCK's operation

- Basic system development had been done from 2008 to 2010.
- Primary kicker system was installed **in 2010.**
- BBF upgrade in 2010 to reduce the ξy = 6→2.
- The operation of high current single bunch of 5mA was started in 2012.
- Low emittance optics of 3.4 →2.4 nmrad was started **in 2013**. 2nd FCK system started.
- 3rd FCK systems operation was started **in 2016.**



Requirements for kicker

Requirements from current ring condition

- In the SPring-8 storage ring, there is no large space to install the FCK system. The another machine components are arranged closely.
- The remaining space to put FCK **is 0.3 m**.
- FCK system must be put at maximum β-place to achieve higher kick efficiency. **There is space limitation**.

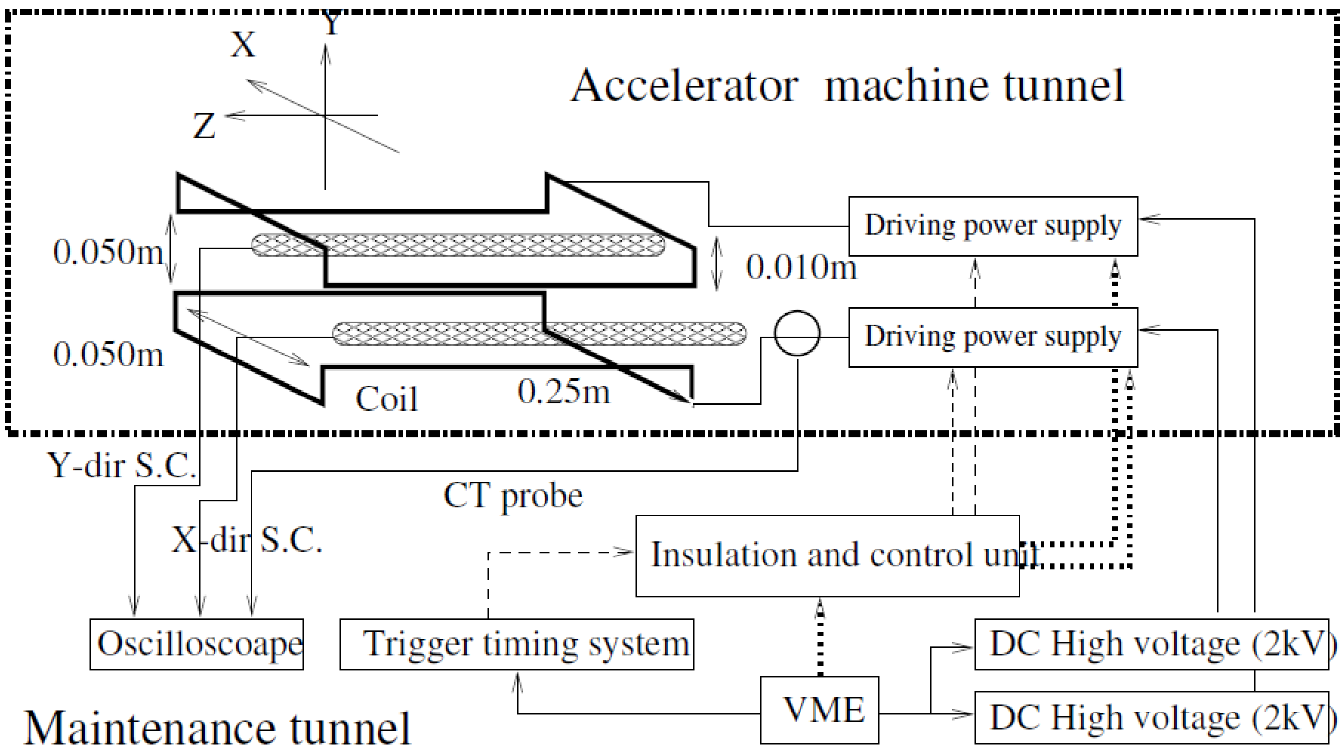
Necessary key points for kicker

- Need a setting flexibility which FCK system can be put anywhere.
- Need large magnetic field even by short magnet length.
- Need fast rising time of magnetic field to match fast oscillation width.
- To reduce the inductance then realize both the fast rising time and large output, the power supply must be put near the kicker magnet.
- Power supply and magnet must be compact as much as possible.

Development item in FCK system and the difficulty

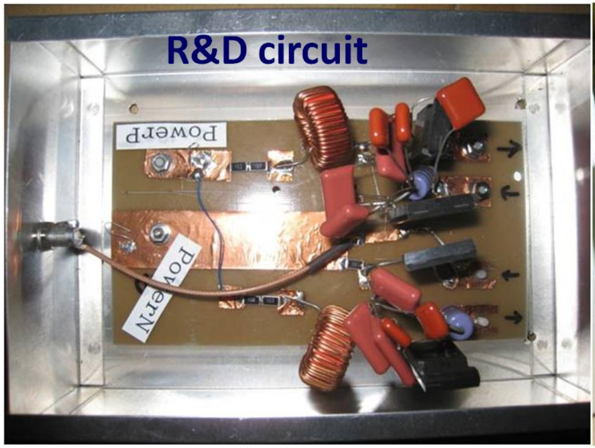
- **Aiming at its compactness**
  - Apply separate function type. DC circuit part and pulsed circuit (driving circuit) part are separated.
  - Use the solid-state switching device.
- **Aiming at fast rising time**
  - 2 turn air-core magnet is applied. Feeder line was improved.
  - Driving circuit is put near to the kicker and is connected each 1 turn coil.
- **Realizing both larger magnetic field and fast rising time**
  - Need the higher voltage output. Need to multi-stack the solid-state switching devices. Need the driving techniques of them simultaneously.
- **Caring for radiation and noise protection**
  - Protect the driving circuit from synchrotron radiation.
  - Protect the circuit from the beam radiation noise and switching noise by itself.

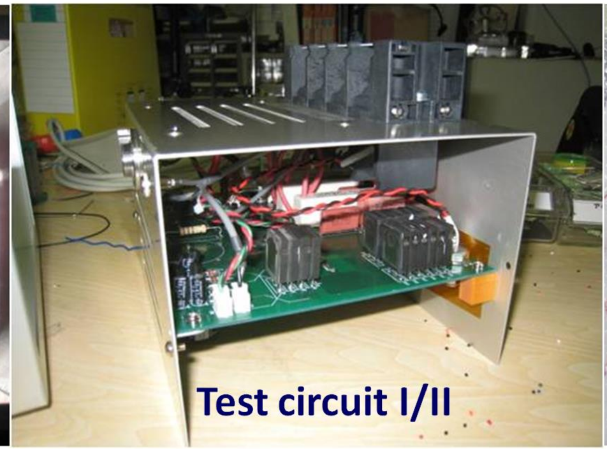
Concept design of FCK system



- Kicker: 2 turn air core magnet (total inductance is 0.7μH involving feeder line for each coil. Magnet length is 0.25m.) Each coil is connected to each driving power supply.
- Power supply: Driving circuit is put near to the kicker within the distance of 1m .

Development of pulsed power supply



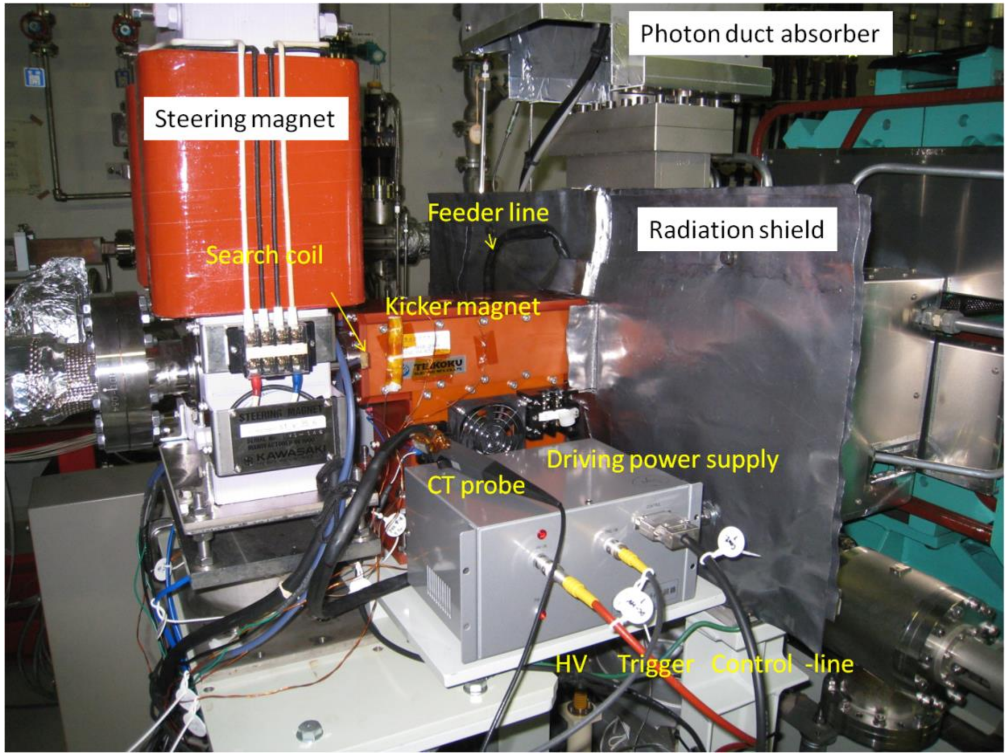


Circuit type (FY)	R&D (2007)	Test-I (2008)	Test-II (2009)	Development (2010)
Current(A/coil/V)	**67/400**	141,397/500	187,260/850	270,555,740/950
Pulse width(us)	**1.1**	1.2,2.5	0.8,1.2	0.8,1.8,2.4
Repetition(Hz)	1	1	10	150
# of MOSFET	**2p**	4p	4p	6p
MOSFET type	2SK3131	STY60NM60Z	STY30NK90Z	IXFB44N100P
Withstanding vol. (V)	500	600	900	1000

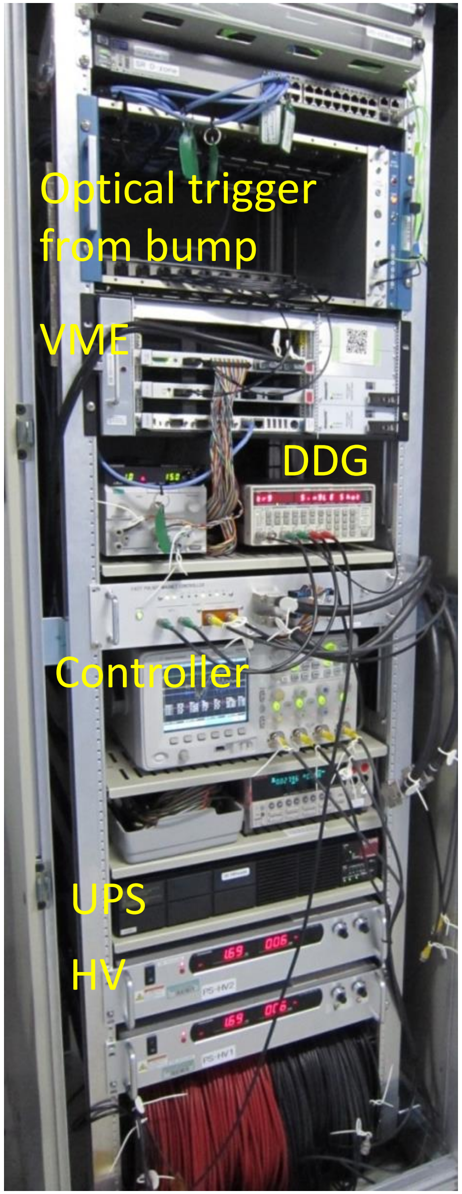
Test setup in 2010

- Size of power supply: 200(L)x120(W)x150(H) <0.005m^3
- Output: 800ns, 270A/coil (950V), 3.2mT, 33μrad@8GeV
- Variable pulse width, Bipolar (for oscillation shape and phase)
- Variable output current (for oscillation amplitude)

Setup in accelerator tunnel



Controller unit outside of accelerator tunnel



Experience through user operation

- Did not achieve the long-life operation of DPS at the beginning of the user operation.
- **The averaged operation time was less than 1 week at the beginning. Minimum operation time was 2 days.**
- We noticed strong correlation between DPS failure and the following conditions.
  - DPS failure did not occur under the operation of pulse width of more than 1.6μs. **→ Operation pulse width dependence**
  - DPS failure was readily occurred under the 203 bunches, multi filling mode and the filling including high current single bunch of more than 3 mA. **→ Beam filling dependence**
  - After all of above cares, DPS operation life time was saturated around about 1 month. **→ Special issue to operate DPS in machine tunnel**

Failure reasons and improvements for long life operation

Dependency	Failure source	Improvement	Operation life time
Operation pulse width	Miss-driving by self switching noise and device uniformity	Driver circuit improving Noise filter Severe SS-device selection	2d~1week
Beam filling mode	Beam radiation noise	System floating Noise shield enhancing	1 month
Saturation of operation life time	Synchrotron radiation damage	Radiation shield enhancing	more than 3 years

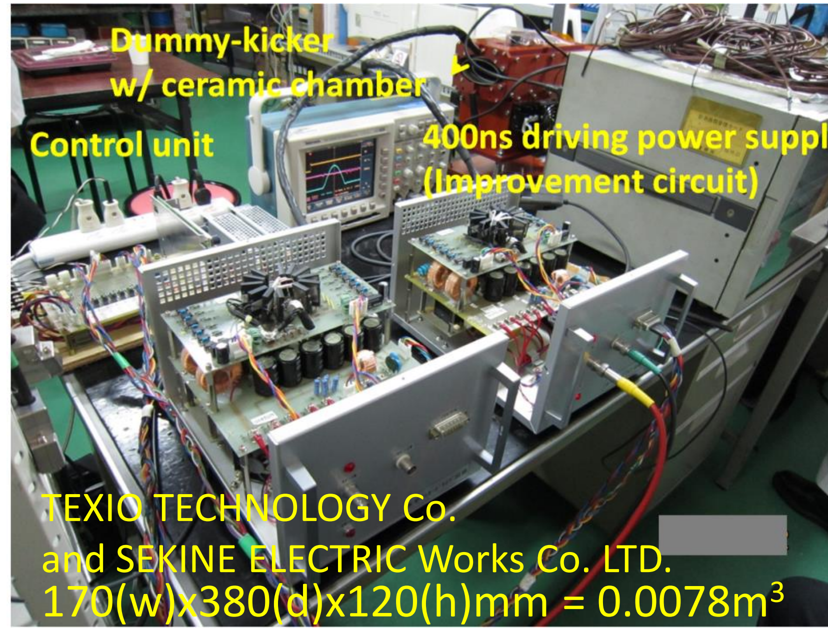
Combining

- We learned from above correlations that the care is necessary to operate the DPS continuously.
- After all of cares by step by step, the operation life time of DPS became more than 3 years and failure got not to occur by beam filling with high current **single bunch of 8 mA.**

Upgrading of pulsed power supply

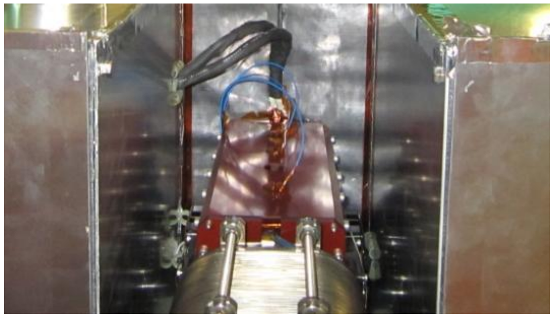
- For user operation, newly developed driving power supply.

Circuit type (FY)	Improvement (2011)
Current (A/coil/V)	232,282,383/1950
Pulse width(us)	0.4,0.5,0.7
Repetition(Hz)	10
# of MOSFET	6px2s
MOSFET type	IXFB30N120P
Withstanding vol.	1200/2400 (for all)

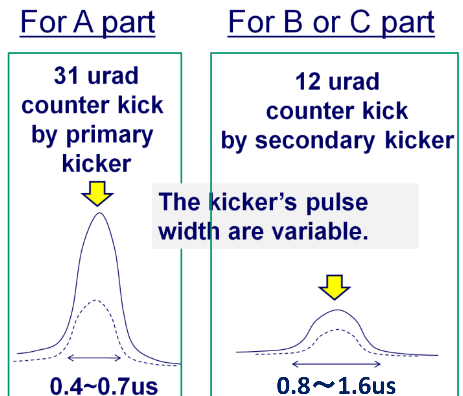


Applying long user operation in 2012

- ☐ Both side of kicker, the shield boxes are put.
  - ☐ Beam RF noise shield
  - ☐ Radiation shield
- ☐ Standby P.S. also is put in the shield



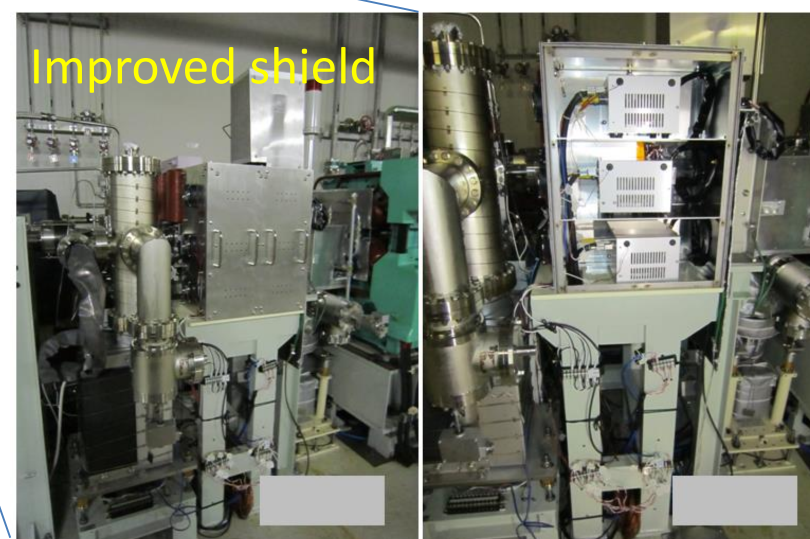
Primary fast kicker
L = 0.25m, @βx = 39m



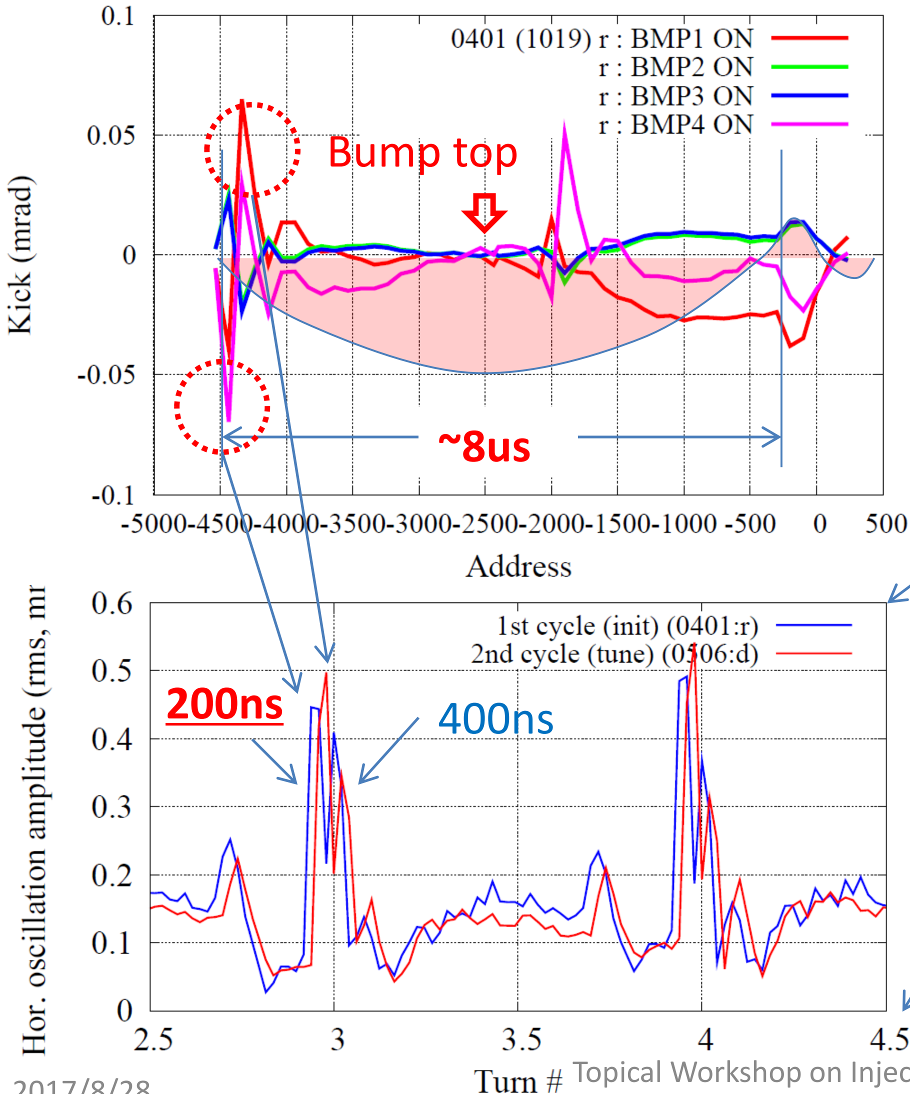
Secondary fast correction kicker
L = 0.22m, @βx = 32m

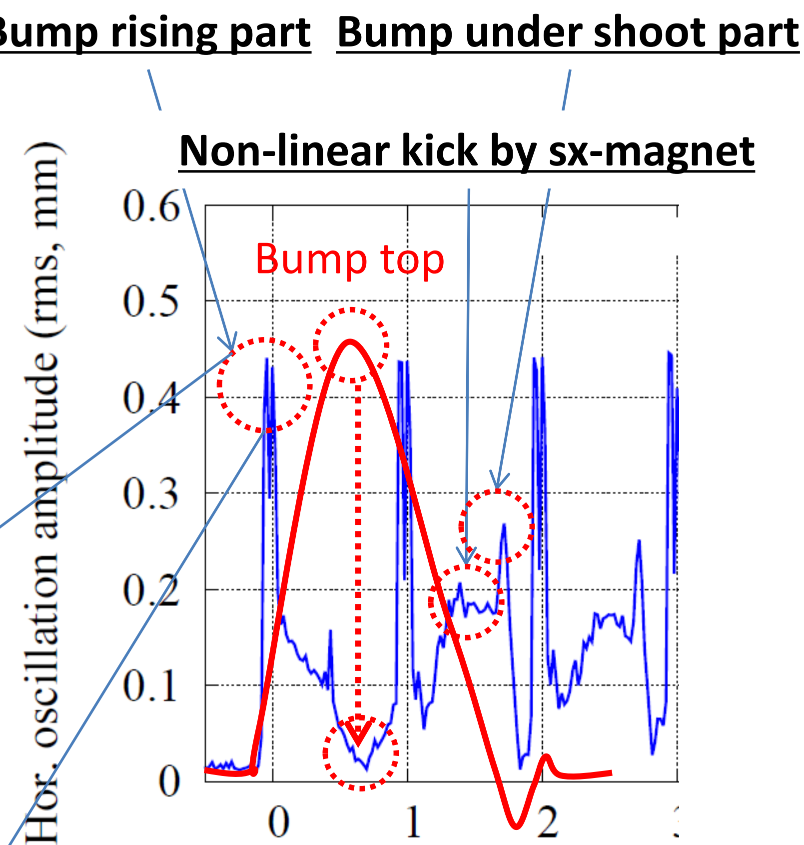
400ns, 230A/coil
700ns, 383A/coil
(1.95kV applied)

800ns, 270A/coil
1600ns, 540A/coil
(1kV applied)



Necessary of tertiary FCK system

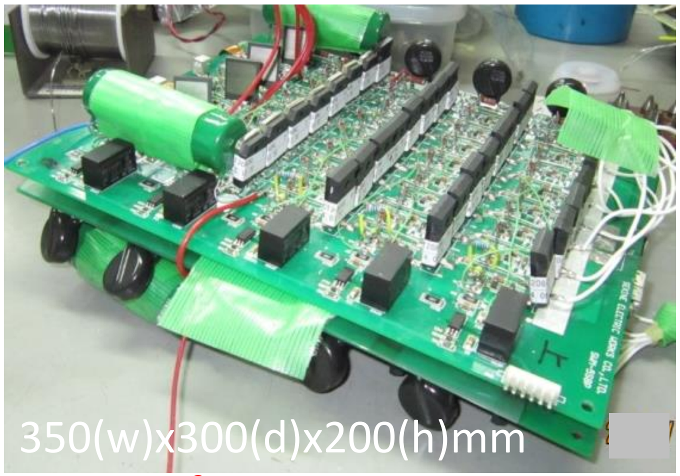




Single spike-like oscillation has a double peak oscillation structure. Need faster FCK system adding to them.

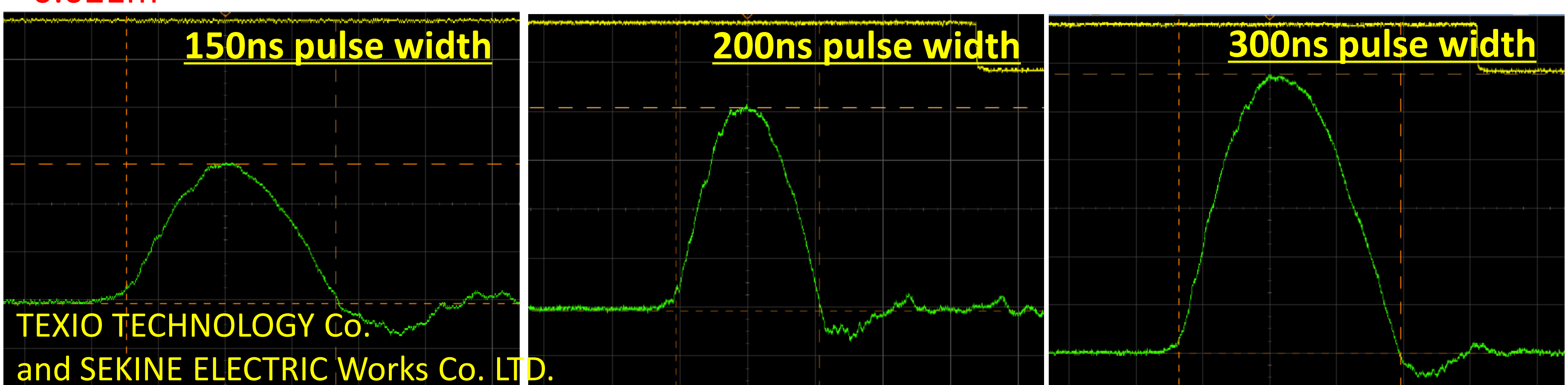
Power supply further upgrading for 3rd FCK

6.0 kV DPS for 3rd kicker



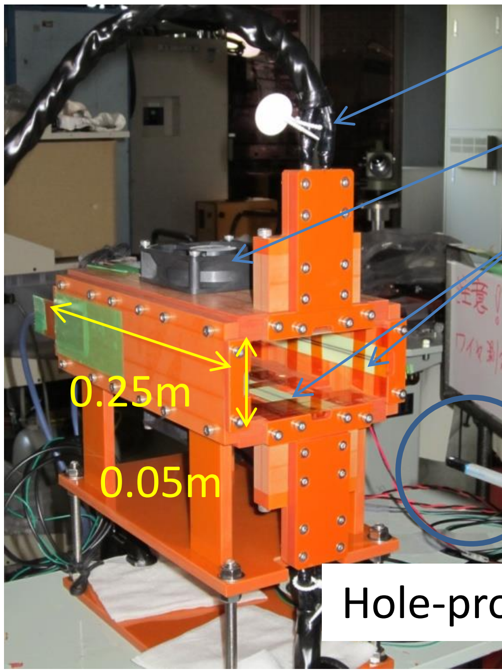
=0.021m^3

Circuit type (FY)	1st kicker (2011)	3rd kicker (2015)
Current (A/coil/V)	232,282,383/1950	192,263,384/5000
Pulse width(us)	0.4,0.5,0.7	0.15,0.2,0.3
Repetition(Hz)	10	10
# of MOSFET	6px2s=12	**8px5s=40**
MOSFET type	Si-MOSFET	**SiC-MOSFET**
MOS HV Res.	1200V	1200V
Module HV	2.4kV	**6.0kV**



Tertiary kicker installation -kicker

Air-core kicker magnet made by Bakelite

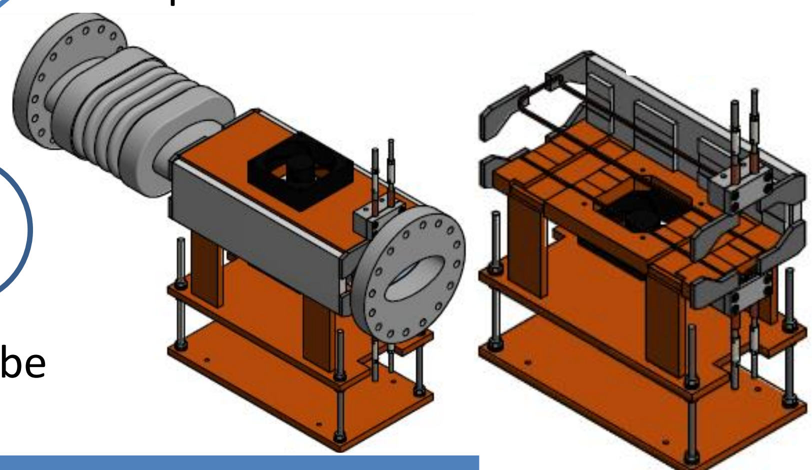


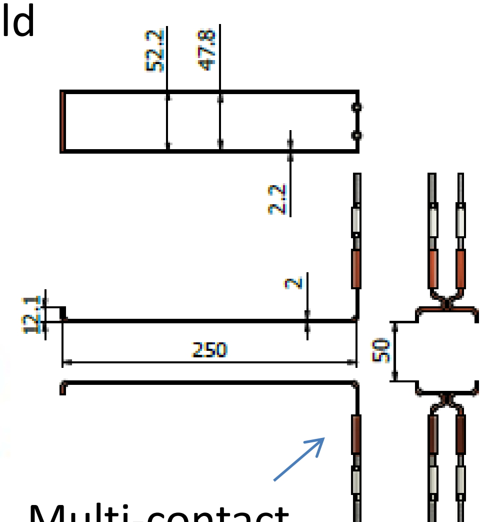
Feeder-line made by litz-line (0.8m, 20x0.3sq BEMAEX)

Fan to cool the chamber heated by beam

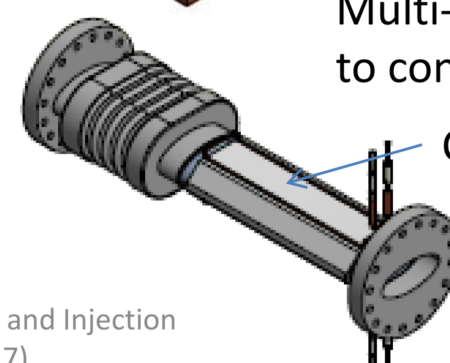
Pick-up coil to measure hor. and ver. field

Hole-probe





Multi-contact
to connect to each driver

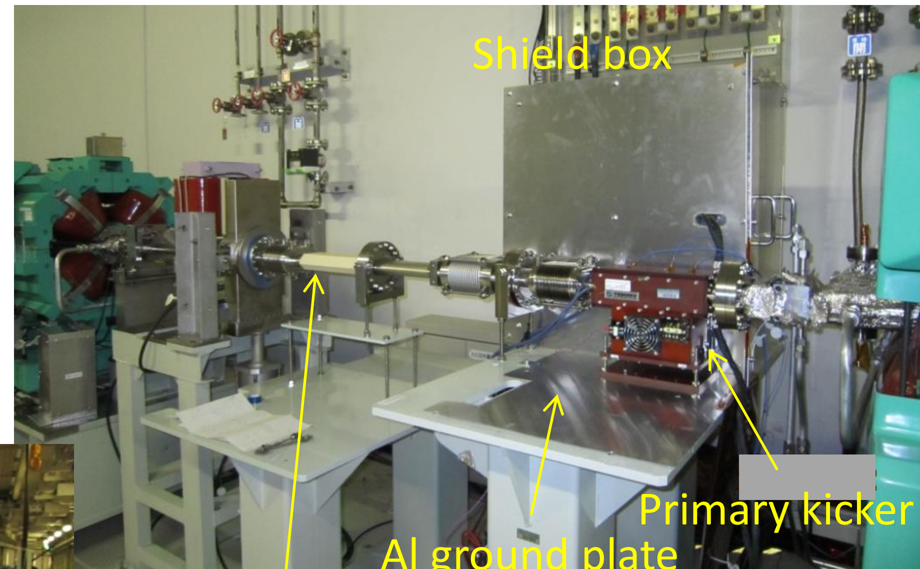


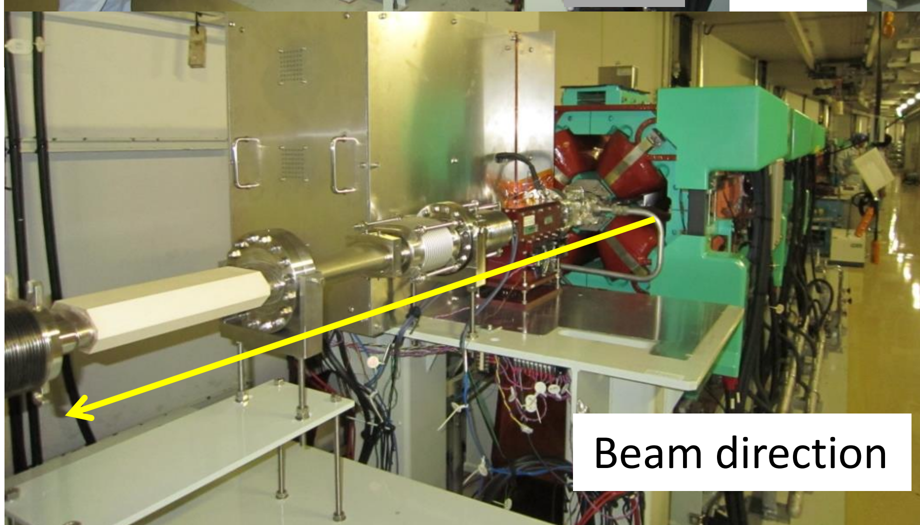
Ceramic chamber

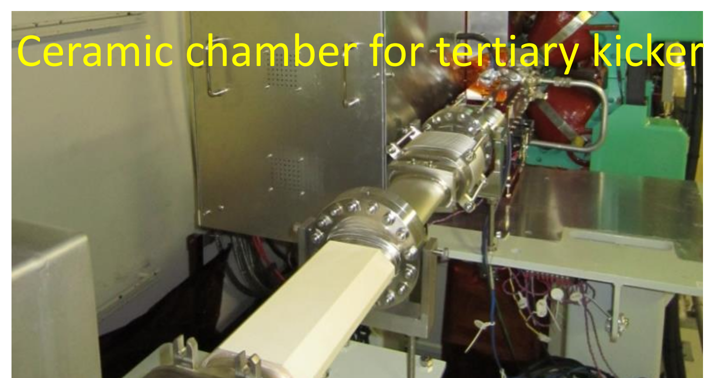
item	Value
Required kick angle	0.4mm oscill.:16urad
Kicker performance	23urad/190A/5kV/150ns
Dc-fan influence	65nrad, 2um oscill.

Tertiary kicker installation -chamber

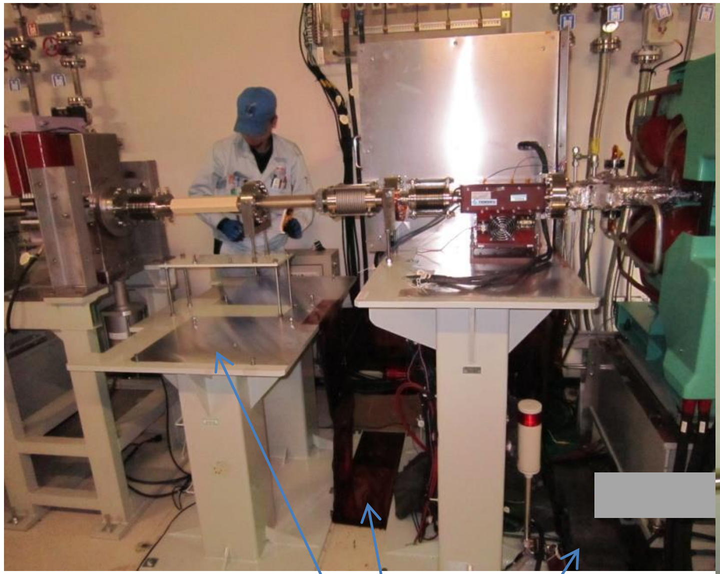
Ceramic chamber installation to neighbor of primary kicker

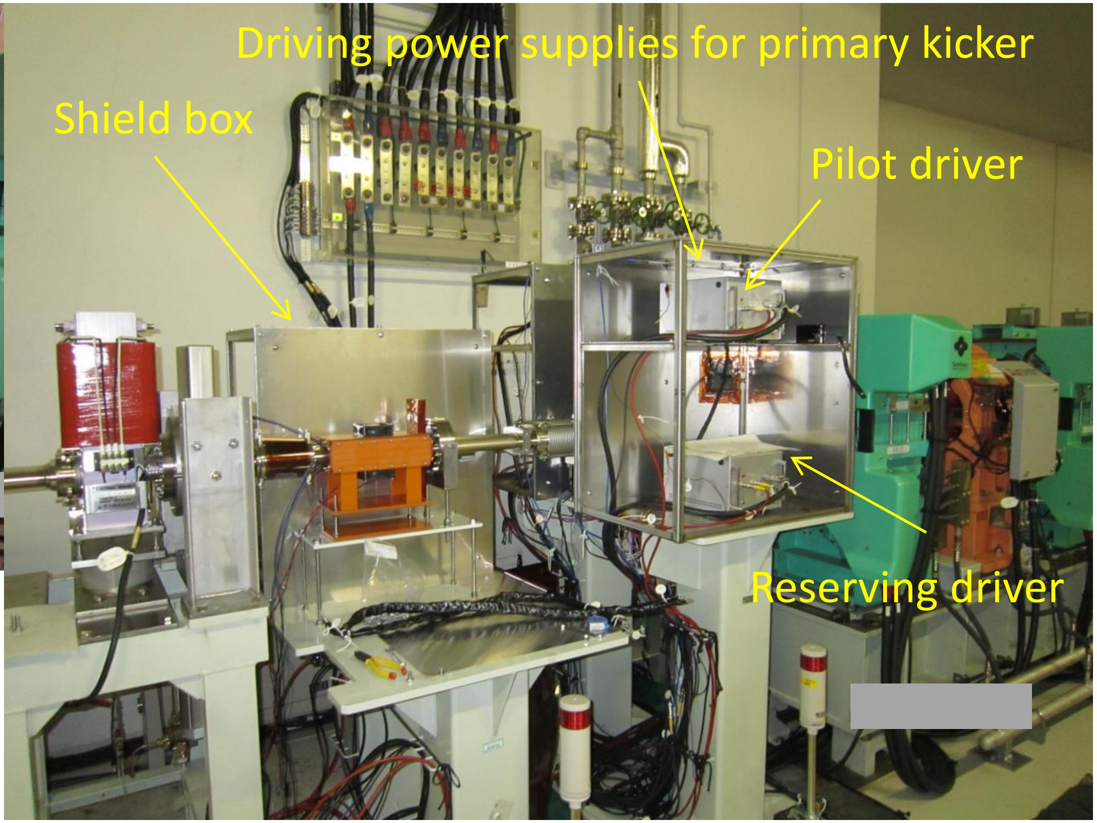






Tertiary kicker installation -grounding

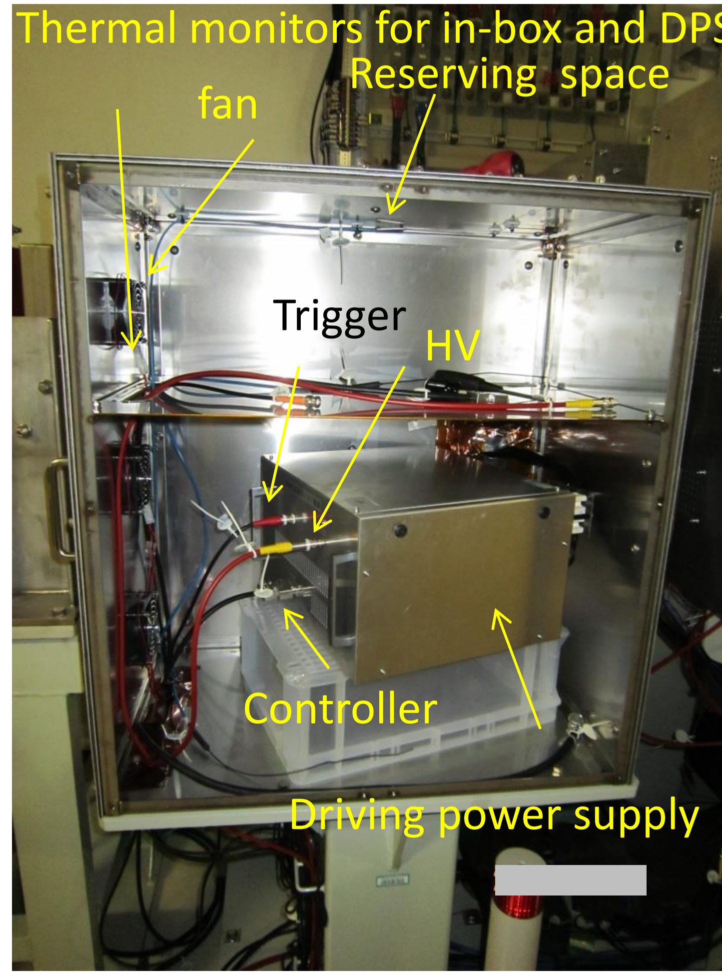


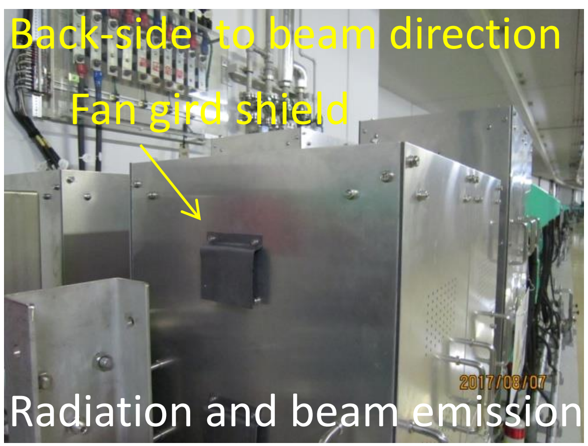


Ground connection for shield box
Al (0.5t) ground plate + Cu (0.5t) ground line

Tertiary kicker installation -shielding

Front-side to beam direction

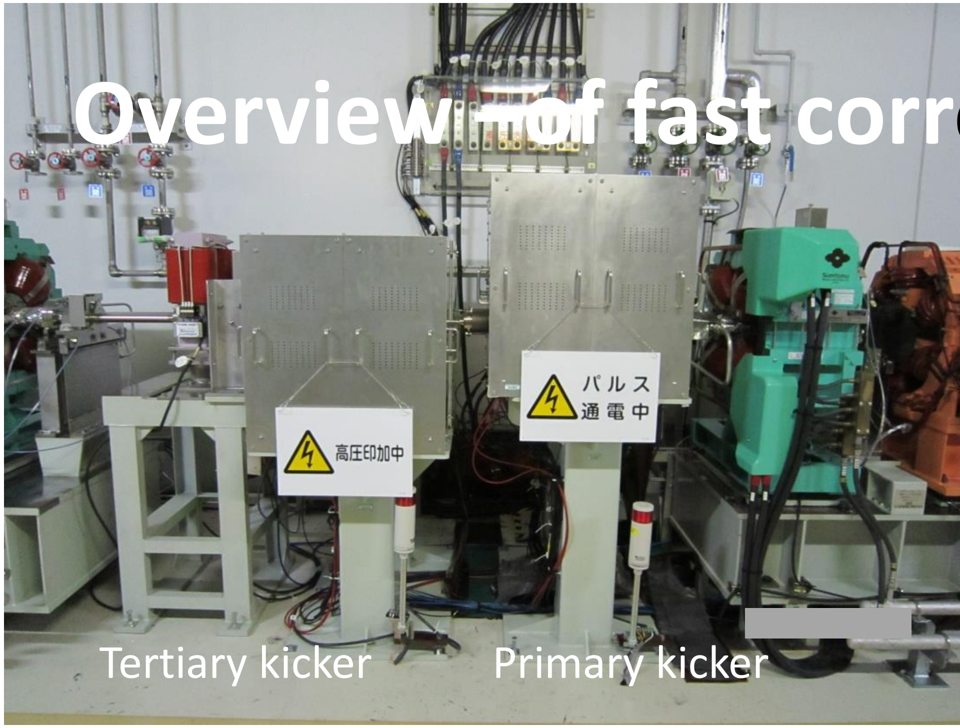


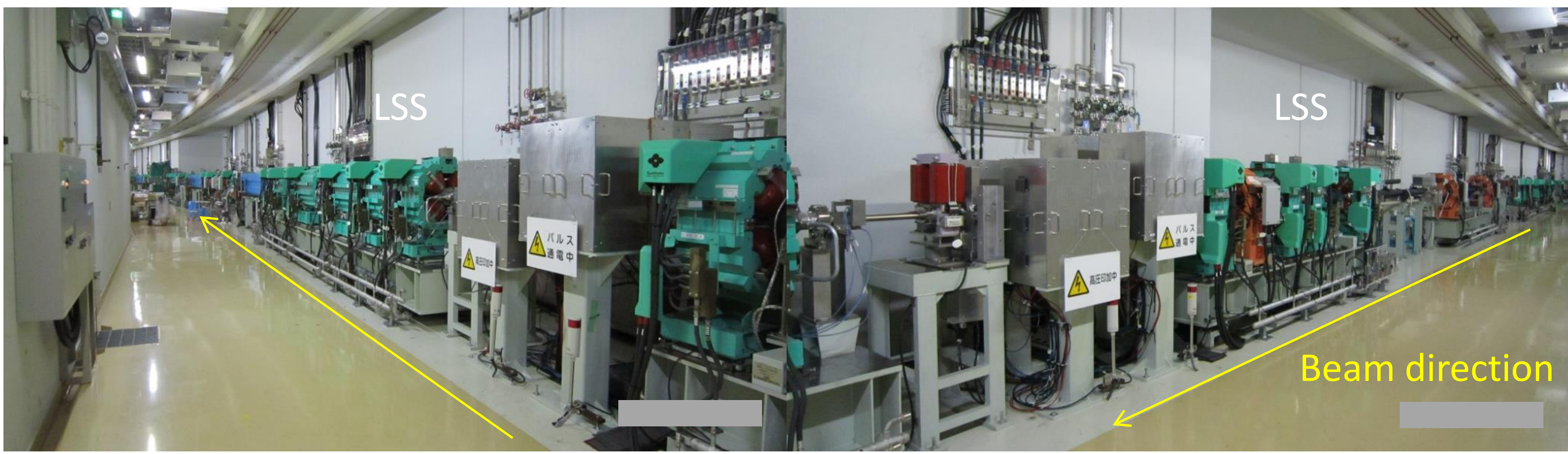


Radiation and beam emission noise shield box

Al(1.5t)+Pb(4t)+Al(1.5t) clad structure

Overview of fast correction kickers at LSS





Summary of FCK systems

***W/ ceramic chamber, actual feeder-line**

	Primary kicker	Secondary kicker	Tertiary kicker
Location	Unit cell 30 (LSS)	Unit cell 48 (unit cell)	Unit cell 30 (LSS)
β(x)	39.9m	32m	39.9m
Magnet length	0.25m	0.22m	0.25m
Magnet gap	50mm		
Inductance	672 nH @ 400ns	618 nH@800ns	641 nH@150ns
Max. kick angle	24.8μrad@400ns	35.5μrad@800ns	17.8 μrad@150ns
Pulse width	400, 500, 700ns	800,1000,1600ns	150, 200, 300ns
Rated current (*)	200A/coil @ 400ns 350A/coil @ 700ns	316A/coil @800ns 632A/coil @1600ns	121A/coil@150ns 321A/coil@300ns
Withstanding vol./Rated vol.	2.4kV/1.95kV	1.2kV/0.9kV	6.0kV/5.0kV
DPS volume	$0.0078m^3$	$0.005m^3$	$0.021m^3$

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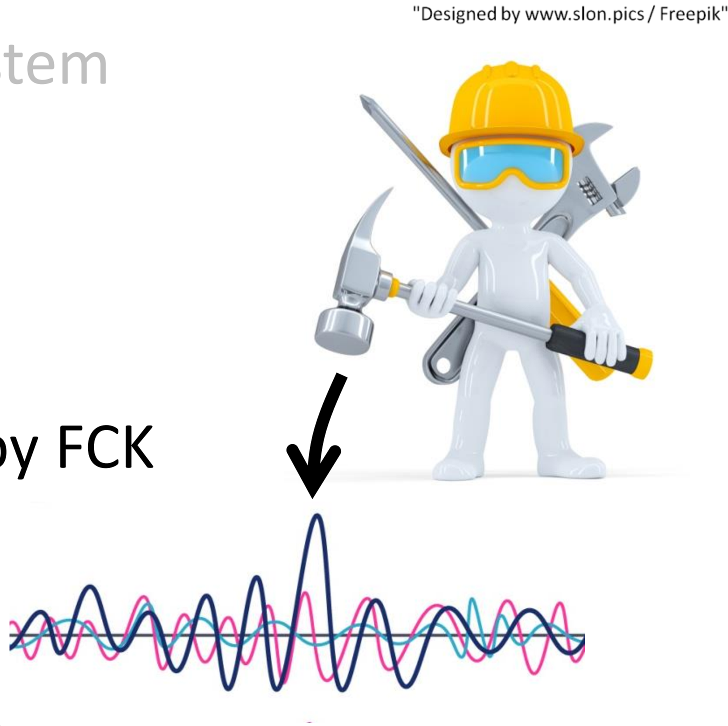
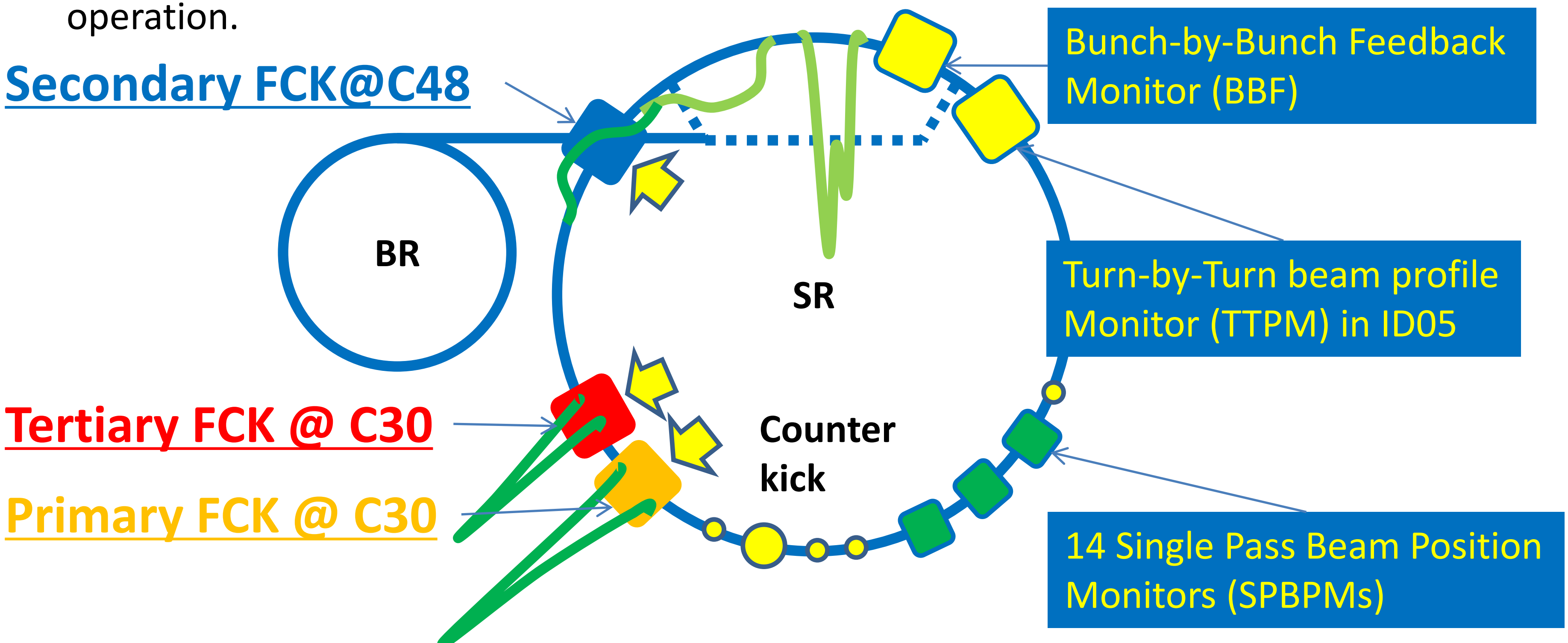


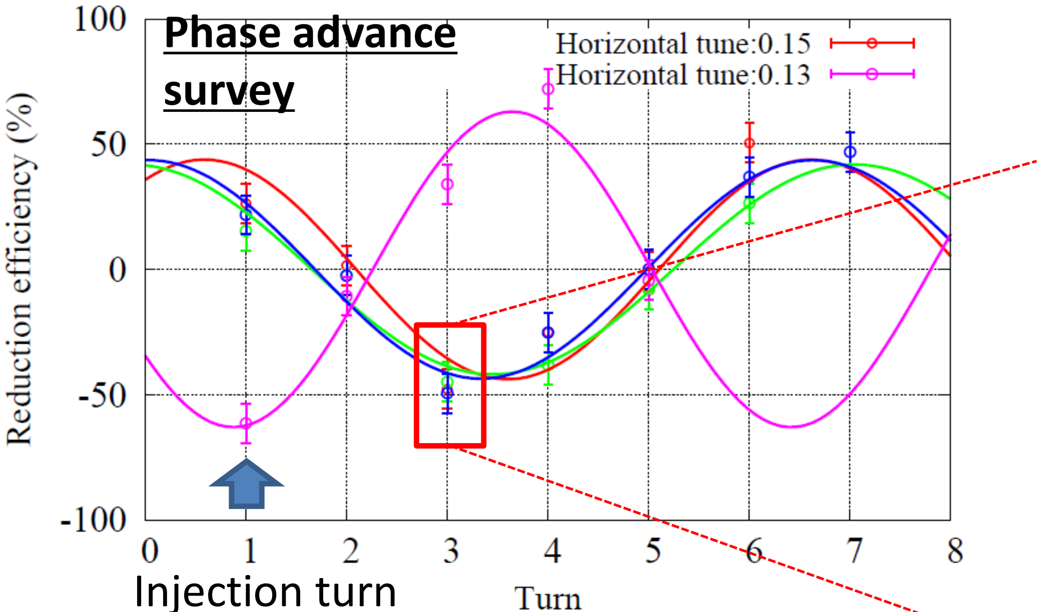
Monitor systems and FCK

- Kicker tuning before user cycles：By using Single-Pass Beam Position Monitor (14 SPBPMs), the oscillation suppression is confirmed. FCK timing and kick angle is adjusted in order to reduce the oscillation amplitude. βx=16.1m @ SPBPM
- In the user operation：Bunch-by-Bunch Feedback (BBF) monitor, X-ray Turn-By-Turn Beam Profile Monitor (TTPM) are used to observe the reduction efficiency in the user operation.



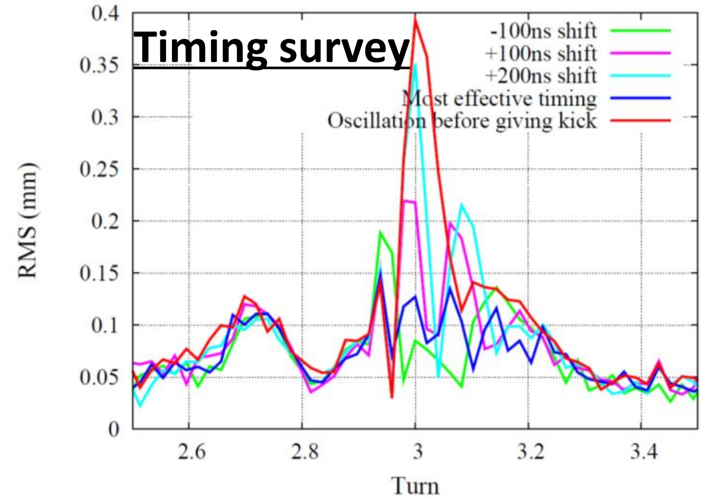
Phase advance survey and timing tuning

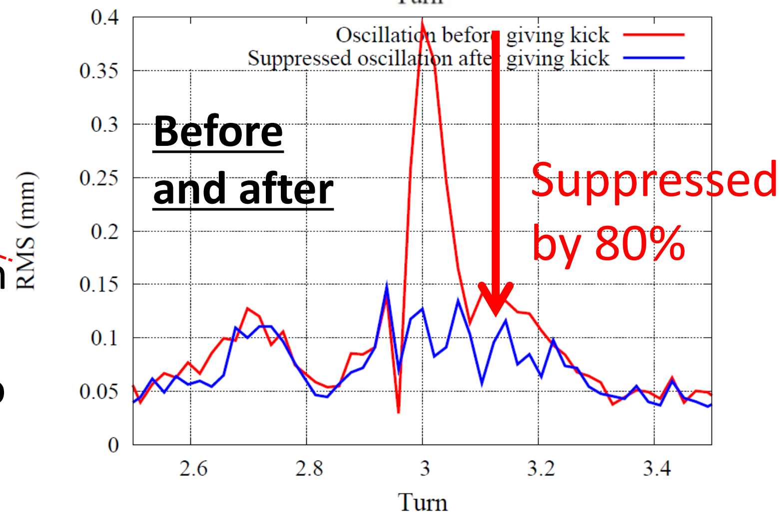
- Kicker position is fixed. Phase advance is surveyed by shifting FCK timing by turn-by-turn.



- The maximum reduction efficiency achieved within 7 turns, because horizontal tune value is 0.15.
- At that turn, the kick timing is precisely adjusted to get good coincidence between kicker peak and oscillation peak timing by 100ns.

Example for, primary FCK

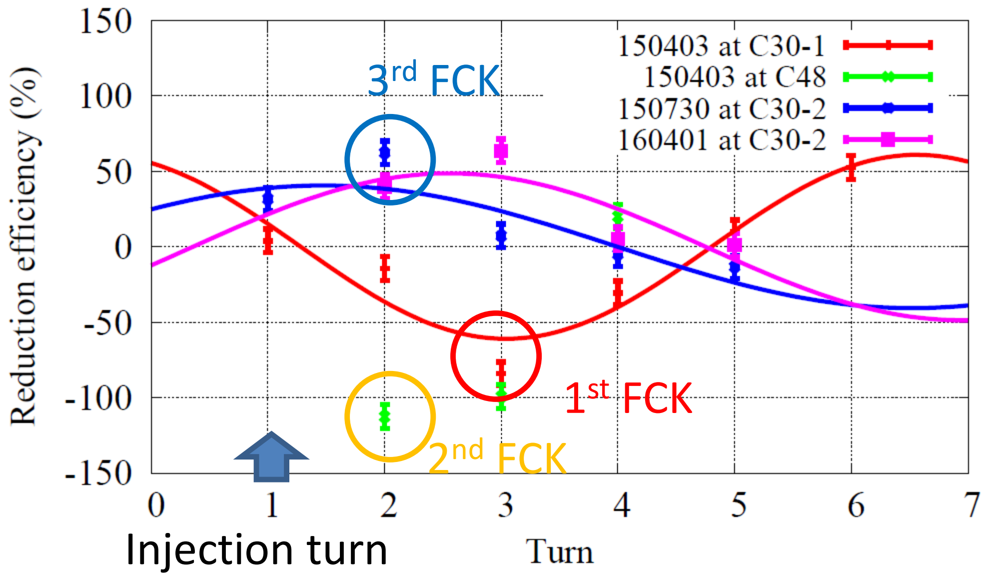




Phase advance and timing tuning

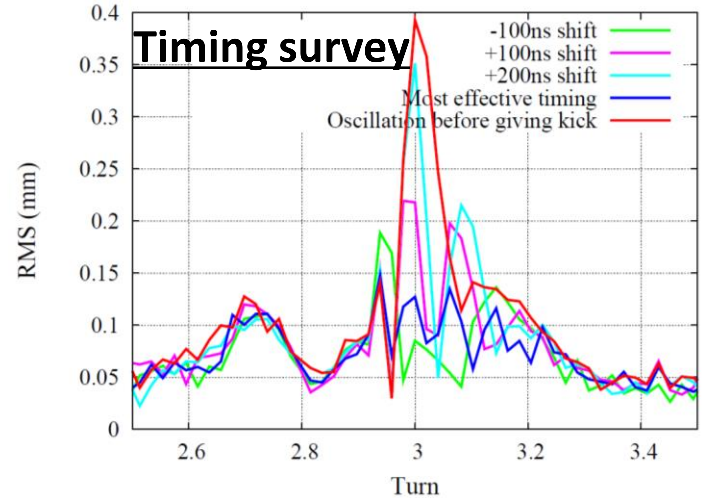
- Kicker position is fixed. Phase advance is surveyed by shifting FCK timing by turn-by-turn.

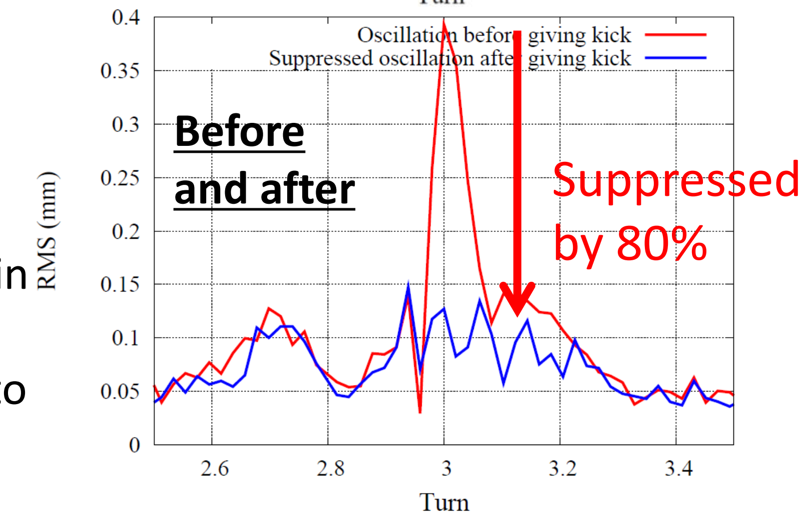
Phase advance survey for all FCKs



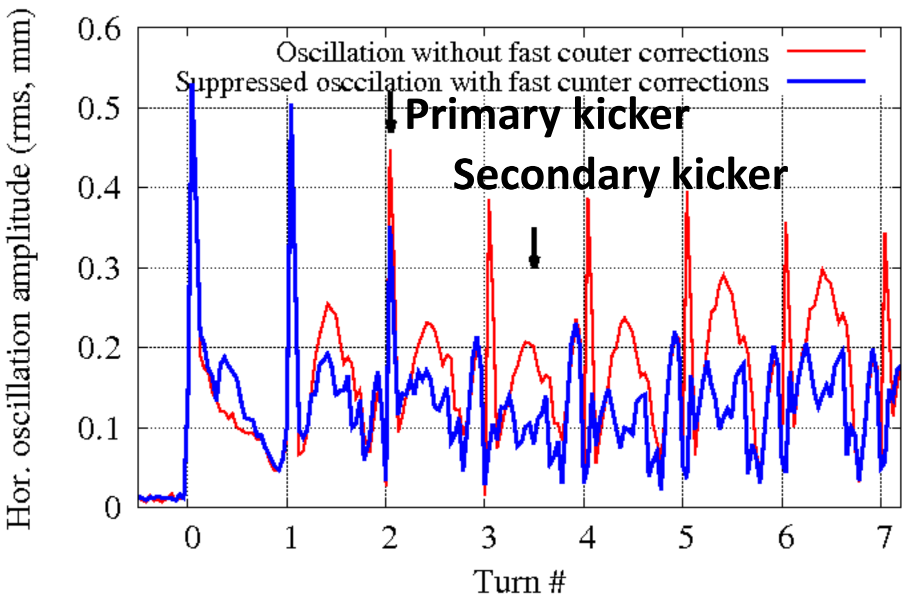
- The maximum reduction efficiency achieved within 7 turns, because horizontal tune value is 0.15.
- At that turn, the kick timing is precisely adjusted to get good coincidence between kicker top and oscillation peak timing by 100ns.

Example for, primary FCK





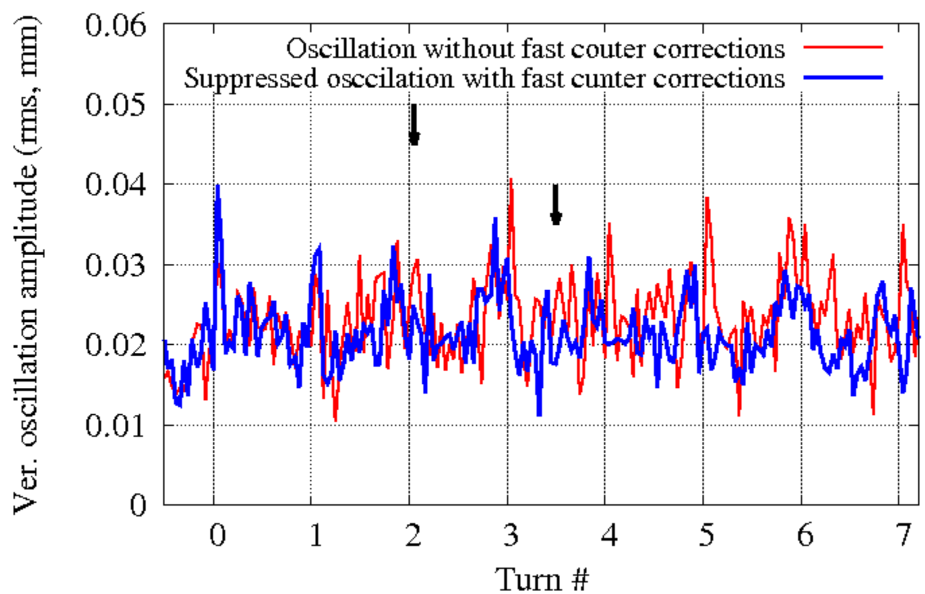
Results of oscillation suppression



* In this case, 2 FCK system were used.

- ☐ **Suppression horizontal oscillation**
  - ■Primary kicker : 31μrad/500ns
  - ■Secondary kicker : 12μrad/1400ns
- ☐ Reduction efficiency
  - ■Primary kicker : 90%
  - ■Secondary kicker : 50%
  - ■ Residual oscillation <0.15mm

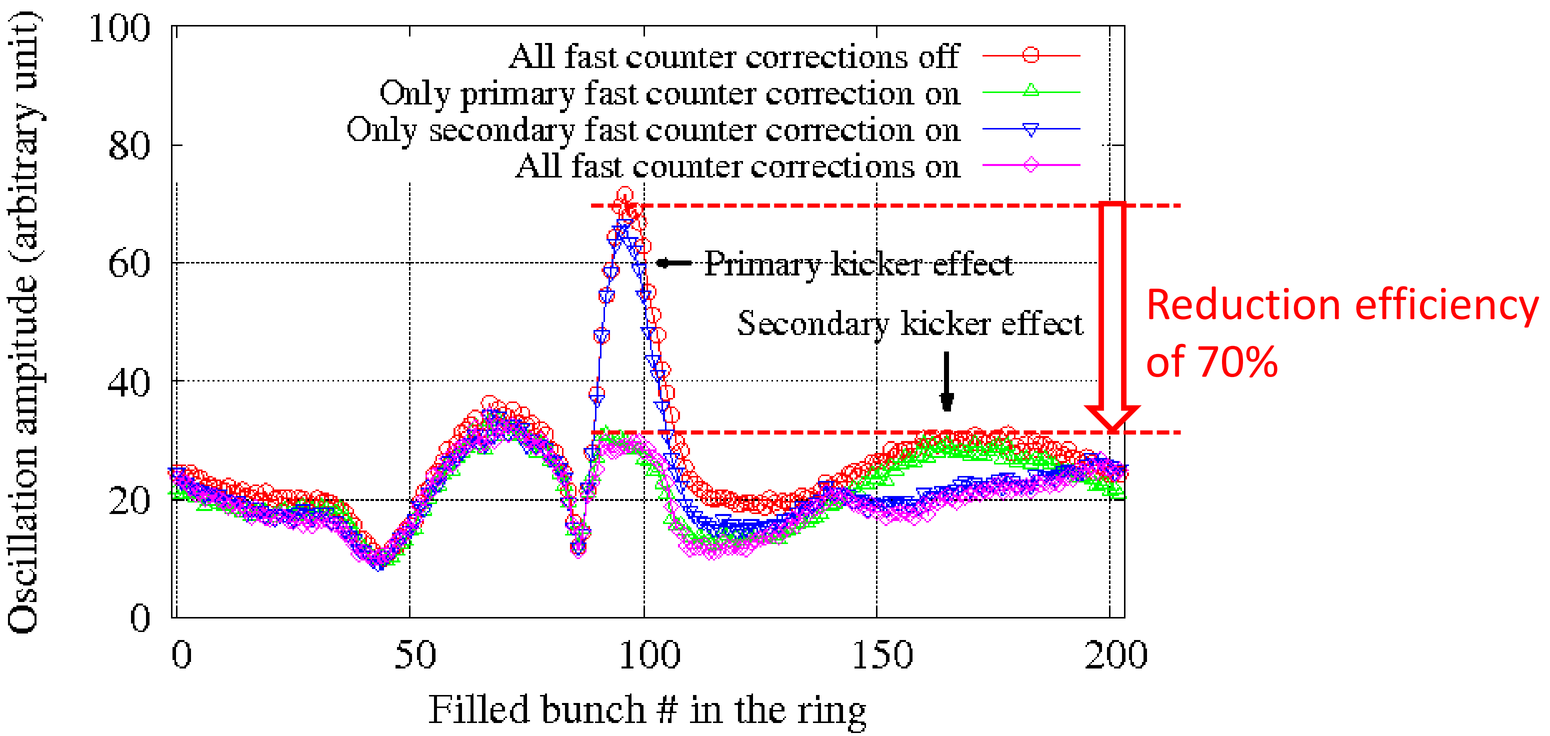
- ☐ **Suppression of vertical oscillation**
- ☐ Skew error of optical magnets exists along the storage ring. By this error, the beam tiles vertically. The horizontal oscillation has an effect to vertical direction.
- ☐ Suppression by FCK has an impact on the vertical oscillation.



Results of turn-by-turn convolution by BBF monitor

- With BBF pick-up monitor, Bunch-By-Bunch, Turn-By-Turn, 2000 turns oscillation amplitude data are available during user operation.
- In the 203 bunch filling mode, each bunch oscillation are convoluted up to 128 turns.

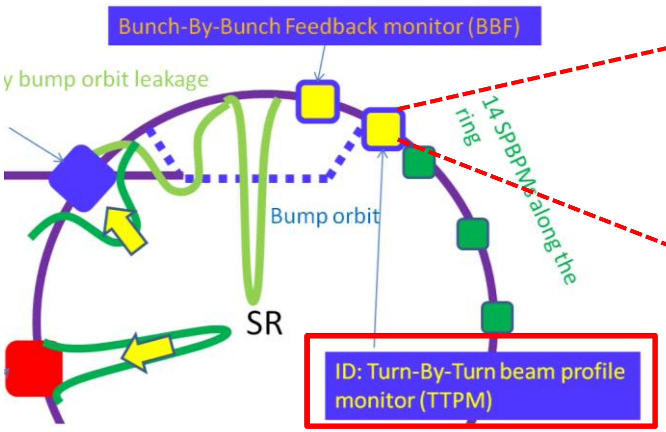
* In this case, 2 FCK systems were used.

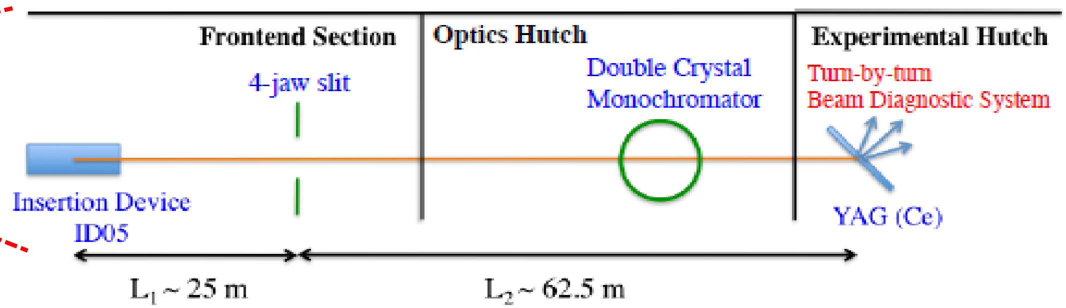


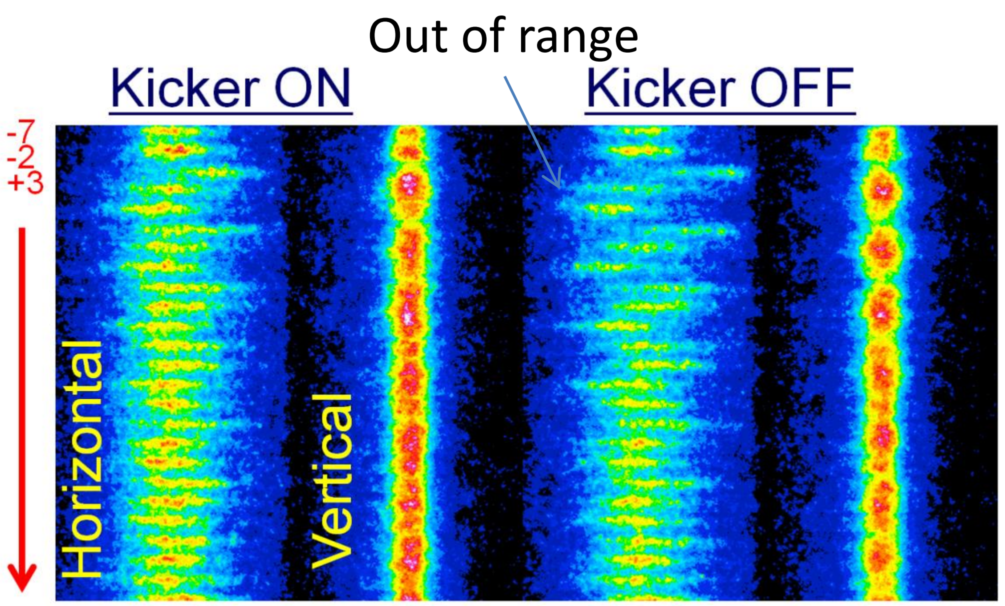
Turn-By-Turn Beam Profile Monitor

- ☐ We confirmed the suppression of the light axis angular oscillation by the TTPM.

M.Masaki, Proceedings of IBIC2012, Tsukuba, Japan, TUPB63, p1, 2012.





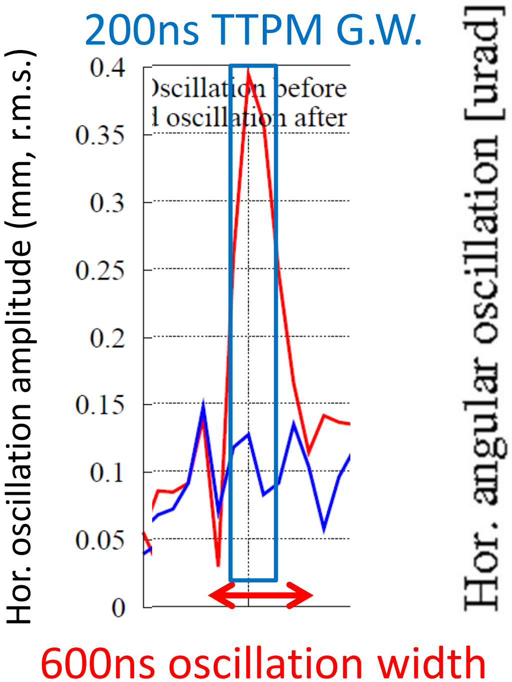


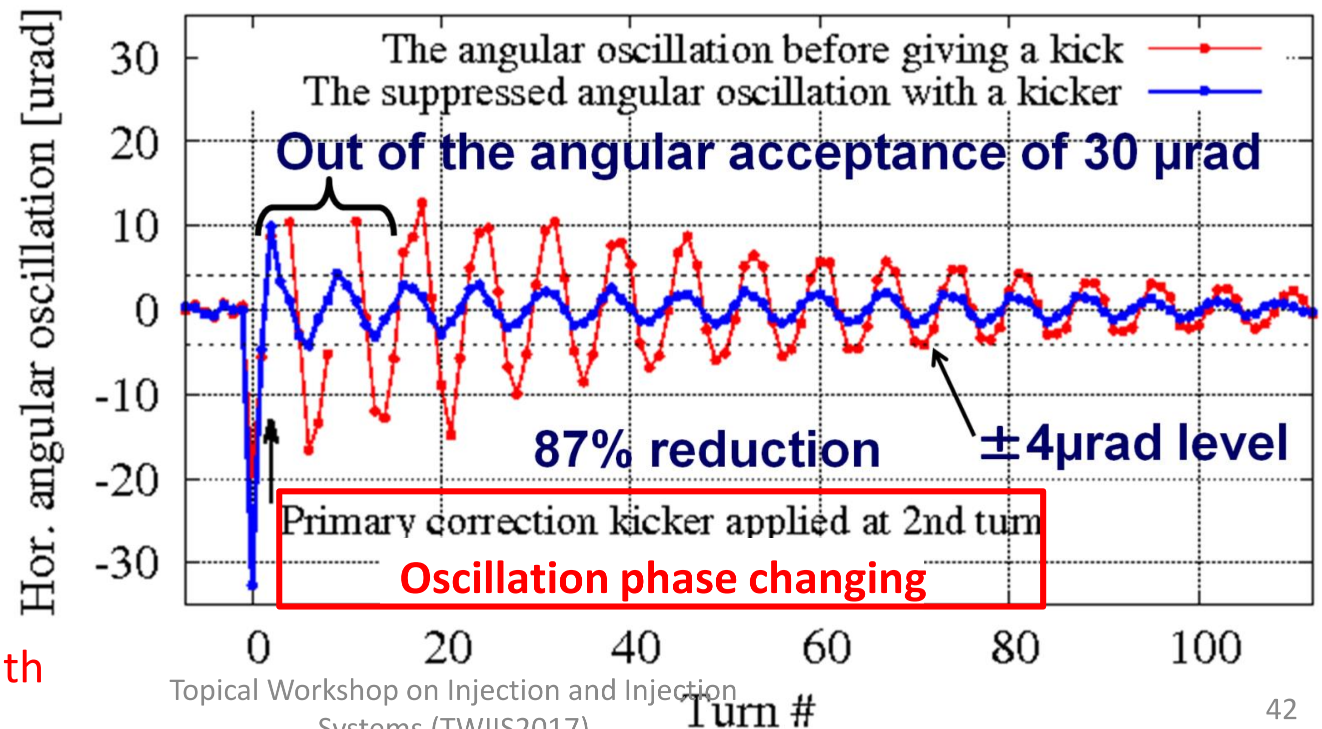
- ☐ In 2012, TTPM system is developed. TTPM can observe the monochromatic X-ray from insertion device of undulator in C5.
- ■ Oscillation at injection.
- ■ Energy spread by beam instability.

Fast transition phenomenon can be observed.

Horizontal light axis angular oscillation

- Gate window timing was fixed to maximum oscillation point. And, turn-by-turn light axis angular oscillation was observed.
- It took 3 turns to reduce the oscillation amplitude from 30 µrad to 4 µrad. The reduction ratio was 87%. Without kick correction, it takes 80 turns to reduce the oscillation down to 4 µrad with BBF ON.
- The oscillation damping time was improved by 30%. Kicker helps BBF correction.

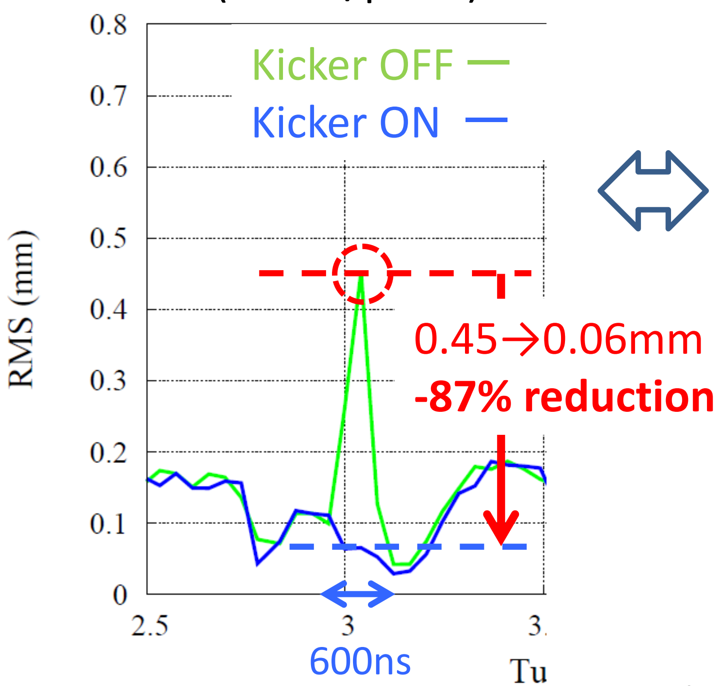




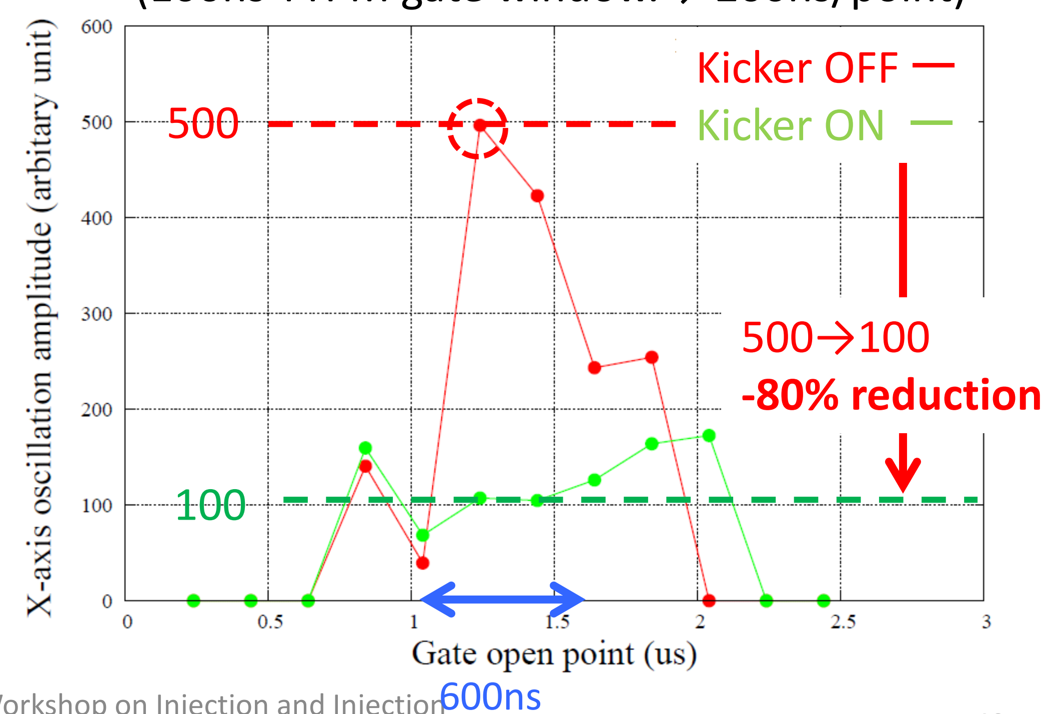
Comparison between light axis and beam oscillation distribution

- The distribution of light axis angular oscillation was observed by TTPM by shifting TTPM gate window with 200ns steps.
- The oscillation structure and reduction ratio was same as data achieved by SPBPM

SPBPM data
(200ns/point)



FFT data for 128 turns convolution
(100ns TTPM gate window.→ 200ns/point)



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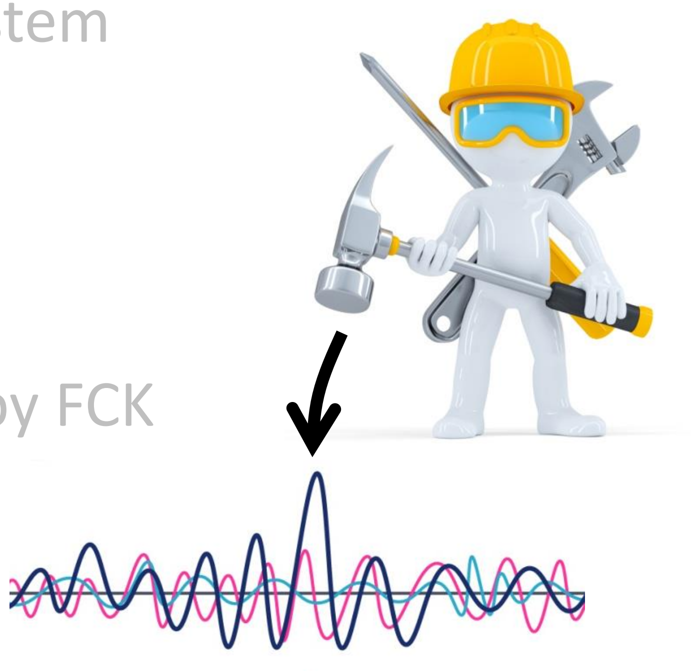
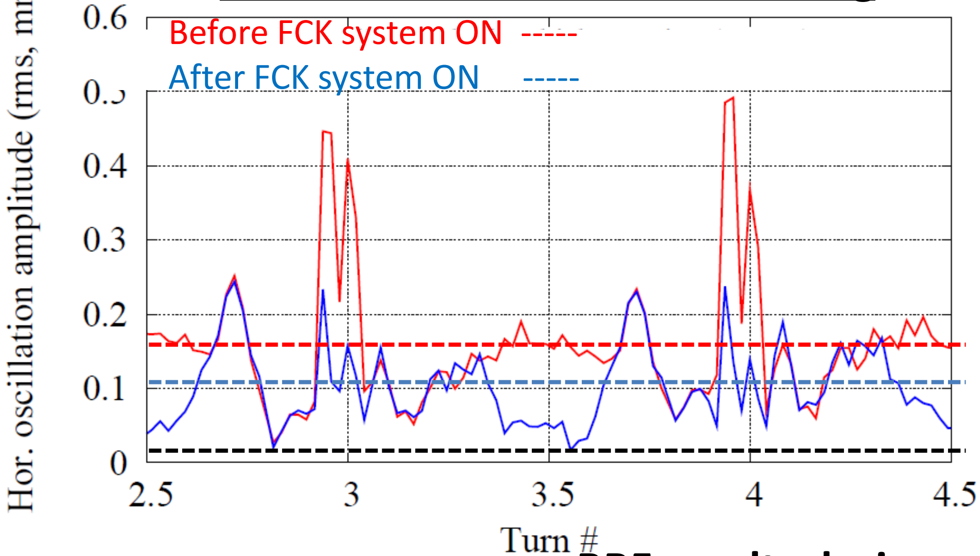


Current results including tertiary FCK

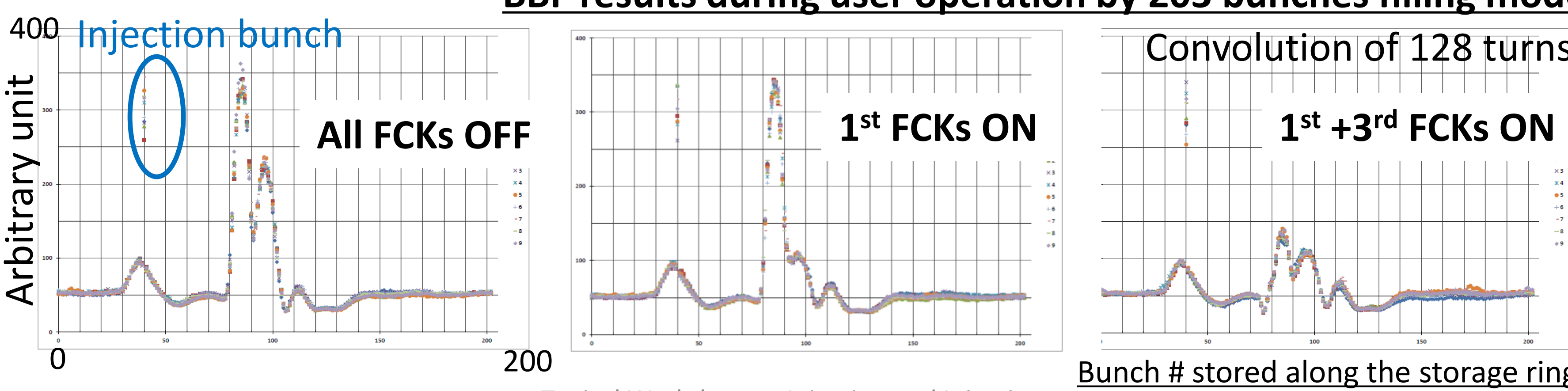
SPBPM results in machine tuning



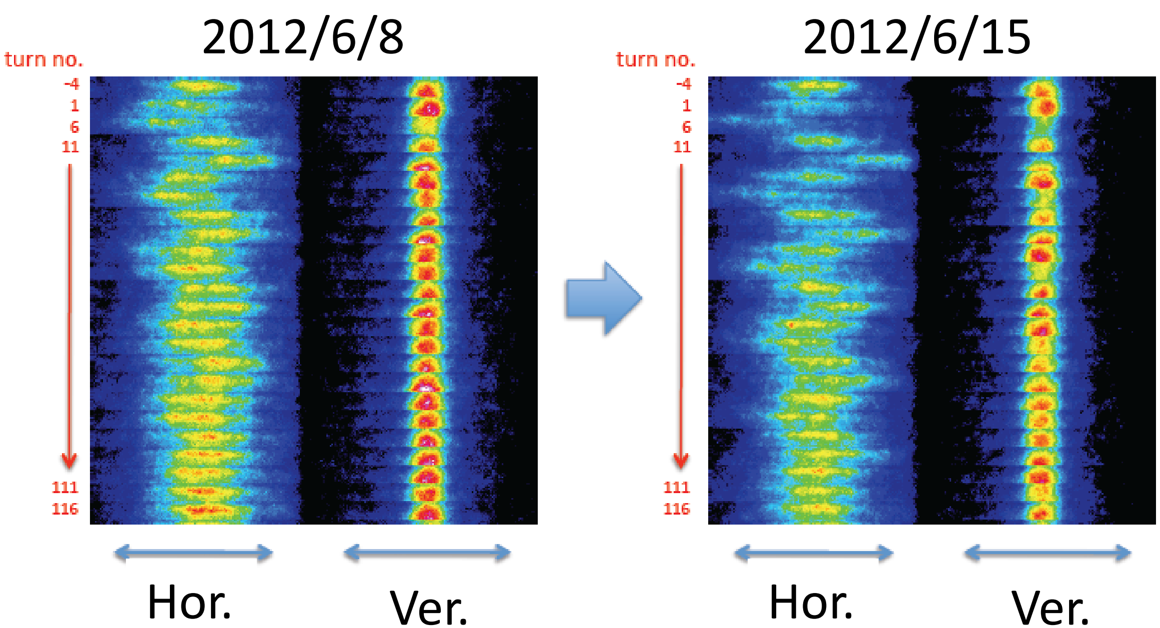
Condition	Avg. oscillation (mm)
Before 2013	0.3
w/o injection	0.016
at bump top	0.016
Without FCK	0.165
With FCK	0.119

Averaged oscillation amplitude is reduced by 30% within 8 turns.

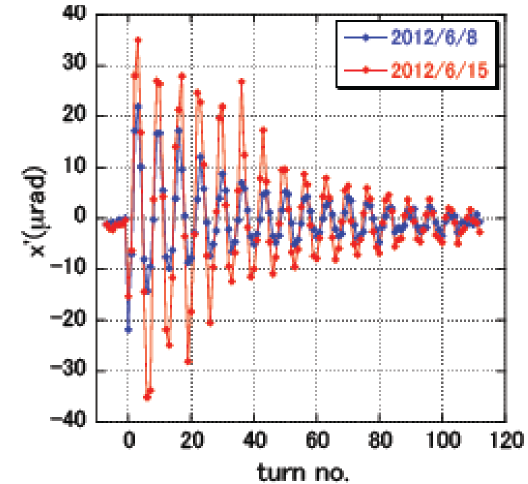
BBF results during user operation by 203 bunches filling mode

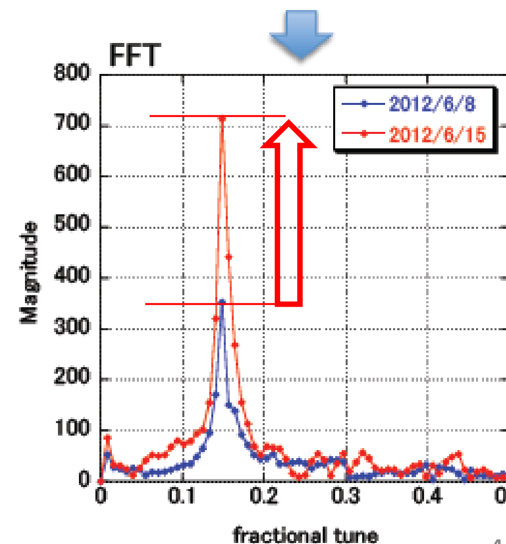


Observed the efficiency loosing in TTPM



Rising part of bump wave

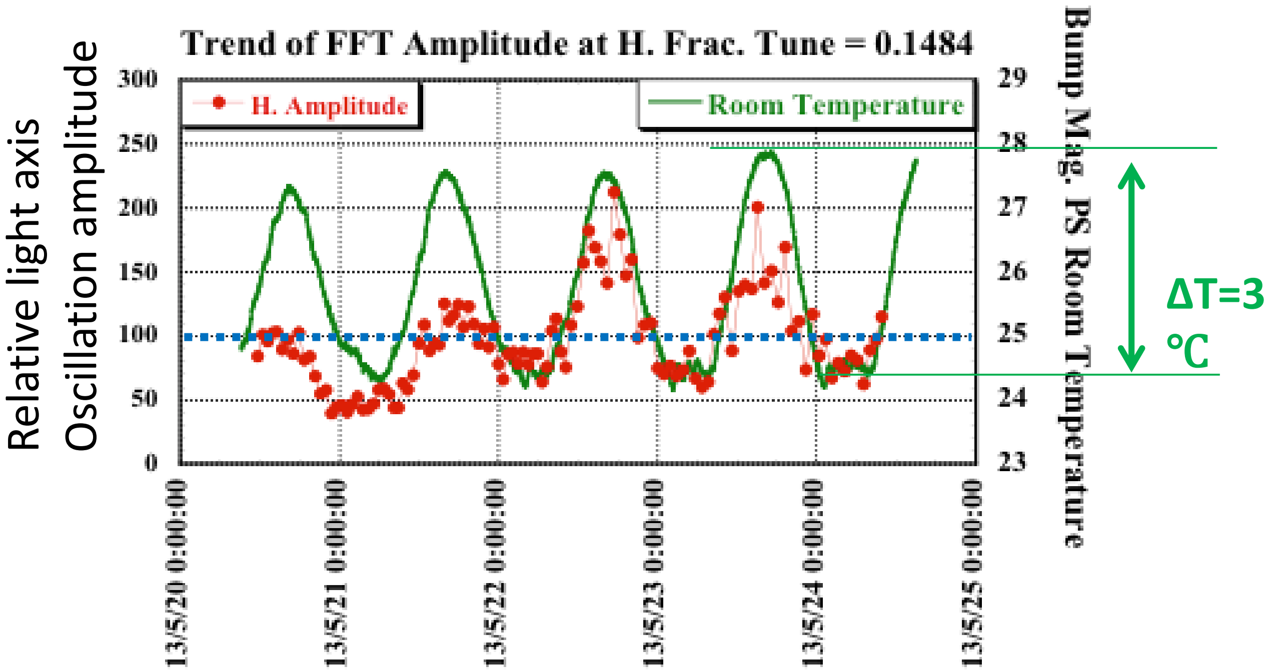




- In user operation, we watched whether the suppression efficiency was kept or not continuously in opening the gate window of TTPM at rising part of bump wave.
- In this measurement, we noticed that the efficiency was lost by a factor of 2 in a week. In this period, the bump timing drift of 100ns was monitored.
- This phenomenon was also observed in BBF, the result was consistent .

Observed D/N variation in TTPM

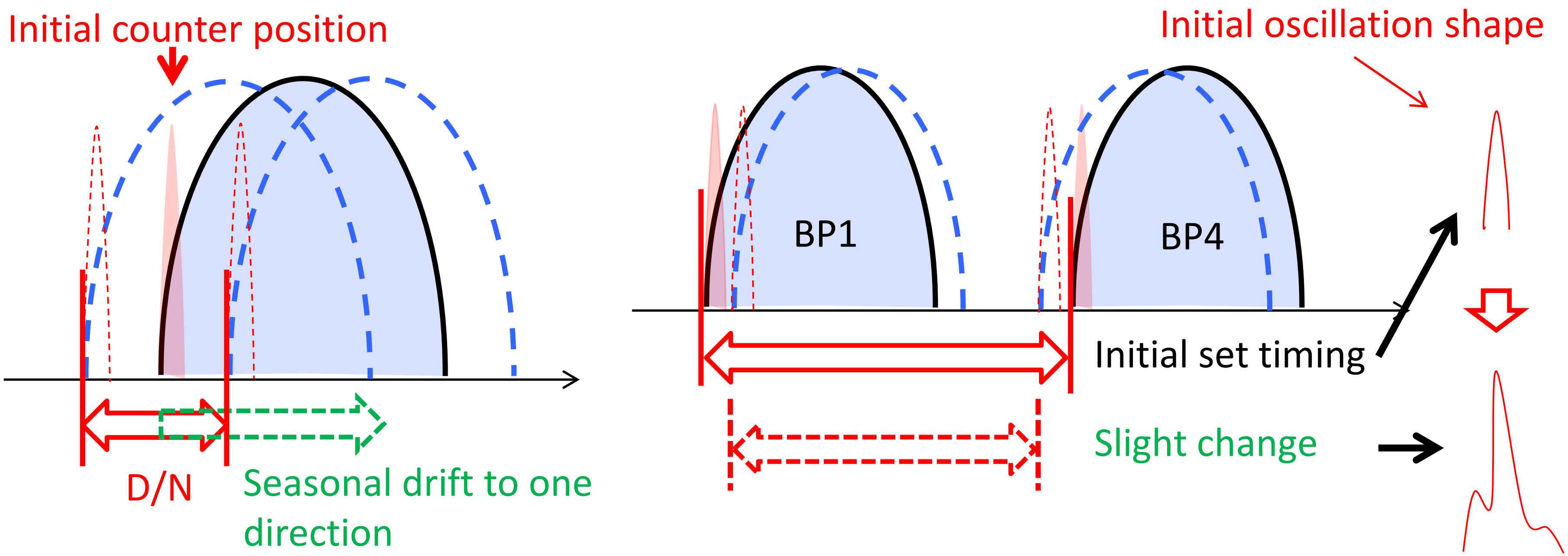
- Light axis oscillation amplitude w/o kicker > 500 (out of range of below figure)
- **Initial suppression level at light axis oscillation peak was 100 (dot-line in the figure)**



- Suppressed light axis oscillation changed by D/N variation. The variation was strongly correlated with the D/N variation of bump P.S. room temperature. In this period, ±35ns bump timing variation was monitored.
- The suppressed oscillation level was gradually loosed by increasing of room temperature.

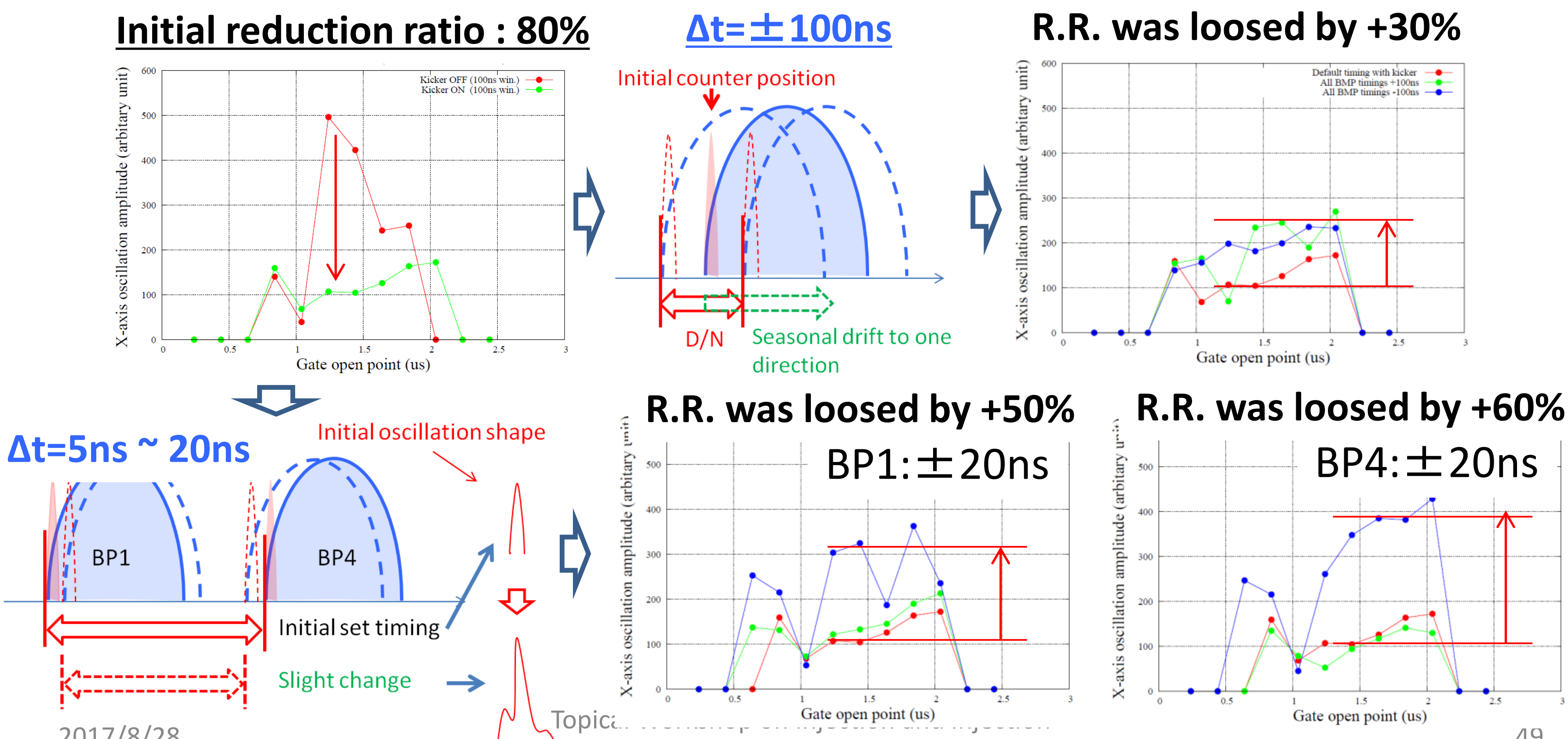
The mechanism of suppression efficiency loosing

- There are two phenomenon about the loosing suppression efficiency.
  - D/N variation and seasonal drift of current output timing of bump P.S. →**Simultaneous motion**, **Oscillation peak position and amplitude change**
  - The changes of the timing differences for 4 bump P.S. from an initial condition.→**Individual motion**, **Oscillation shape and amplitude change**

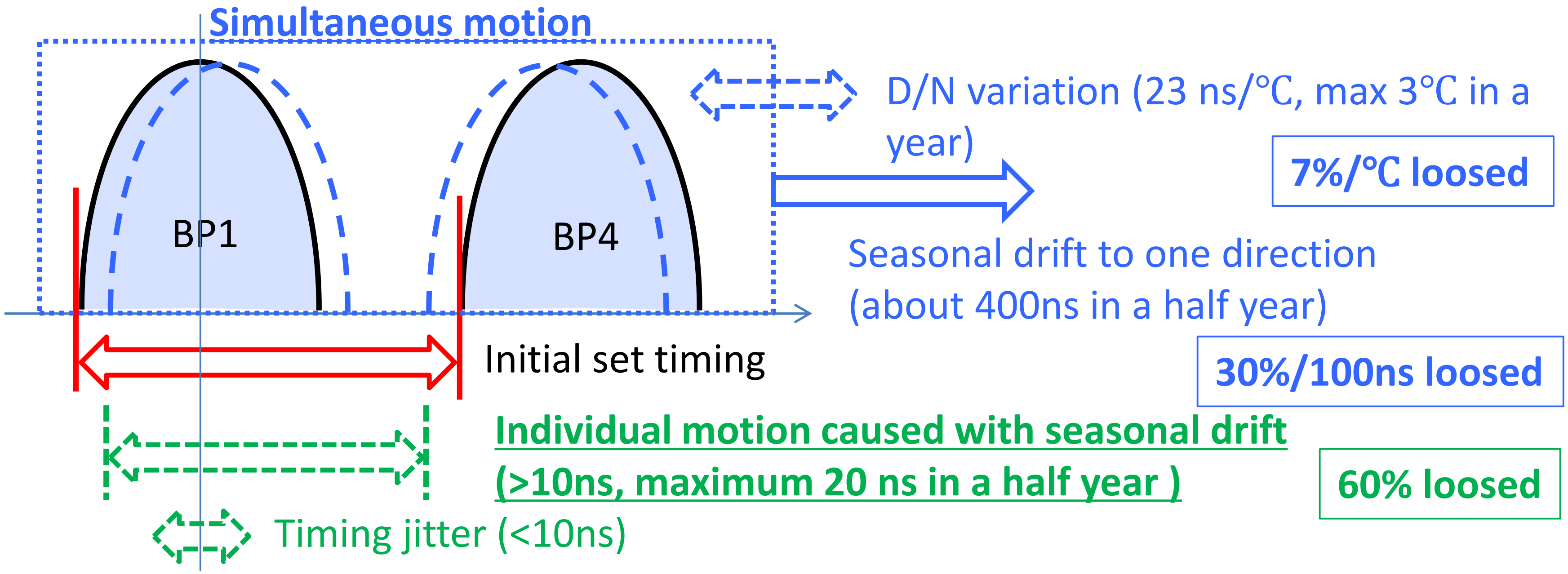


The verification for suppression efficiency loosing by using TTPM

- The timing difference changing was simulated by shifting the output timing of each bump actually from 5 ns to 20 ns individually or all bumps to same direction of 100 ns, In this test, the FCK was ON. The oscillation distribution was observed by TTPM G.W.



Summary of the suppression efficiency loosing



- Timing jitter of 7ns and the timing shift less than 10 ns in simultaneous motion , the oscillation suppression efficiency is not loosed in this case.
- The timing difference changing between bumps is corrected by bump timing tuning in the machine tuning period between user operation cycles, because this change is caused very slowly.
- Room temperature was stabilized by ΔT<1.0°C, regular kicker timing adjustment is now being applied to trace the bump seasonal drift.

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Summary

- The FCK system contribute not only to the light axis stability but also to high current single bunch storing.
- The achieved suppression efficiency is more than 80% at the oscillation peak. This value is consistent with all monitor results.
- By feed-forward (FF) scheme, the light axis oscillation angle more than 30 μrad at the initial level is suppressed to 4 μrad within 3 turns. And, the damping time is improved by 30%. Complementary works for BBF is as expectation.
- In FF scheme, the bump output timing changes causes the suppression efficiency loosing by slight shift of a few 10 ns. We are applying combination scheme of feed-back by regular FCK timing and bump timing adjustment between user cycles based on watching results of bump output timing.

End

- ***Acknowledgement***
  - I would like to thank my colleagues for great support.
  - JASRI: K. Fukami, K. Kobayashi, M. Masaki, M. Oishi, Y. Shimosaki, M. Shoji, K. Soutome, and M. Takao
  - SES: T. Honiden, and T. Matsuzaka
  - Sekine Electric Works Co. Ltd: N. Sekine
  - A part of this work was supported by Harima Branch, RIKEN.
- ***Thank you so much for your kind listening!***