# Orbit control at IP

Y. Funakoshi
for the IP orbit control working group

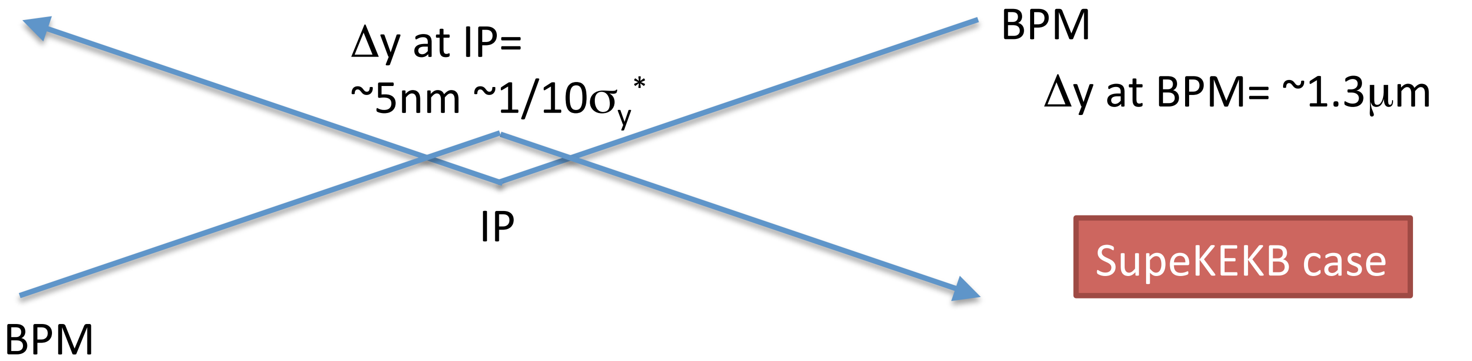
The 17th KEKB Accelerator Review
Feb. 20 2012

# Contents

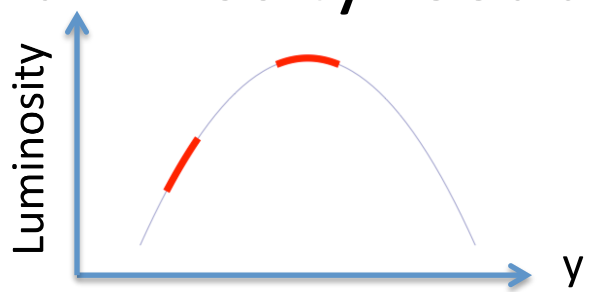
- Algorism of orbit control
- QCS vibration issues
- Dithering method for luminosity FB

# Orbit feedback at IP :Algorism

- Beam-beam deflection (SLC, KEKB vertical)

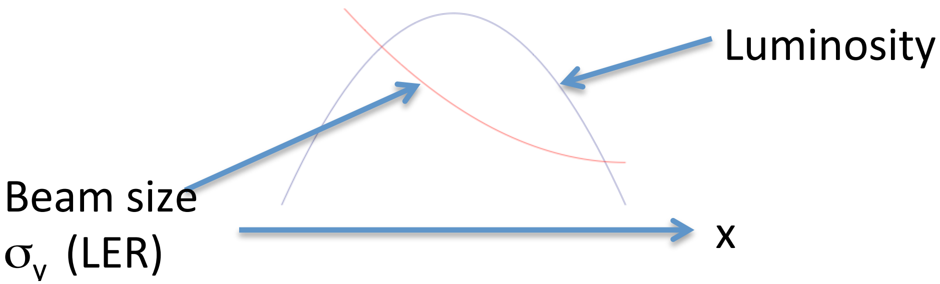



- Luminosity feedback (dithering)(PEP-II)




When we shake the beam at around the peak of the luminosity, there appears twice of the frequency of the dithering frequency.

- Beam size feedback (KEKB horizontal)



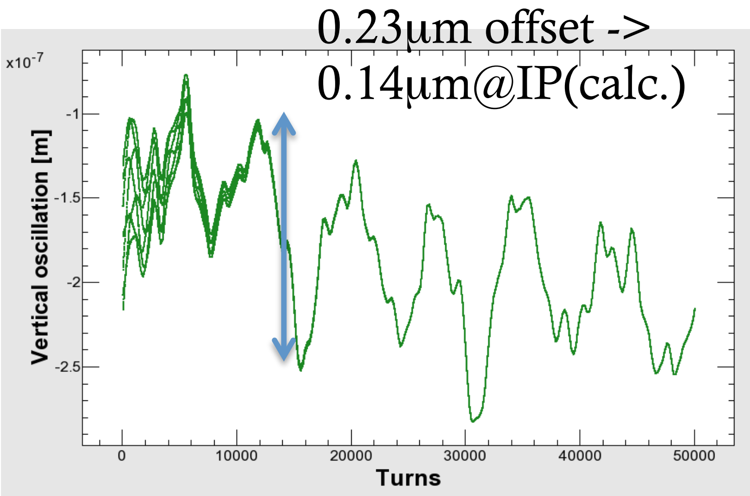

At KEKB before installation of crab cavities, the vertical beam of LER was used for the horizontal orbit feedback at IP.

# QCS Vibration issues

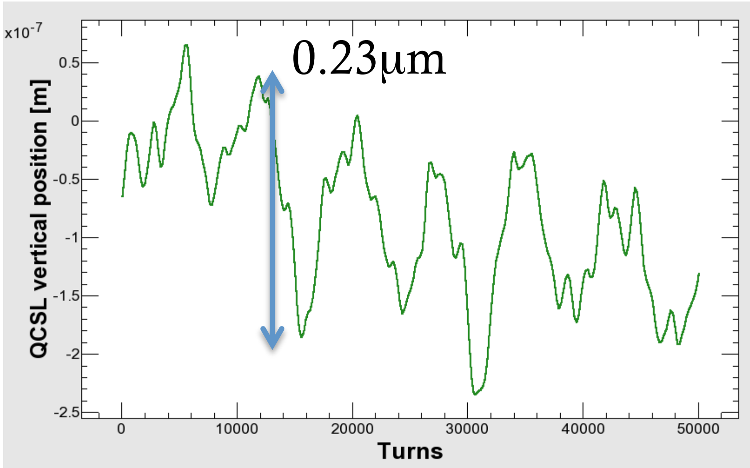
- The most serious source of orbit change at IP
- Recent progress
  - Coherency of vibration of QC1{RL}E and QC1{RL}P
  - Further damping of vibrations by using high damping materials
  - Suppression of orbit difference by orbit feedback system (H. Fukuma)

# QCSL vertical position oscillation (measurement) and orbit change (tracking) : KEKB LER

**Vertical orbit at IP (simulation)**




**QCSL vertical position (measurement)**

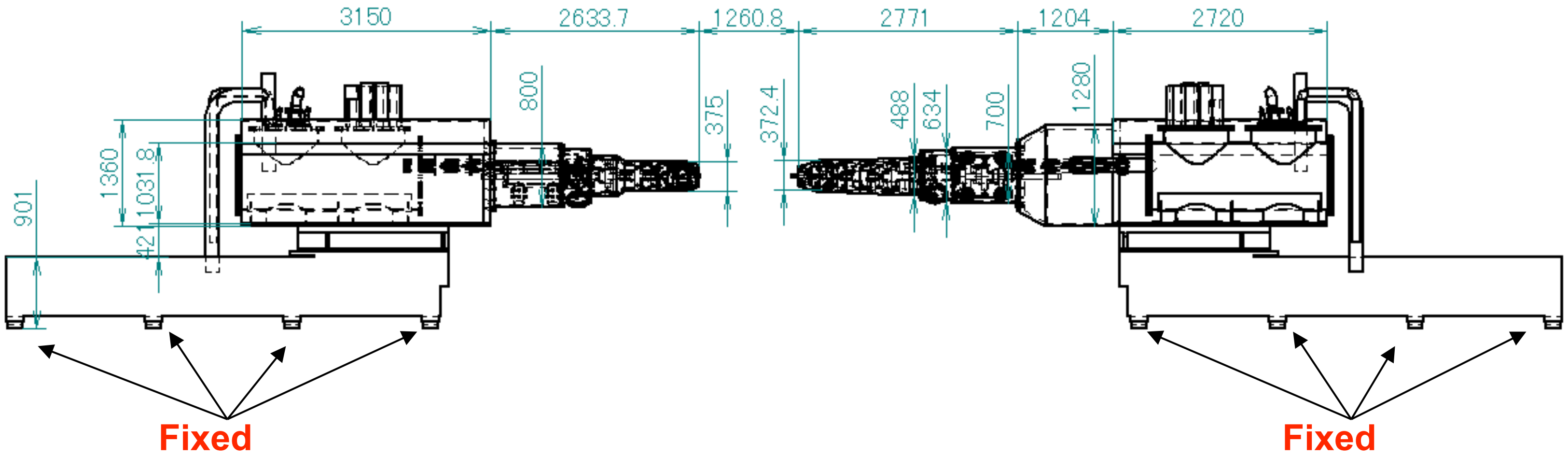


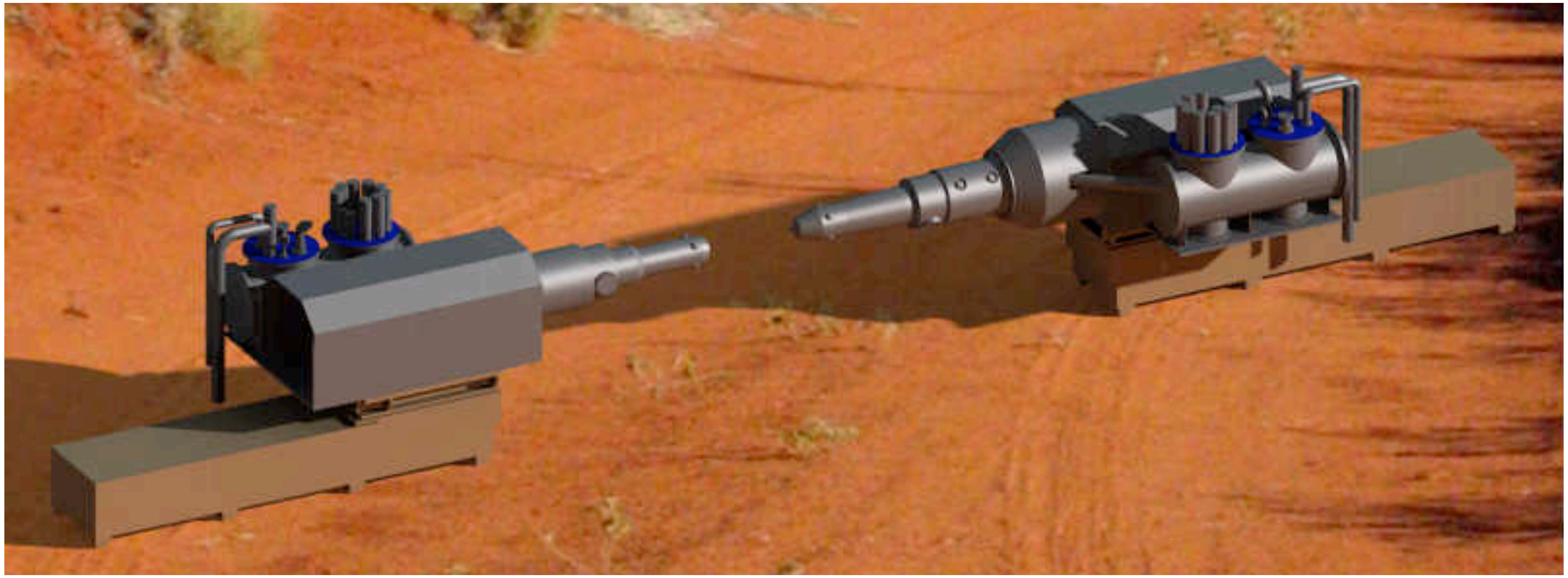
# Simulation on vibrations of QCS magnets (H. Yamaoka)

- Simulation using ANSYS
  - Modal calculation
    - Resonant modes: ~26, 36, 39, 53 Hz
  - Oscillation amplitude (PSD (power spectrum density)
    - Input of simulation: Measured data on floor vibration
  - Coherency of vibrations of QC{12}RE and QC{12}RP or QC{12}LE and QC{12}LP
    - Coherency is very high
  - Further damping with high damping materials

# FEM model

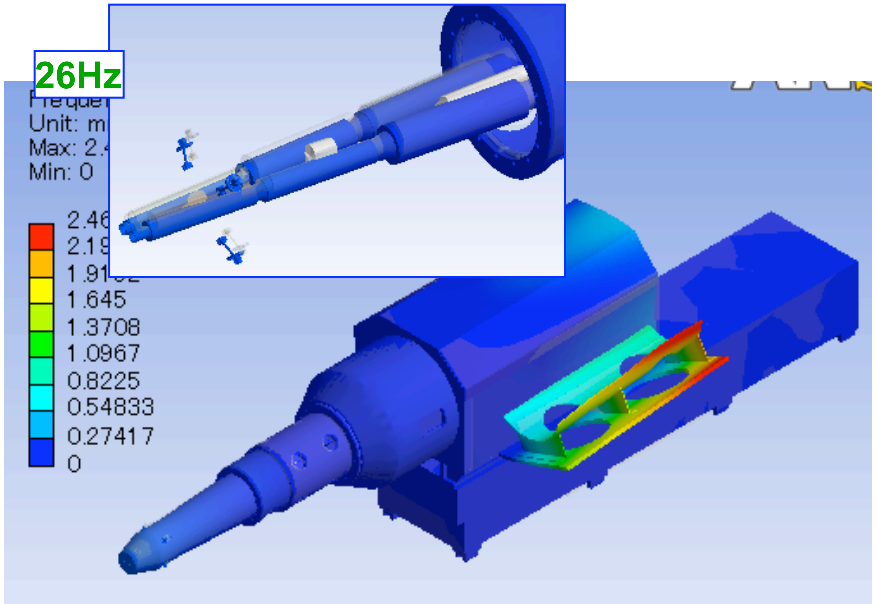
H. Yamaoka

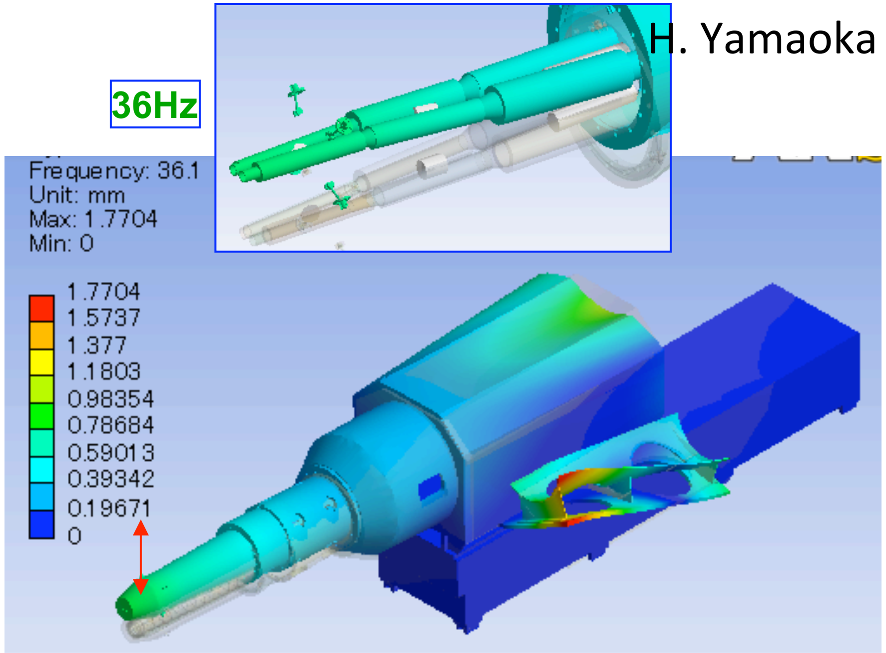


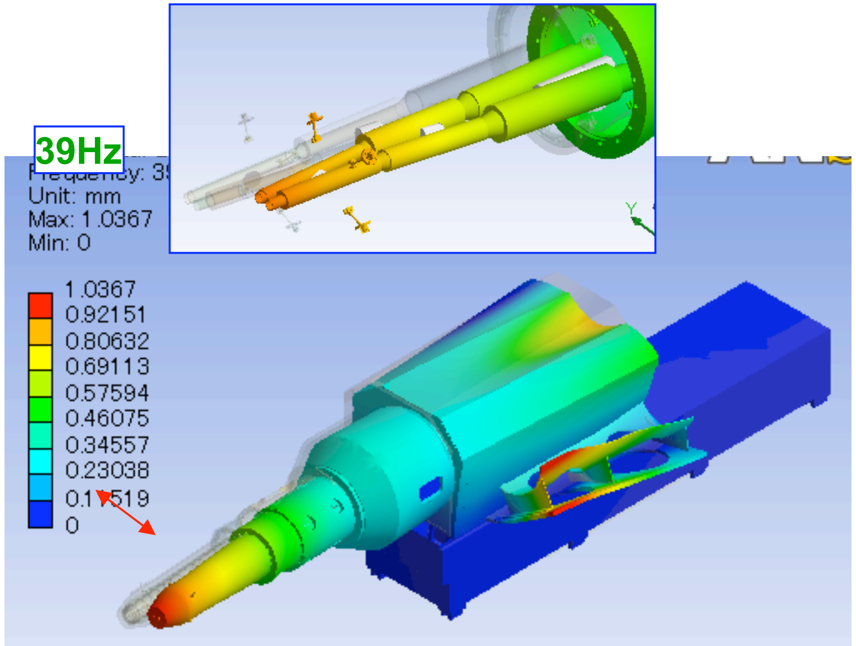



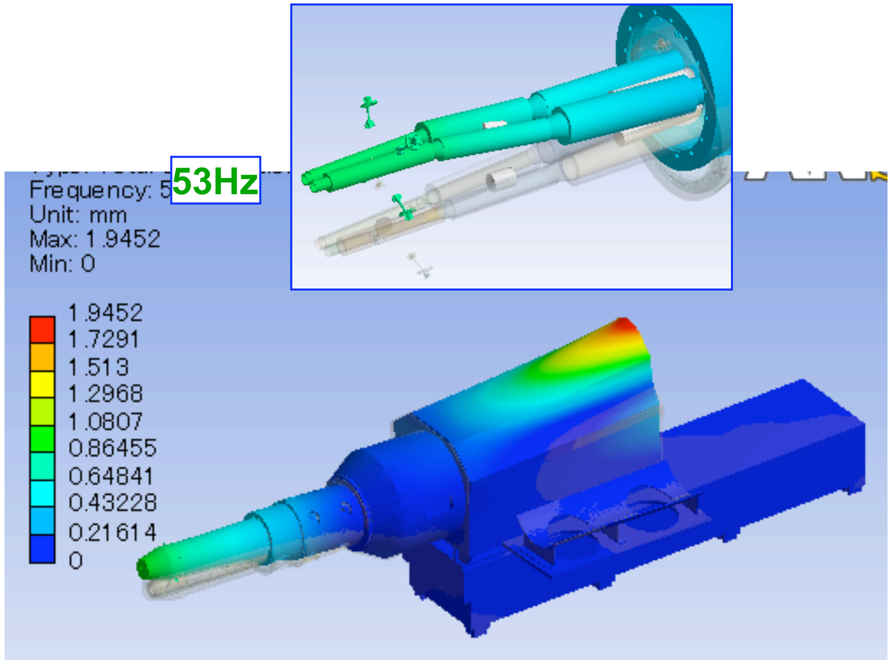
# Modal calculation

H. Yamaoka



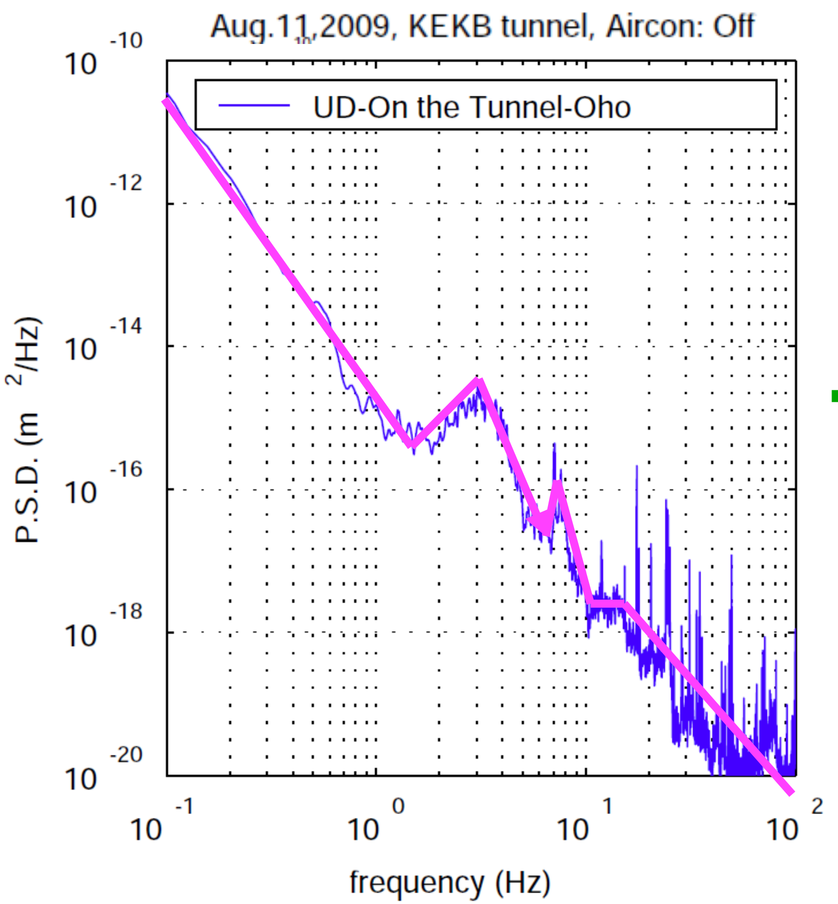



# P.S.D. (Power Spectrum Density) analysis

H. Yamaoka

## In the vertical direction

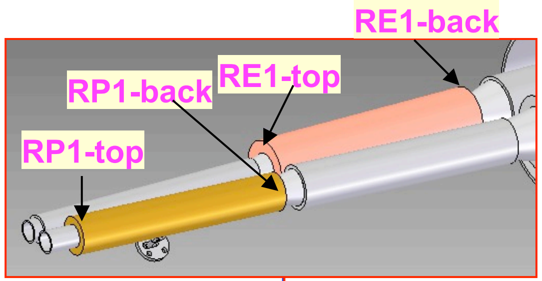


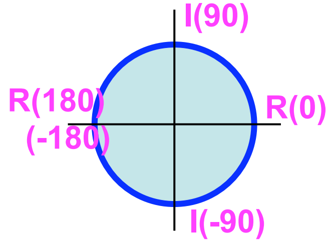

| Freq.(Hz) | P.S.D.($m^2$/Hz) |
|---|---|
| 0.1 | 5e-11 |
| 1.5 | 5e-16 |
| 3.0 | 5e-15 |
| 6.5 | 5e-17 |
| 8.0 | 1e-16 |
| 10. | 3e-18 |
| 16. | 3e-18 |
| 100. | 5e-21 |

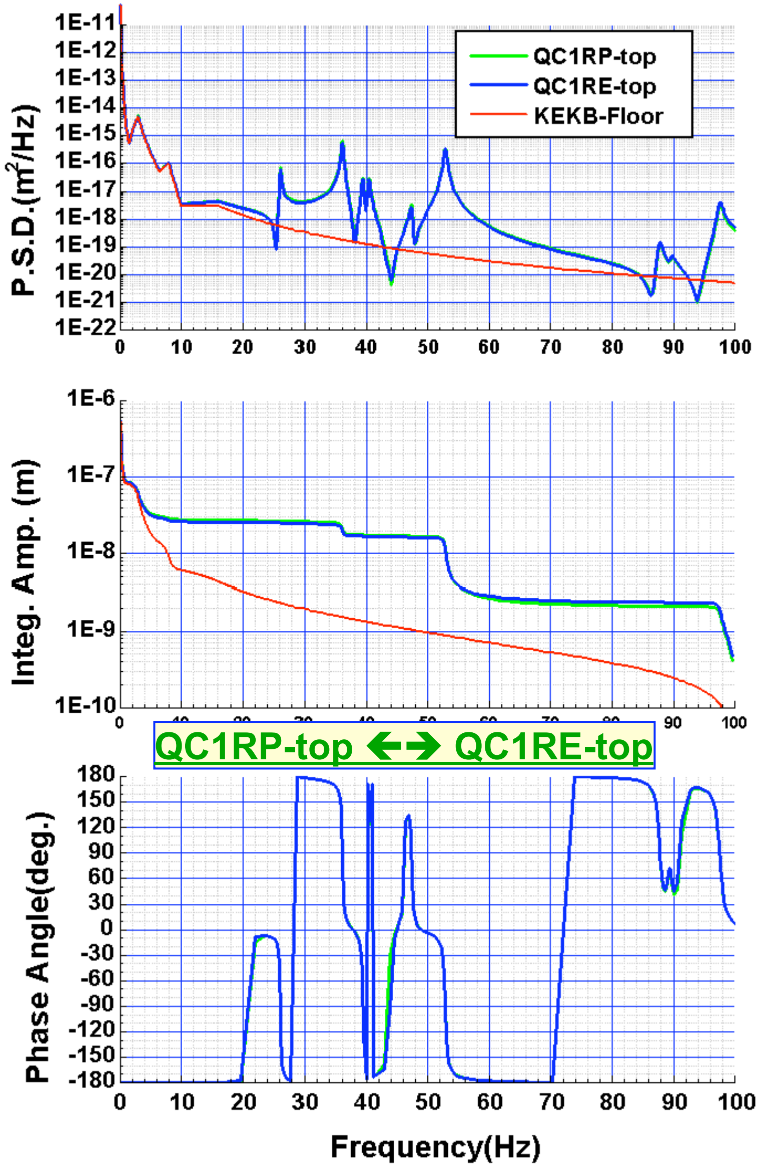
***damping= 0.5%***

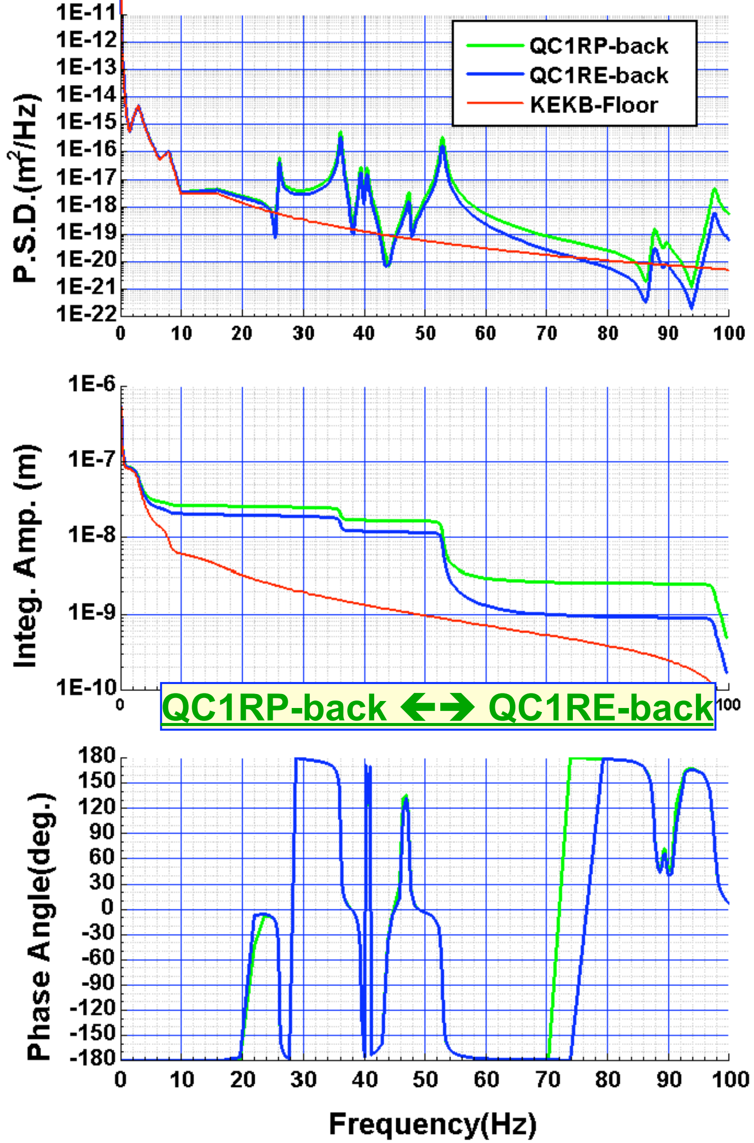
# Results(*Vertical direction*)

H. Yamaoka



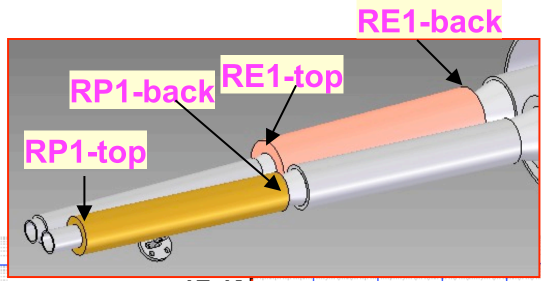



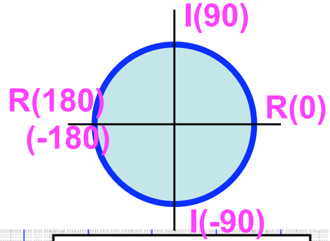



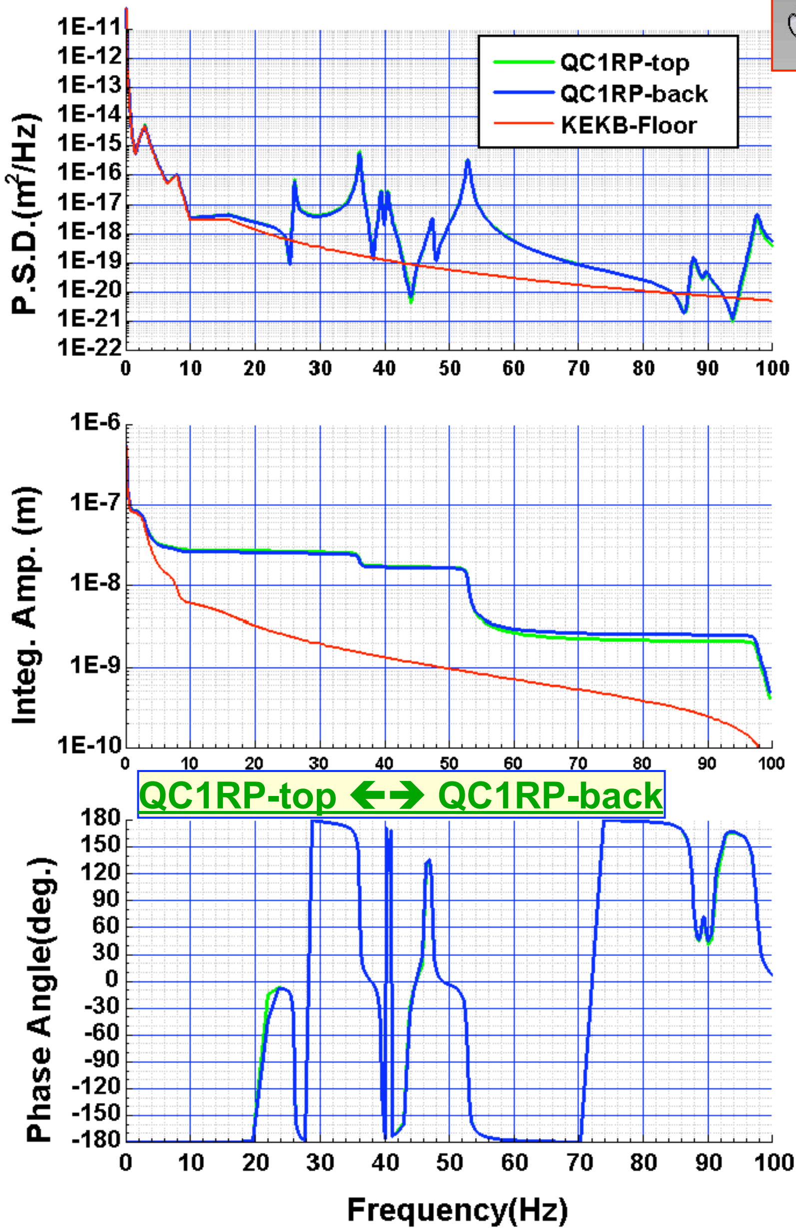



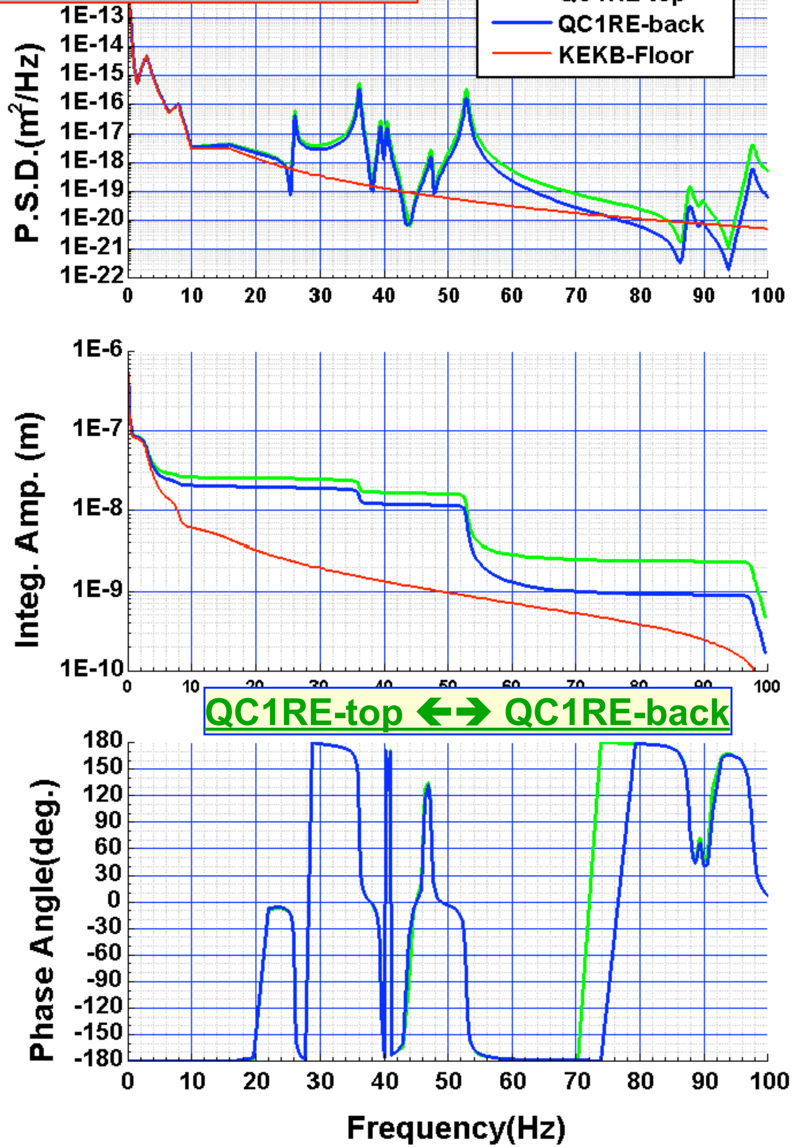
# Results(*Vertical direction*)

H. Yamaoka



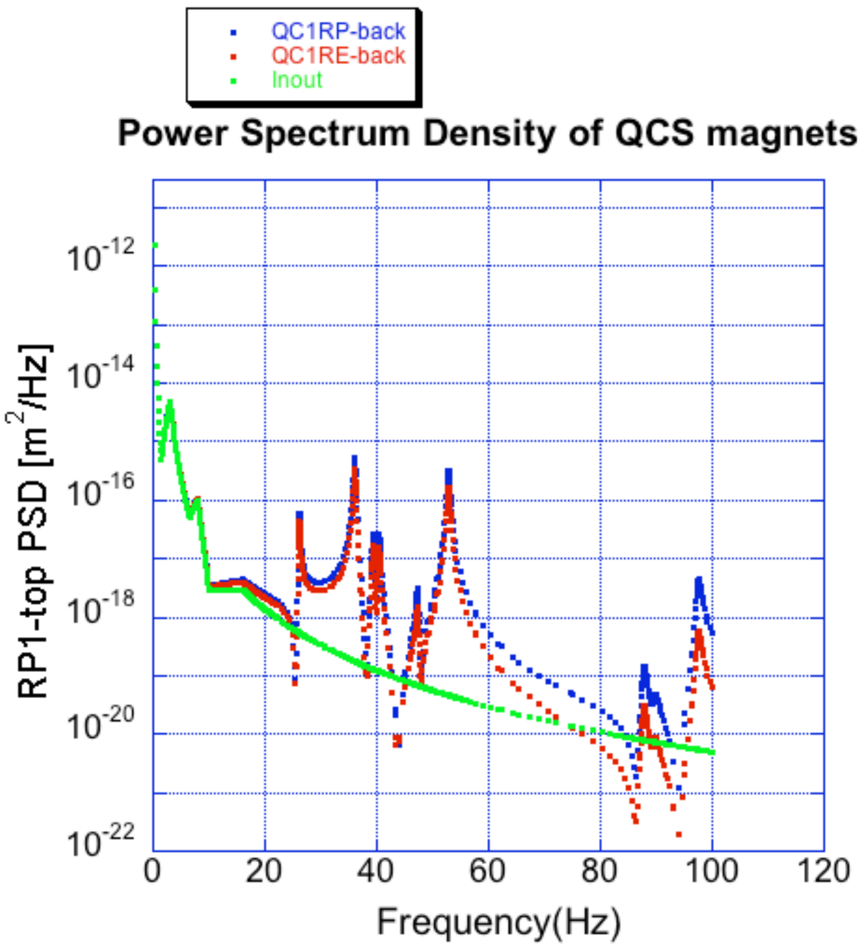
# Orbit change at IP with 1 μm offset of QCS magnets

| | | K1 (/m) | Distance from IP [m] | $\beta_Q$ [m] | $\beta_{IP}$[mm] | $\Delta\psi_y/2\pi$ | COD@IP for 1μm Q-offset [μm] | |
|---|---|---|---|---|---|---|---|---|
| QC1L | LER | -1.717 | 0.912 | 2504.3 | 0.27 | 0.24995 | -0.706 | > |
| | HER | -1.142 | 1.390 | 5462.4 | 0.3 | 0.24997 | -0.731 | |
| QC1R | LER | -1.712 | 0.912 | 2567.7 | 0.27 | 0.24996 | -0.713 | > |
| | HER | -1.070 | 1.430 | 5592.6 | 0.3 | 0.24997 | -0.693 | |
| QC2L | LER | 0.84161 | 1.9099 | 962.2 | 0.27 | 0.25004 | 0.2145 | > |
| | HER | 0.65023 | 2.6799 | 1923.3 | 0.3 | 0.25030 | 0.2470 | |
| QC2R | LER | 0.83924 | 1.9760 | 924.6 | 0.27 | 0.25005 | 0.2097 | > |
| | HER | 0.55577 | 2.9449 | 1806.9 | 0.3 | 0.25004 | 0.2046 | |

COD $$\Delta y = \frac{1}{2\sin\pi\nu}\sqrt{\beta_Q\beta_{IP}}\cos\left(\pi\nu - \left|\Delta\psi\right|\right)\vartheta$$

If QCS magnets for LERとHER move coherently、orbit difference of the two beam becomes much smaller (1/10 ~ 1/20) than non-coherent case.

# Time domain vibration data to reproduce PSD from Yamaoka



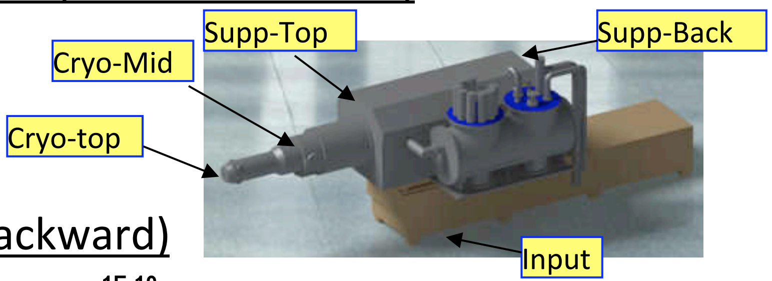

- To make a mode to reproduce the floor vibration (Ornstein-Uhlenbeck process )

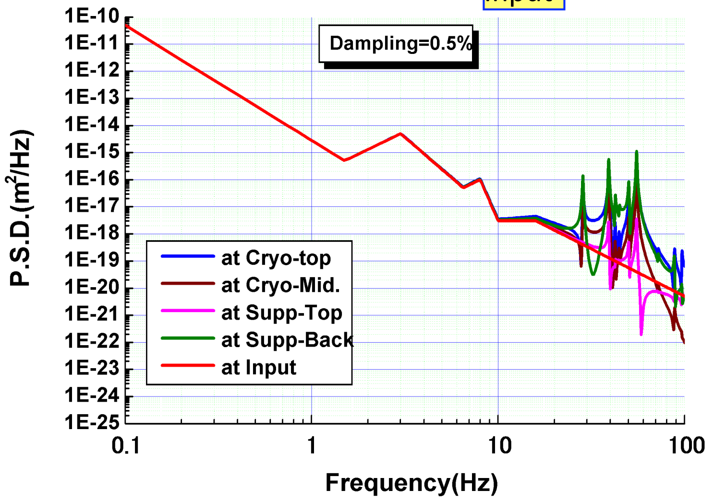
- 3 resonant modes (3, 36 and 53Hz) are created.

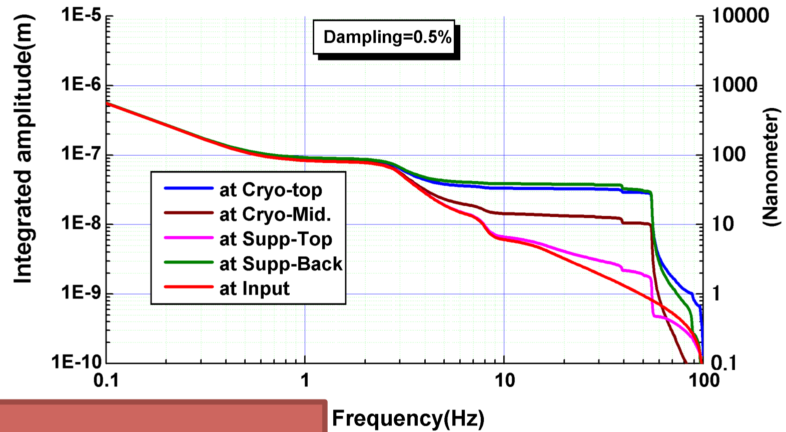
# Results(*Vertical direction*)

H. Yamaoka

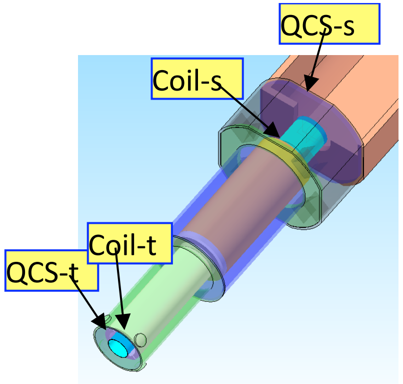
(Backward)

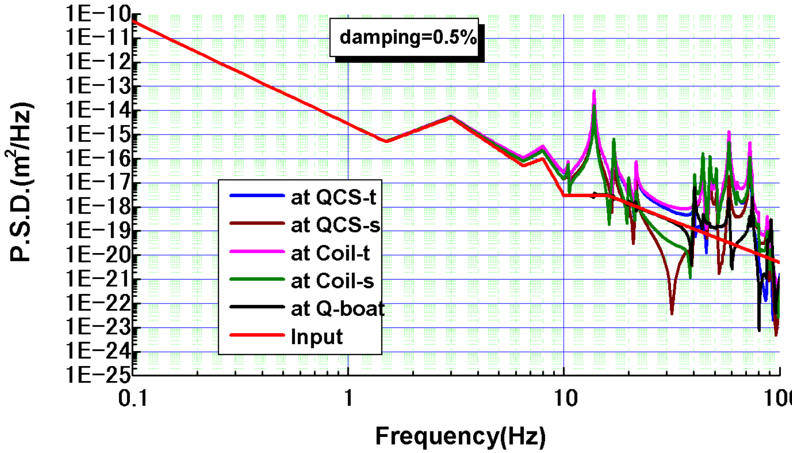


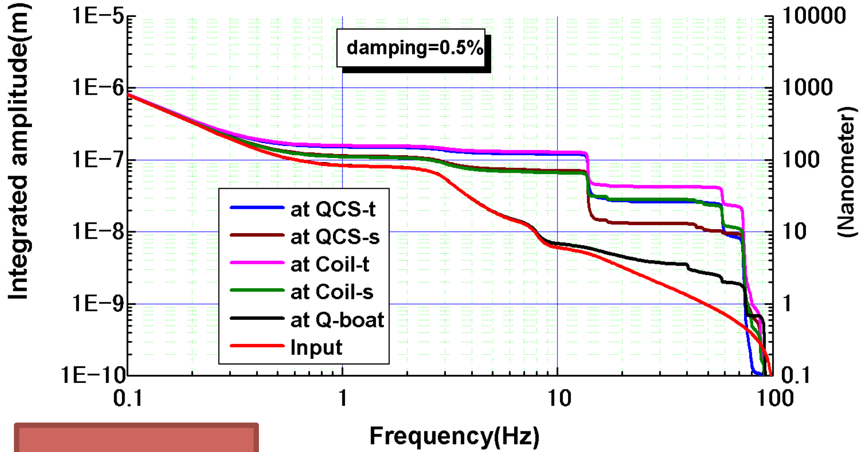




SuperKEKB

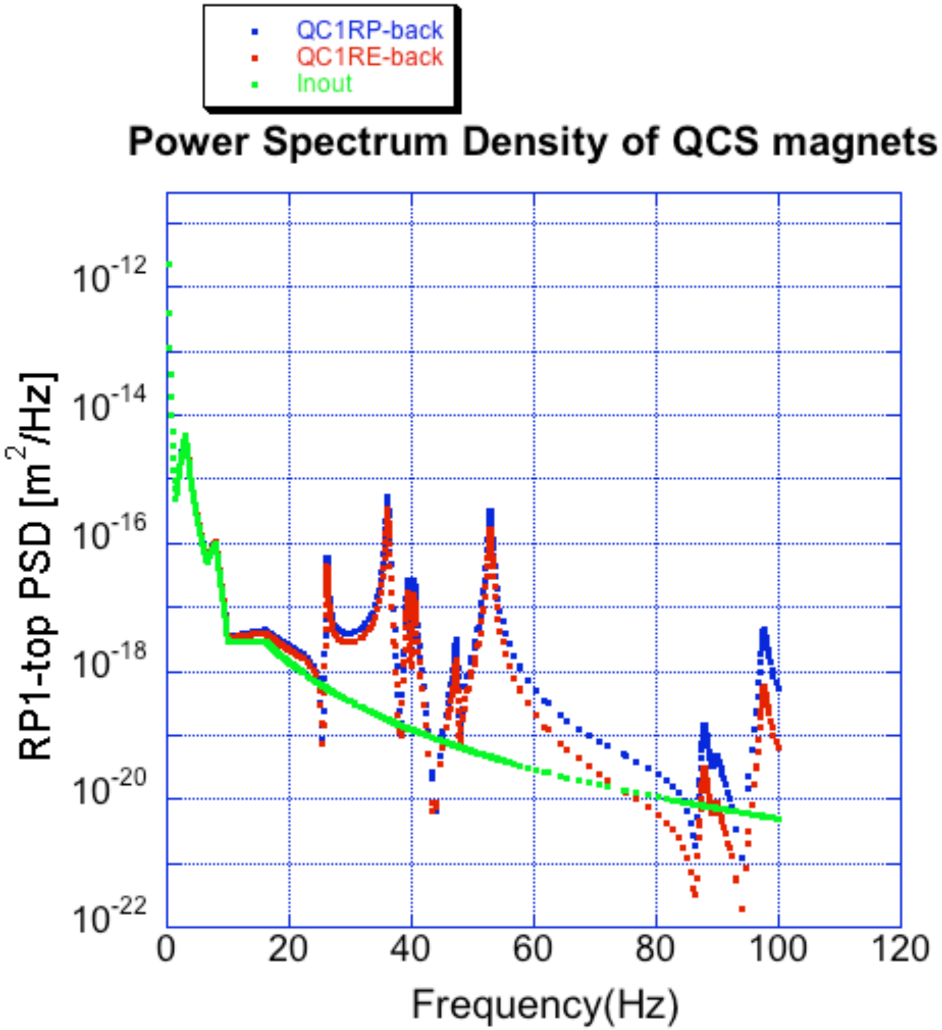


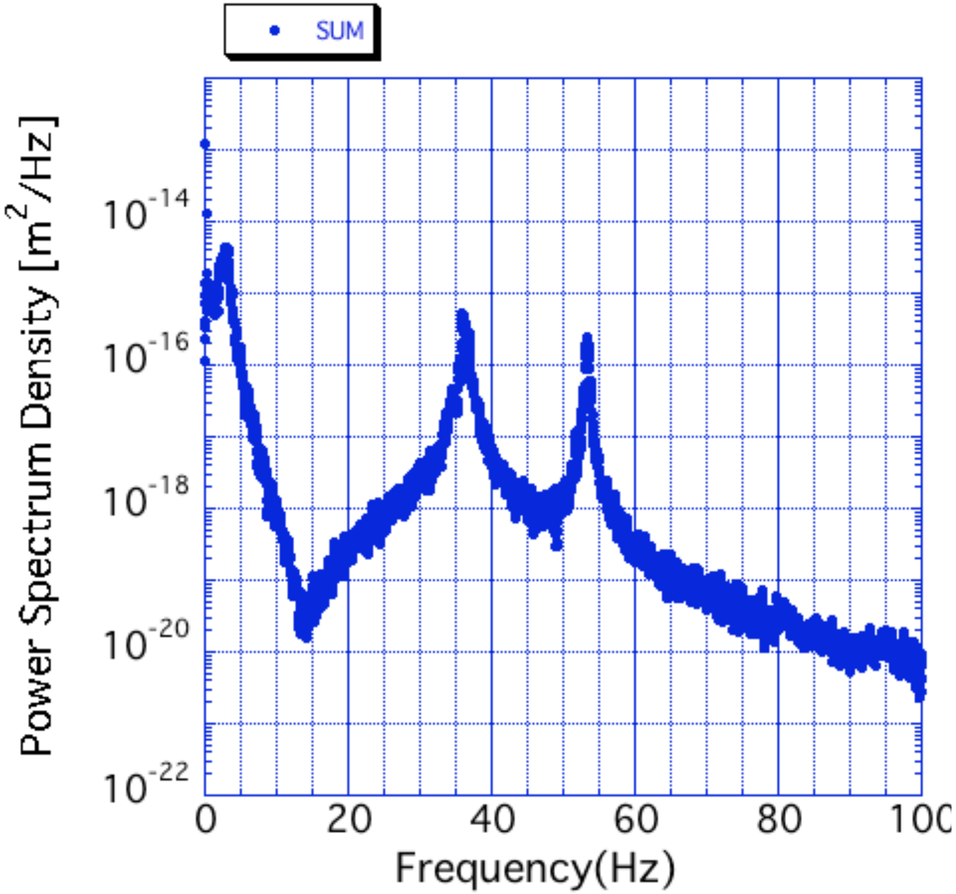




KEKB

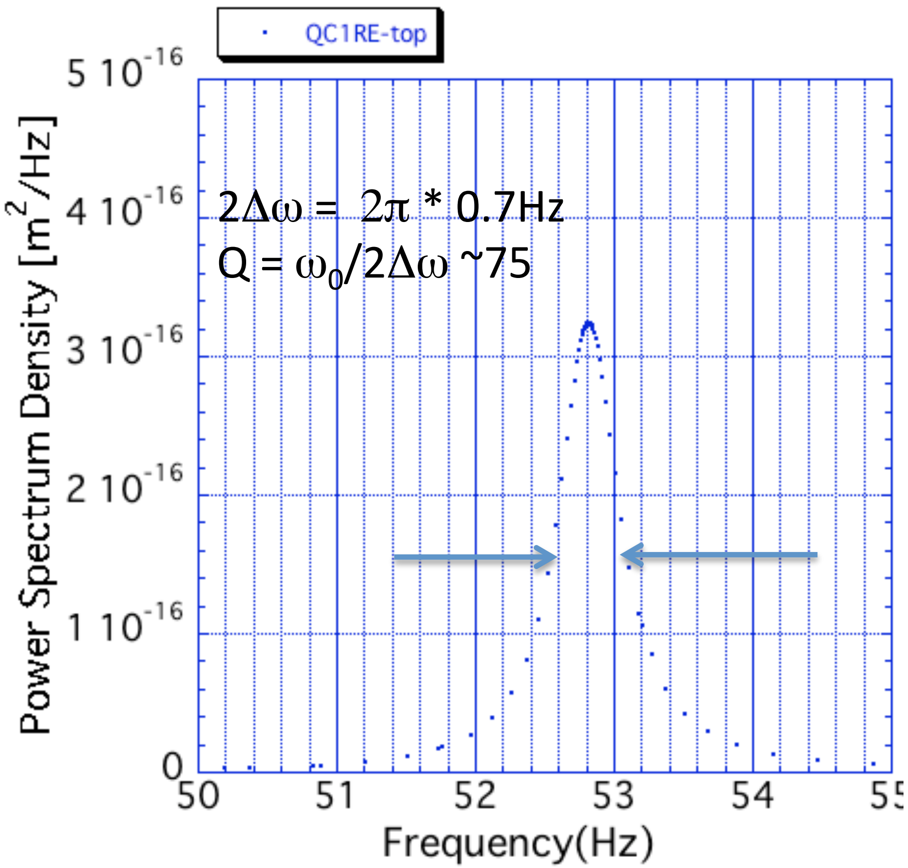
# Reproduced PSD



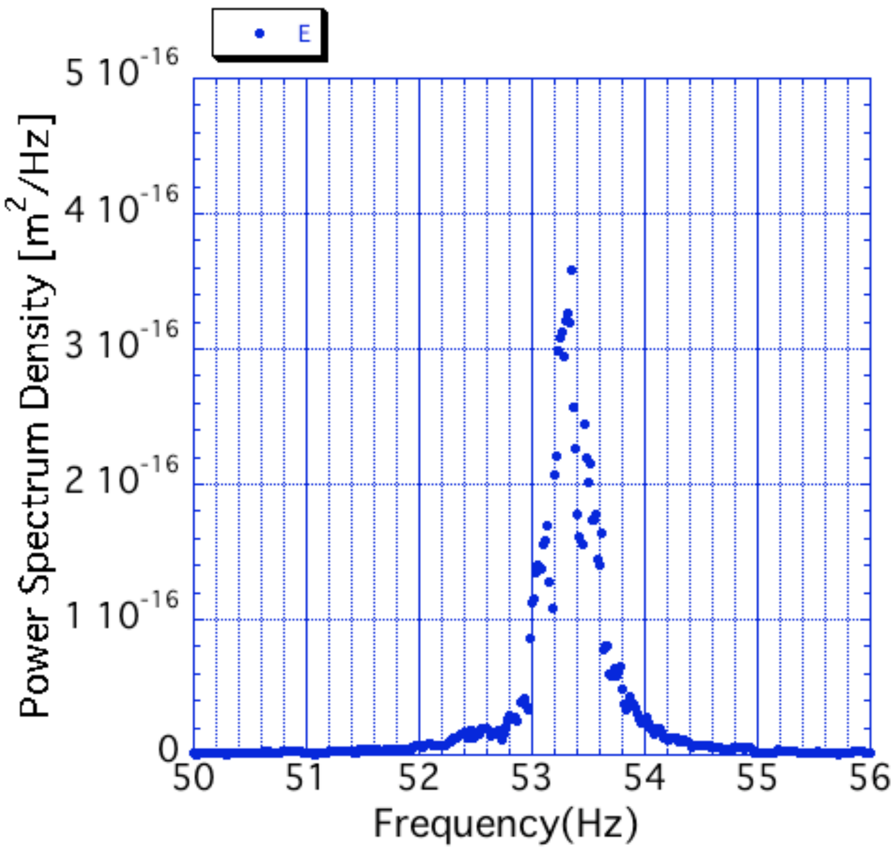



# Resonance at ~53Hz

PSD from H. Yamaoka

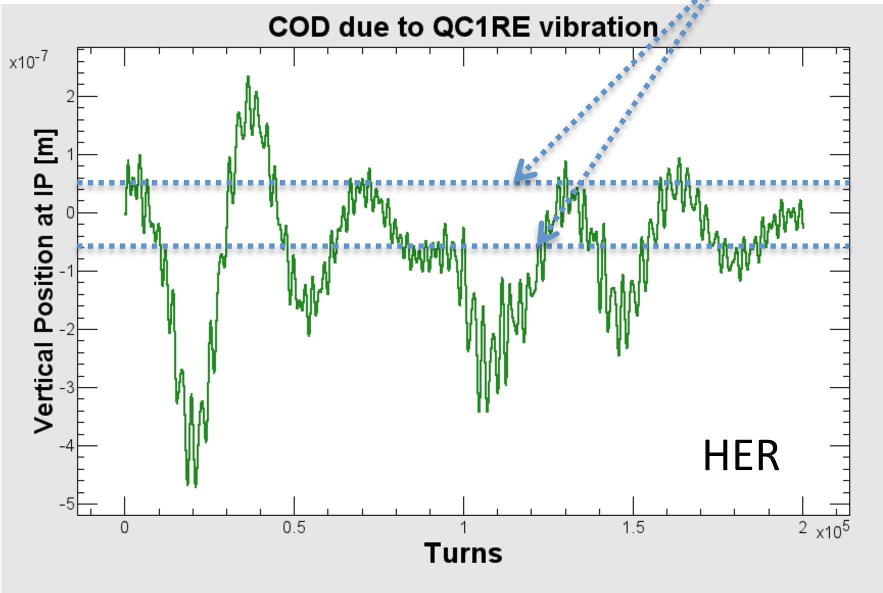


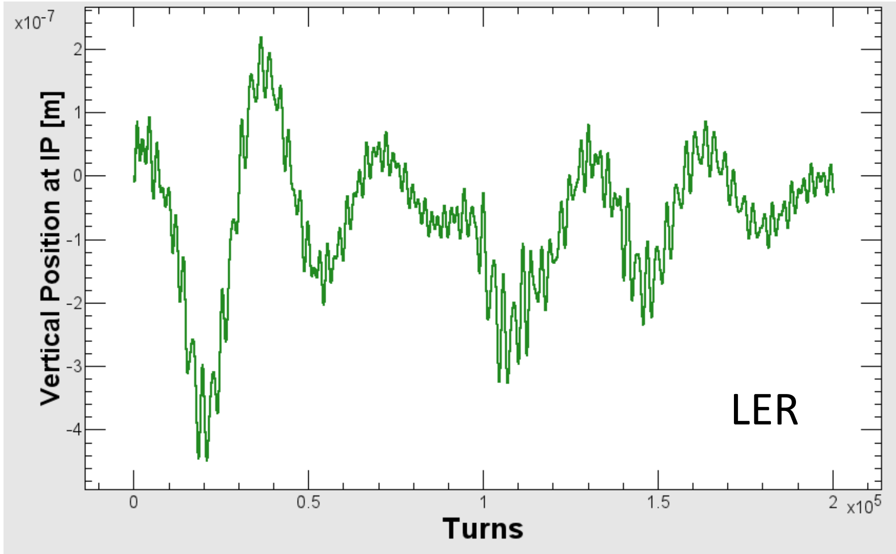

Reproduced by Funakoshi

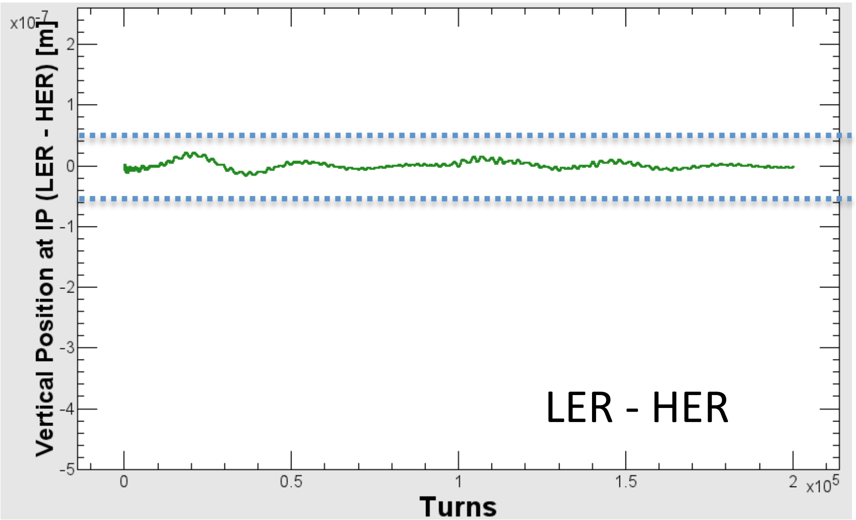


# COD simulation due to QC1R vibration in case that QC1RE and QC1RP move in the same way

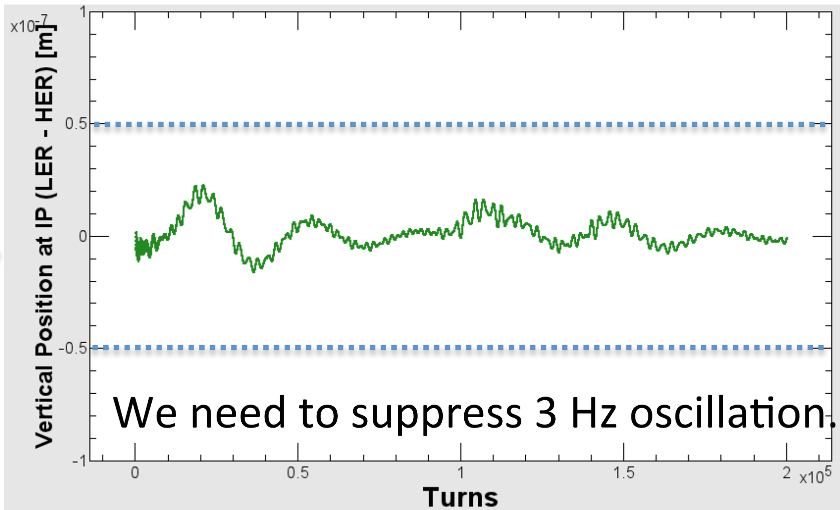
$\pm 1\sigma_y$



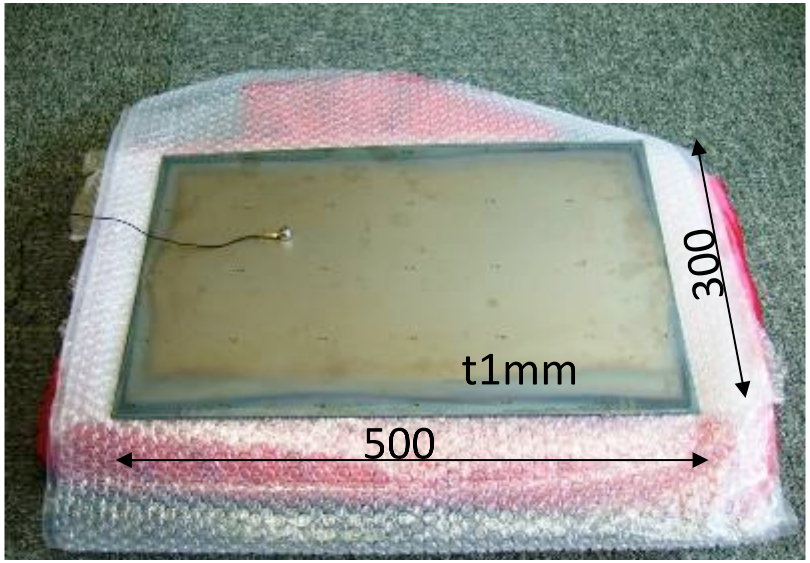



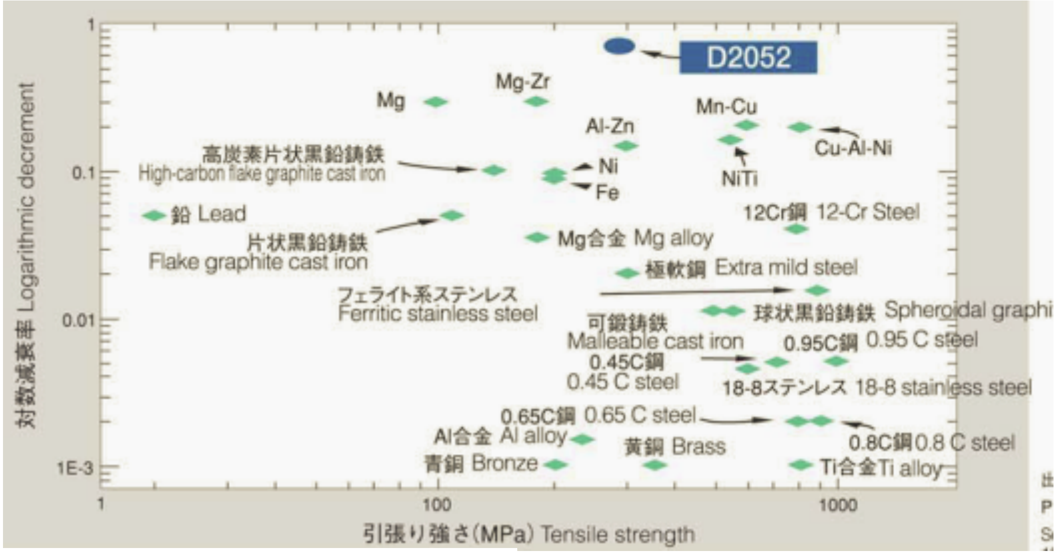

Magnify



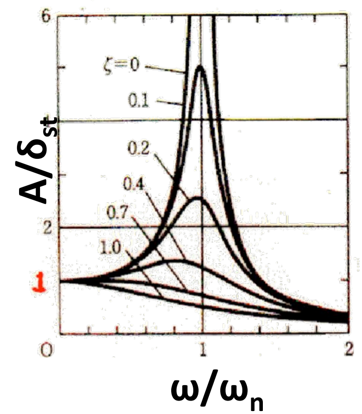
# High Damping Material: D2052

H. Yamaoka




Mn-base damping alloy




**代表的な化学成分** Typical chemical composition

| Mn | Cu | Ni | Fe | 単位 Unit |
|---|---|---|---|---|
| Bal. | 22.4 | 5.2 | 2.0 | wt% |
| Bal. | 20.0 | 5.0 | 2.0 | at% |

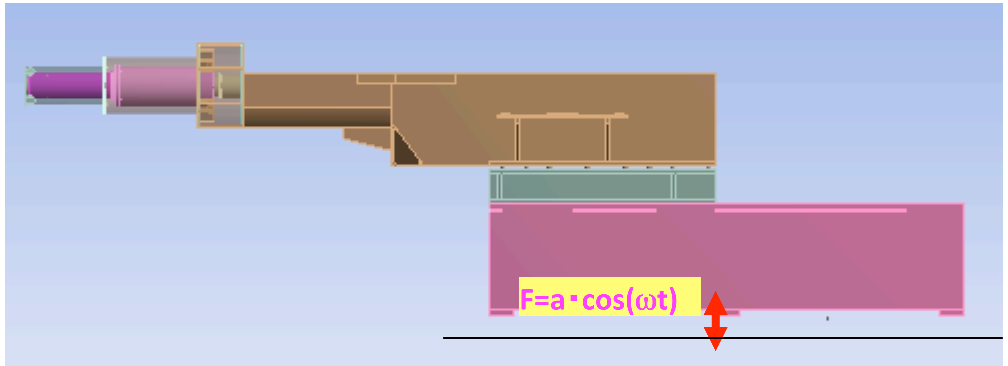
**主な物性値** Typical properties

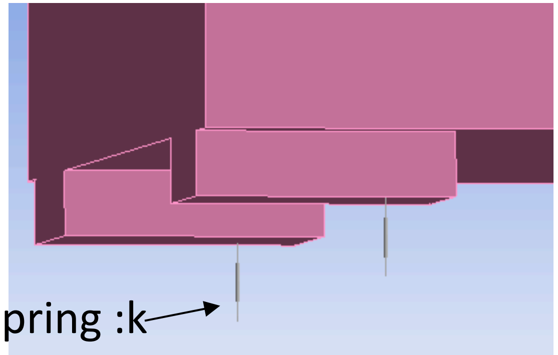
| 物性 Property | 値 Value | 近い元素 Approximate element |
|---|---|---|
| ヤング率 Young's modulus | 80 GPa (300K) | Al、Ag、Cd |
| 熱伝導率 Heat conductivity | 10 W/(m·K) (300K) | Ti、Sb、Pb、Bi |
| 比熱 Specific heat | 512.7 J/(kg·K) (300K) | Ti、Fe、Cr |
| 熱膨張率 Coeficient of thermal expansion | 22.4 $\times 10^{-6}$/K (300K) | Al、Ag、Sn、Cu |
| 密度 Density | 7.25 $\times 10^{3}$kg/m$^{3}$ | Fe、Mn |
| 硬さ Vicker's hardness | 120~140 | |

**機械的強度** Mechanical strength

| | 引張強さ Tensile strength | 耐力 (0.2%) Yield strength | 伸び Elongation | 絞り Reduction of area | 疲労強度 (×10$^{7}$回) Fatigue strength(×10$^{7}$times) |
|---|---|---|---|---|---|
| 標準材 Standard material | 530MPa | 265MPa | 40% | 61% | 125MPa |

H. Yamaoka




F=1x10$^4$N

k=2x10$^5$N/mm

**Materials（w/o damping material）**

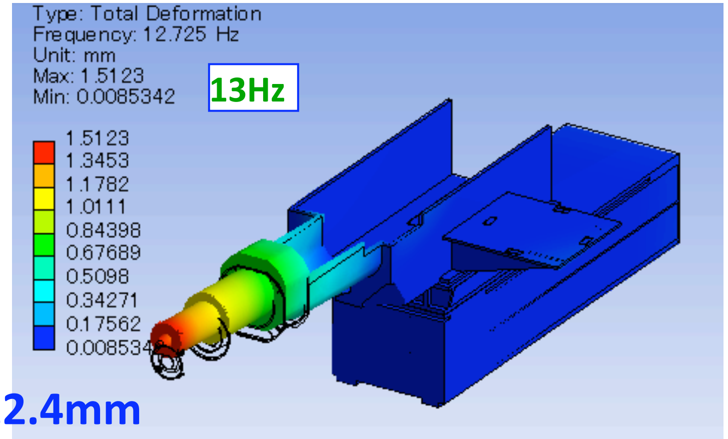
**Cryostat: SUS**

**Coil: Cu**

**Supp.-rod: Ti-alloy**

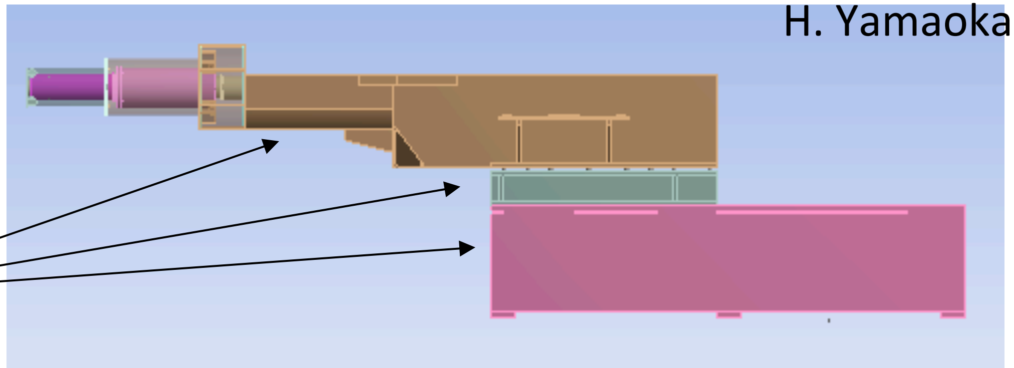
**QCS table: SS400**

***damping= 0.5%***




➔ **Response displacement： 12.4mm**
**eigen-frequency： 13Hz**

H. Yamaoka



Materials

Cryostat: SUS

Coil: Cu

Supp.-rod: Ti-alloy

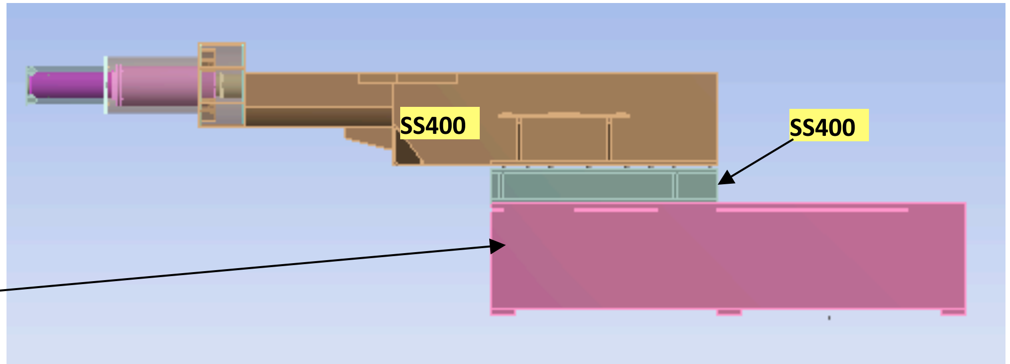
QCS tables: damping material

*damping= 5%*

bolts： damping material

➔ **Response displacement： 3.2mm(damping: 74%)**

**eigen-frequency： 9Hz**




Materials

Cryostat: SUS

Coil: Cu

Supp.-rod: Ti-alloy

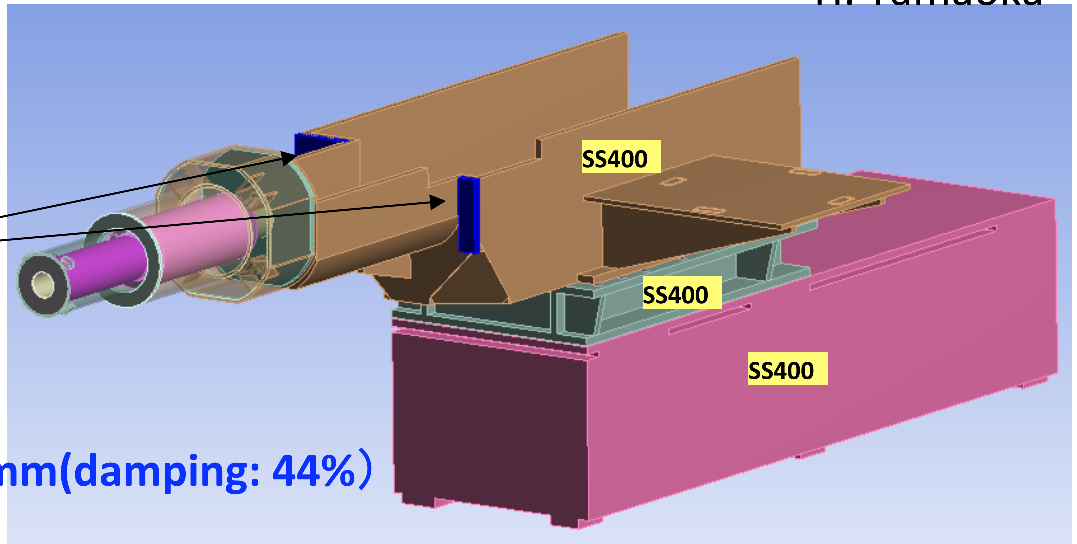
QCS table: damping material

bolts： damping material

➔ **Response displacement： 6.0mm(damping: 51%)**

**eigen-frequency： 11.6Hz**

H. Yamaoka

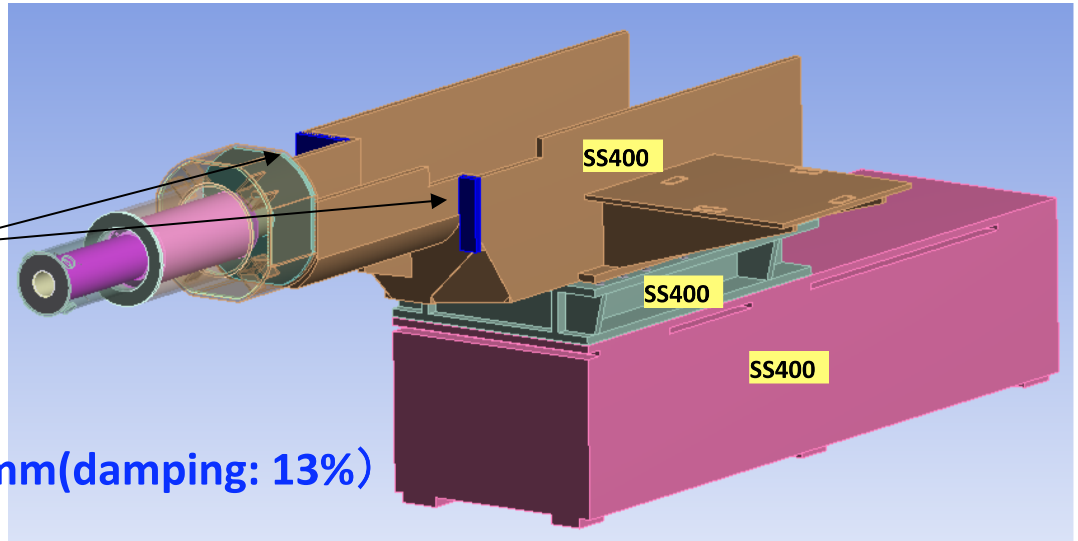



Materials

Cryostat: SUS
Coil: Cu
Supp.-rod: Ti-alloy
QCS table: damping material
welding (t45mm)
bolts: damping material

➔ Response displacement: 6.9mm(damping: 44%)
eigen-frequency: 13.7Hz

This case seems realistic.

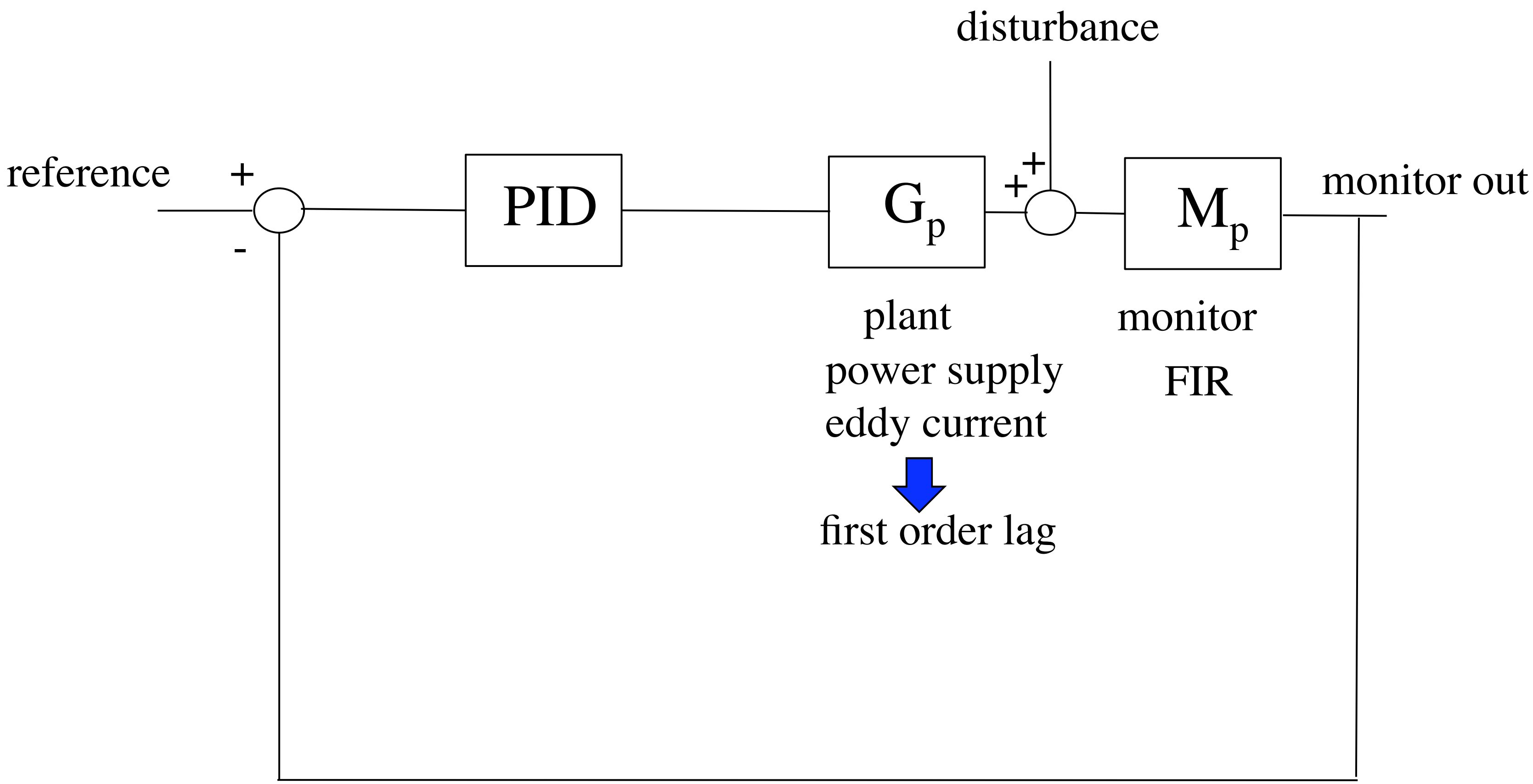



Materials

Cryostat: SUS
Coil: Cu
Supp.-rod: Ti-alloy
QCS table: steel instead of damping material welding(t45mm)
bolts: damping material

➔ Response displacement: 10.8mm(damping: 13%)
eigen-frequency: 13.7Hz

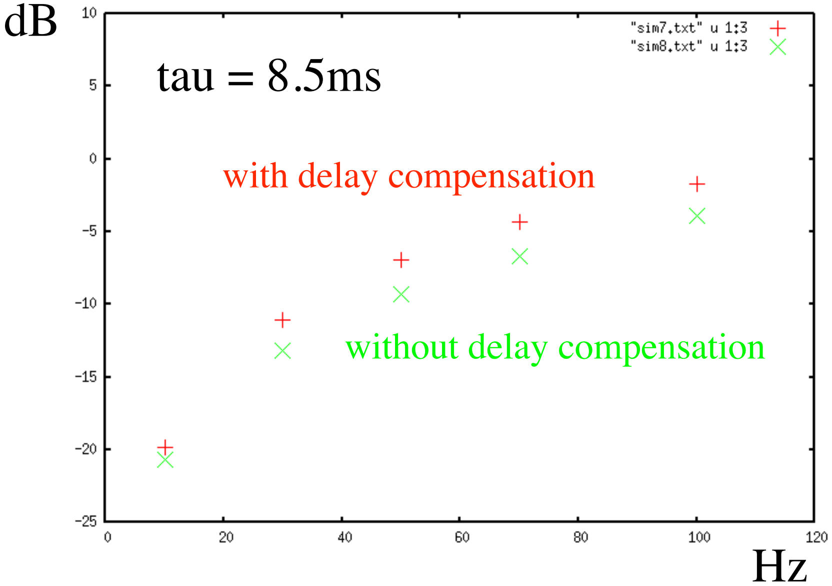
# Orbit Feedback System

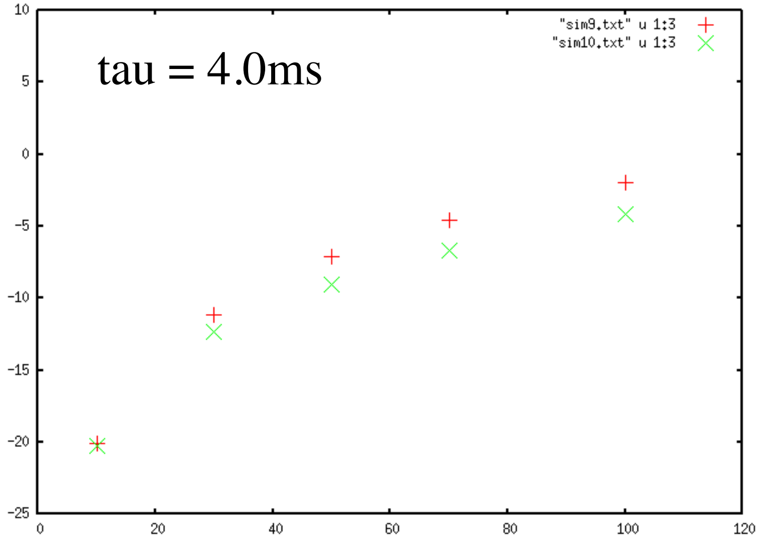


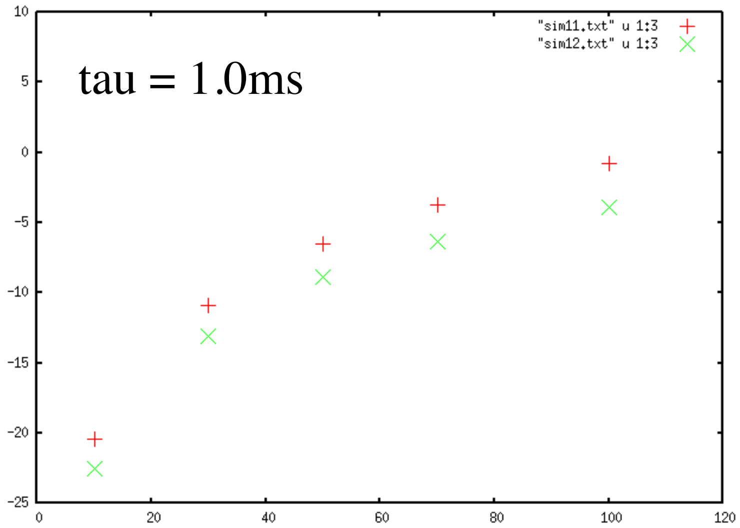

H. Fukuma

# Analysis of FB system by H. Fukuma

group delay = 5 samples (1.1ms)




Disturbance suppression is weaker with delay compensation.

If group delay is reduced to 1ms, rejection gain at 10/100Hz is -22/-5 dB, and gain is almost not dependent on time constant of the plant.

Tau is the time constant of the plant coming from eddy current and delay in power supply etc.

# Horizontal orbit feedback

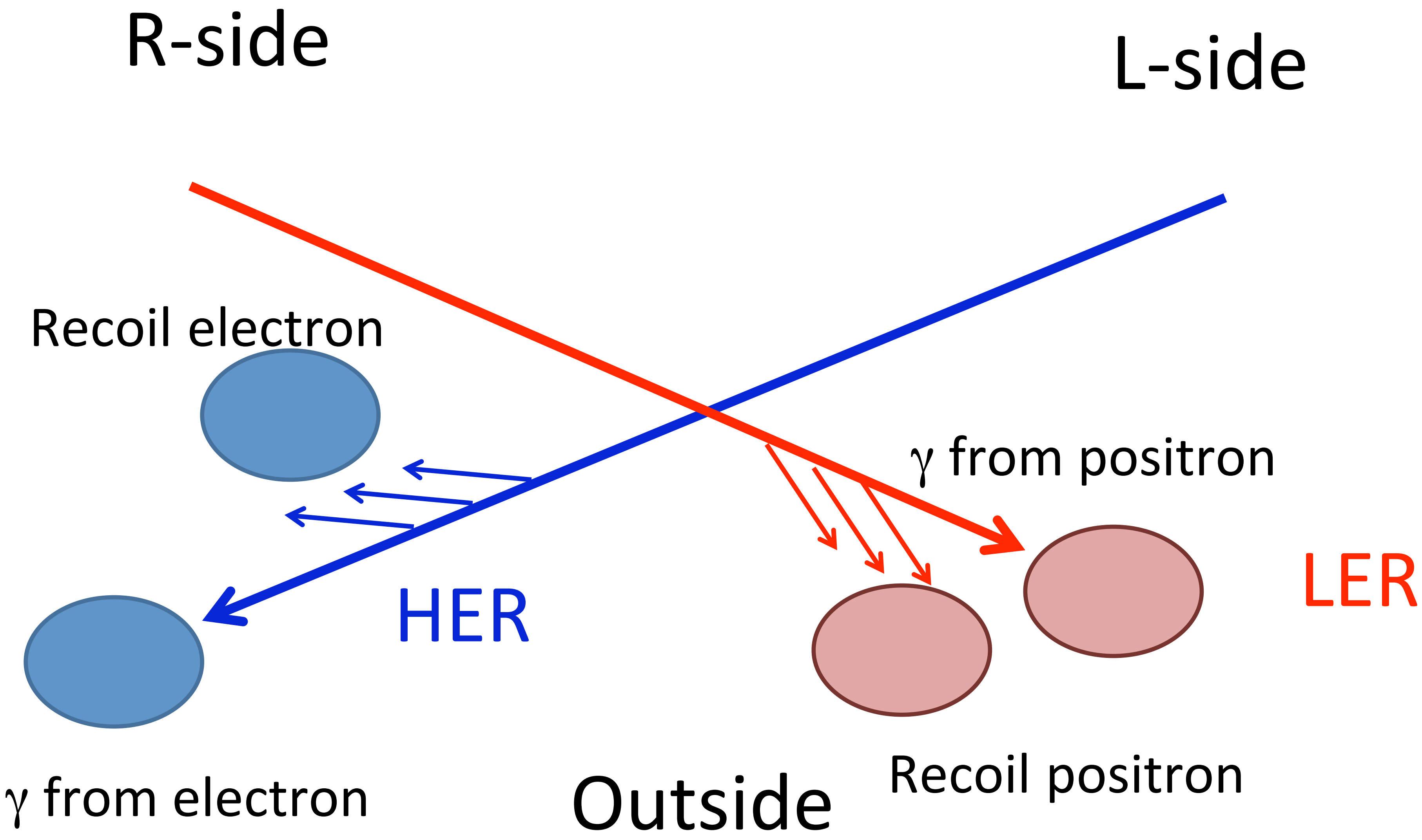
- Difficulty to develop FB based on the beam-beam defection like the vertical case
  - Small ξx
    - ξx ~ 0.0028(e+), 0.0017(e-)
  - Two sources of horizontal beam-beam kick
    - Horizontal offset and shift of collision timing
- Maybe we need a different method for the Hor. feedback.
  - Luminosity feedback (dithering) (like PEP-II)
  - Beam size feedback (like KEKB Hor. feedback before crab)
- Effect of horizontal offset with crab waist scheme
  - Due to Hor. offset, the two beams collide at the position which is shifted from the waist point.
  - The crab waist seems to compensate this shift of waist.
  - However, the situation becomes worse with the crab waist, since we have to keep the both beams at the design collision point with crab waist scheme.
- Feedback speed
  - Orbit change at IP due to fast vibration of IR quads is small. We do not need very fast feedback.

# Dithering for Horizontal FB

- We have started to consider the dithering system based on experience at PEP-II.
- Conceptual design
  - Monitoring
    - Fast luminosity monitor (ZDLM)
      - Detect gamma-ray  or lost particles from radiative Bhabha scattering
  - Magnets for dithering
    - Dithering frequency: 60 < Freq. < 100Hz
    - Amplitude of dithering: ~<$0.5\sigma_x$ -> steering kick angle: ~< 5$\mu$rad
    - Steering magnets: magnets with air core coils
  - Electronics
    - Lock-in amp (PEP-II) -> spectrum analyzer
  - Steering magnets for orbit correction
    - Use usual DC steering magnets for FB

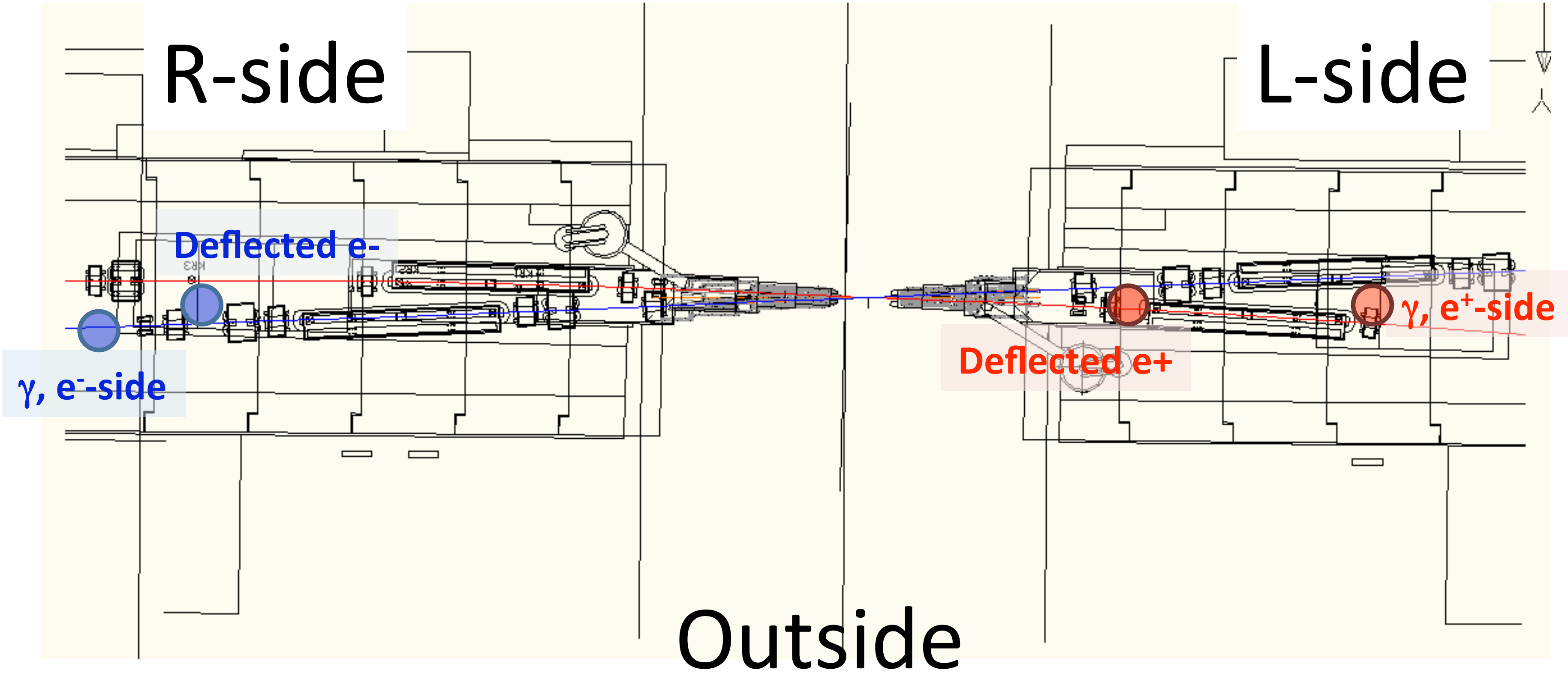
S. Uehara

# Where are the signals?



S. Uehara

# Possible locations

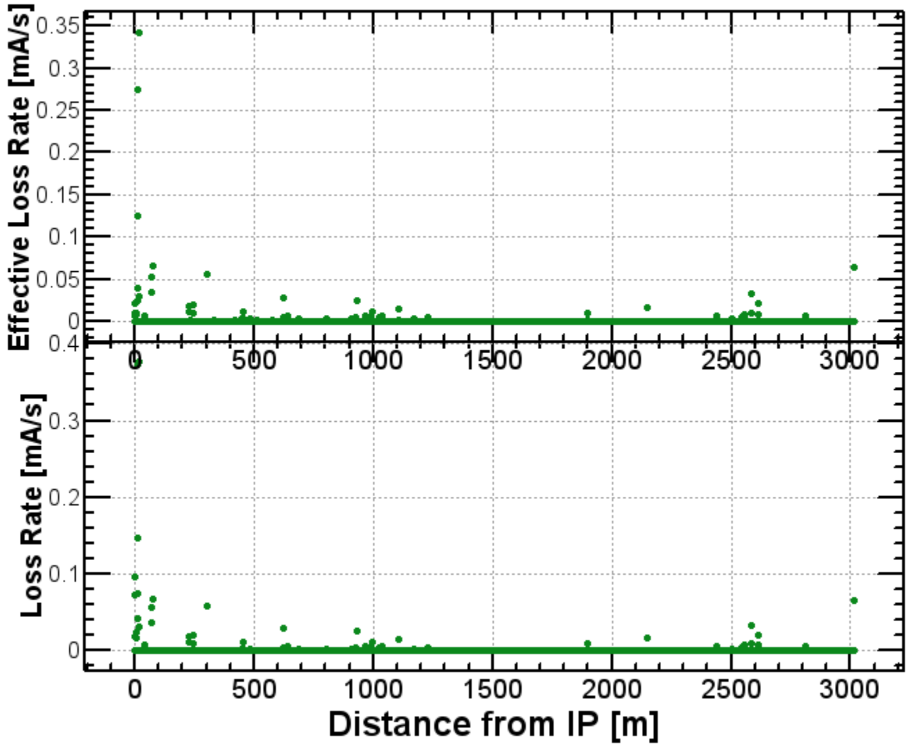


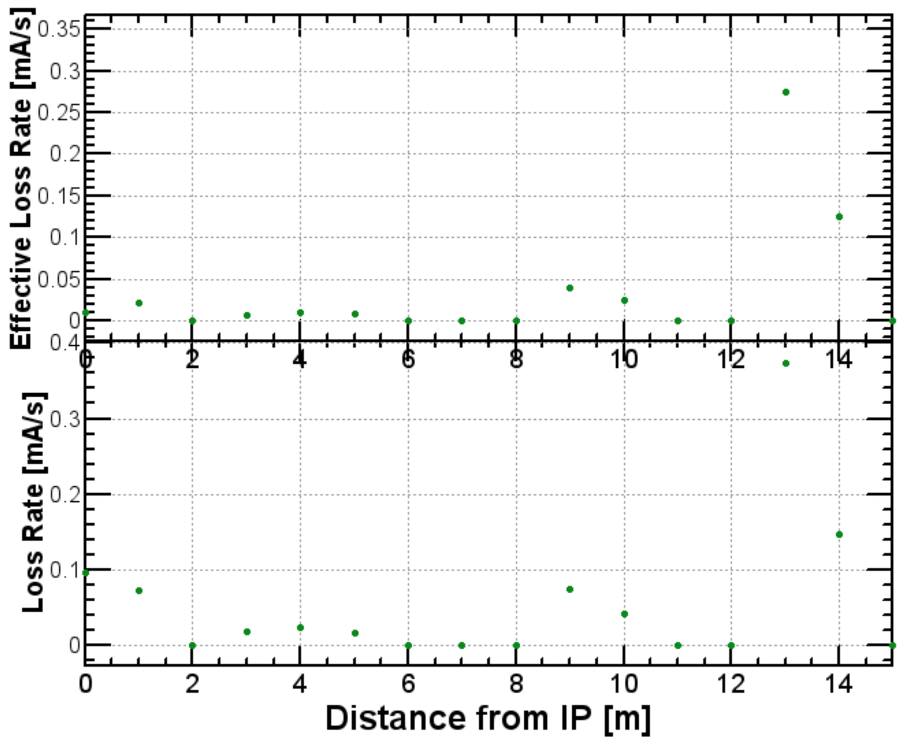

Possible problems:

Material quantity of the beam chamber in r.l.

Undesirable sensitivity to angle and position/size of the beams at IP

# Beam loss simulation from raditive Bhabha: LER Loss Position & Rate



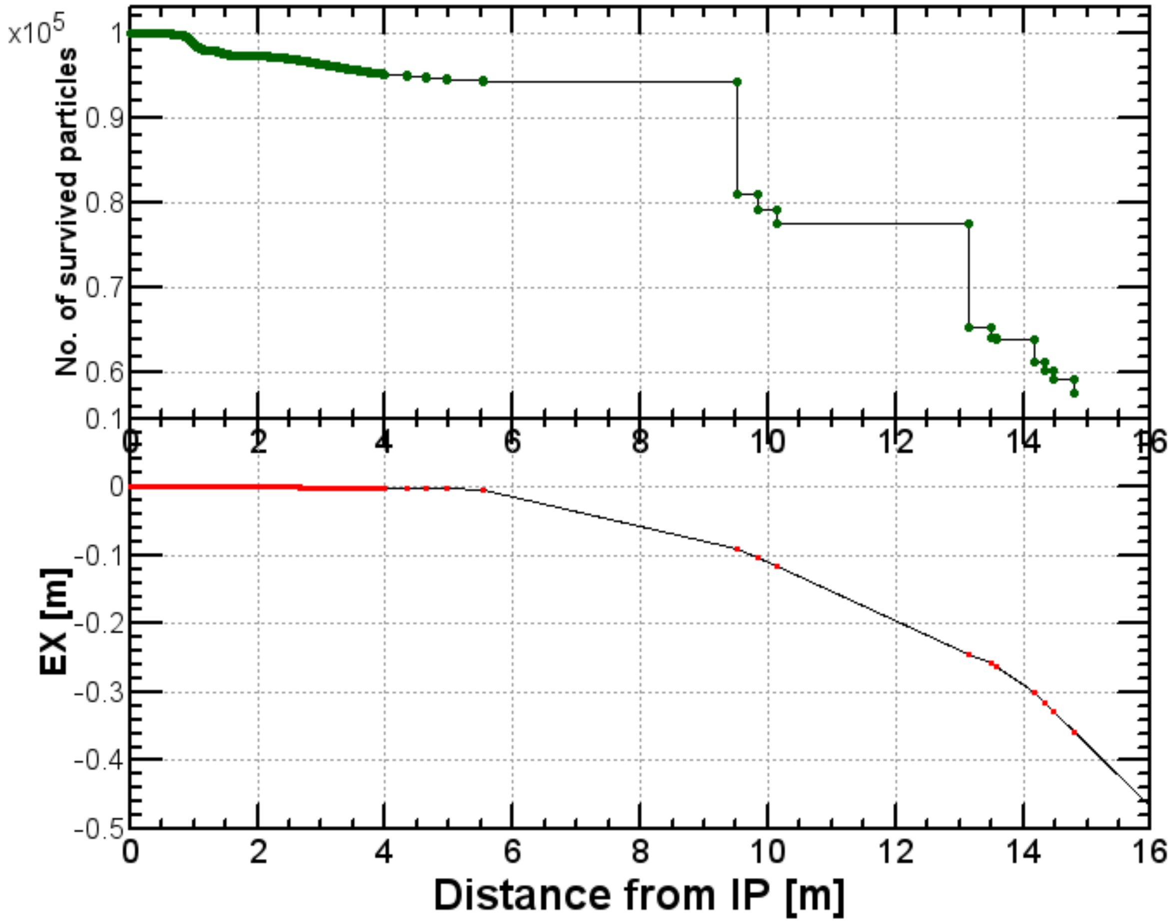

Loss rate: $R_{Loss}$ [mA/s] $= 1000N$ [partices/s] $e\ f_0$

$e = 1.602 \times 10^{-19}$ [C]

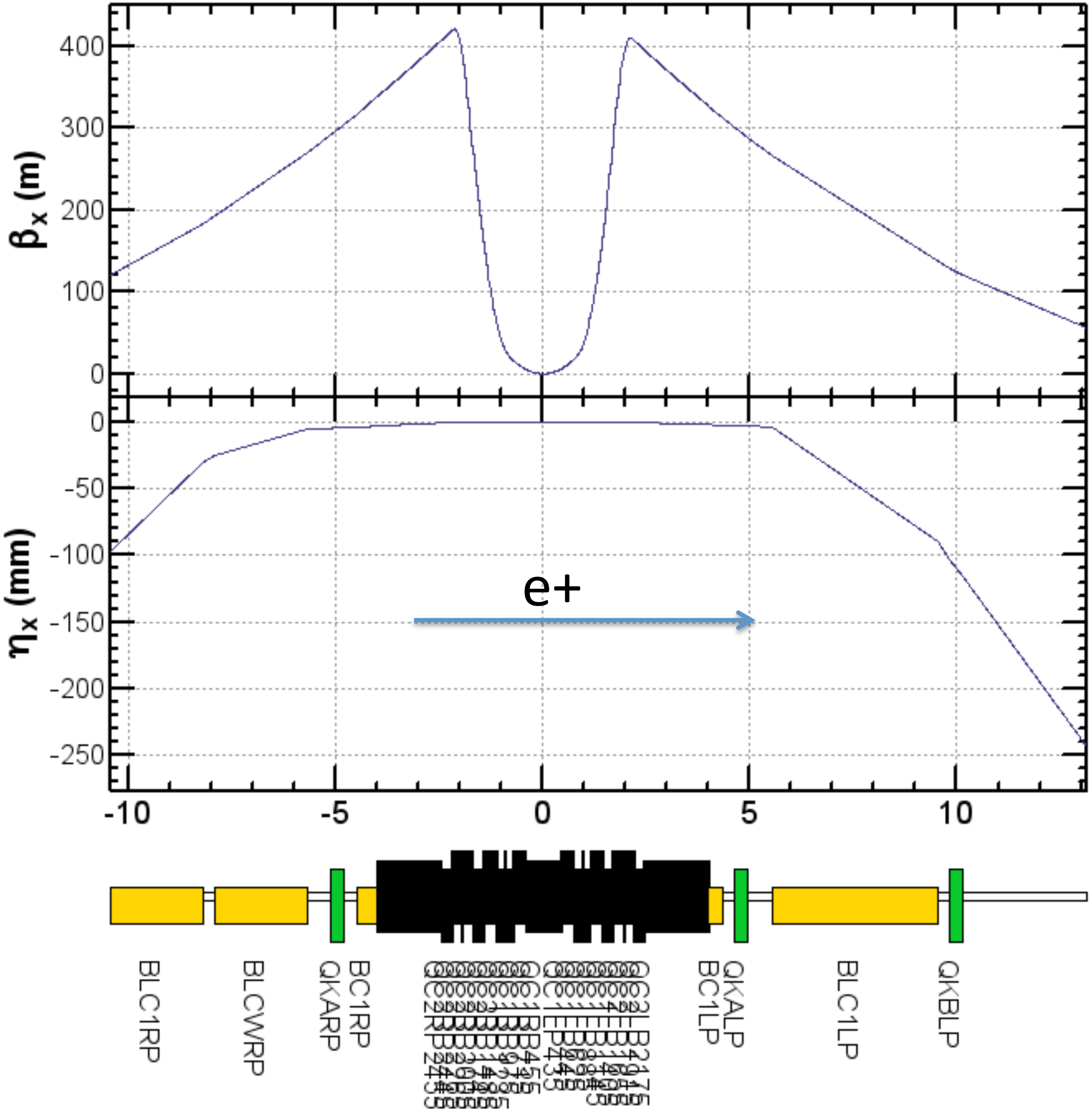
$f_0 \cong 100$ [kHz]

0.1mA/s -> 6.2GHz

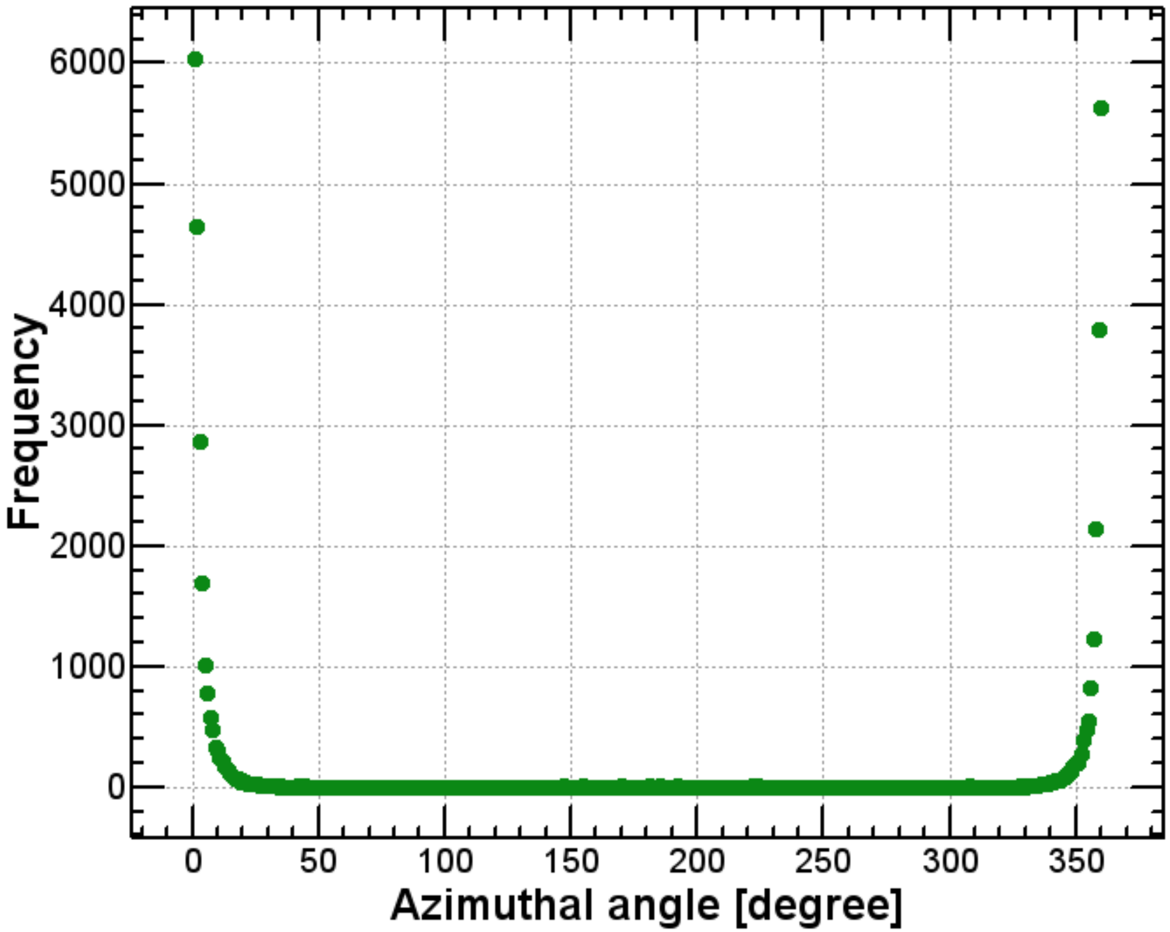
# # of survived particles (LER)



# LER IR Optics



# Azimuthal angle distribution of lost particles (LER)




Zero degree: horizontal (outside of ring)

Lost position: 4m < s < 16m from IP

# Expected ZDLM rate (Uehara)

0.1mA/s -> 6.2GHz

- Funakoshi-san's coefficient
- The rate should be proportional to luminosity

  $10^{35}$ luminosity --- ~ 1GHz

- Effective detector length --- ~ 0.1m
- Efficiency --- 10%

  (angular coverage and shower loss)

Expected Rate --- 0.1mA/s → 10 MHz

LER 4 m point (upstream BLC1LP) ~ 2MHz @$10^{35}$

9 m point (downstream BLC1LP) ~ 2MHz @$10^{35}$

# Luminosity Dithering Monte Carlo simulation

S.Uehara(KEK)

S. Uehara

# Parameters

- A set of measurement: measure the change of ZDLM rate for one second
- Sampling rate **1024Hz**

  measure every 0.977ms

- Dithering —— frequency $f = 77\text{Hz}$

$r \sim \sin 2\pi f t$

*Assume that the luminosity depends on r with a Gaussian distribution.*

$L(t) \sim \text{Exp}[-(q+p \sin 2\pi f t)^2/2]$

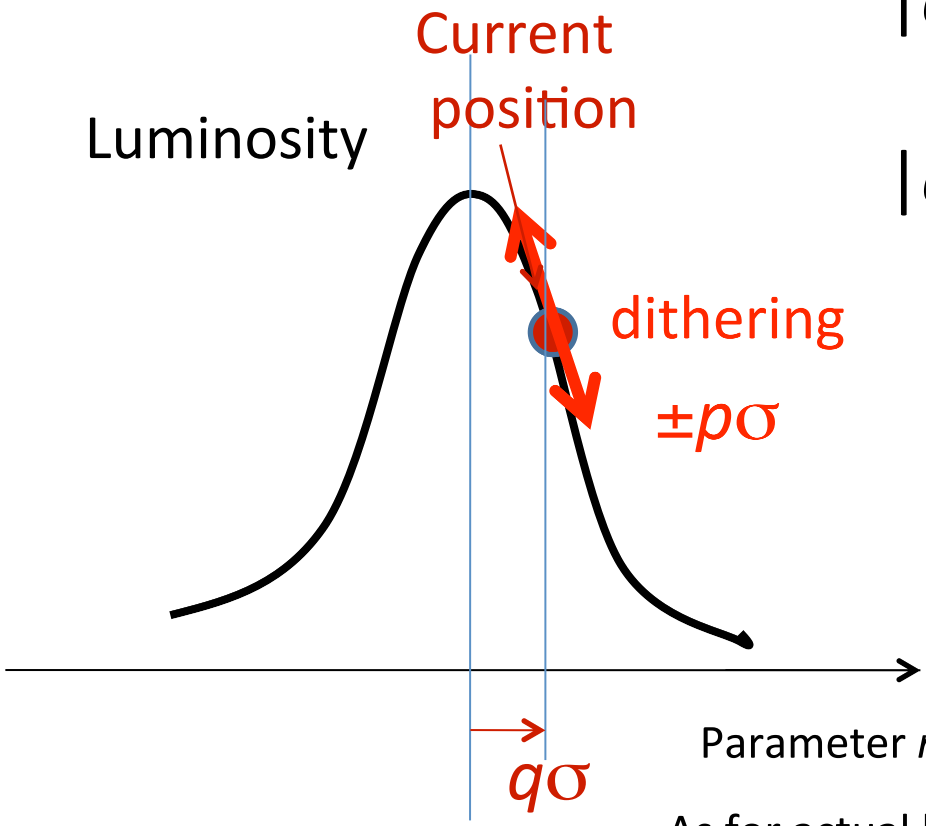
$q$ : offset

$p$ : dithering amplitude

$f$ : dithering frequency （here we assume f=77Hz)

S. Uehara

# Dithering




$|q|>p$ – move along slope

$|q|<p$ -- move around peak

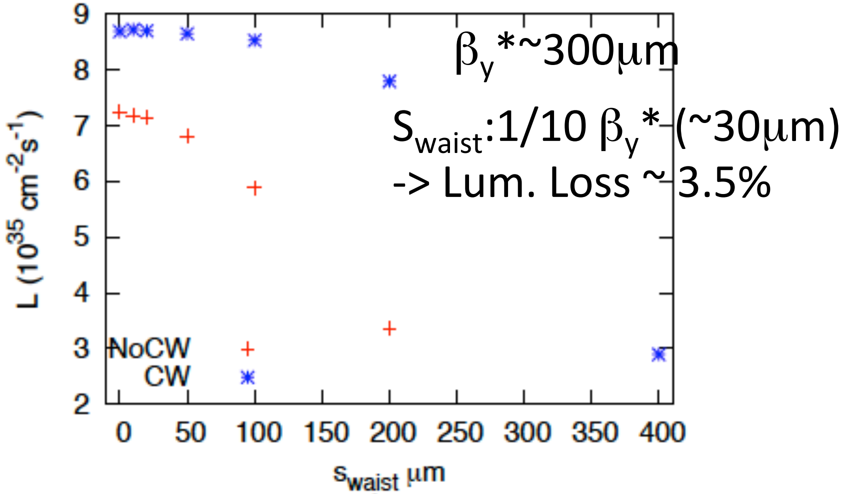
Parameter *r* for dithering

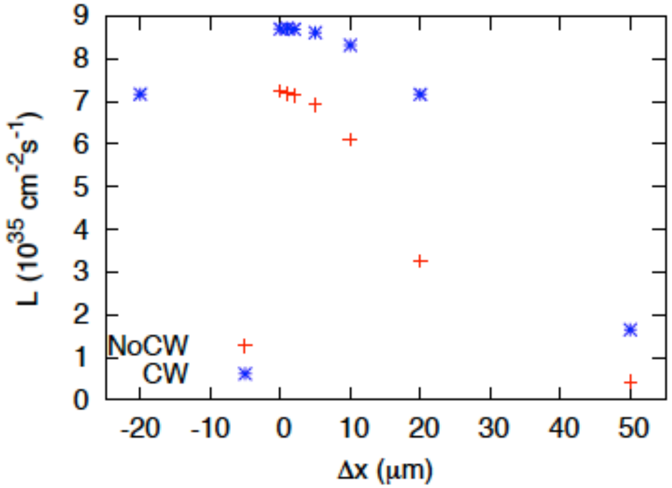
As for actual luminosity dependence on the orbit offset , we have to rely on the beam-beam simulation. Such simulation predicts that the luminosity loss with 1 $\sigma_x$ offset is about 15%.

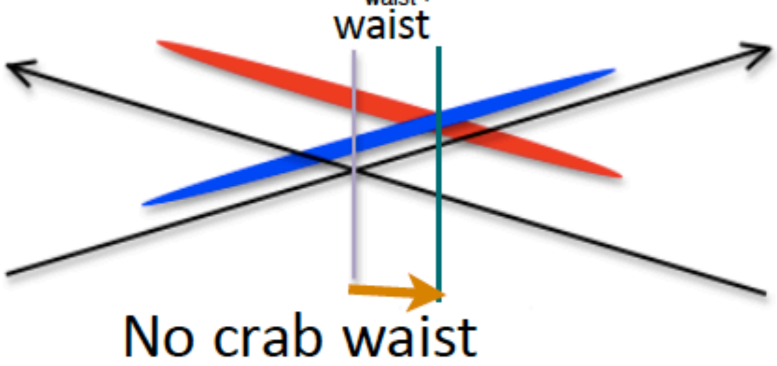
# Tolerance of collision condition
# Horizontal collision offset and waist

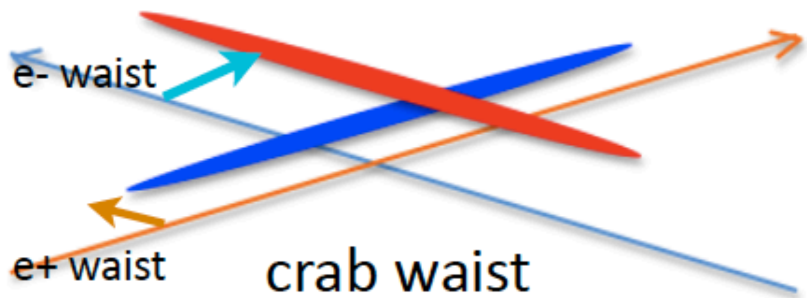
K. Ohmi

- Horizontal offset and waist are related to each other.
- The cross point of the waist is only one in x-z plane for the crab waist scheme.



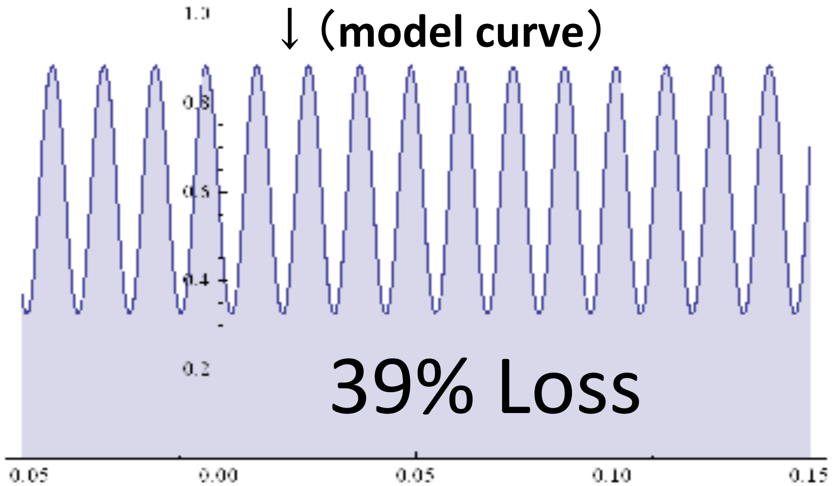
S. Uehara

# Result with Mathematica8

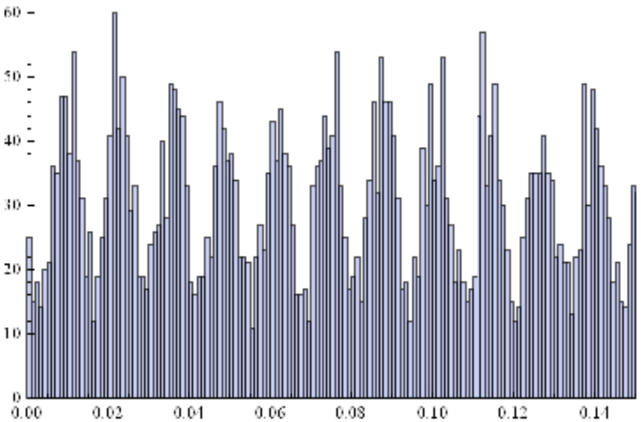
*p* =0.5, *q*=1.0, event rate=10kHz

Luminosity

↓ (**model curve**)

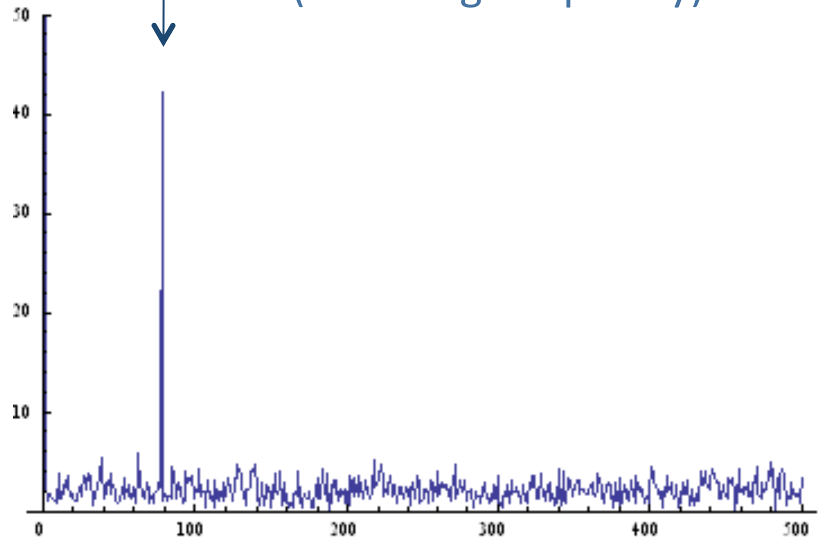



**(MC data)**
→



Sqrt of Power Spectrum

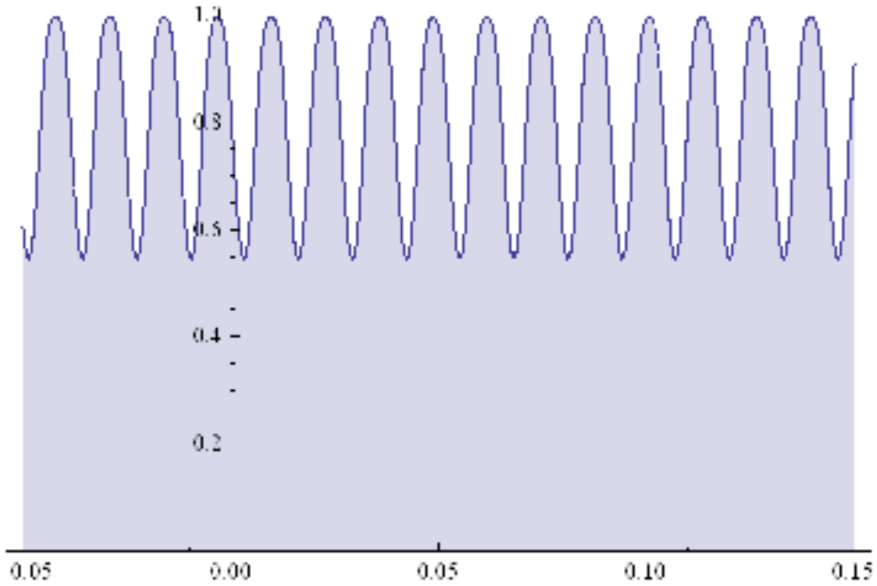
77Hz (dithering frequency)



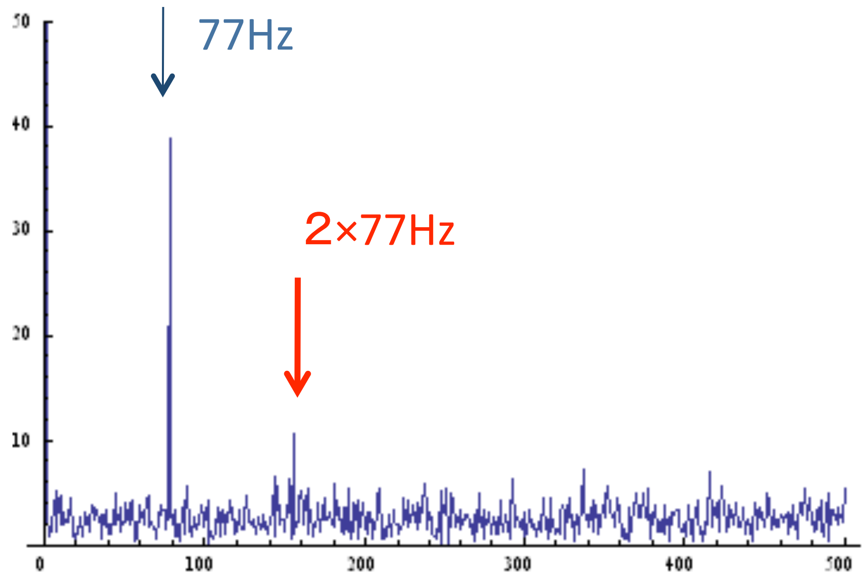
S. Uehara

# $p$ =0.5, $q$=0.6, event rate=10kHz

Luminosity




Sqrt of Power Spectrum

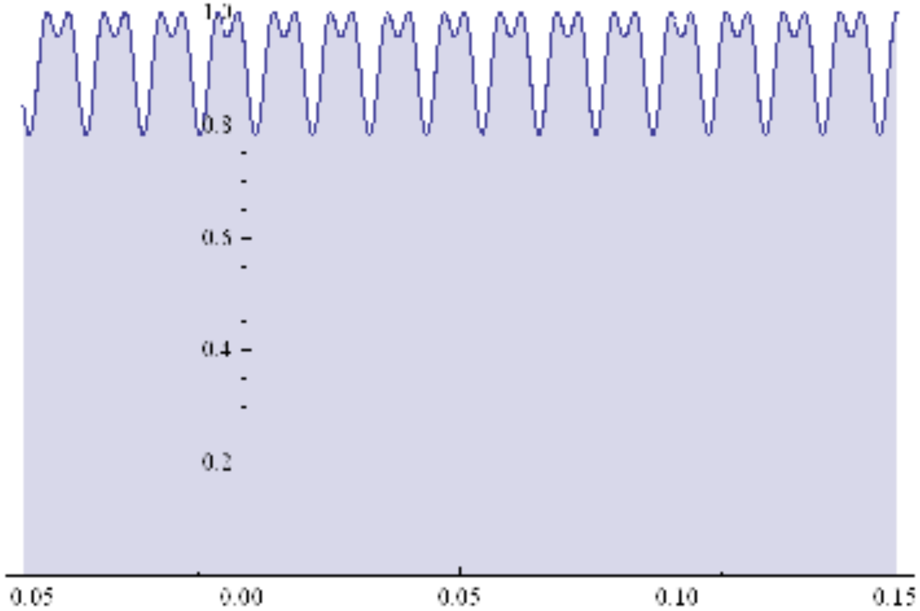



20% Loss

S. Uehara

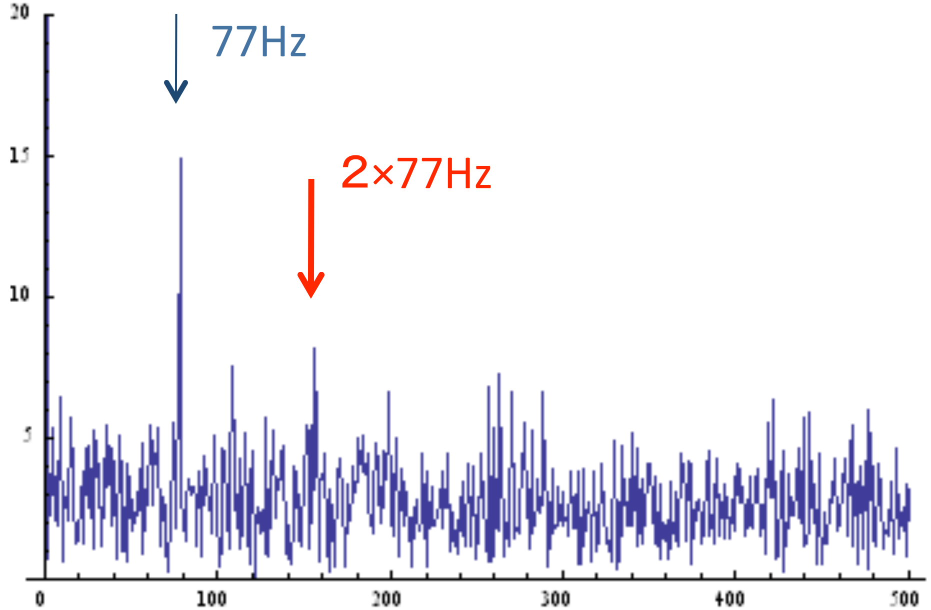
# *p* =0.5, *q*=0.2, event rate=10kHz

Luminosity




8% Loss

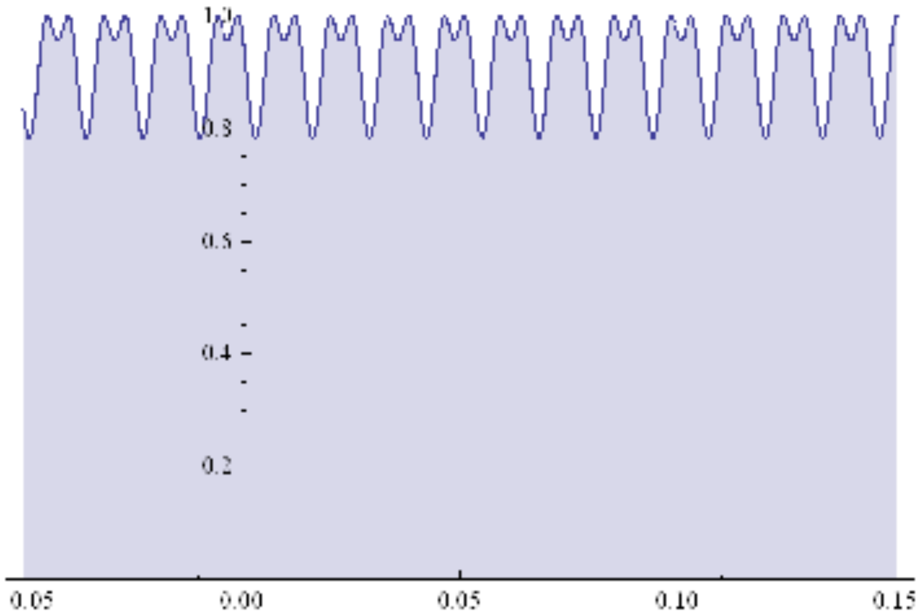
Sqrt of Power Spectrum



S. Uehara

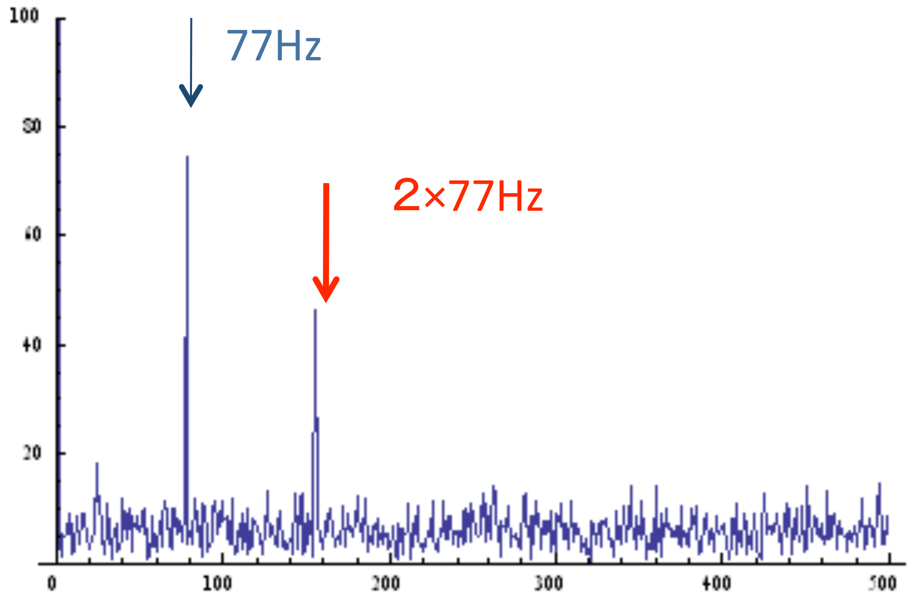
# $p$ =0.5, $q$=0.2, event rate=50kHz

Luminosity




8% Loss

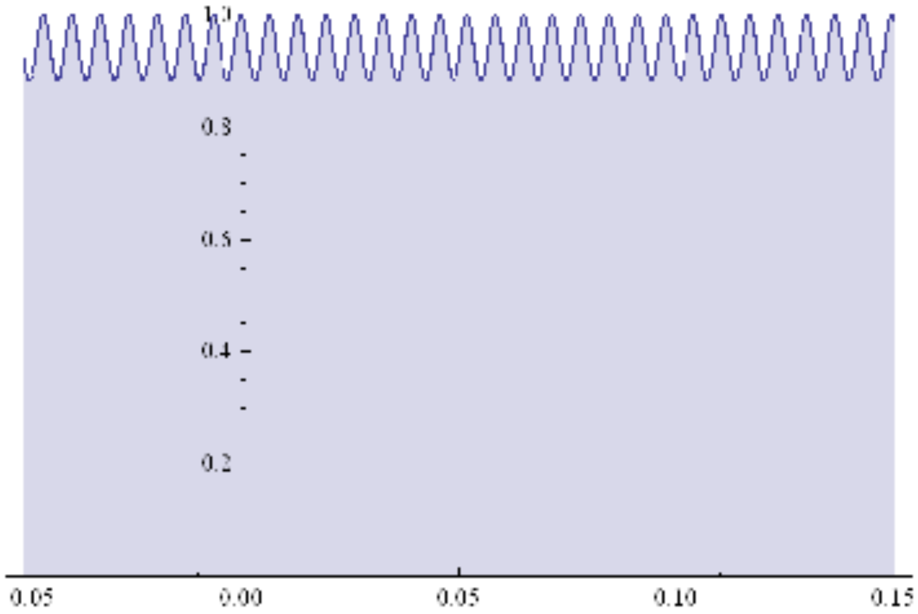
Sqrt of Power Spectrum



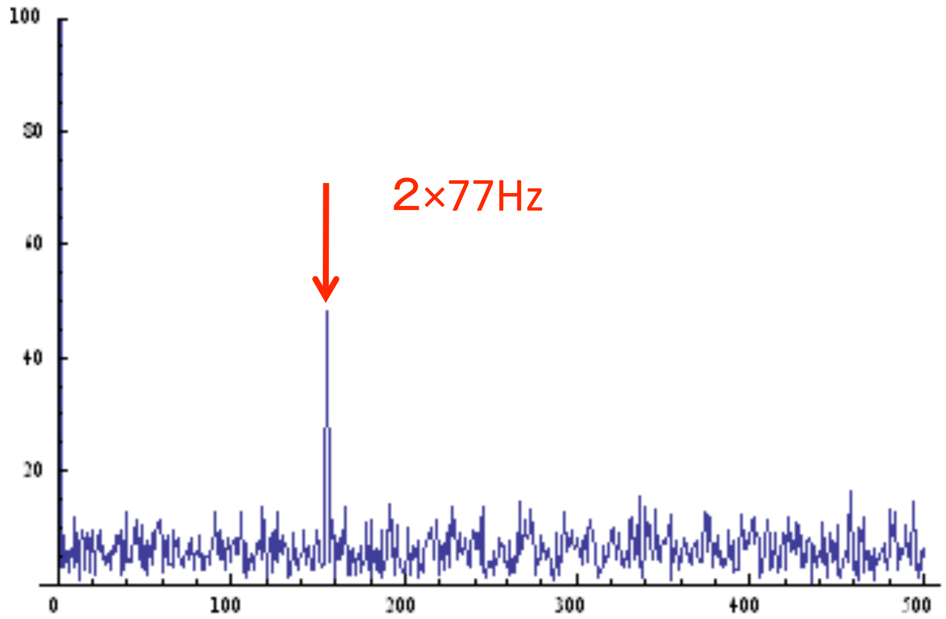
S. Uehara

# $p$ =0.5, $q$=0, event rate=50kHz

Luminosity




Sqrt of Power Spectrum

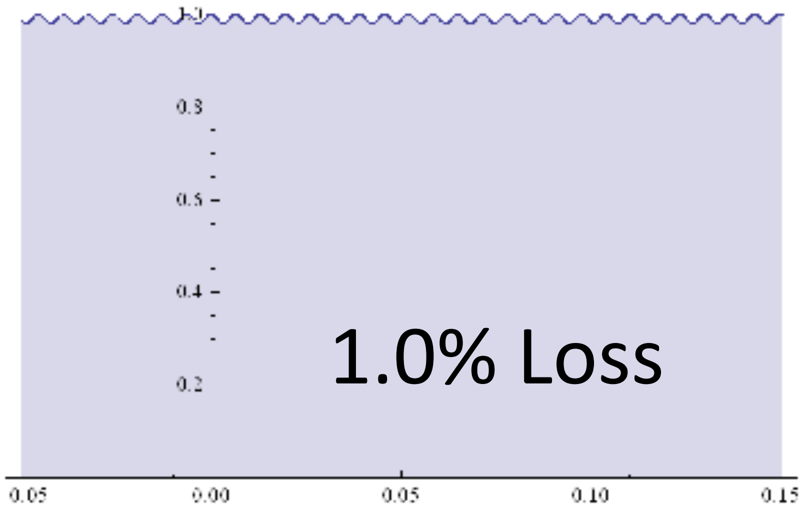



6% Loss

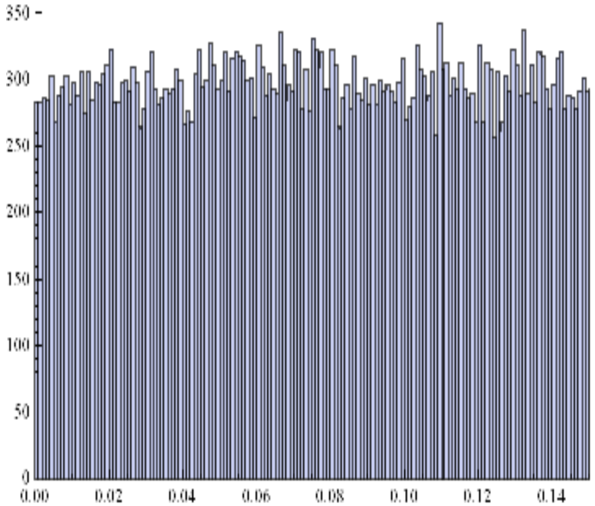
S. Uehara

# $p$ =0.2, $q$=0

Luminosity



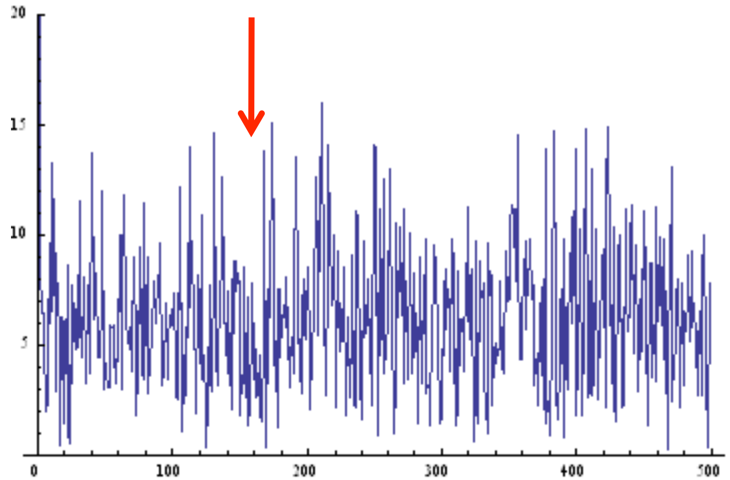

300kHz



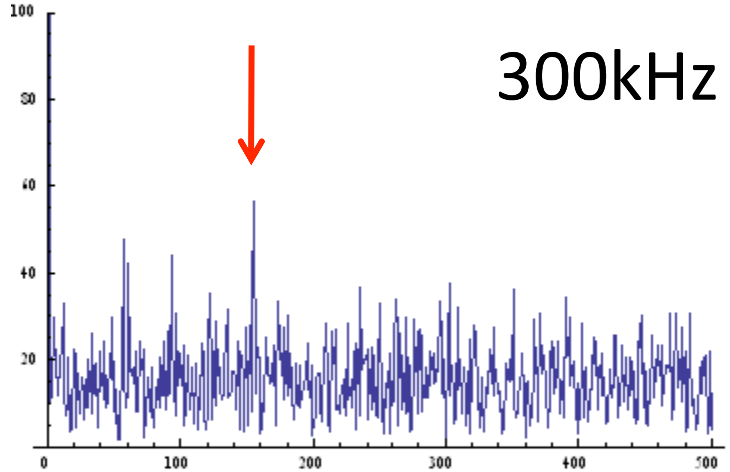
Sqrt of Power Spectrum

50kHz

2×77Hz



300kHz



S. Uehara

# Conclusion of dithering simulation

- Dithering with 0.5σ amplitude
  - 50k event/s : OK
  - 10k event/s: not sufficient
  - Luminosity loss: ~6% at peak of luminosity
- Dithering with 0.2σ amplitude
  - We need > 300k event /s.
  - Luminosity loss: ~1% at peak of luminosity
- Expected event rate in case of measuring lost particles
  - ~ 2MHz @ $10^{35}$ $cm^{-2}$ $s^{-1}$

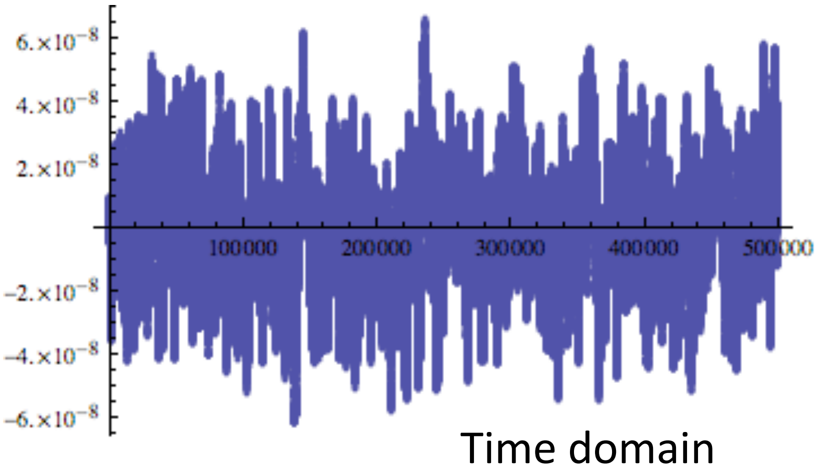
# Summary

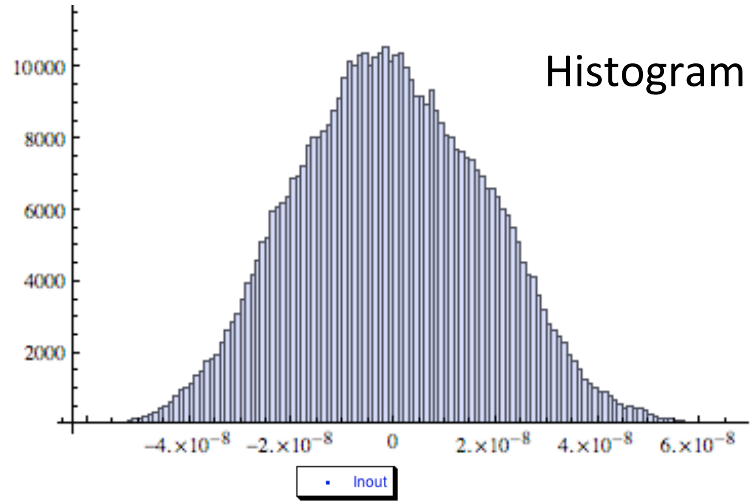
- Algorism of orbit control
  - Vertical: beam-beam deflection based on BPM measurement
  - Horizontal: dithering method or beam size feedback
- QCS vibration issues
  - We found that coherency of QC1 and QC2 for electron and positron is almost complete on both sides of IP.
  - Further suppression of the vibration (~ 50%) is possible by using high damping material.
  - The coherence of vibration of the two rings may help.
- Dithering for horizontal orbit control
  - We just started considered the dithering method for horizontal orbit control.
  - Our study is on a primitive stage. We have conducted some simulations on the event rate of fast luminosity monitor.

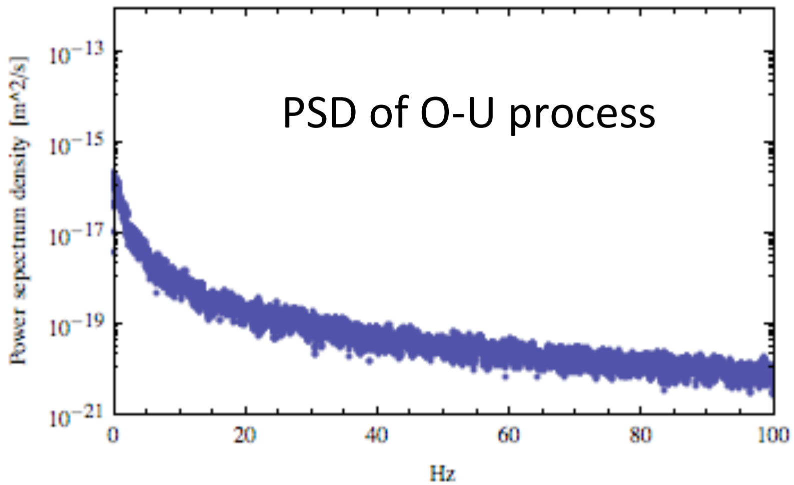
# Spare slides

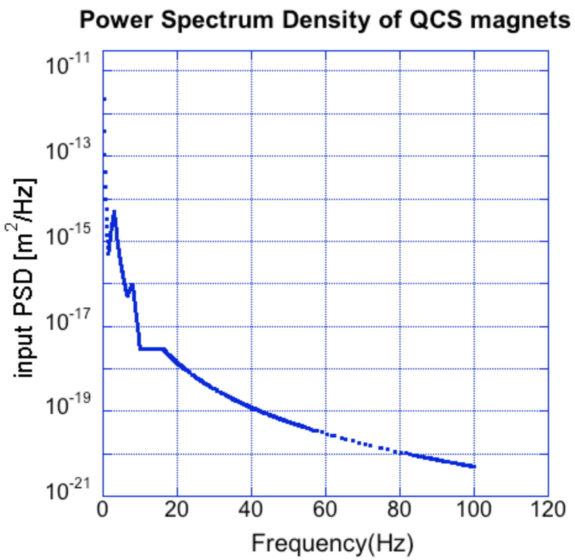
# Ground motion data created by using Ornstein-Uhlenbeck process

$\tau$= 0.2, c = 1 x 28^-10, $\Delta$t=1/53/50



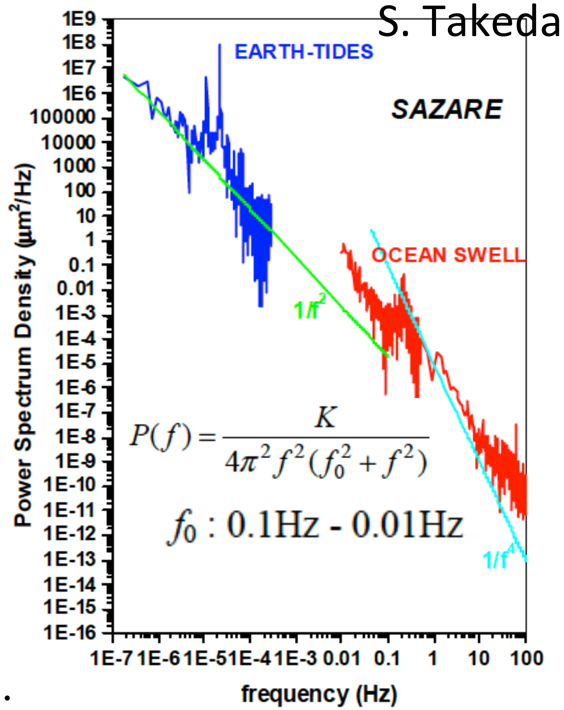



# Ornstein-Uhlenbeck process

- Measurement on ground motion
  - -consistent with Brownian motion in low frequency region （S. Takeda）
- Brownian motion
  - \- Explained by Einstein using diffusion equation (1905)
  - \- Analyzed by P. Langevin using continuous Markov process (1908)
- Ornstein-Uhlenbeck process (sort of continuous Markov process)
  - \- Used in analysis of Brownian motion

S. Takeda




$$X(t+dt) = X(t) - \tau^{-1} X(t)\,dt + c^{1/2} n (dt)^{1/2}$$

$n$ : sample value of radom variable N=N(0,1)

N(0,1) is Gaussian distribution with mean=0, $\sigma$=1.

$$X(t+\Delta t) = X(t) e^{-(1/\tau)\Delta t} + \left[\frac{c\tau}{2}\left(1 - e^{-(2/\tau)\Delta t}\right)\right]^{1/2} n \quad \text{(<- Exact update formula)}$$

$$\langle X(t) \rangle = x_0 e^{-(t-t_0)\tau} \to 0\,(t \to \infty),\ \text{var}\{X(t)\} = \frac{c\tau}{2}\left(1 - e^{-2(t-t_0)\tau}\right) \to \frac{c\tau}{2}\,(t \to \infty)$$

Power spectrum density $S_X(f) = \dfrac{2c\tau^2}{1 + (2\pi\tau f)^2} \sim \dfrac{1}{f^2}$

# System of harmonic oscillator with damping and external force

- Modeling of magnet vibrations

$$y = \sum_{i=1}^{n} y_i \quad (i\text{: each resonant mode})$$

- Equation for $y_i$

$$\ddot{y}_i + \frac{2}{\tau_i}\dot{y}_i + \omega_i^2 y = C_i F$$

$\tau_i$ : damping time (determine Q value of resonance)

$\omega_i$ : angular resonant frequency

$C_i$ : coupling between floor vibration and magnet

$F$ : external force (substitute floor vibration data for this force)

- Solution of equation
  - $\omega_i = 2\pi$ x (3Hz, 36Hz, 53Hz) : solve with Runge-Kutta method
  - Coupling and damping time were chosen so that the resonances are reproduced.
  - Sum up three solutions

# Summary of MAC in 2011

- The IP orbit control at SuperKEKB is much more difficult than that at KEKB.
- Major difficulty comes from the mechanical vibration of IR quadrupoles.
  - Simulation on the quads of SuperKEKB has given a better result than KEKB.
  - Further suppression of the vibration may be possible.
  - The coherence of vibration of the two rings may help.
- In parallel to the efforts to suppress the quadrupole vibration, we will develop the orbit feedback based on the beam-beam deflection.
- BPM requirement
  - Resolution: 1μm is enough. 5μm is tolerable?
  - Bandwidth: ~ 1kHz
- Horizontal orbit feedback
  - We need to develop a method other than the beam-beam deflection such as luminosity feedback or beam size feedback.

# IP machine parameters

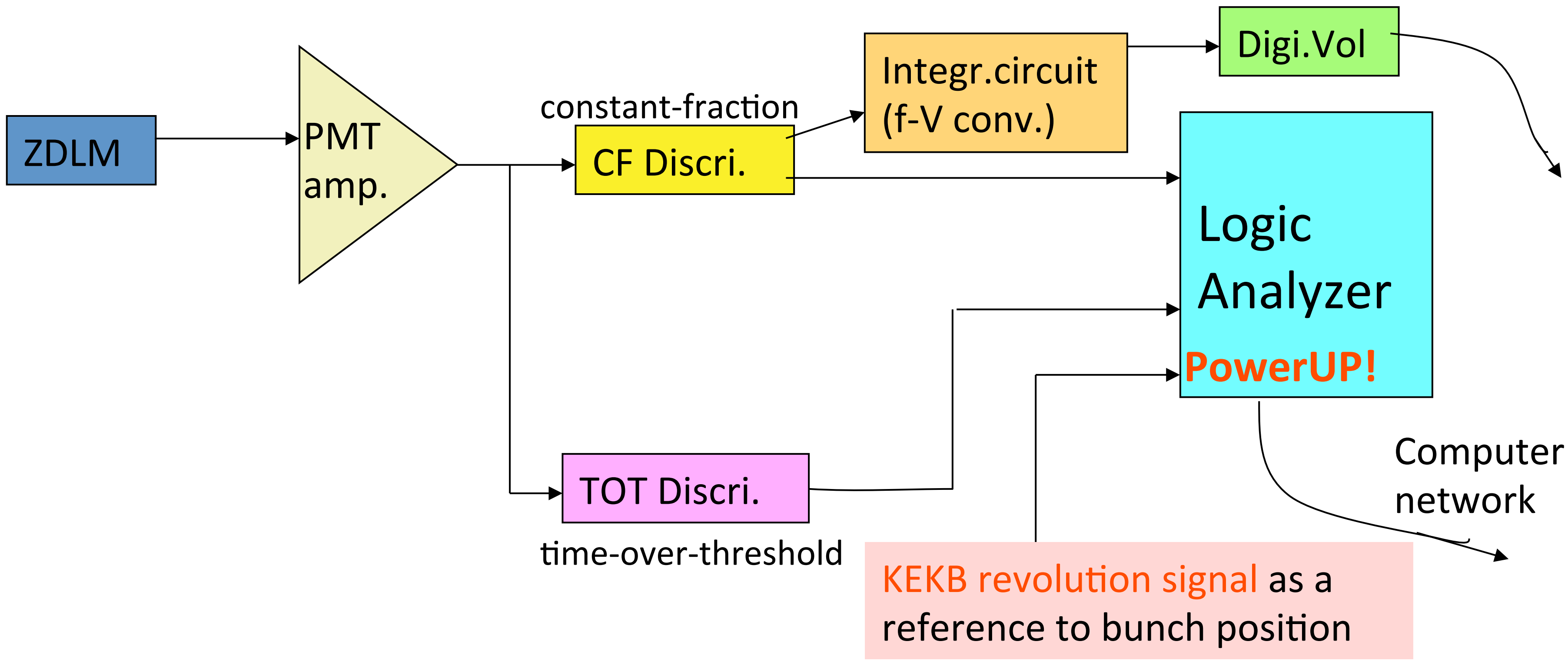
| | KEKB | | SuperKEKB | | |
|---|---|---|---|---|---|
| | LER | HER | LER | HER | |
| $\varepsilon_x$ | 18nm | 24nm | 3.2 | 5.0 | |
| $\varepsilon_y$ | 0.15nm | 0.15nm | 8.6pm | 13.5pm | ~1/4 |
| $\kappa$ | 0.83 % | 0.62% | 0.27% | 0.25% | |
| $\beta_x^*$ | 120cm | 120cm | 32mm | 25mm | |
| $\beta_y^*$ | 5.9mm | 5.9mm | 0.27mm | 0.31mm | ~1/4.5 |
| $\sigma_x^*$ | 150μm | 150μm | 10μm | 11μm | |
| $\sigma_x'^*$ | 120μrad | 120μrad | 450μrad | 320μrad | |
| $\sigma_y^*$ | 0.94 μm | 0.94μm | 48nm | 56nm | ~1/20 |
| $\sigma_y'^*$ | 0.16mrad | 0.16mrad | 0.18mrad | 0.22mrad | |
| iBump horizontal offset | | +/- 500μm | | +/- 30μm? | |
| iBump vertical offset | | +/- 150μm | | +/- 7.5μm? | |
| iBump vertical angle | | +/- 0.4mrad | | +/- 0.4mrad? | |

# Measurements by ZDLM

Luminosity measurements

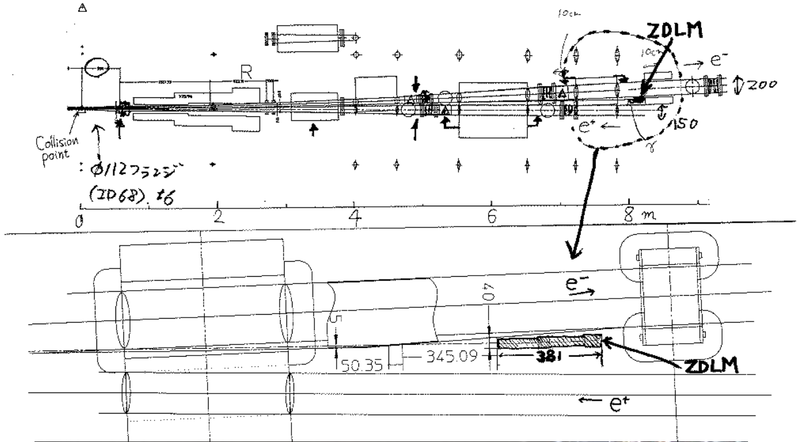
(1) Counting rate variation with continuous measurement

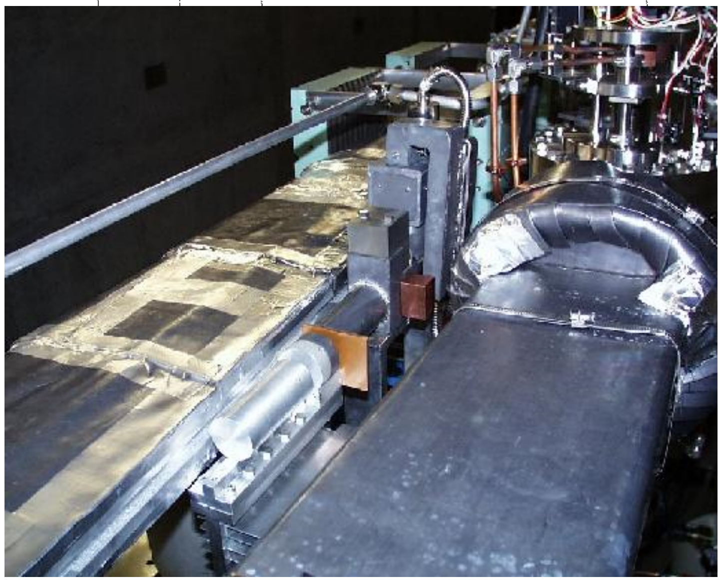
(2) Bunch-by-bunch Luminosity – time critical measurement in rather short terms

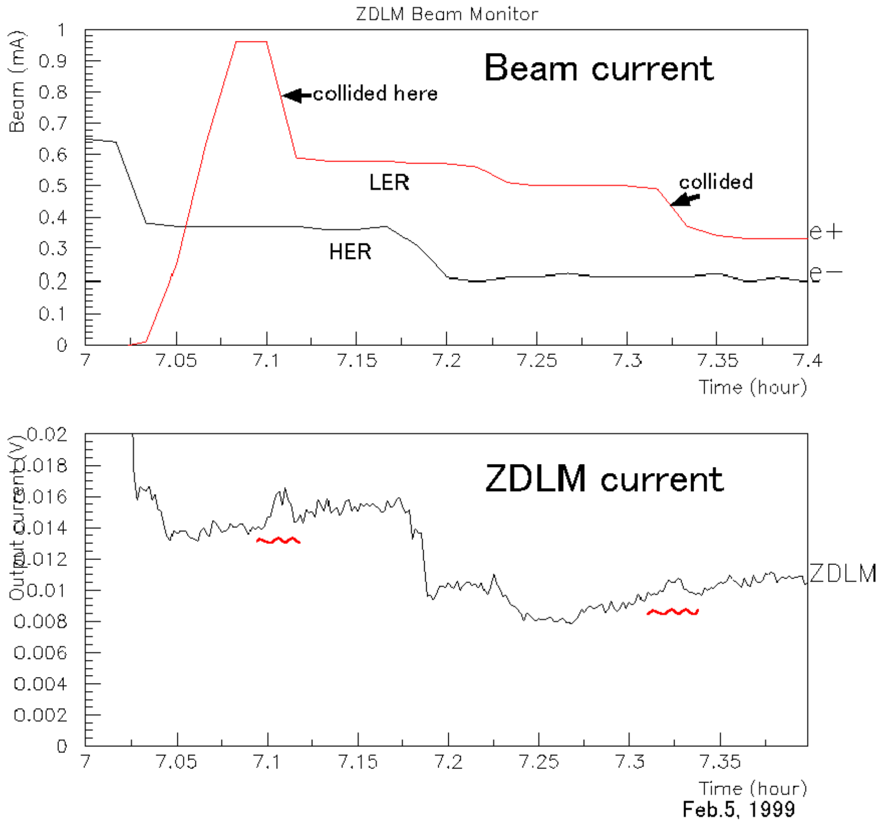


# ZDLM-1 in KEKB Commissioning

"Real-time luminosity monitor for a B-factory experiment"
T.Hirai, S.Uehara and Y.Watanabe, Nucl. Instr. Meth. A458 (2001) 670-676.






The first collision signal of KEKB
Before installation of Belle

# ZDLM-5@KEKB/Belle in 2010

- Quartz Cherenkov radiator

  on the deflected e- region (low efficiency)

  (The photons were blocked by thick beam chamber (~ 15 r.l. Cu)

  Can obtain the timing information

  → bunch-by-bunch luminosity measurement.

  $\sigma_t$ = 0.5 ns using a CF discriminator

# Contributions from other magnets

- IP vertical orbit change due to 0.1μm position change
  - QC1LP ($\beta_y$ ~ 2519m, $K_1$ ~ 1.68) -> 69nm @ IP
  - QC5LP ($\beta_y$ ~ 1570m, $K_1$ ~ 0.15) -> 4.9nm @ IP
  - Q (typical in arc) ($\beta_y$ ~ 20m, $K_1$ ~ 0.2) -> 0.75nm @ IP
- Collective effects of many Q magnets
  - Number of Q magnets per ring: ~400
  - Assume no correlation of movements of the magnets: -> expected offset at IP -> 0.7 x Sqrt(400) ~ 15 nm

# Effect of BPM resolution