Beam Orbit Stability Issues for User Operations at TPS

Chih-Hsien Huang

2017/12/11

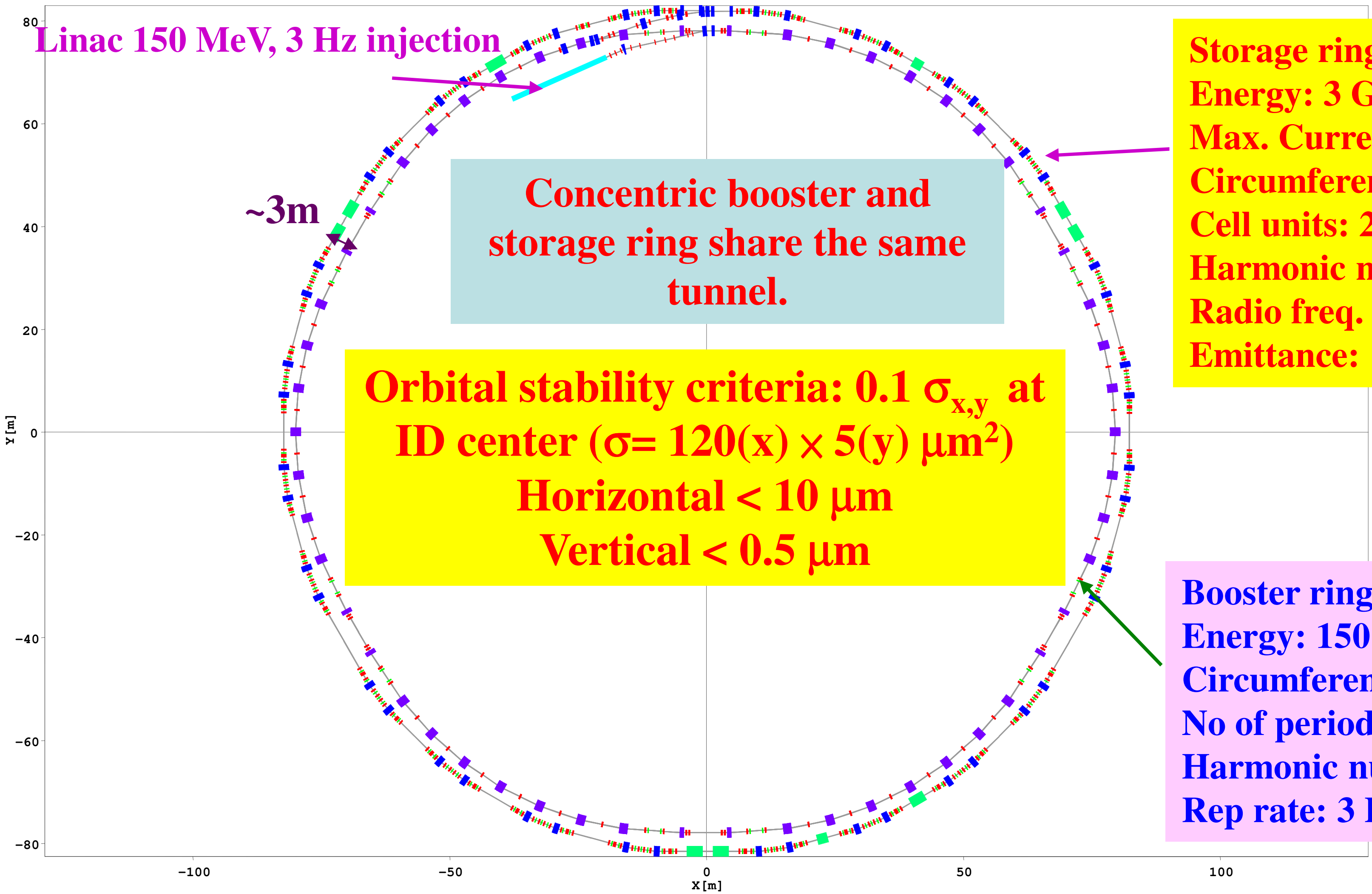
On behalf of the TPS Team

NSRRC

Outline

- **Orbit stability criteria of TPS**
- **Measurement tools**
- **Ground motion and its effect on orbit stability**
- **Vacuum pump and cooling water effects**
- **Vibrations of vacuum chambers and magnets vs. beam motion**
- **Effect of grounding in RF transmitters**
- **Cooling fans effect**
- **Suppression of residual beam motion to submicron by FOFB to satisfy users' requirements**
- **Summary**

Requirement of orbit stability

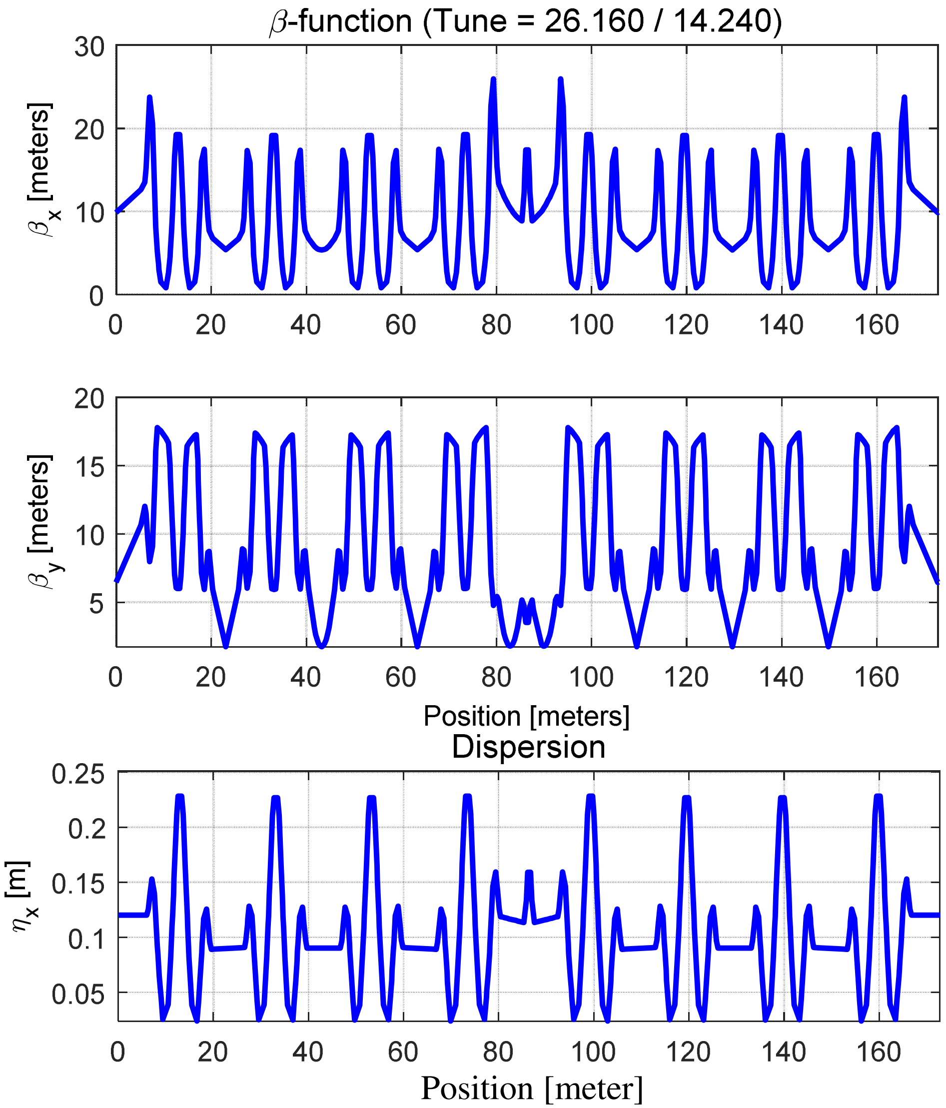


Storage ring
Energy: 3 GeV
Max. Current: 500 mA
Circumference: 518.4 m
Cell units: 24 DBA
Harmonic number: 864
Radio freq. : 499.654 Hz
Emittance: 1.6 nm-rad

Booster ring
Energy: 150 MeV to 3 GeV
Circumference: 496.8 m
No of period: 6
Harmonic number: 828
Rep rate: 3 Hz

The beam size at 7 m straight center is 120 $\times$ 5 μm^2 (1% coupling).

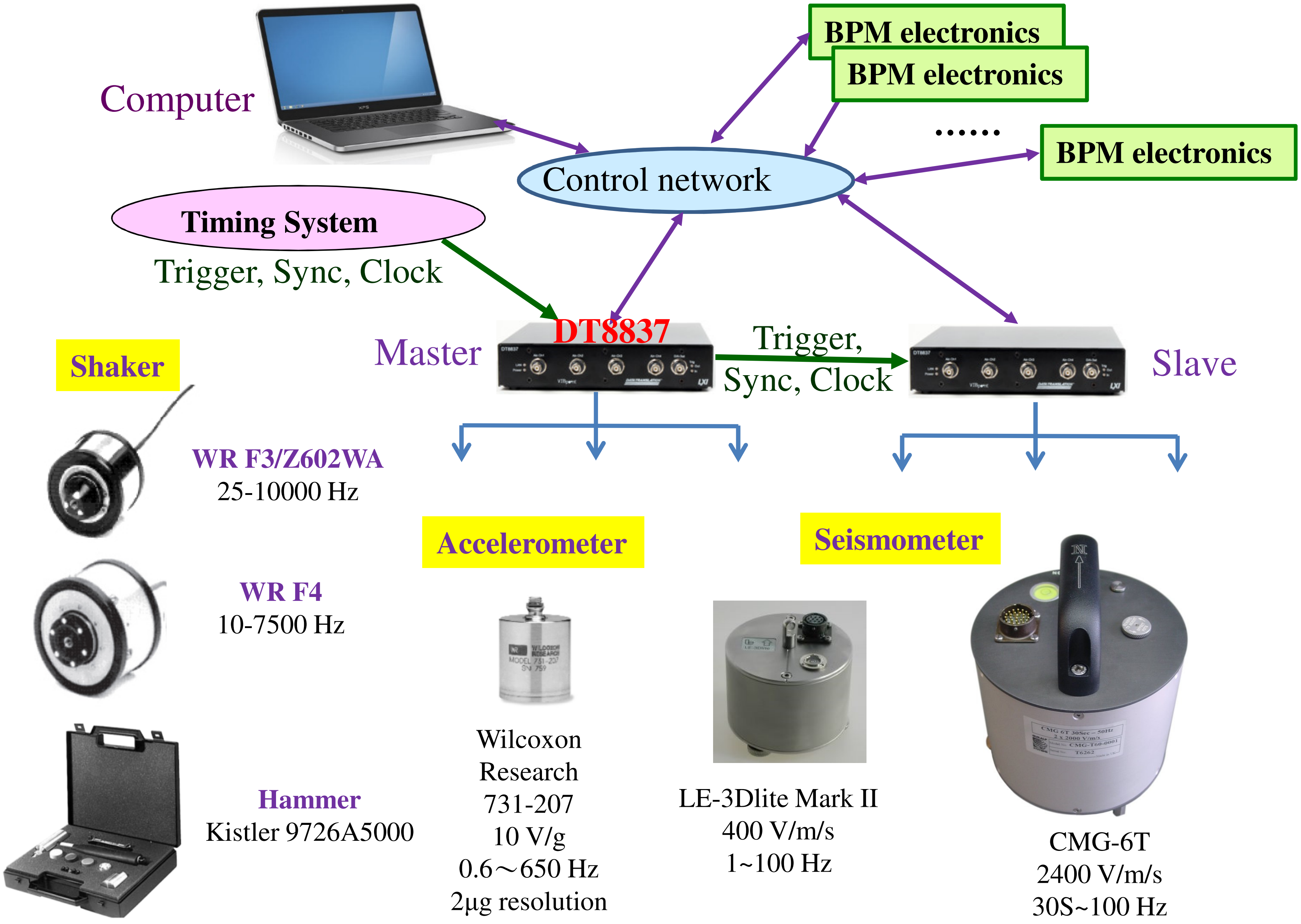
Storage ring lattice (double vertical beta waist lattice)



Vertical beta is reduced to accommodate small gap IDs in three long straights by inserting quads in the centers.

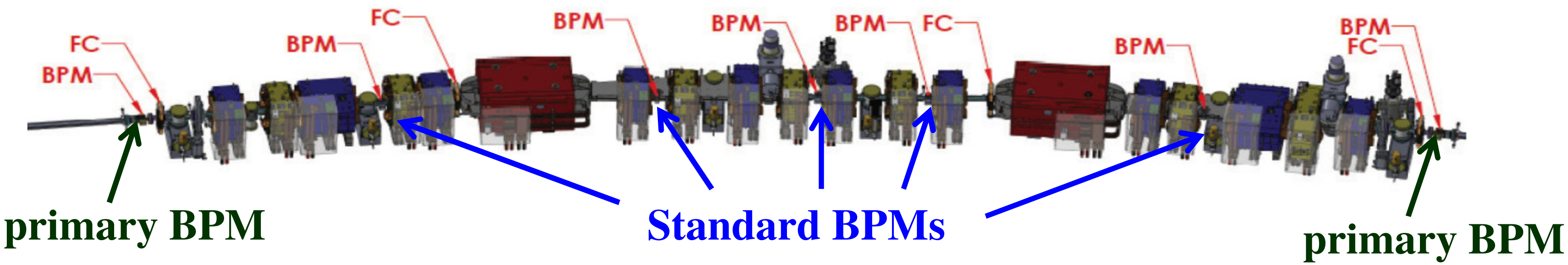
Circumference [m]	**518.4**
Beam energy E [GeV]	**3.0**
Nat. emittance ε_x [nm-rad]	**1.6**
Betatron tune ν_x/ν_y	**26.16/14.24**
Nat. chromaticity ξ_x/ξ_y	**-75/-29**
RF frequency [MHz]	**499.654**
Harmonic number	**864**
Momentum compaction α_1/α_2	**2.4×10^{-4}/ 2.1×10^{-3}**
Energy spread σ_E/E	**8.86×10^{-4}**
Energy loss/turn (dipole) [MeV]	**0.8527**
Straight section	**12m(x3) 5m(x2x3) 7m(x18)**

Measurement tools

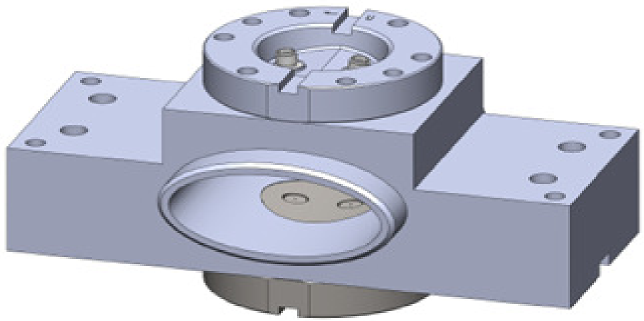


Beam position monitoring (BPM) system

7 BPMs in each lattice cell
(5 standard BPMs plus 2 primary BPMs near the ID straight sections.) .

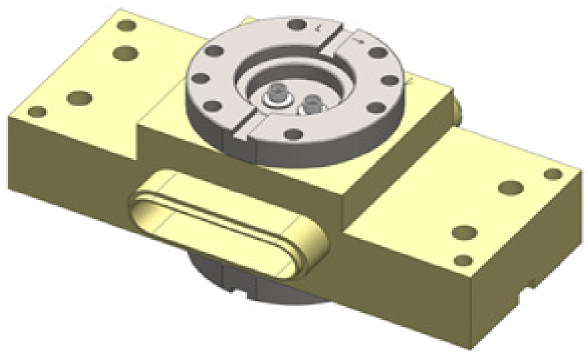


Standard BPM at arc section



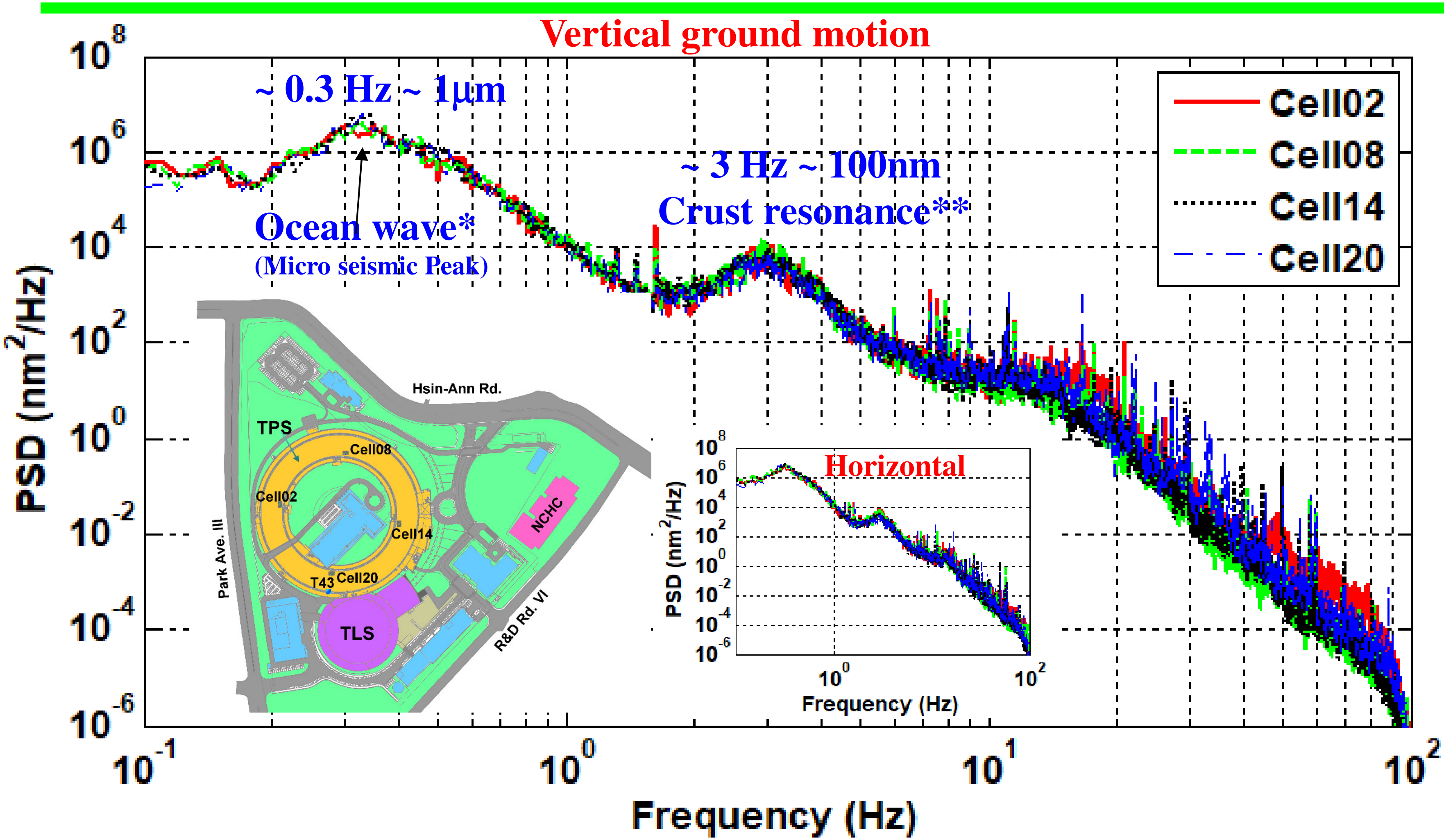
Size 68*30 mm
Button 7.4 mm
kx/ky 13.8/12.73

Primary BPM at straight line



Size 64*16 mm
Button 7.4 mm
kx/ky 6.58/8.89

Vertical ground motion in TPS tunnel



One-sided $PSD(f) = 2D(f)D^{*}(f)/T$ Integrated_RMS(f_1_f_2)=$\sqrt{\int_{f_1}^{f_2} PSD(f)df}$

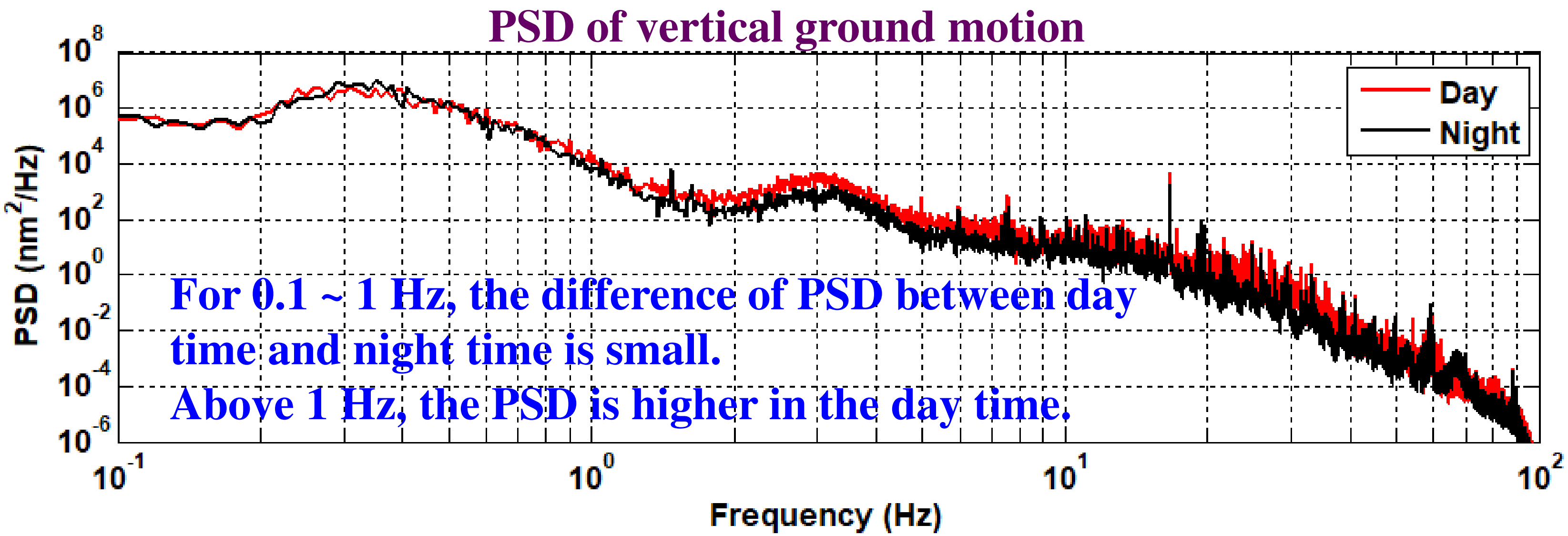
$D(f)$:Signal (D) in frequency domain T: Measuring time

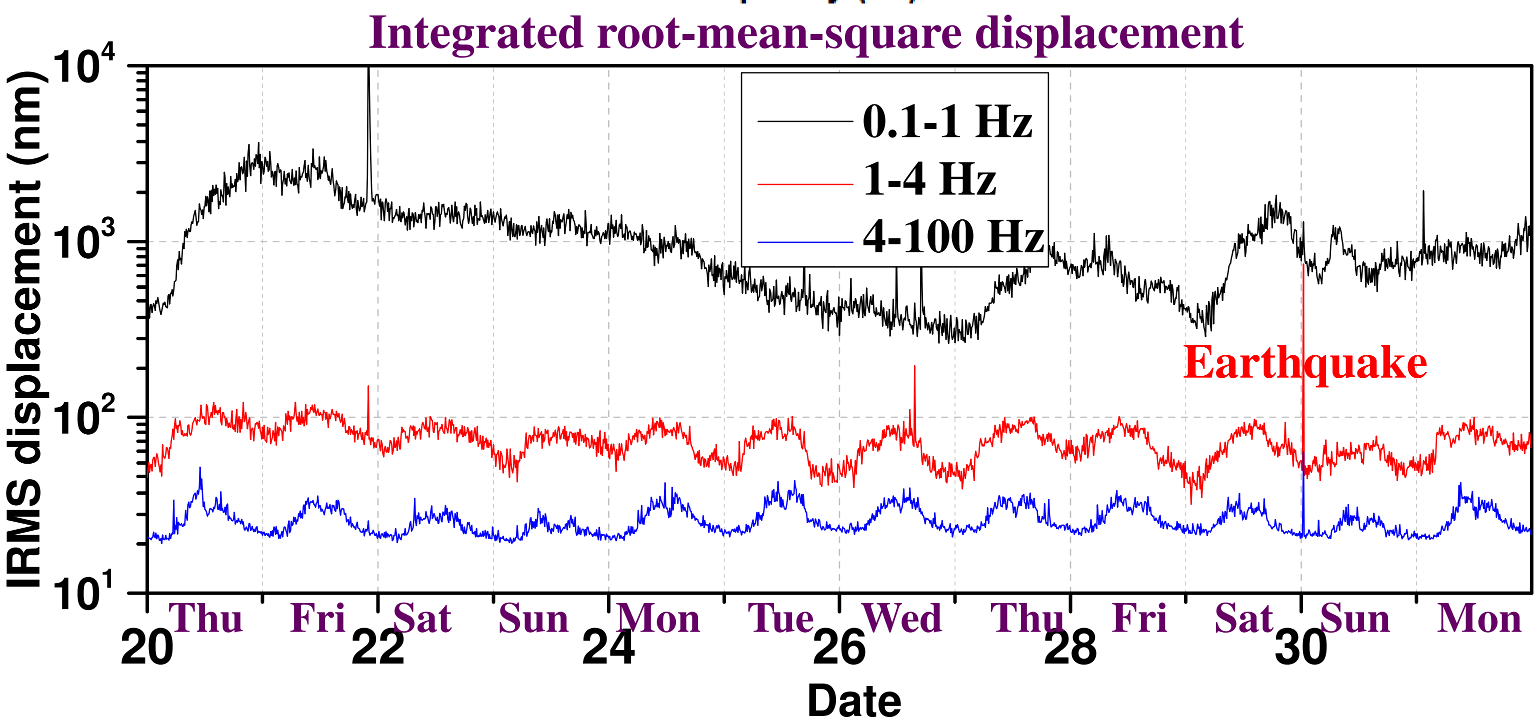
* https://www.nature.com/nature/journal/v445/n7129/pdf/nature05536.pdf

* http://onlinelibrary.wiley.com/doi/10.1029/2011JC006952/full

** http://www.desy.de/~sahoo/WebPage/Ground%20Motion.htm

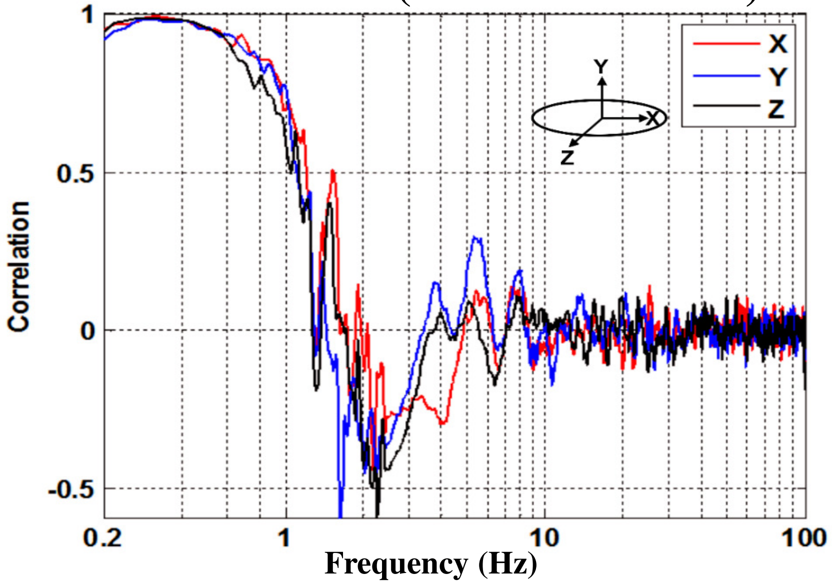
Vertical ground motion in Cell 20



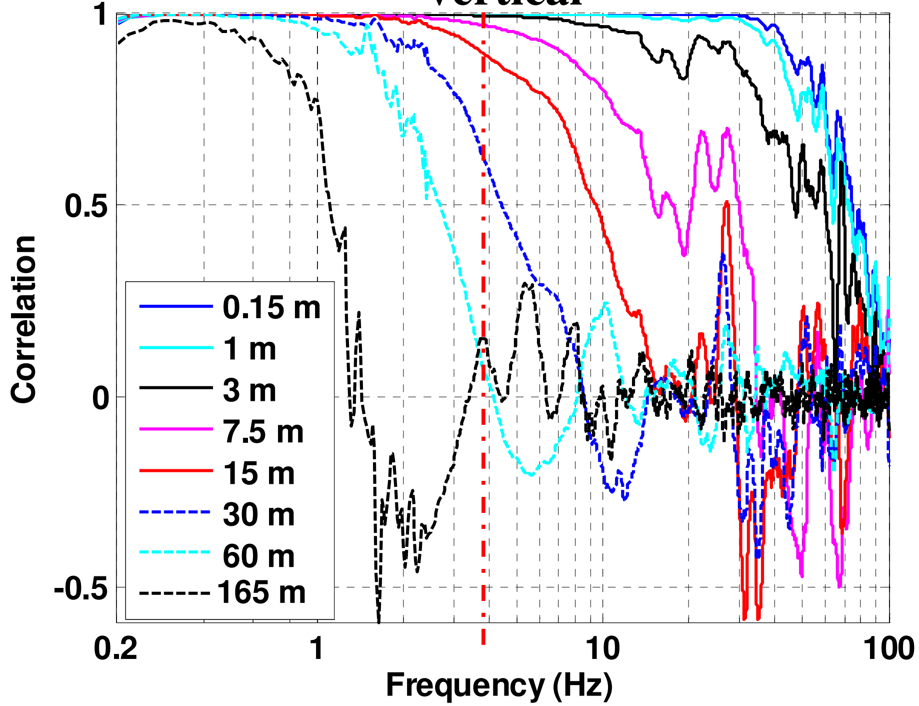


Ground motion - correlation

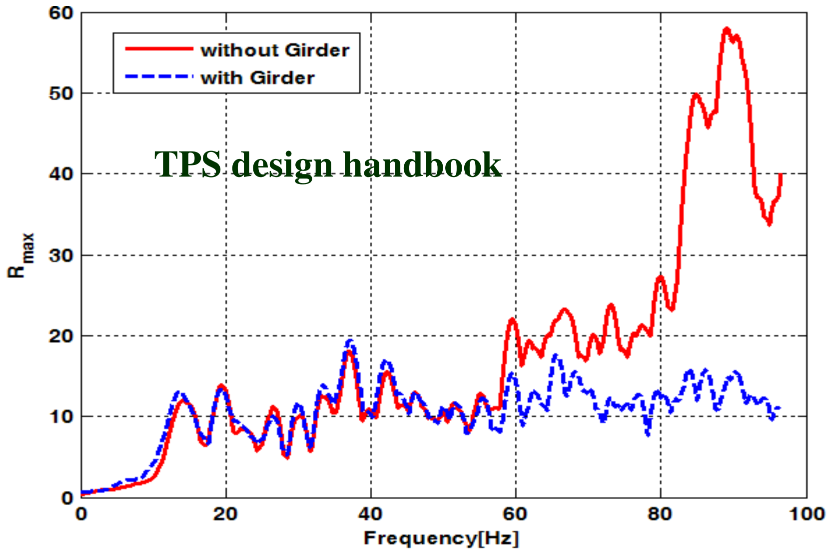
165 m (diameter of TPS)



Vertical



Amplification factor from ground motion to beam motion (assuming girder amp. factor = 1)



Cross spectral density $CSD_{12}(f) = D_1(f)D_2^*(f)/T$

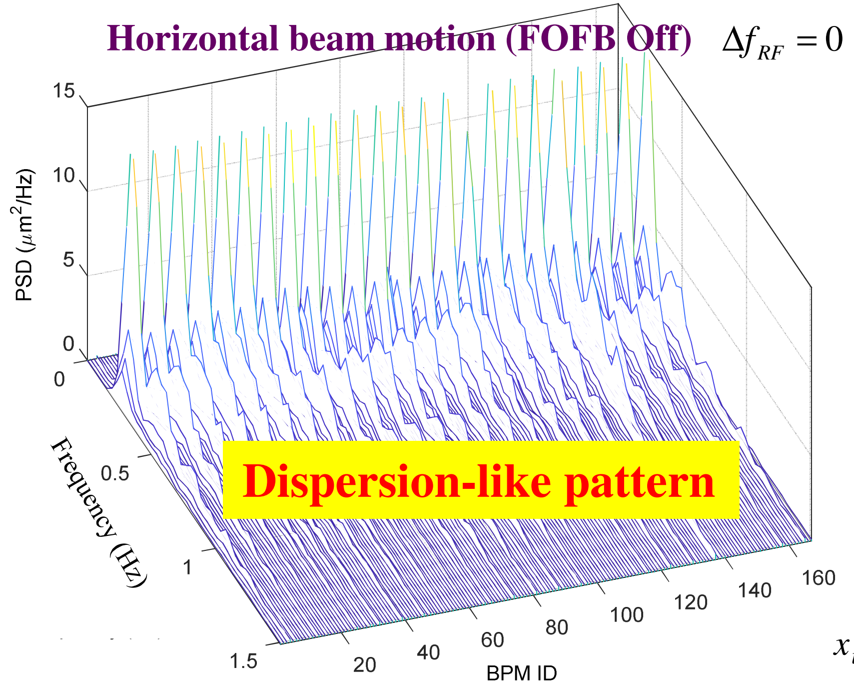
Correlation=$Re(CSD_{12}/\sqrt{CSD_{11}CSD_{22}})$

The ground motion at 0.2 -1 Hz is almost in phase in all ring.
The ground motion at 1-4 Hz is almost in phase within one cell.

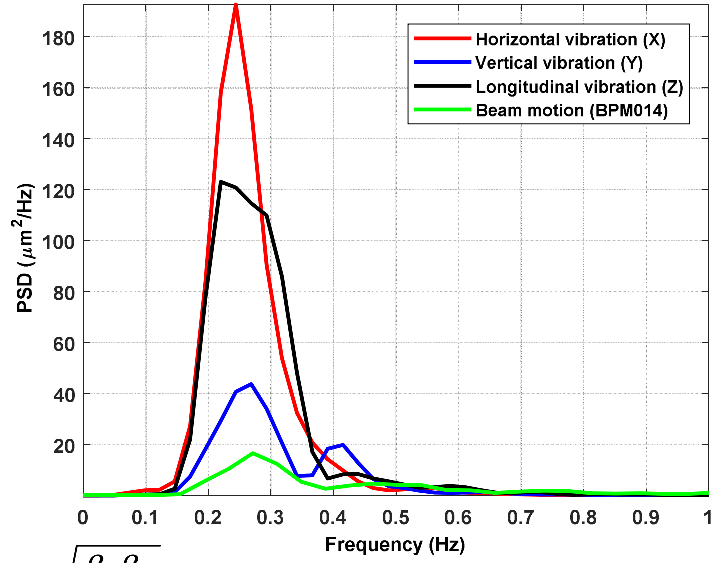
C. Collette, et.al, Phys. Rev. ST Accel. Beams 13, 072801 (2010).

Beam behavior vs. ground motion

Horizontal beam motion (FOFB Off) $\Delta f_{RF} = 0$



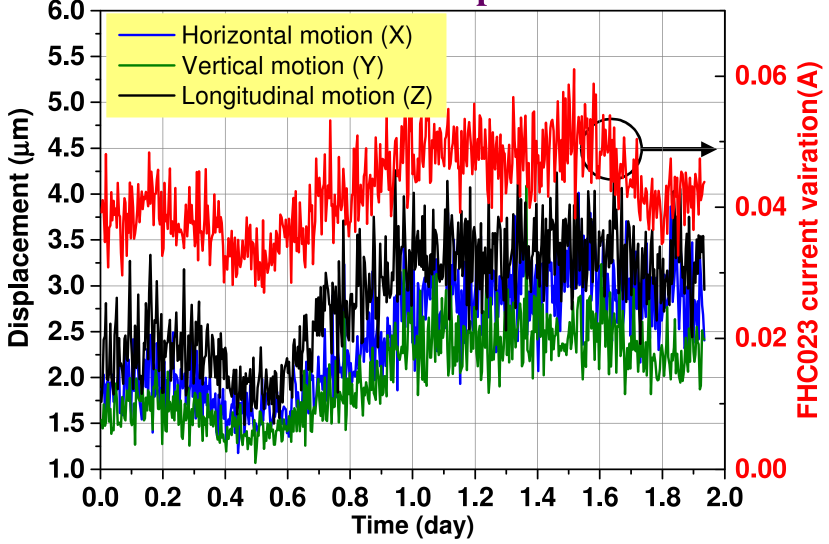
PSD of ground and beam motion (FOFB Off) $\Delta f_{RF} = 0$



$$x_i = \sum_j \left(\frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \theta_j \cos(|\phi_i - \phi_j| - \pi\nu) - (1/\alpha_1)(\theta_j \eta_j / C)\eta_i \right)$$

$$\delta = \frac{1}{\alpha}\left(\frac{\Delta C}{C} - \frac{\Delta f_{RF}}{f_{RF}}\right), \quad \Delta C = \sum_j \theta_i \eta_i \approx \sum_j K_j L_j \eta_j \langle \Delta x_{quad} \rangle$$

FOFB On **Band pass 0.1 ~ 0.5 Hz**



0.3 Hz horizontal beam motion is observed with dispersion-like pattern. The frequency spectrum is similar with that of ground motion.

During the routine operation, FOFB is on. This motion is eliminated by FOFB. The amplitude of beam motion is proportional to the current variation of corrector power supply (CPS).

The trend of current variation of CPS is similar to the ground motion displacement for 0.1-0.5 Hz.

Orbit perturbation due to crane operation - Horizontal

Error source estimation in horizontal axis

vs. crane position in TPS

Time: 2016/02/13 22:25-22:45

During the movement of a crane, the orbit is disturbed. From the source analysis by response matrix between the correctors and BPMs, the sources come from the location of original parking position and new parking position.

Orbit perturbation due to the movement of crane - Vertical

Error source estimation in vertical axis

vs. crane position in TPS

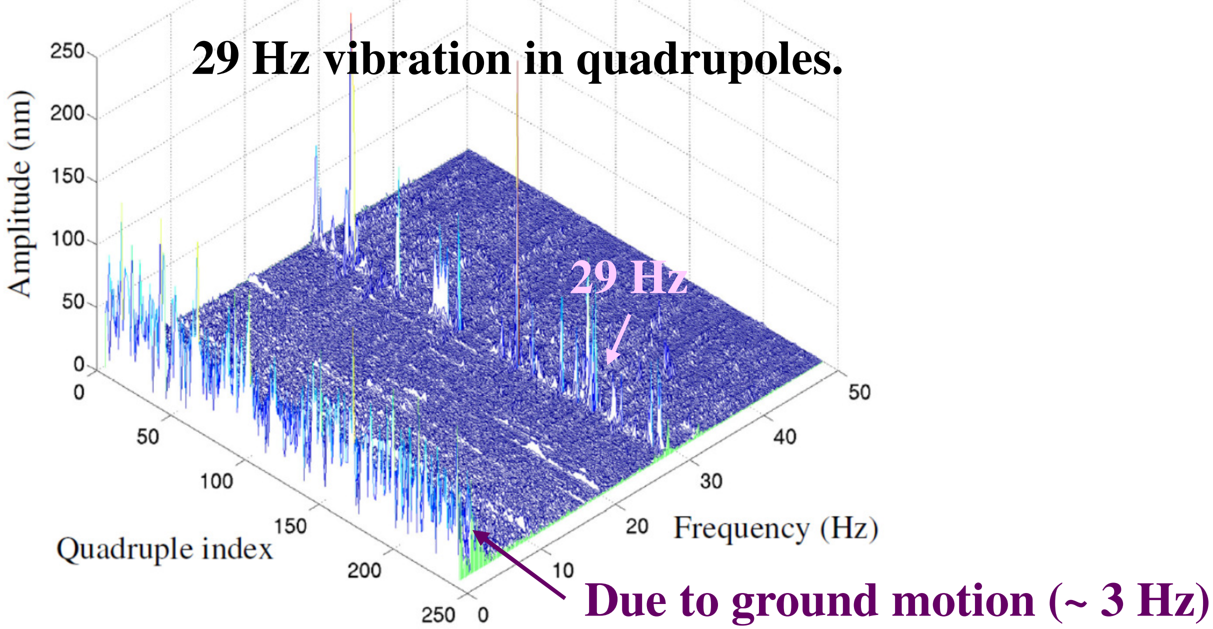
Time: 2016/02/13 22:25-22:45

Summary of ground motion to the beam motion

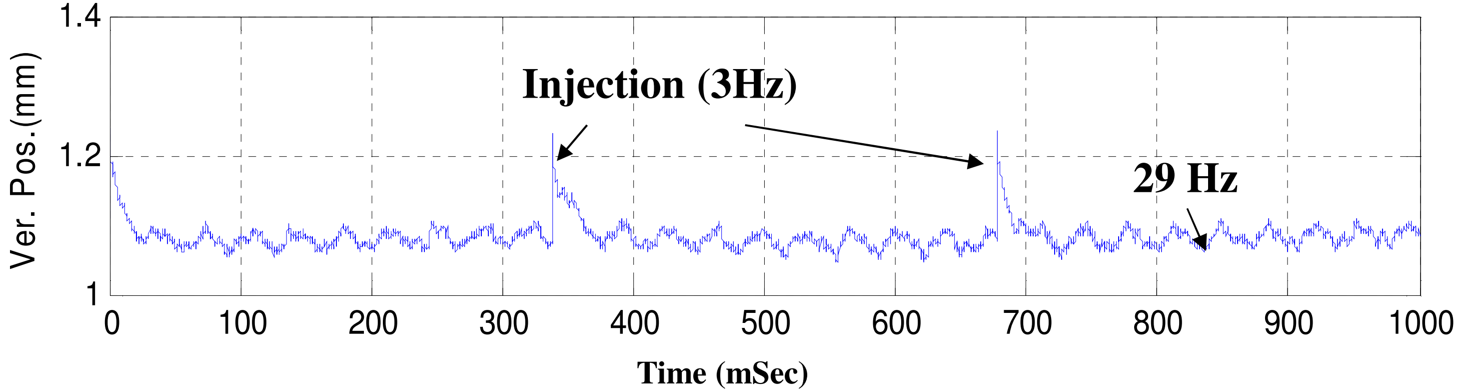
- ✓ **For the frequency between 0.1 to 1 Hz, the integrated rms ground motion is in the order of μm. The motion is almost coherent in all ring.**
- ✓ **The horizontal ground motion between 0.1 to 0.5 Hz disturbs the beam with dispersion-like pattern without feedback. Path length is changed due to horizontal kick in quadrupoles in dispersion region and thus energy is varied without rf frequency compensation. Lower alpha lattice is more prominent.**
- ✓ **For the frequency between 1 to 4 Hz, the integrated rms ground motion is < 100 nm in vertical. The components motion excited by the ground is almost in phase within one cell.**
- ✓ **The location variation of the crane disturbs the beam orbit.**
- ✓ **Thickness of the floor slab is 160 cm in the tunnel and 80 cm in the experiment hall, respectively. The increase of the thickness of floor slab can reduce the ground motion induced by mechanical vibration, especially higher than 4 Hz.**

Quadrupoles vibration vs. Beam motion

Vertical quadrupole vibration



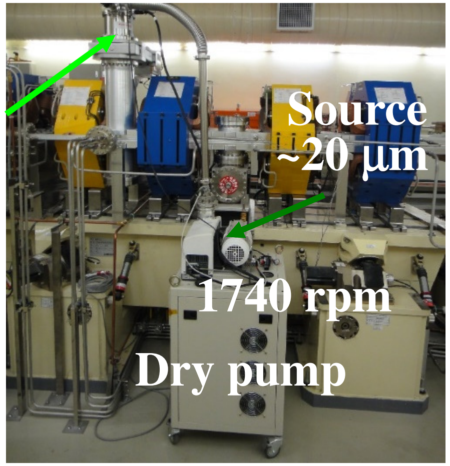
Vertical beam motion in BPM011 (during beam commissioning in 2015)



29 Hz quadrupoles vibration and beam motion were observed during beam commissioning in 2015.

Where is the 29 Hz vibration from ?

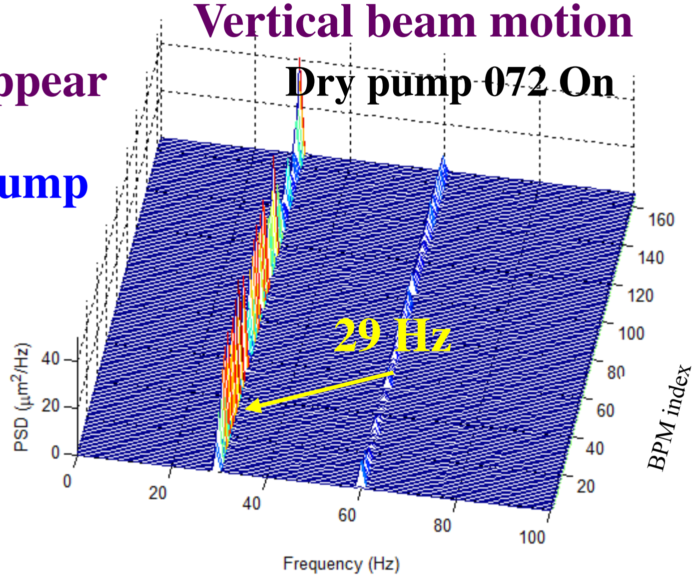
TPM



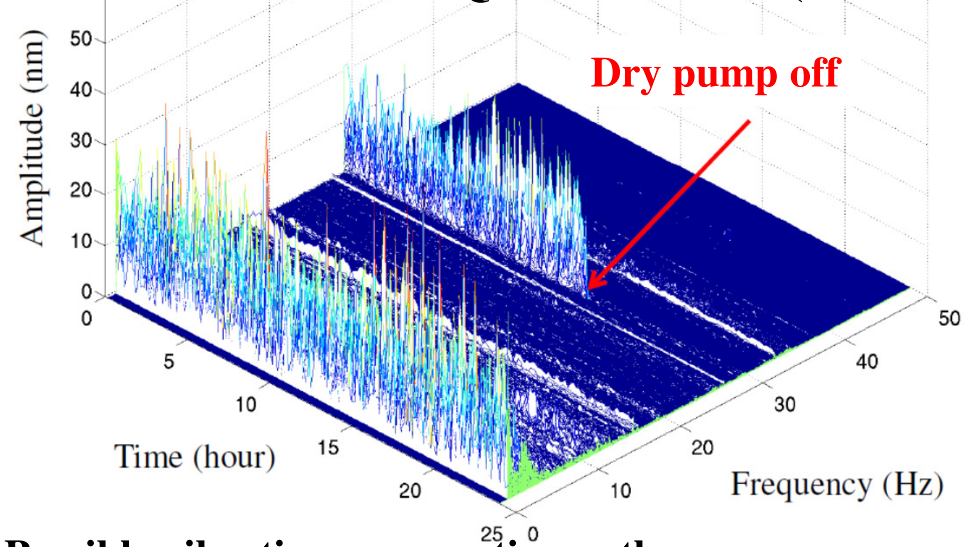
Pump off → 29 Hz disappear

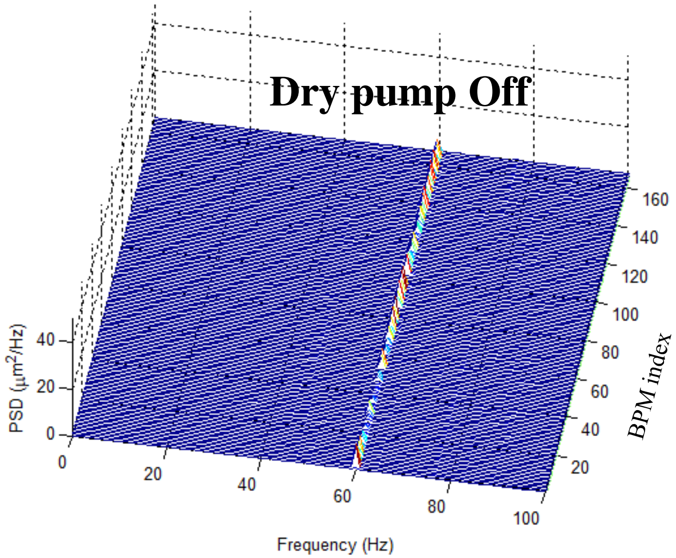
TMP: turbo molecular pump

Vertical beam motion



Vibration of QS5-2 in cell 21 (2015/3/24)





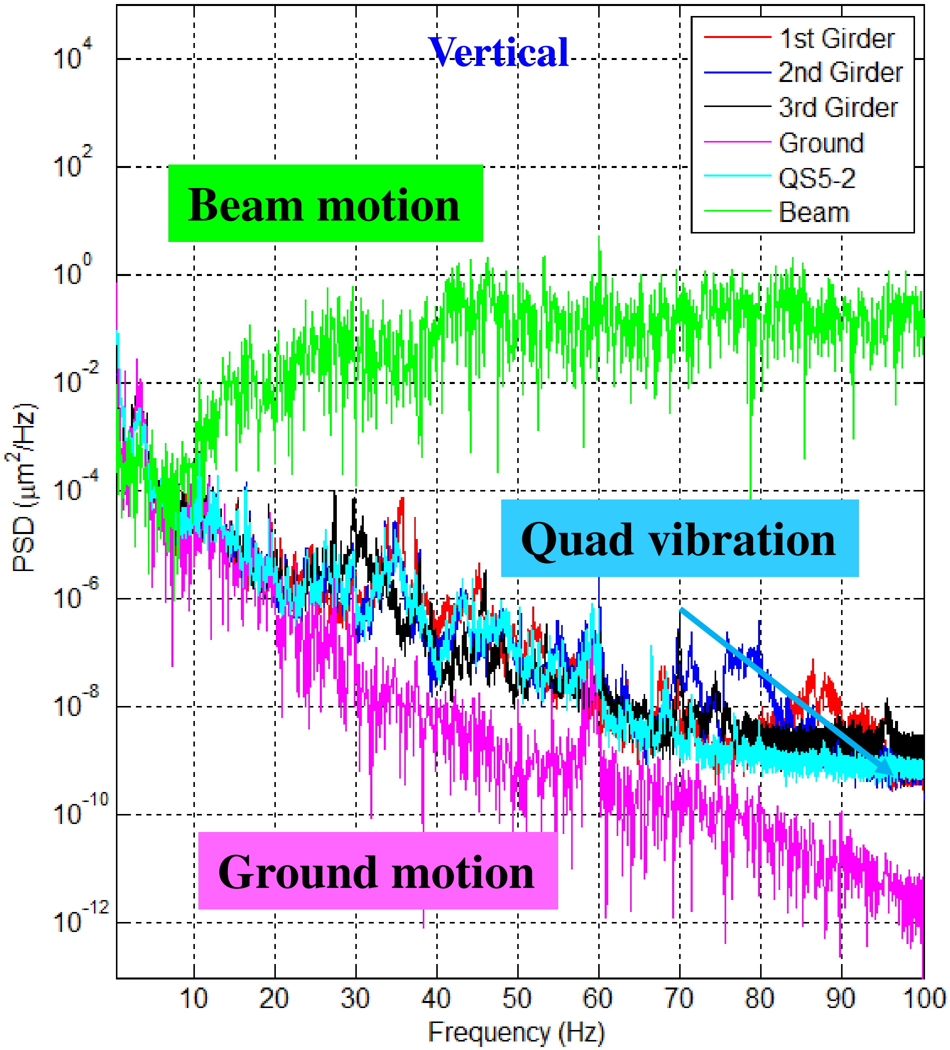
Possible vibration propagation paths

1. Dry pump → pipe → TMP → vacuum chamber → girder→ quadrupole → beam ??
2. Dry pump → pipe → TMP → vacuum chamber → beam ??

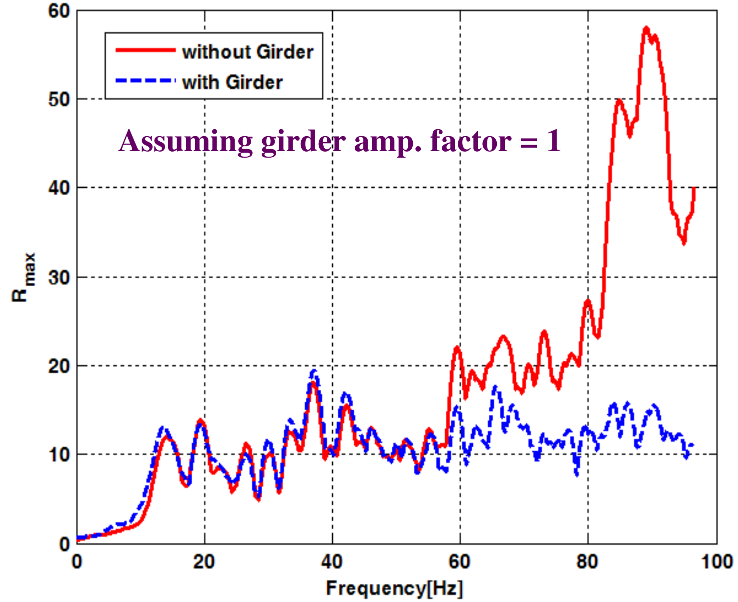
Sakuo Matsui et. al, Jpn. J. Appl. Phy. 42, L338-L341 (2003)

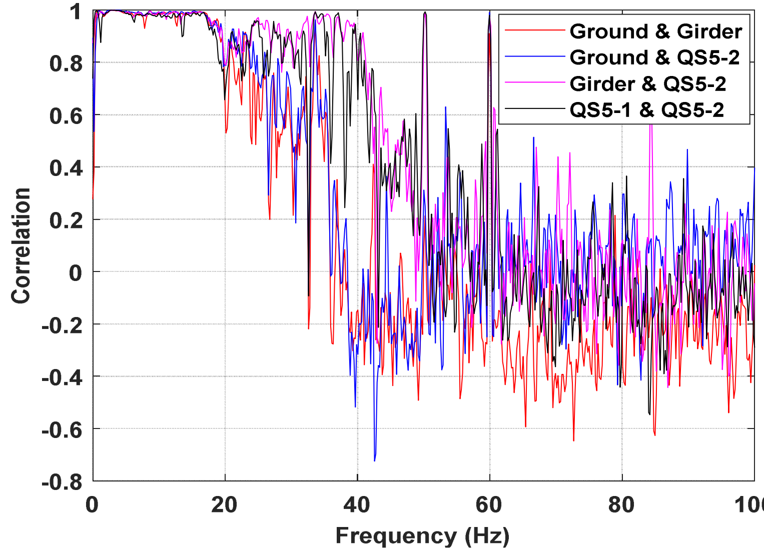
PSD and correlation between beam, girders, magnets and ground

The spectra of beam motion and quad vibration show amplification factors are larger at high frequency.

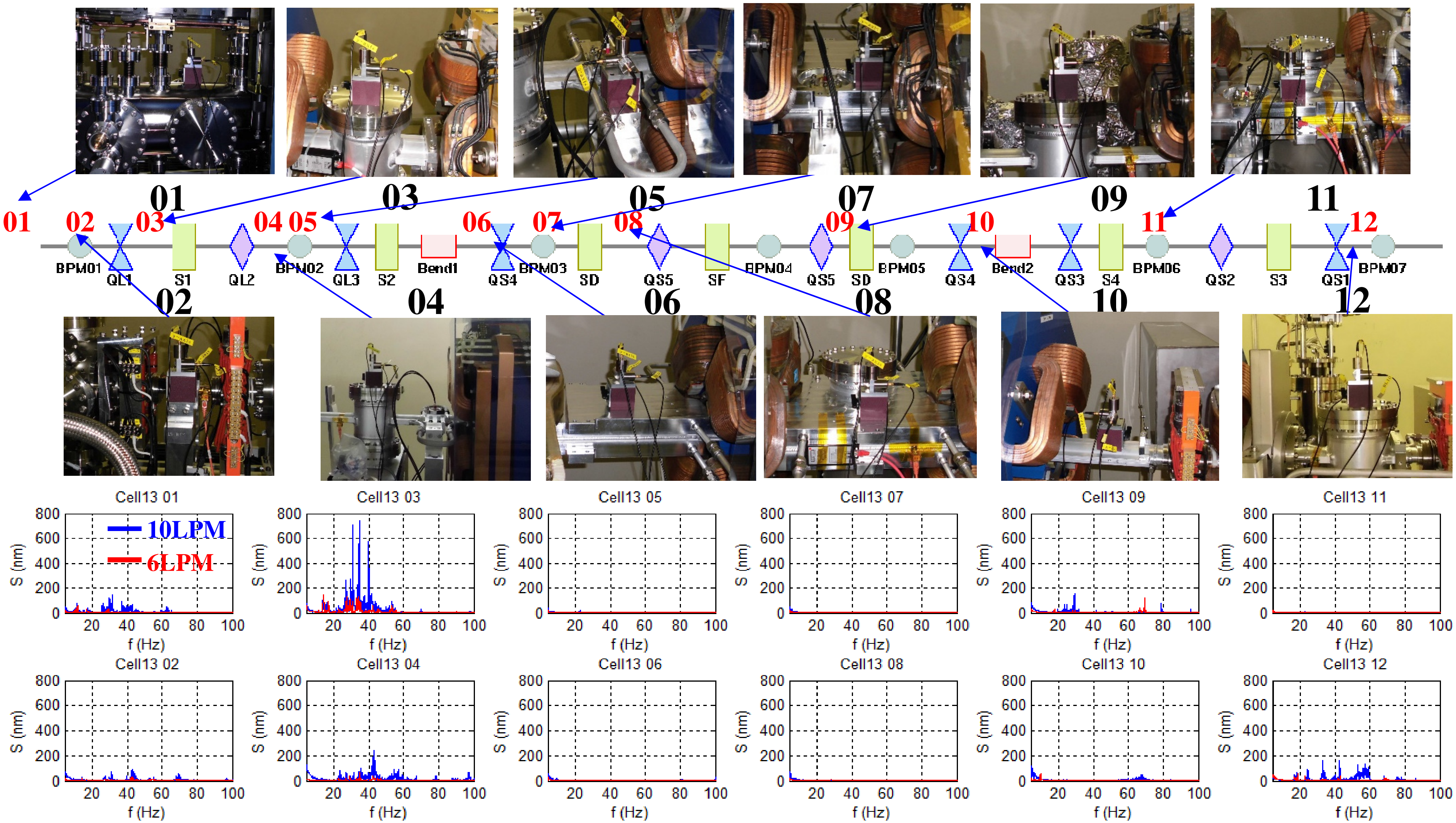


Amplification factor from ground motion to beam motion





The vibration of vacuum chamber with 6/10 LPM water flow



As the water flow rate decreases from 10 LPM to 6 LPM, the amplitudes of chamber vibration become ~ 1/3 around 40 Hz from cooling water induced chamber vibration.

December 13, Section 5, 08:30 - 10:00 Sakuo Matsui et. al, Jpn. J. Appl. Phy. 42, L338-L341 (2003)

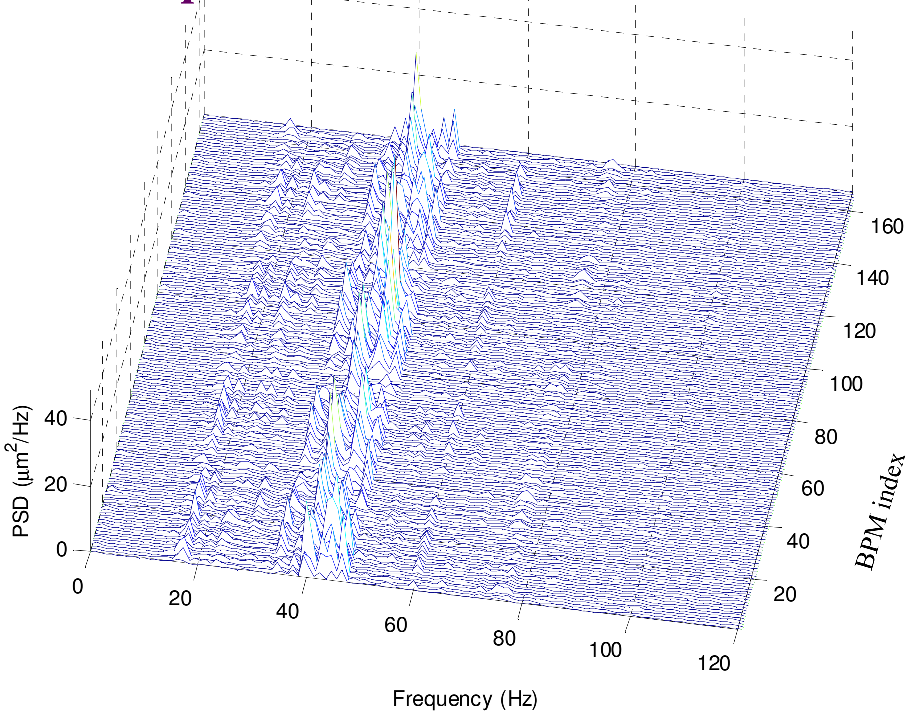
Flow rate of cooling water in vacuum chamber vs. beam motion

Horizontal plane

Water flow: 10 LPM

2015/12/22 17:51:12
Beam current= 27.1 mA

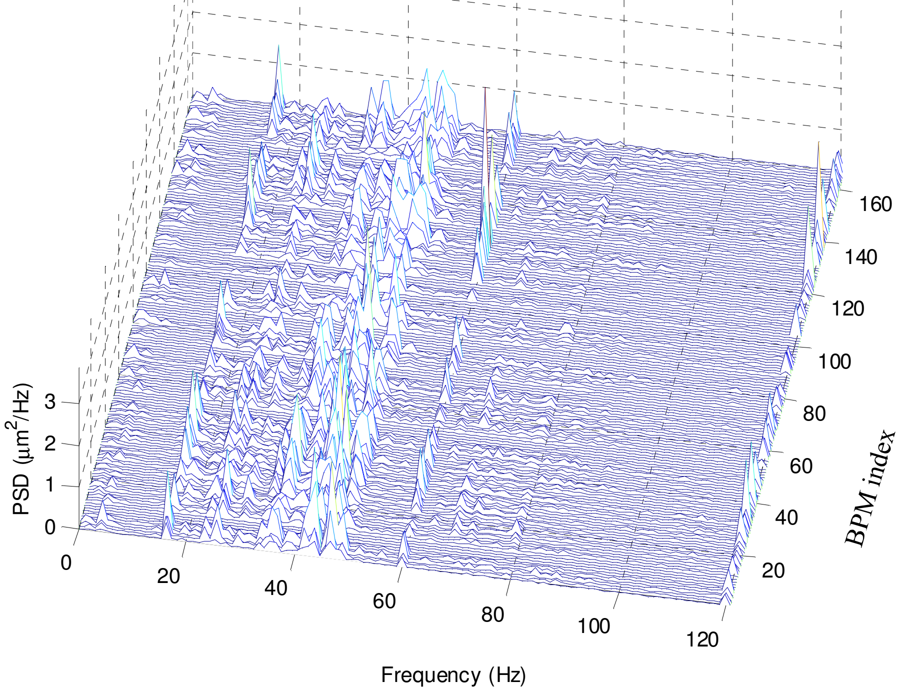
Spectrum of horizontal beam motion



Water flow: 6 LPM

2016/03/17 14:07:24
Beam current= 29.3 mA

Spectrum of horizontal beam motion



As the cooling water flow rate decrease from 10 LPM to 6 LPM, the PSD of the horizontal beam motion becomes ~ 1/10 (amplitude become ~ 1/3)

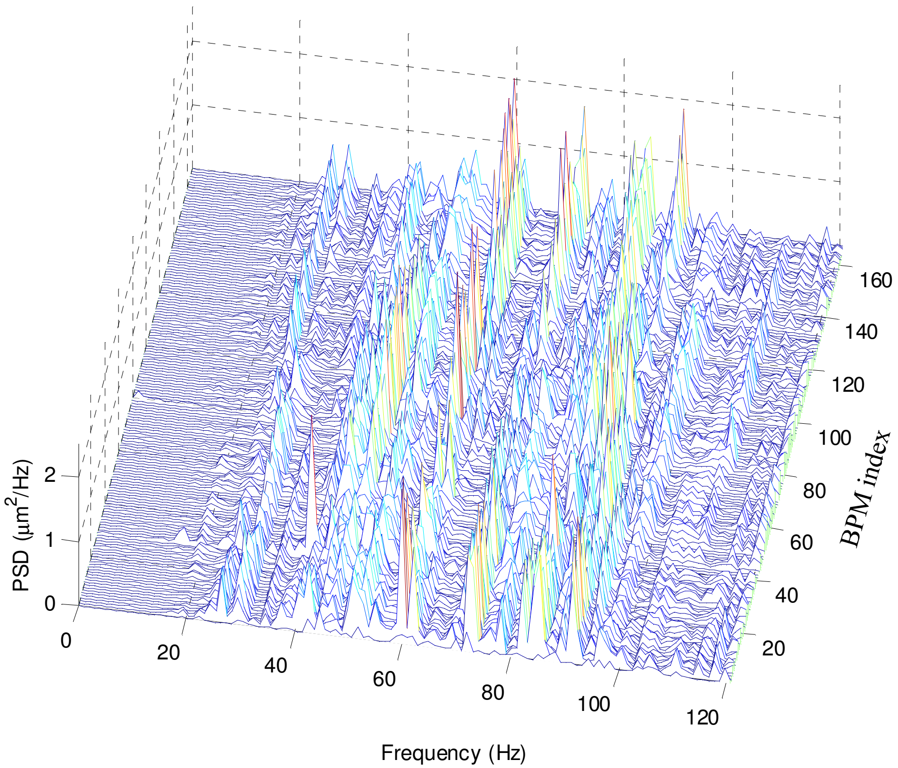
Mechanism: vacuum chamber vibration → eddy current → magnetic field → beam motion

Flow rate of cooling water in vacuum chamber vs. beam motion

Vertical plane

Water flow: 10 LPM

2015/12/22 17:51:12
Beam current= 27.1 mA

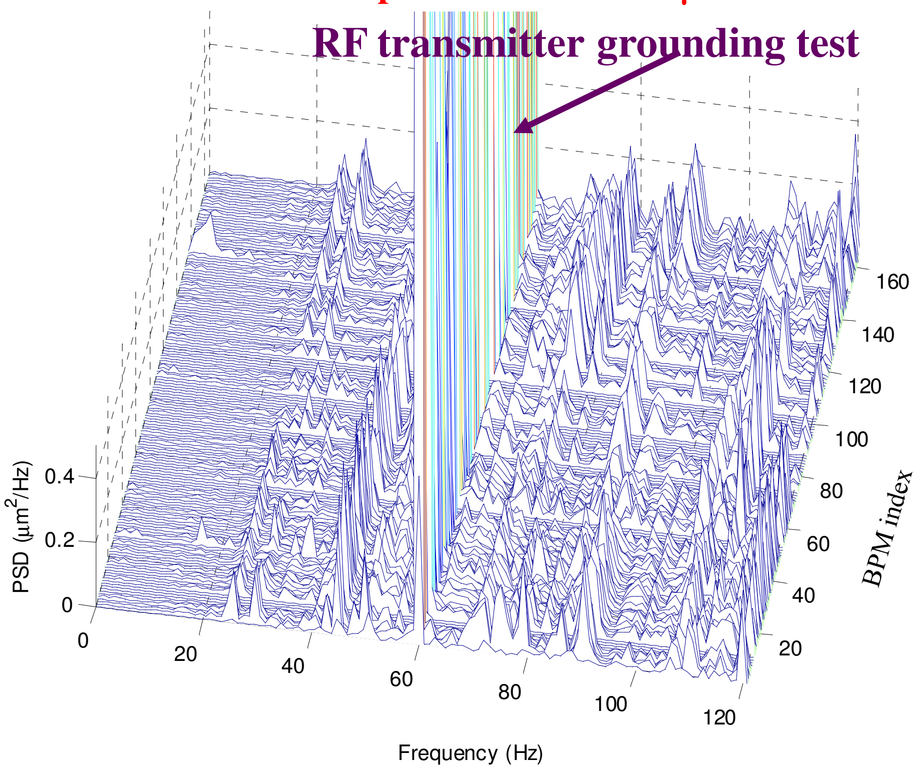


Water flow: 6 LPM

2016/03/17 14:07:24
Beam current= 29.3 mA

The peak of 60 Hz ~10 $\mu m^2/Hz$

RF transmitter grounding test

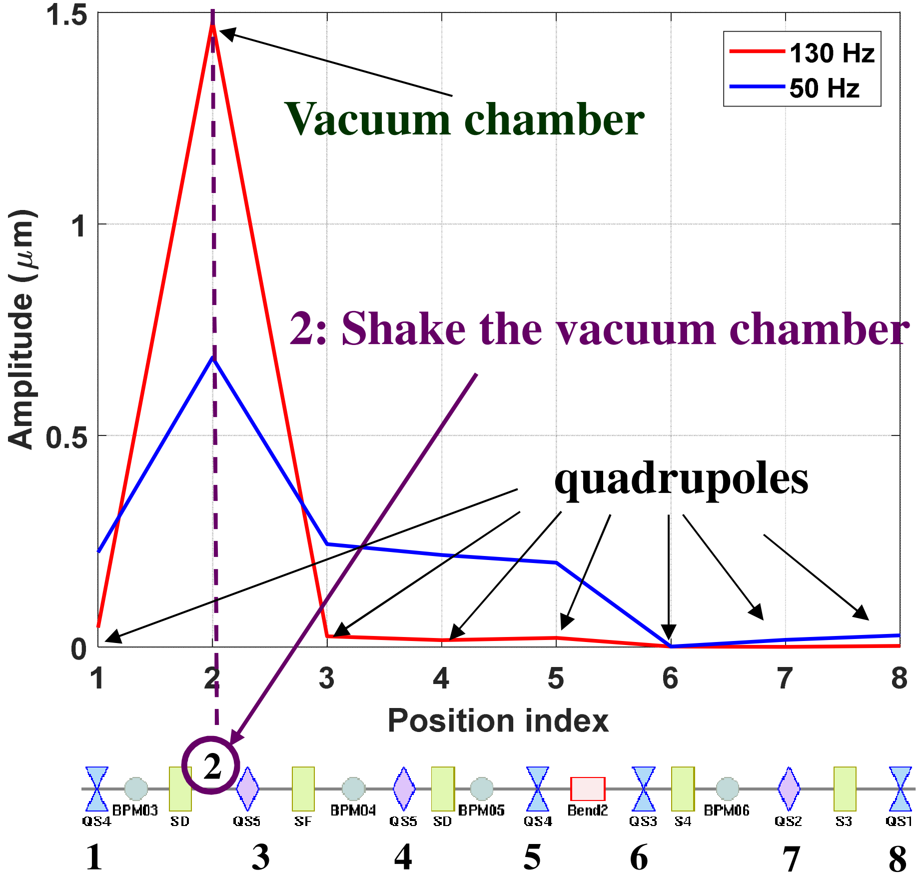


As the flow rate of cooling water decreases from 10 LPM to 6 LPM, the PSD of the beam motion becomes ~ 1/5 (amplitude become ~ 1/2) Remark: Exclude 60 Hz

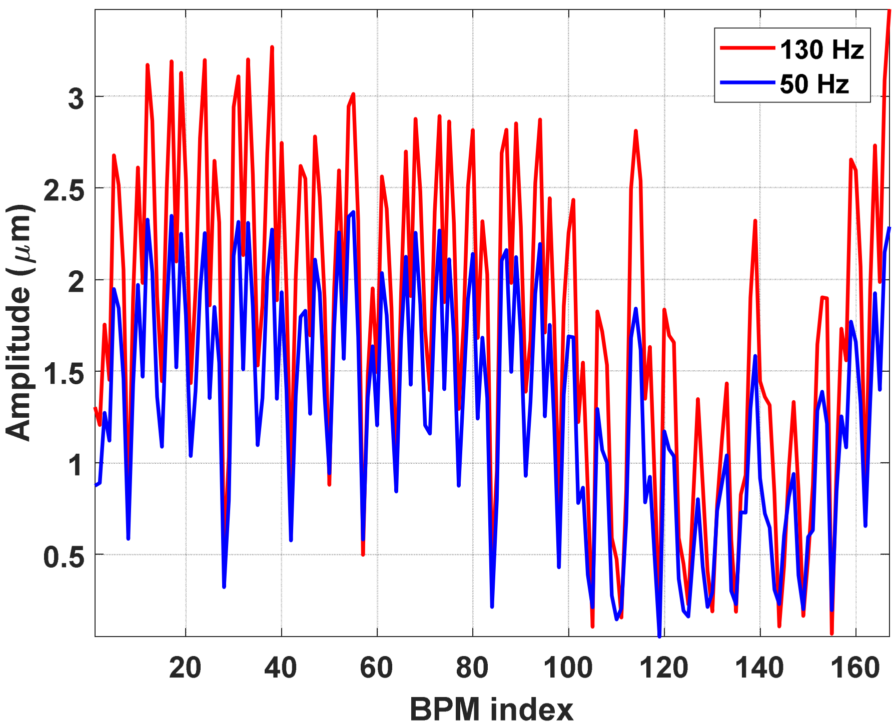
To reduce the beam motion caused by water flow, flow rate reduced from 10 to 6 LPM during routine operation to optimize the induced beam motion and cooling capacity.

Shaking the vacuum chamber vs. beam motion (Vertical)

Vibration of vacuum chamber (2) & quad (1,3,…7)



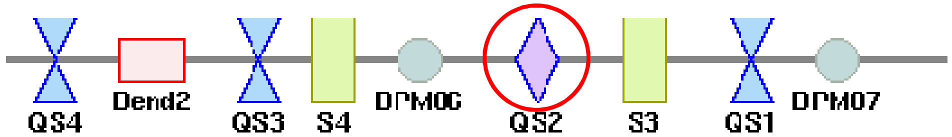
Beam motion



Shaking vacuum chamber at 130 Hz, the vibration of the quadruple is negligible.
Most of the beam motion is contributed by the vibration of vacuum chambers.

Shake the QS2 in cell 7 at 29 Hz

Vertical direction

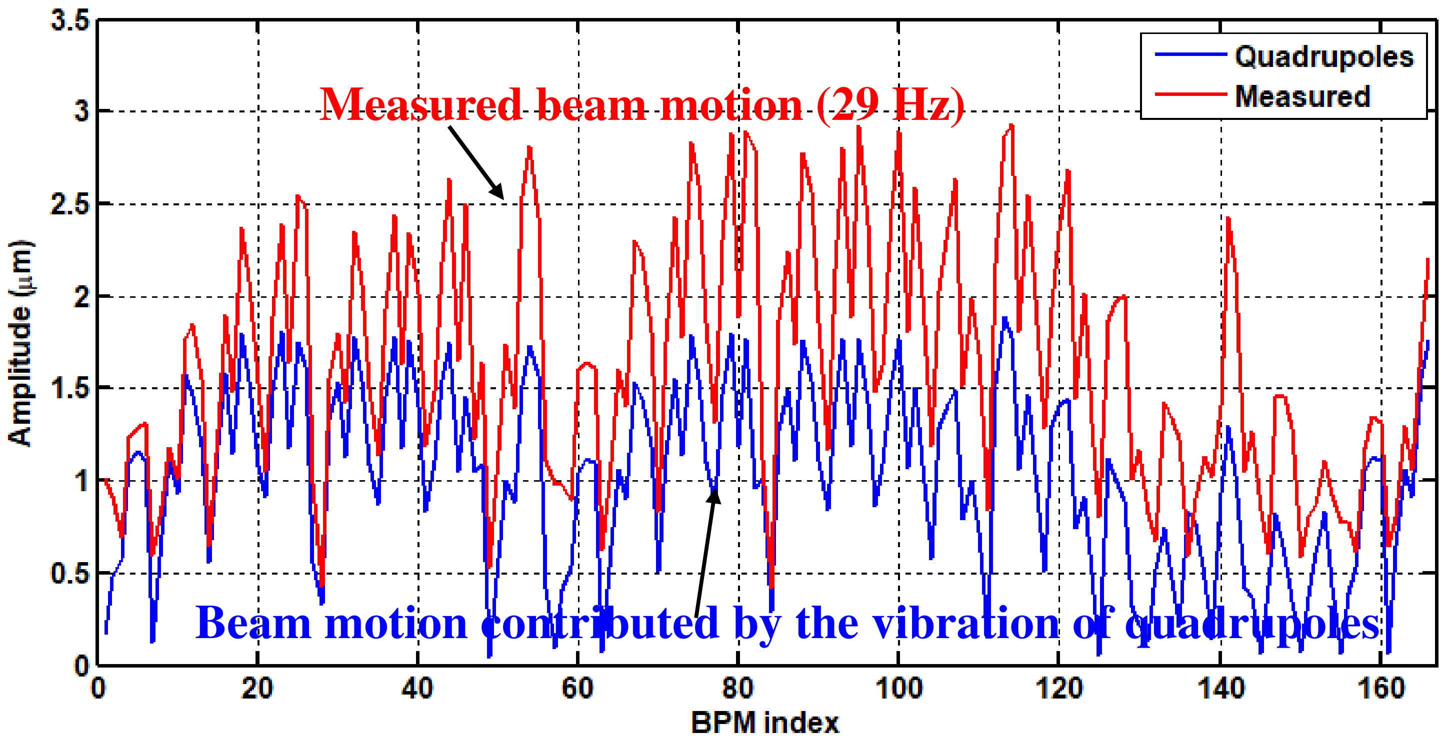


	QS4	QS3	QS2	QS1
Amplitude	398	3024	1475	1867 (nm)
Phase	3.058	0.887	0	-0.951 (Rad)

$$\theta = \frac{P_y}{P_z} = eckyL/E$$

$$\triangle y_j = \frac{\theta_i \sqrt{\beta_i \beta_j} \cos(\pi\nu - |\Psi_j - \Psi_i|)}{(2 sin\pi\nu)}$$

E: beam energy
c: light speed
k: quad strength
L: quad length
y: beam offset



f: vibration freq.
ϕ : phase of quad

$$\Delta y_j = \sum_i eck_i y_i cos(2\pi f t + \phi_i) L_i/E \sqrt{\beta_i \beta_j} \cos(\pi\nu - |\Psi_j - \Psi_i|)/(2 sin\pi\nu),$$

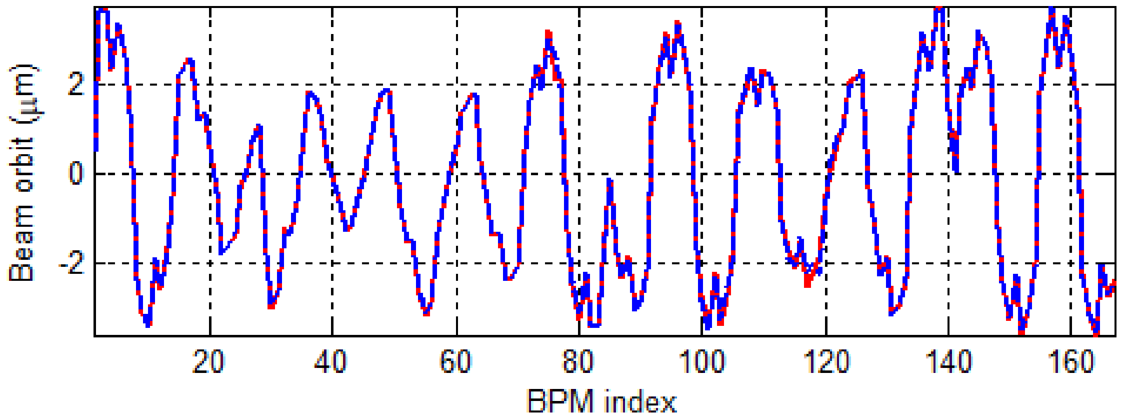
As shaking one quadruple, the nearby quadruples and vacuum chamber vibrate.
The quadruples contribution to beam motion is estimated to be ~2/3 of beam motion.

Hunting 60 Hz orbital noise in vertical plane

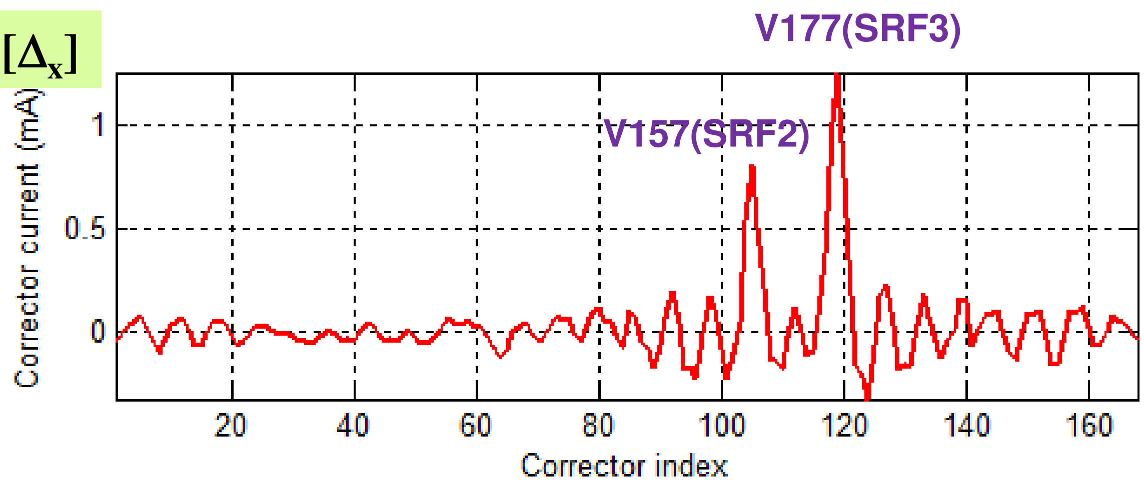
2016/03/22

Corrector vs. BPM Response Matrix R

60 Hz beam orbit



$[R]^{-1}_{BPM\text{-}Corr} * [\Delta_x]$

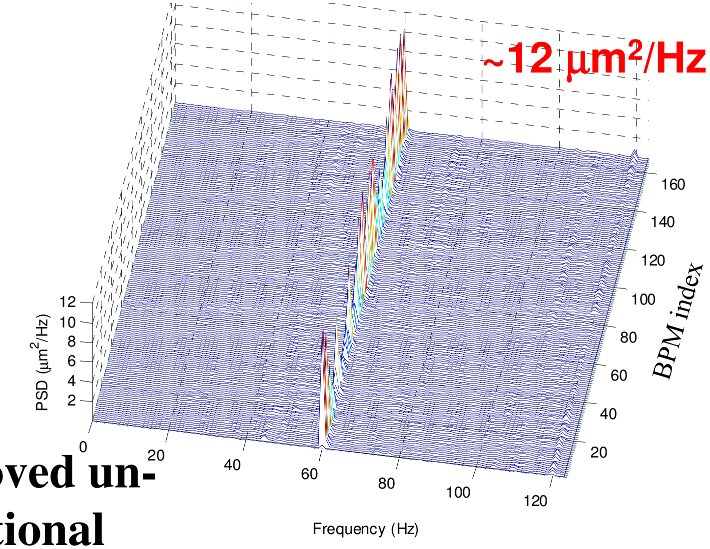


- **No obvious source from power supplies.**
- **Based on the response measurement, error sources were found at the straight sections of cell #15,17, where SRF cavities located.**

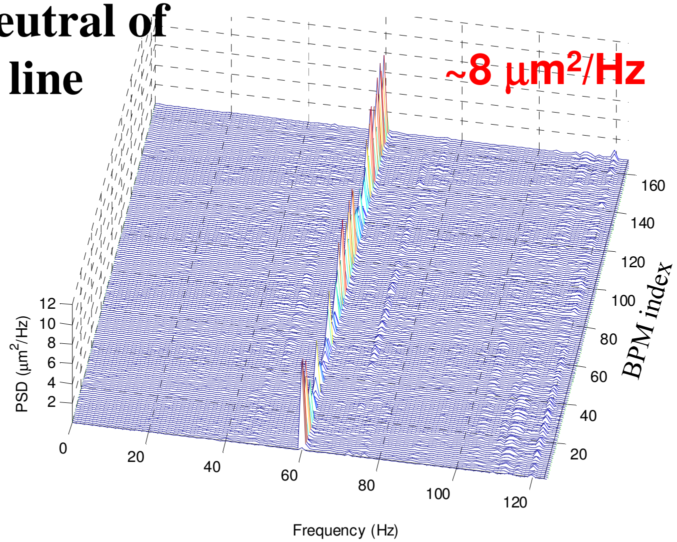
60 Hz beam motion reduced by proper grounding the SRF transmitter

2016/05/11

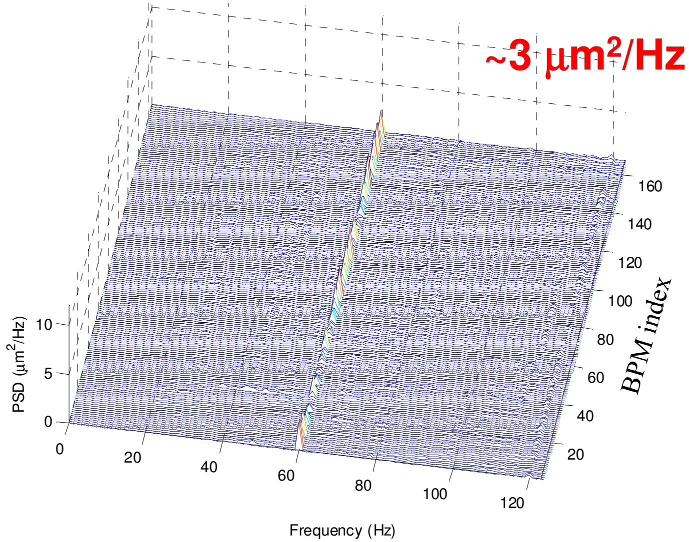
Vertical beam motion



Removed un-intentional contact between Earth and Neutral of power line



2016/06/01



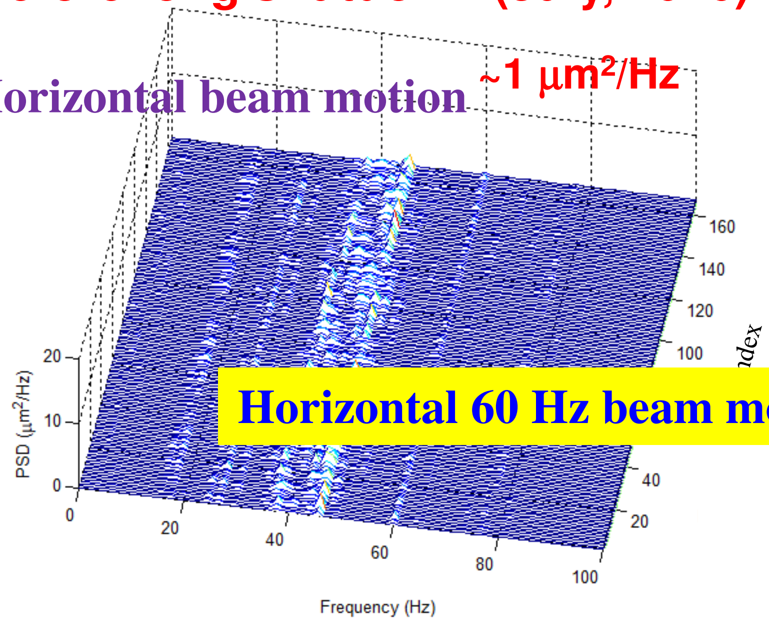
Earth connected to the local grounding bus

After proper rerouting the grounding bus of transmitters, the PSD of 60 Hz beam motion reduced to 3 $\mu m^2/Hz$.

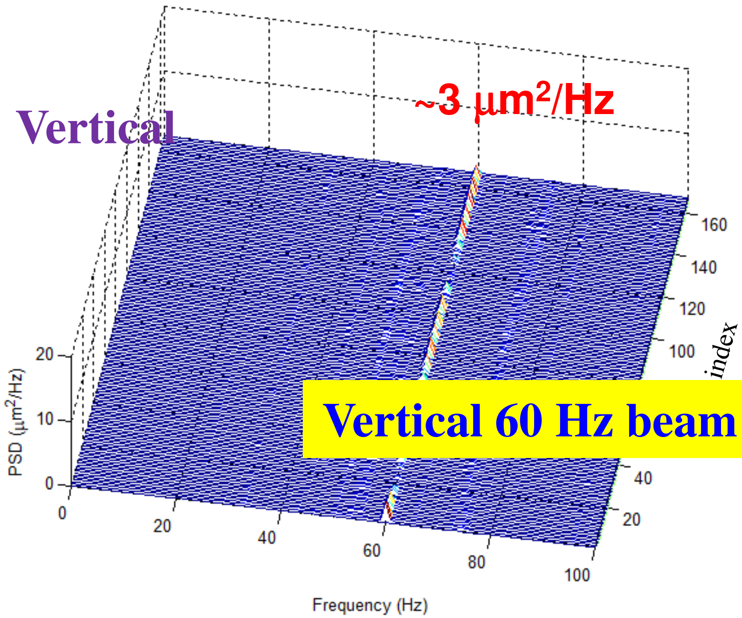
60 Hz issue due to the cooling fans

Before long shutdown (July, 2016)

Horizontal beam motion ~1 $\mu m^2/Hz$

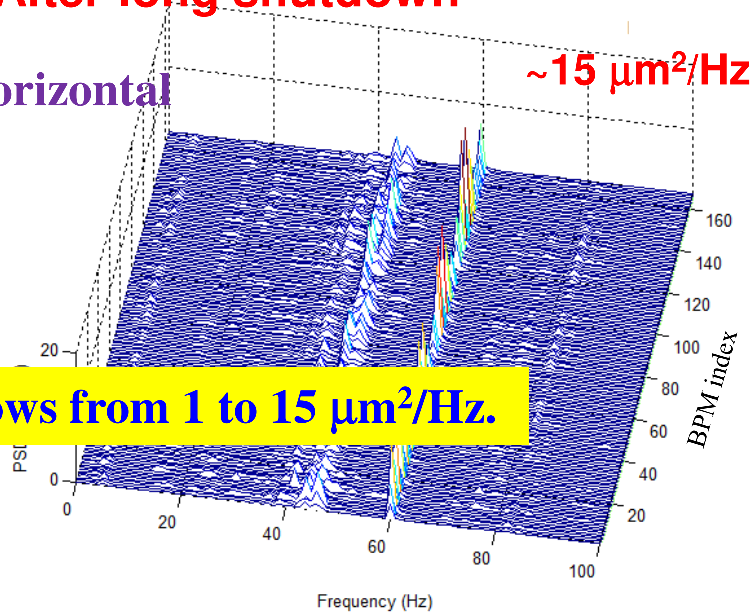


Vertical ~3 $\mu m^2/Hz$

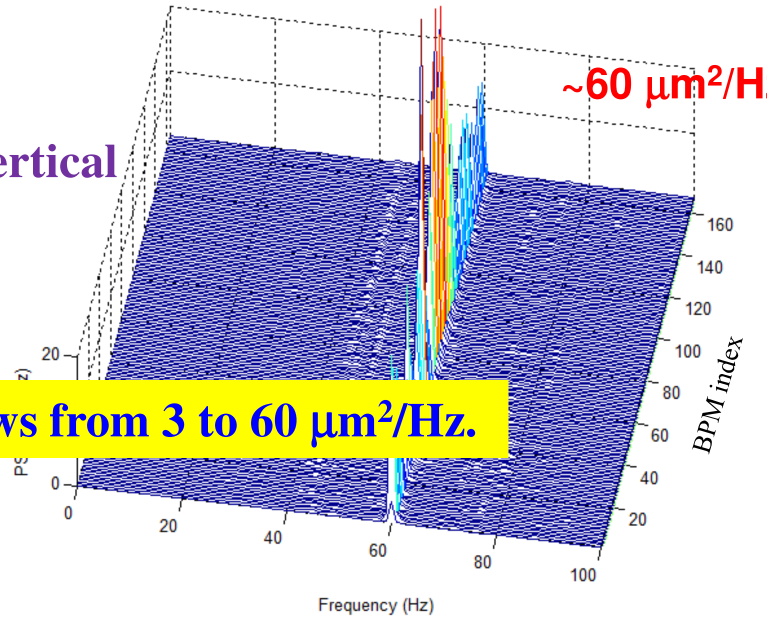


After long shutdown

Horizontal ~15 $\mu m^2/Hz$



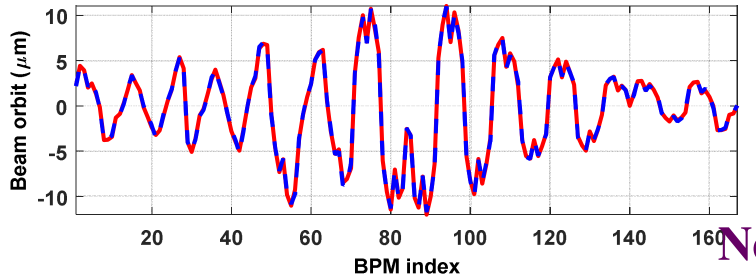
Vertical ~60 $\mu m^2/Hz$

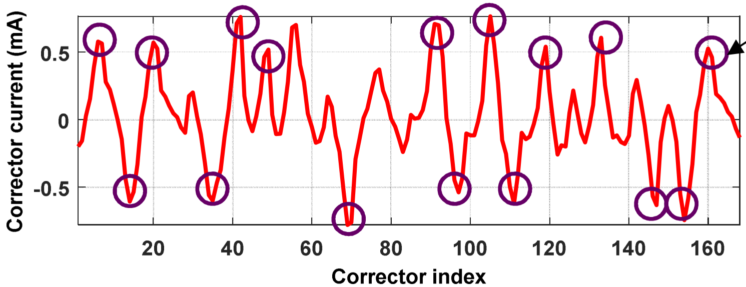


Horizontal 60 Hz beam motion grows from 1 to 15 $\mu m^2/Hz$.

Vertical 60 Hz beam motion grows from 3 to 60 $\mu m^2/Hz$.

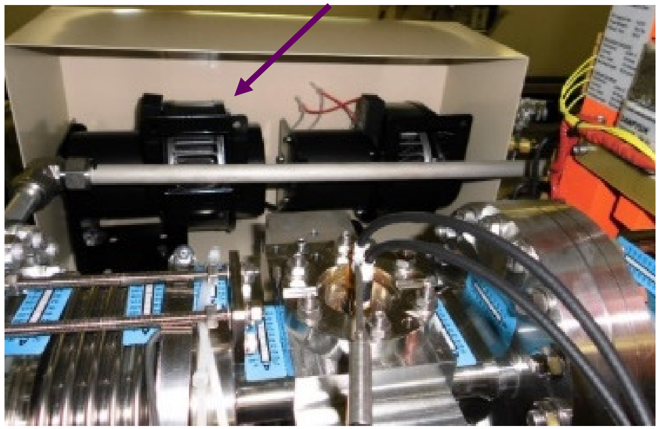
Magnetic field measurement for the cooling fan

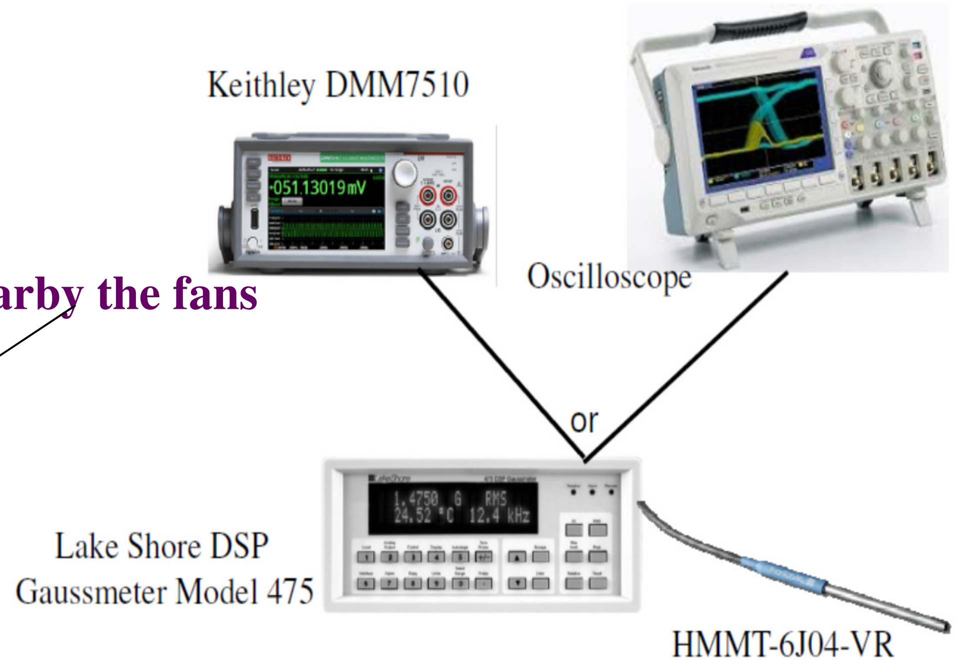


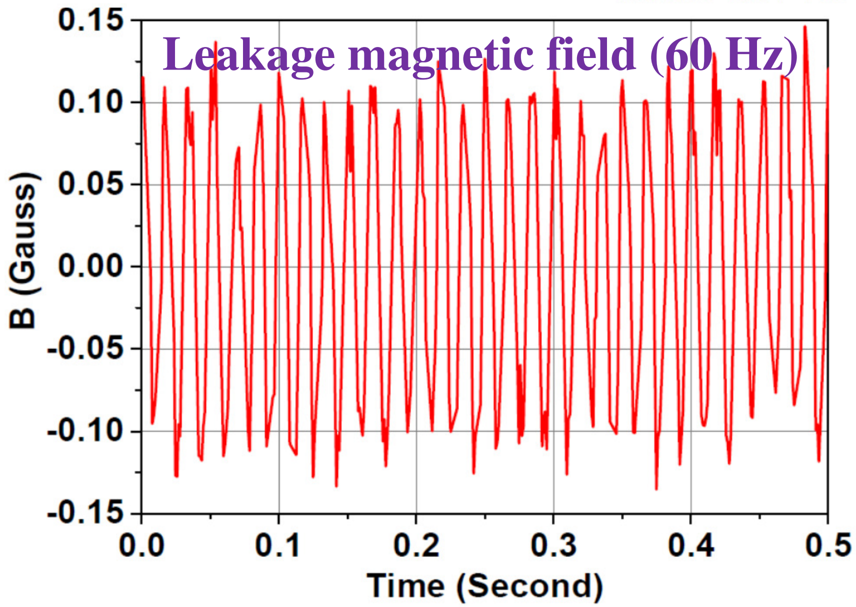


Nearby the fans

The sources come form the magnetic leakage of newly installed cooling fans.

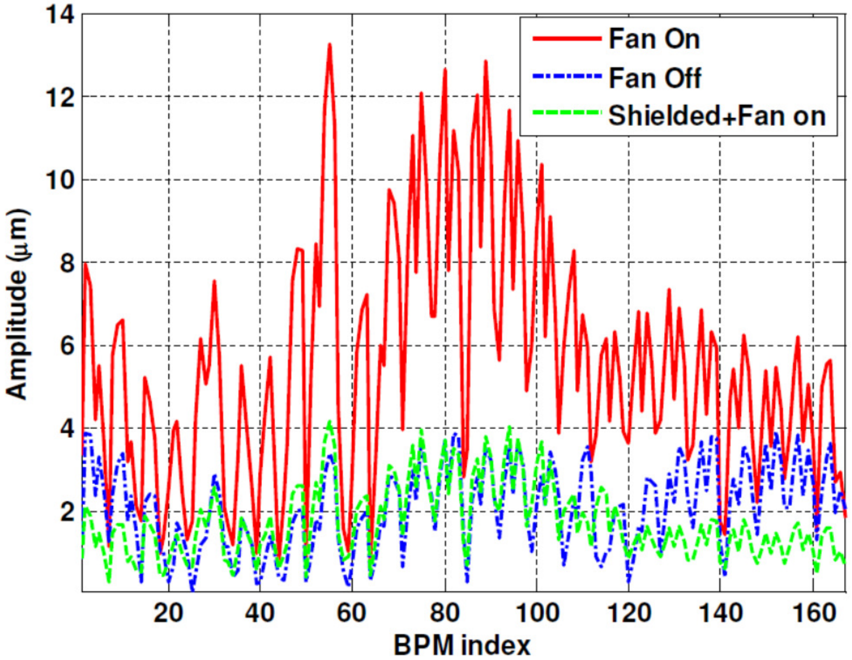


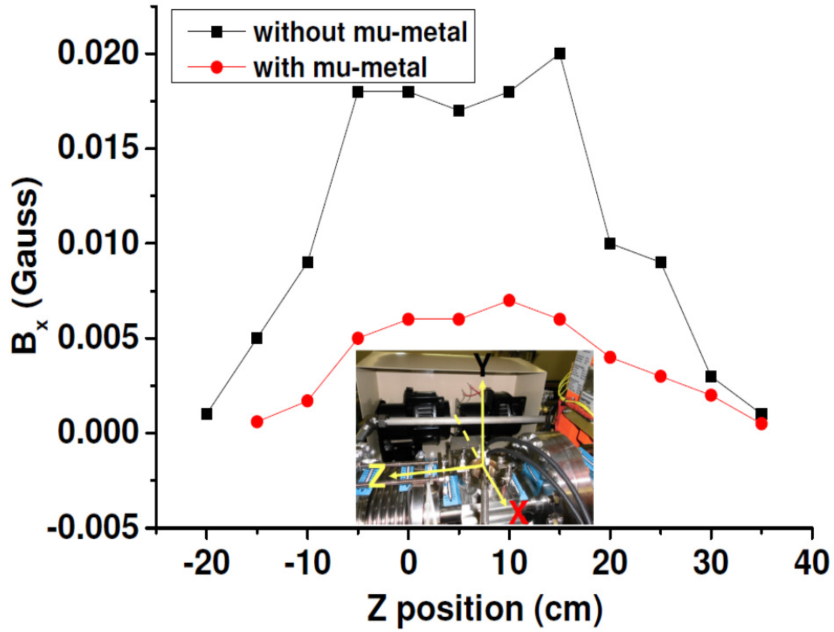




Magnetic field measurement for the cooling fan

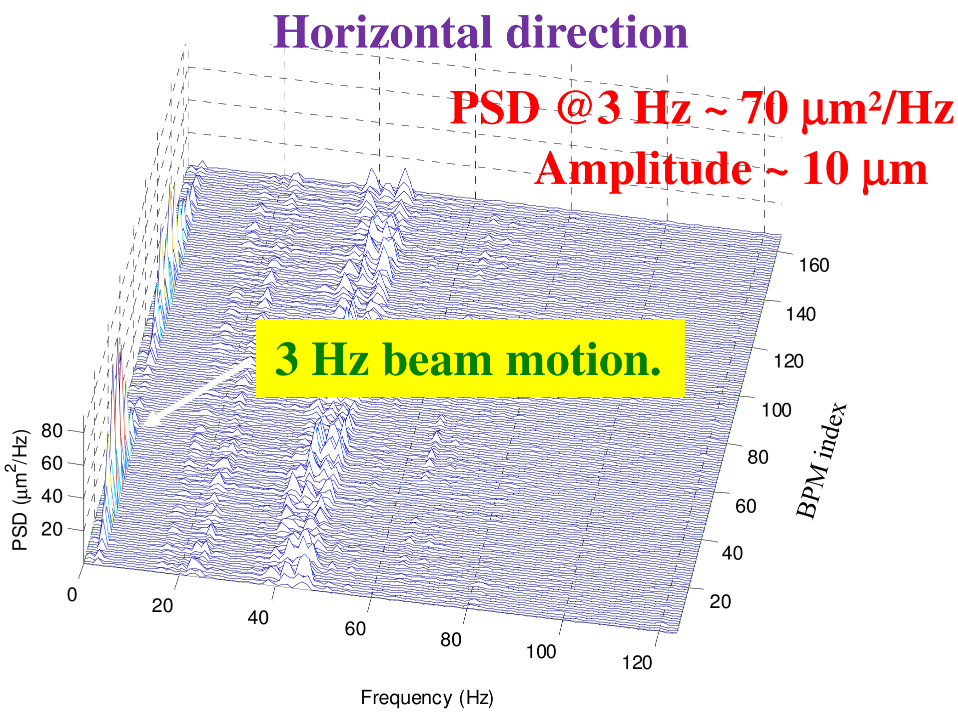
Vertical beam motion

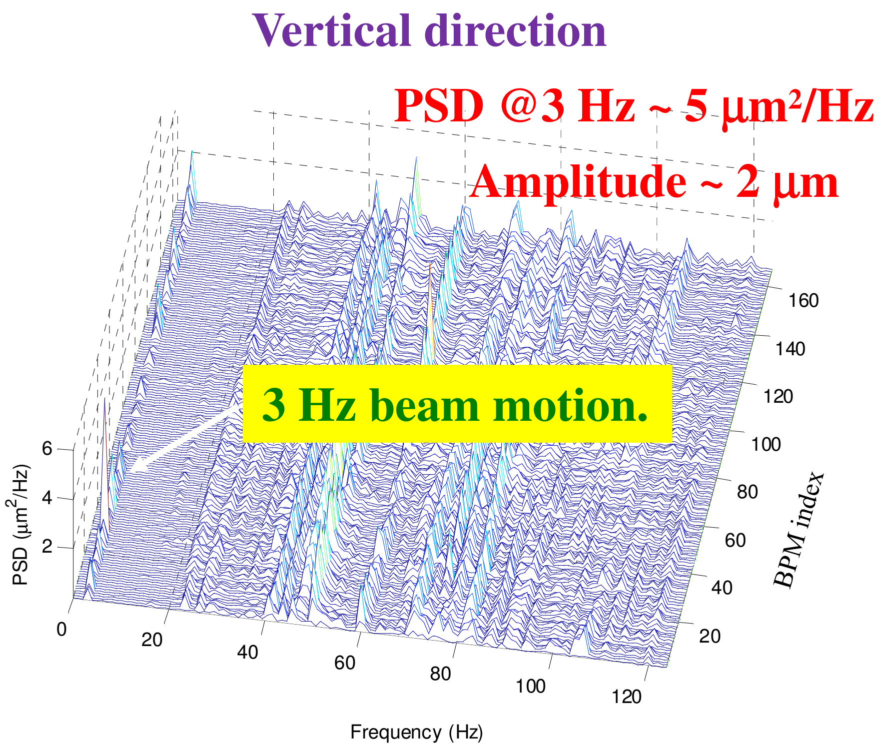




1. **Shielding the leakage magnetic field with mu-metal and putting the fans away from the vacuum chambers more than 30 cm could reduce beam motion from the error sources.**
2. **After these works, the amplitude of beam motion was roughly same as that with all fans off.**

3 Hz beam motion in storage ring caused by booster power supplies

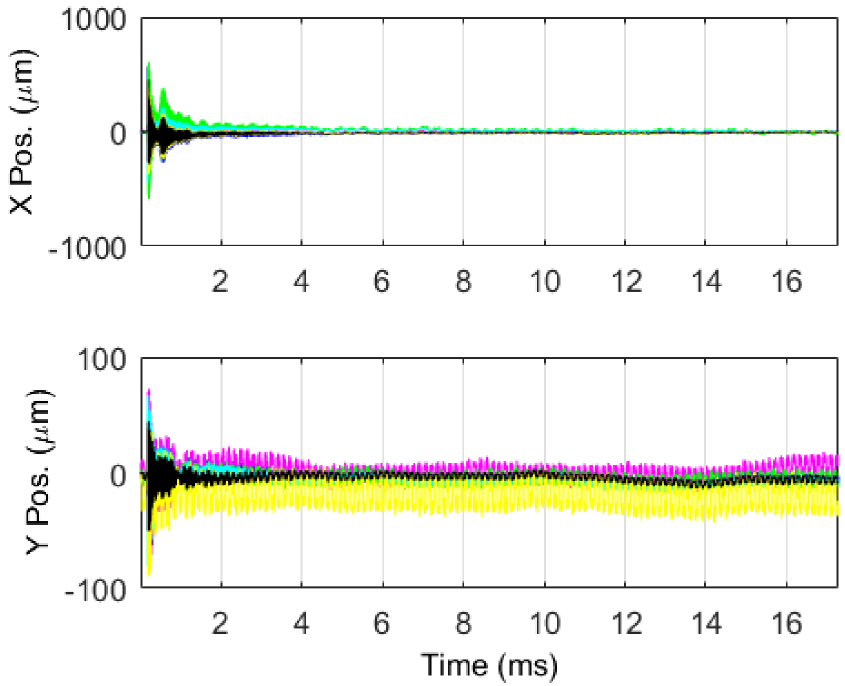




1. **Both storage ring and booster ring are in the same tunnel.**
2. **The distances of the beam orbit are between 2.78 m and 3.79 m.**
3. **The ramping of booster magnets can excite 3 Hz beam motion and is suppressed by FOFB. In routine operation, booster cycling started shortly before reinjection in top-up mode operation.**
4. **We are not sure the paths of the error sources. Study is ongoing.**

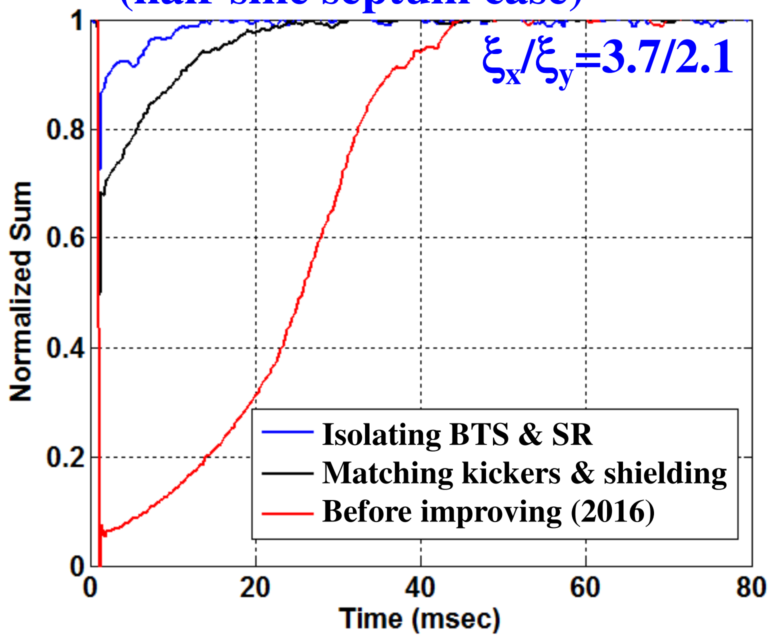
Injection transient effect

Betatron motion induced by injection

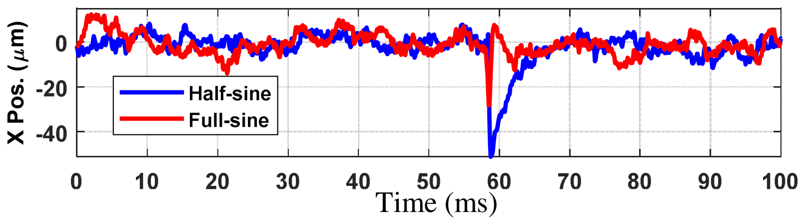


Photon flux drop during injection @Beamline 05A QBPM2

Chromatic decoherence effect (half-sine septum case)



Full-sine septum can reduce the beam motion induced by eddy current.



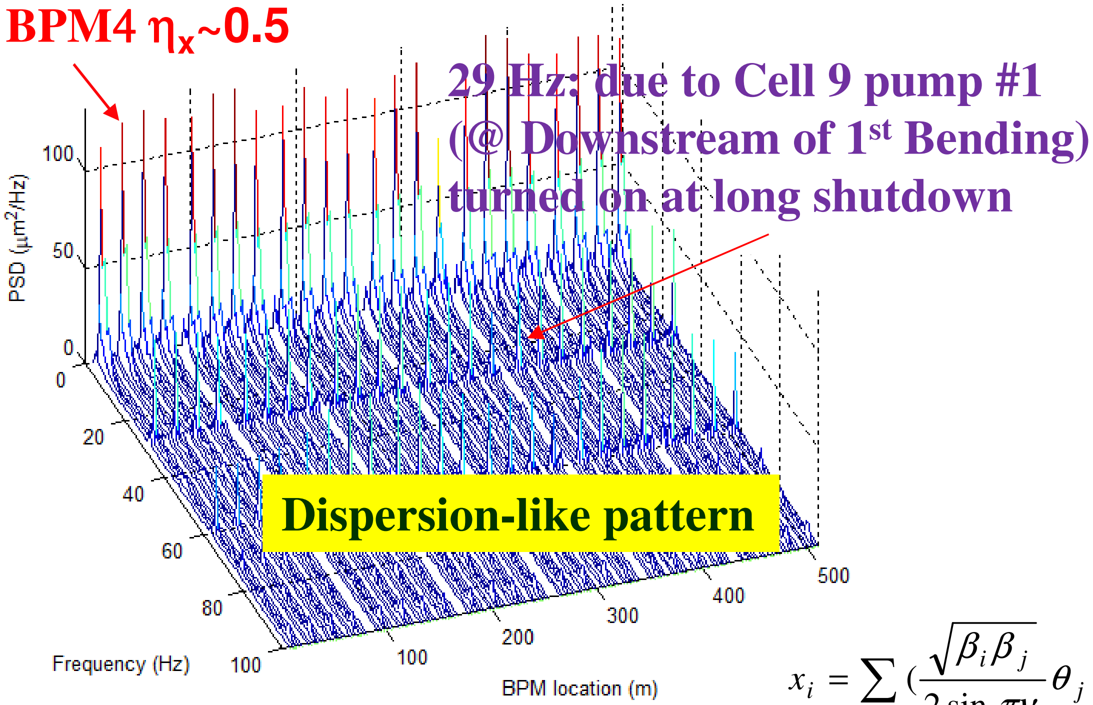
After matching the four kickers; shielding the septa and kickers; isolating the BTS from storage ring, the photon flux drop becomes much lower.

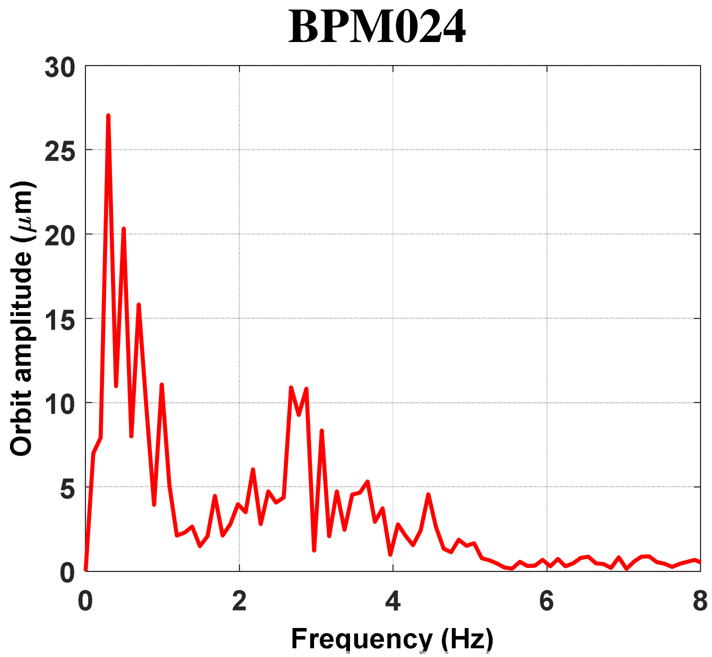
The horizontal and vertical perturbation are around +/- 500 µm and +/- 100 µm max. peak-to-peak from the TBT data.

QBPM: quadrant PIN photodiodes BPM

Orbit motion without feedback at low alpha mode

Horizontal $\alpha_1 = -6 \times 10^{-6}$





$$x_i = \sum_j \left(\frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \theta_j \cos(|\phi_i - \phi_j| - \pi\nu) - (1/\alpha_1)(\theta_j \eta_j / C)\eta_i \right)$$

$$\delta = \frac{1}{\alpha}\left(\frac{\Delta C}{C} - \frac{\Delta f_{RF}}{f_{RF}}\right),$$

$$\Delta C = \sum_i \theta_i \eta_i \approx \sum_i K_i L_i \eta_i \langle \Delta x_{quad} \rangle$$

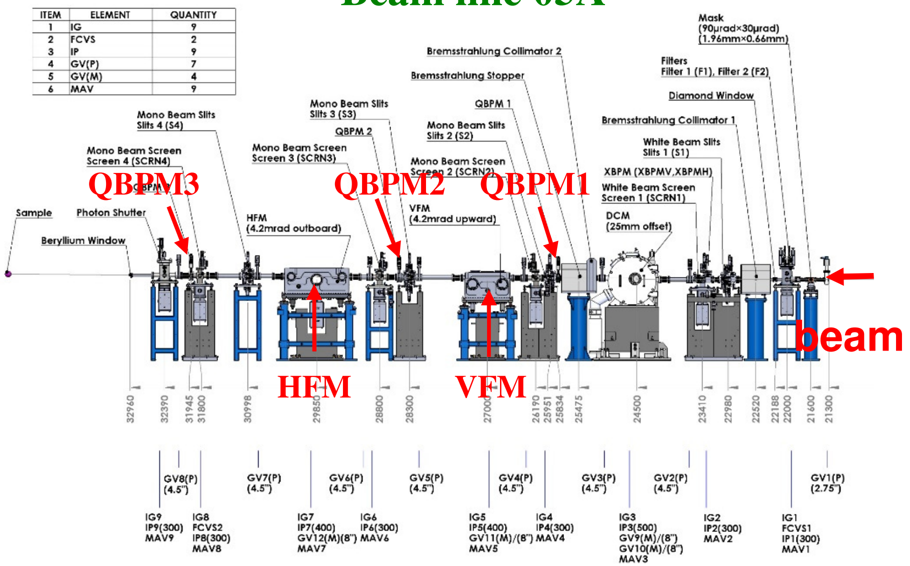
α ↓ → PSD of beam motion ↑

***K*: quad strength**
***L*: quad length**
Δ*x*: quad vibration amplitude

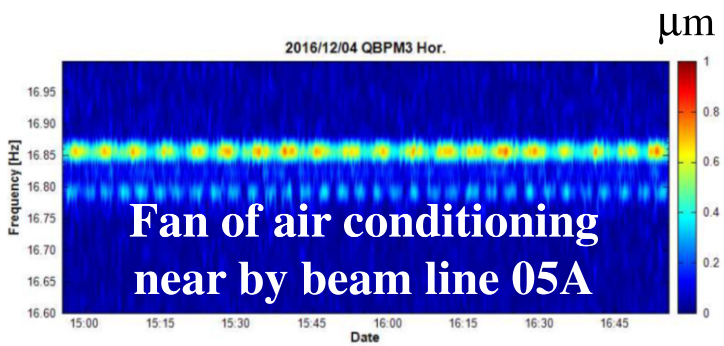
1. **In the low alpha mode, dispersion-like pattern rather than betatron-like pattern is caused by various noises such as ocean wave, mechanical vibration, etc.**
2. **The dispersion-like beam motion comes from the energy offset due to the path length change induced by kicks in dispersion region.**

Vibration at beamline - an example

Beam line 05A

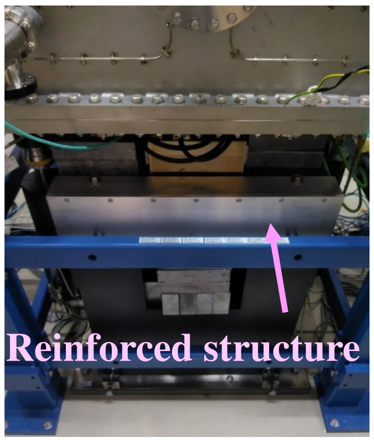


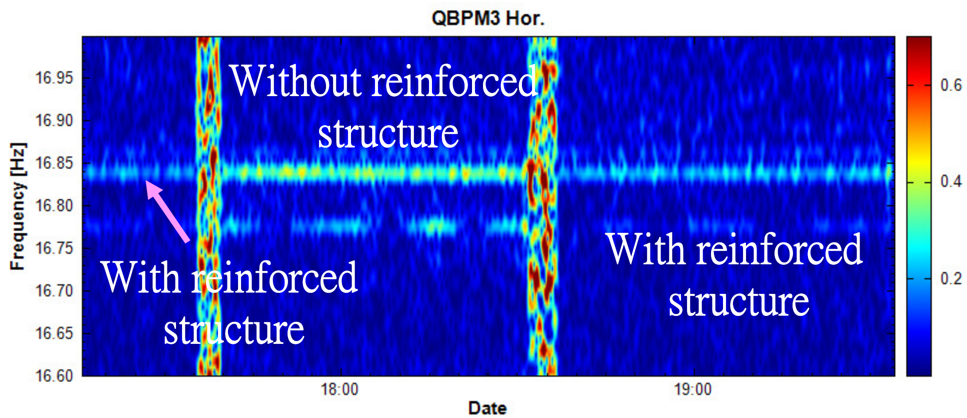
QBPM 3
Hor. Position
(After HFM)



- ✓ **16.8 Hz horizontal photon beam motion is observed downstream of the HFM.**
- ✓ **Upstream of the HFM, the beam motion at this frequency is tiny.**

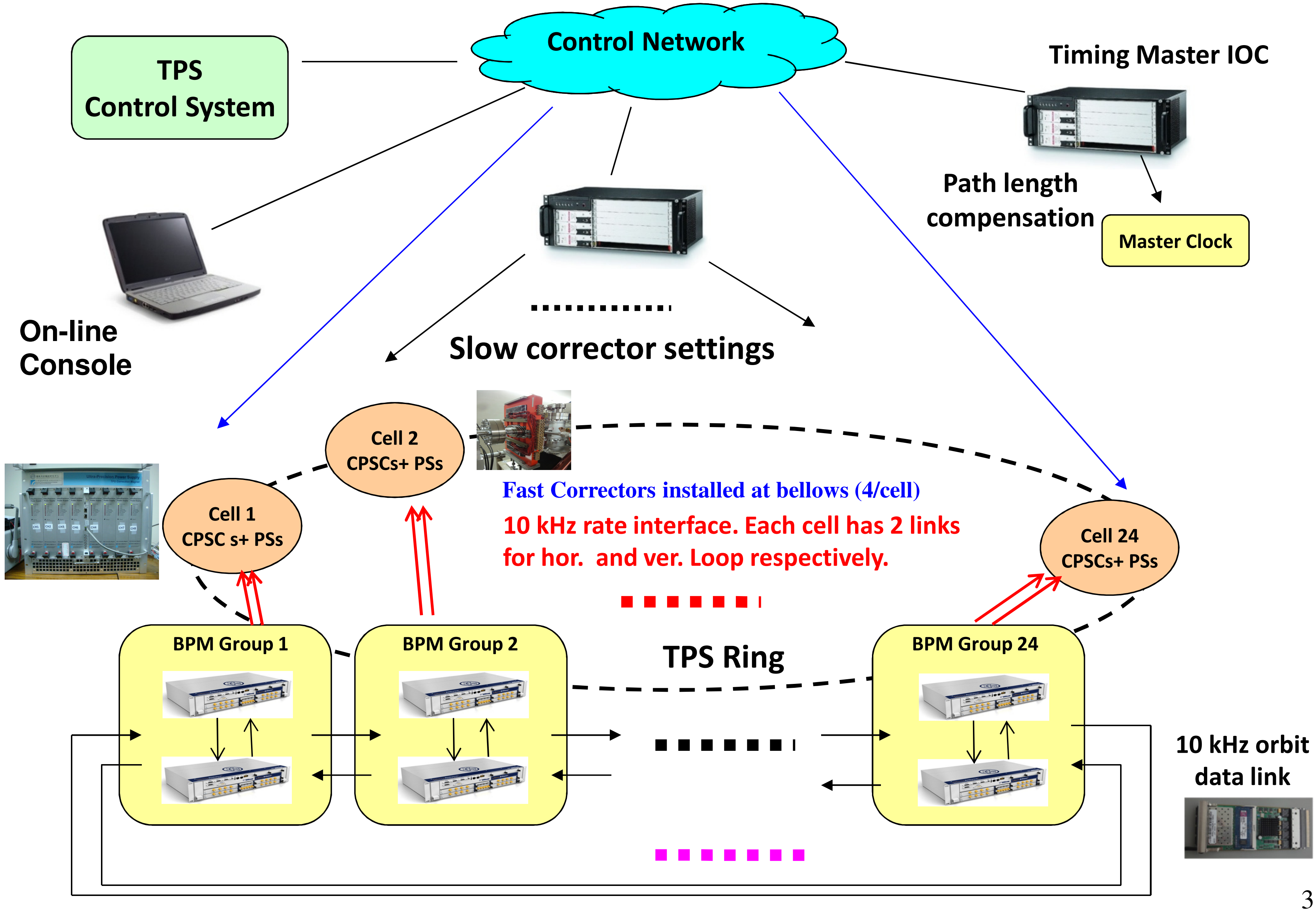
HFM: horizontal focusing mirror



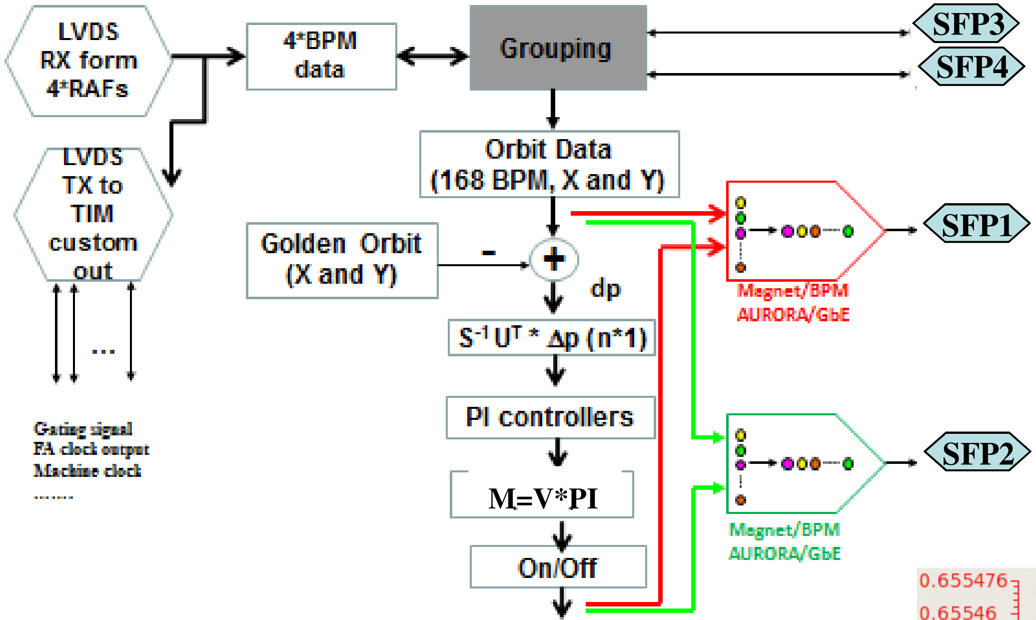


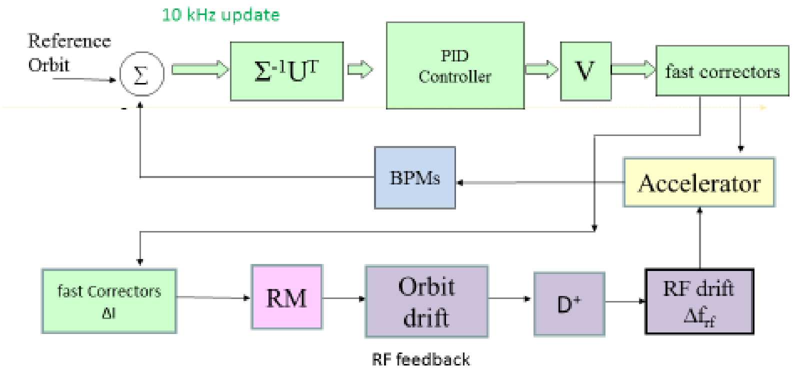
Using the reinforced structure in the HFM, the horizontal beam motion at QBPM3 is reduced.

FOFB Infrastructure / BPM system

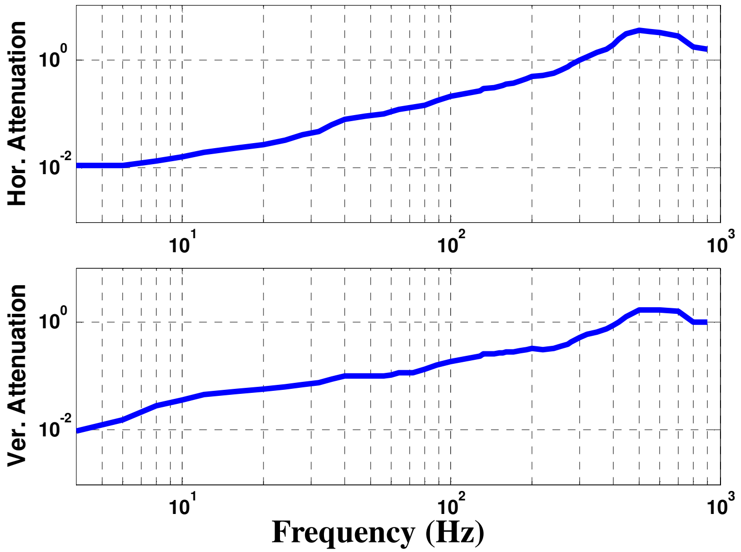


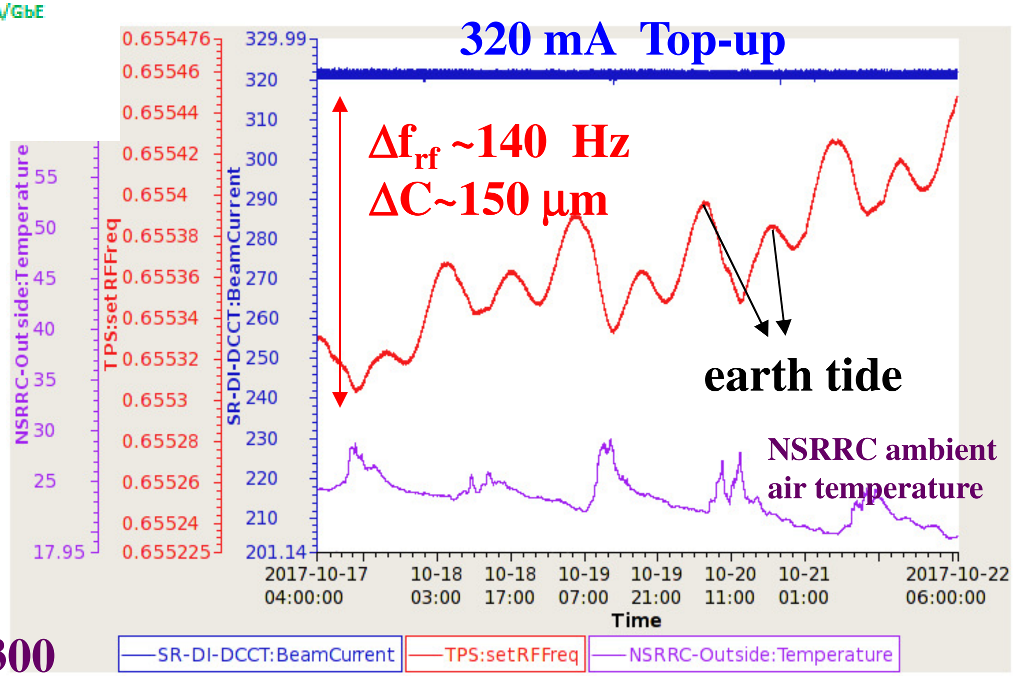
FOFB / RF adjustment computation model and performance





Corrector Response Matrix $RM = U\Sigma V^T$
Dispersion Matrix D
Inverse Dispersion Matrix D^+

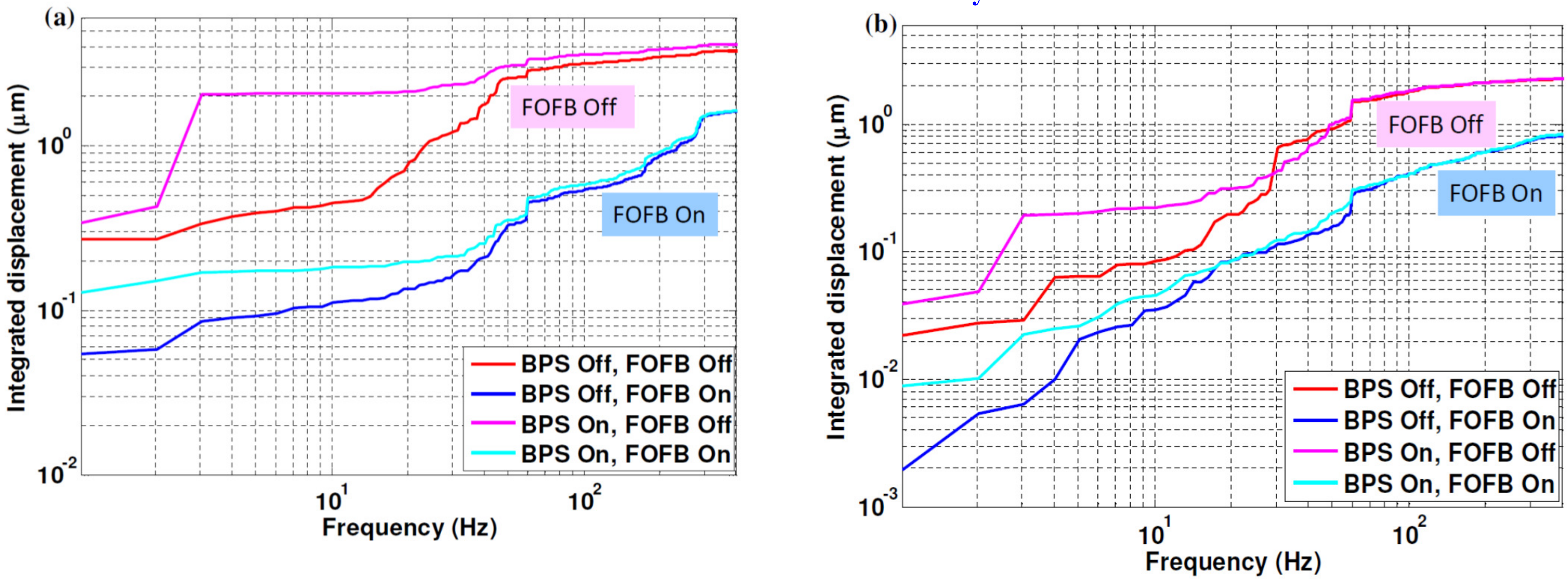




The estimated bandwidth of FOFB is ~ 300 Hz for both horizontal and vertical plane.

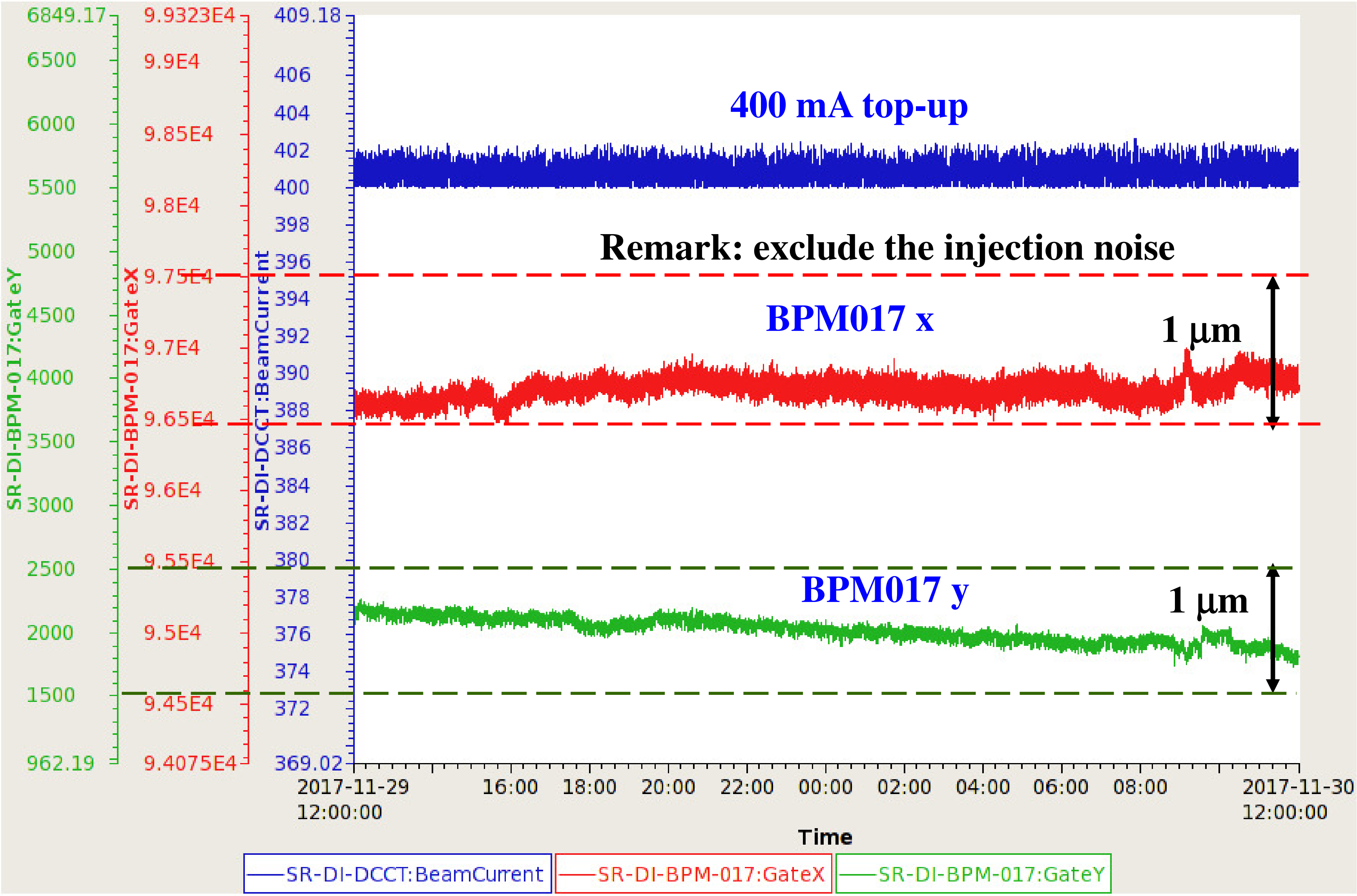
Beam orbit stability

Horizontal **BPM021 σ_x=130μm, σ_y=9.8μm** **Vertical**



1. **After removing error sources and before applying FOFB, the integrated RMS displacement from 1-100 Hz was around 2 μm in both horizontal and vertical directions for the ID BPM.**
2. **When the FOFB was turned on, the integrated RMS became smaller than 0.5 μm from 1 to 100 Hz.**
3. **The results fulfill the design criteria. (beam motion less than 10% beam size)**

Orbit long term drift (FOFB On + RF adjustment)



Submicron beam orbit stability is achieved (BPM 10Hz rate, 1Hz archives)

Summary

- **Possible noise sources:**
  - **Ground motion**
  - **Mechanical vibration (girder, magnet, pump, cooling water, etc.)**
  - **Electrical and magnetic field noises**

- **The process to hunt/eliminate/suppress/study noise sources to the beam**

  - **Ground motion:**
    - ✓ **Horizontal ground motion at ~ 0.3 Hz disturbs the beam with dispersion-like pattern especially @ low-alpha mode**
    - ✓ **The dispersion-like orbit pattern is from path length change due to kicks in dispersion region**

  - **Dry pump: Induction motor induced vibration ~ 29 Hz**
    - ✓ **Turn off dry pumps => solved!**

  - **Vacuum chamber vibration due to cooling water:**
    - ✓ **10 LPM → 6 LPM (minimum requirement) can improve about one order in PSD.**
    - ✓ **The beam vibration ~ a few μm .**
    - ✓ **Possible mechanism : vacuum chamber vibration with magnets => induced eddy current => generate magnetic field => affect orbit**

Summary - cont.

- **Injection transient:**
  - ✓ **Kickers mismatch**
  - ✓ **Septa leakage field and eddy current (full sine septa solved)**
  - ✓ **Decoherence effect due to chromaticity**
  - ✓ **New injection method**

- **60 Hz beam perturbation due to RF transmitter noise:**
  - ✓ **The effect becomes lower after rerouting the grounding bus.**

- **Cooling fans for bellows and BPMs:**
  - ✓ **Shielding the fans with mu-metal**
  - ✓ **Keep more than 30 cm away from the vacuum chamber.**

- **Booster ramping induced noise can be suppressed by FOFB**

- **Submicron stability is achieved by active orbit feedbacks (FOFB) including path length compensation with RF frequency adjustment.**

Acknowledgement

- **We thanks the members of the light source division and instrumentation develop division for the helpful discussion and cooperation during observing and eliminating the error sources.**
- **We also thanks the members of instrumentation & control group and beam dynamics group for their consulting and advices to complete this work.**

國家同步輻射研究中心
National Synchrotron Radiation Research Center

Thanks for your kind attention.

NSRRC