Precise Magnet Alignment for the SPring-8 Upgrade

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   VWM : Vibrating Wire Method
3. Common girder alignment by laser Tracker
4. Summary

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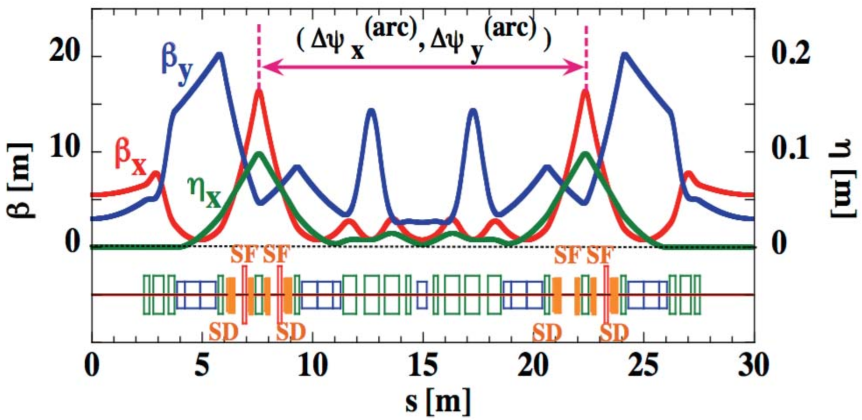
1. Introduction

SPring-8 storage ring major upgrade “SPring-8-II”



H. Tanaka, et al., "SPring-8 Upgrade Project", IPAC2016.

	SPring-8-II	SPring-8
Energy (GeV)	6	8
Stored current (mA)	100	100
Circumference (m)	1435.45	1435.95
Effect. emittance (nmrad)	0.157 ~0.10 w/ ID	2.8

3 key developments for the SPring-8-II magnet system

1. Electromagnets based multipole magnets
   High field gradient, compact, stable -> Feasible by existing technology
2. Permanent magnet based bending magnets -> Under development
3. **Precise alignment**
   Critical for keeping enough dynamic apertures -> Today's talk

Magnet	Max. field	#/ring		cf. SPring-8
Normal bend (NB)	0.95 T	44	220	88
Longitudinal gradient bend (LGB)	0.86 T	176		
Quadrupole	56 T/m	924		470
Sextupole	2,700 T/m^2	352		288

May change later.

Alignment Scenario

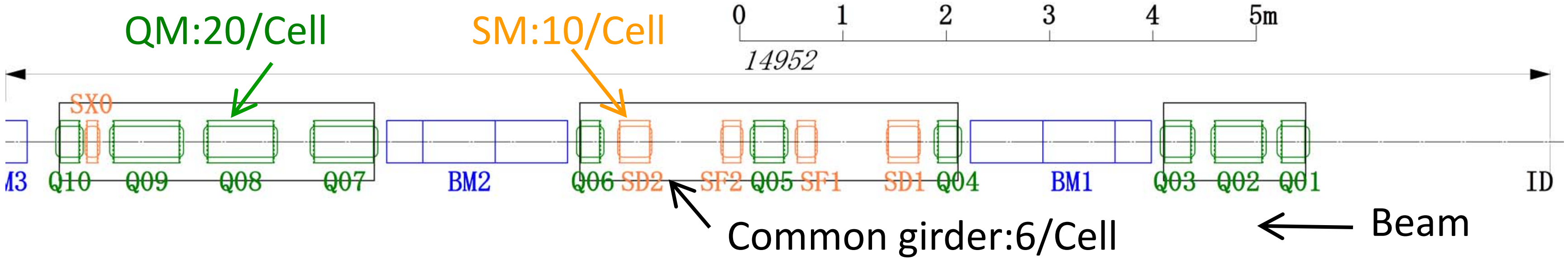
Need to align 1000+α magnets along 1.4[km] in a year !

Alignment tolerances

magnet to magnet on girder : Δx, Δy < 25[μm](1σ), Cut-off ±2σ

girder to girder : Δx, Δy < 45[μm](1σ), Cut-off ±2σ

Half-cell (Length ~15m)



Magnet alignment on common girder (Out of the Machine Tunnel)

-> Vibrating Wire Method (VWM) without conventional fiducialization (< 10[μm])

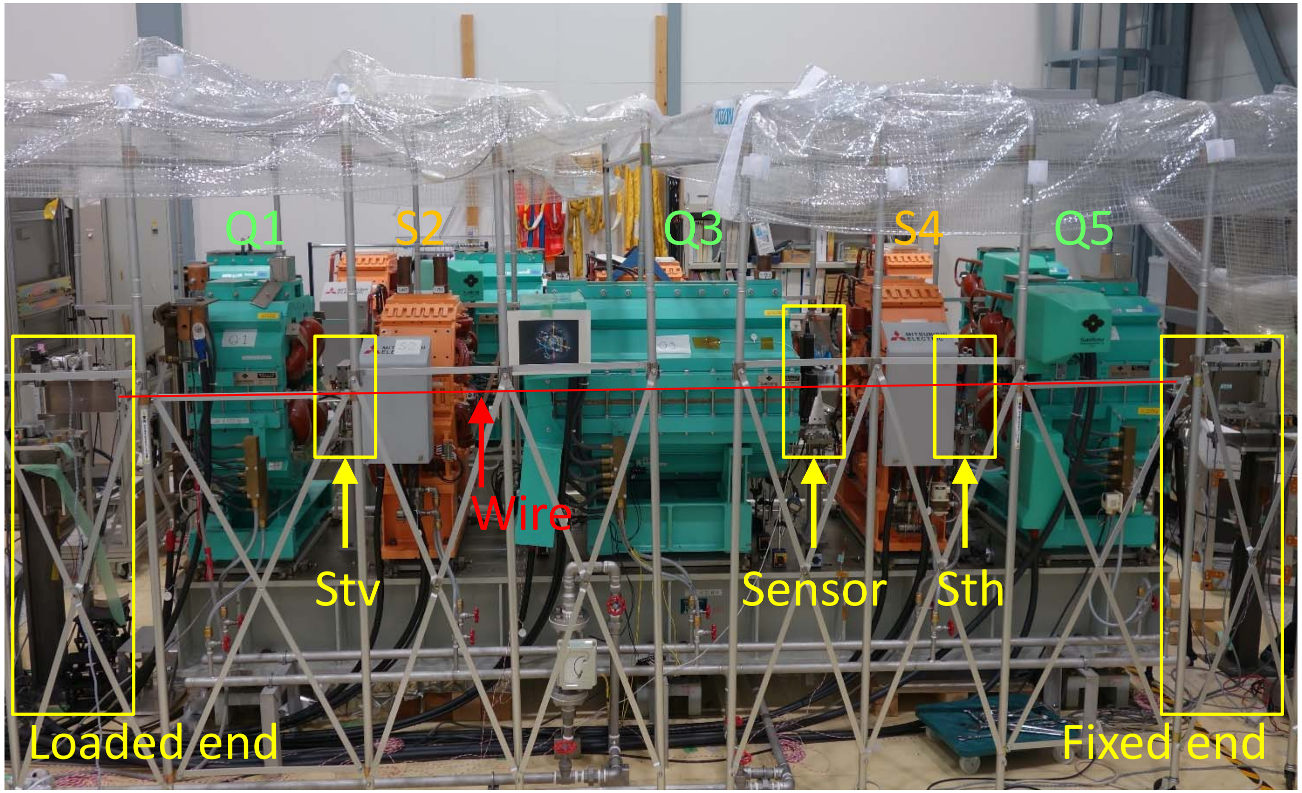
Transport to the machine tunnel

Girder Alignment (In the Machine Tunnel)

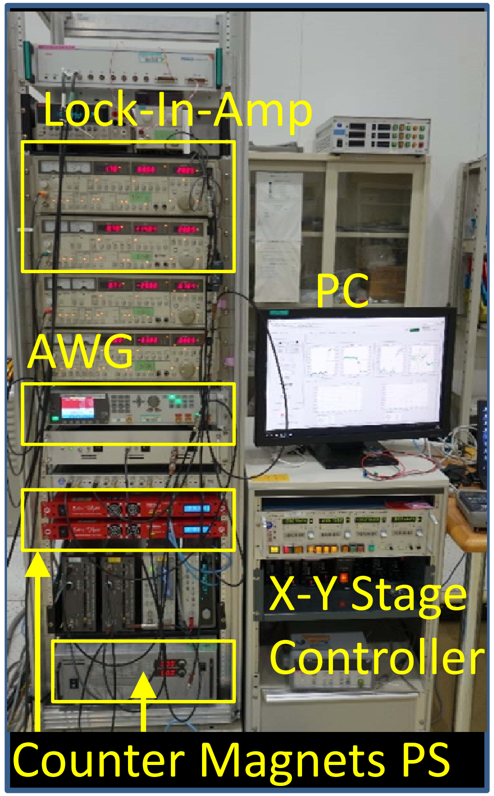
-> Laser Tracker

VWM Test Setup

Magnets and Girder



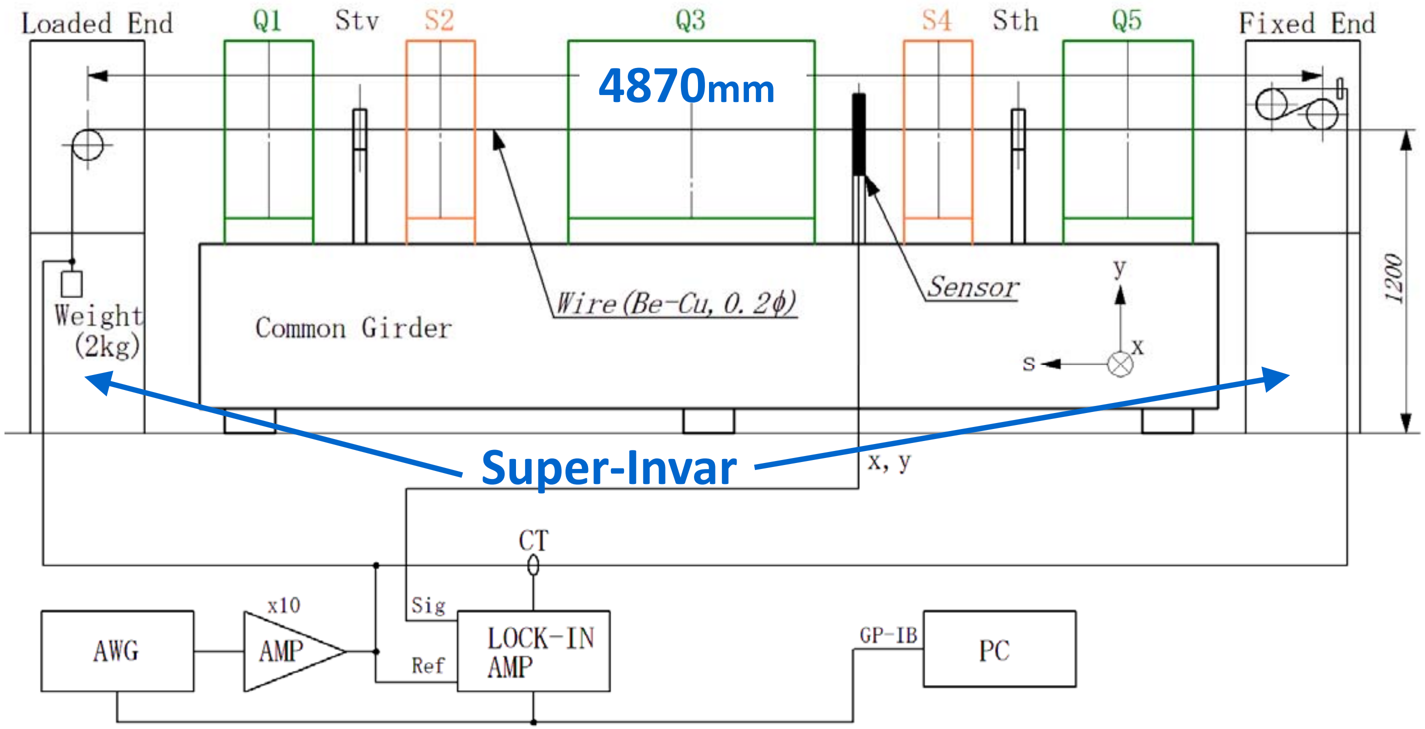
Circuits



Wire girders were made of "Super-Invar".

VWM Principle

When a tensioned wire is excited with its resonance frequency, the wire vibrates.
The wire in Q/S magnets does not vibrate at the position of the magnetic center.
-> We can find out the magnetic center.



Wire :
Be-Cu, 0.2[mm]ϕ
Tension :
T = 2.0 [kgw]
Resonance :
f_1=28.0[Hz]
Sag :
S_{max}=390[μm]

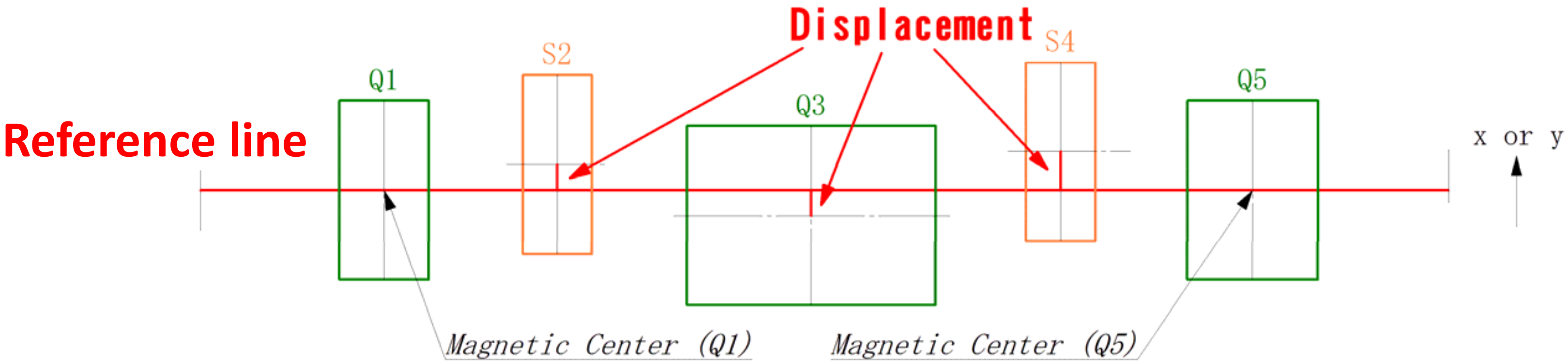
Outline of the test magnets and test girder. The wire was scanned using x-y stage.

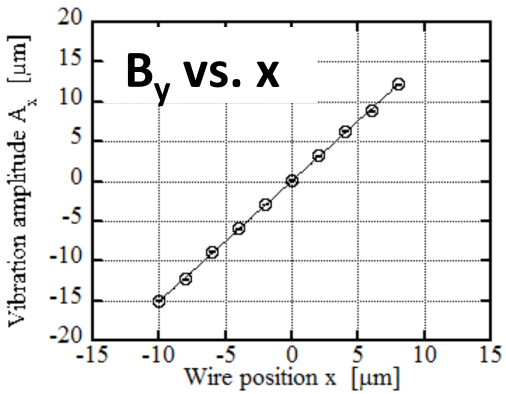
VWM Demonstration

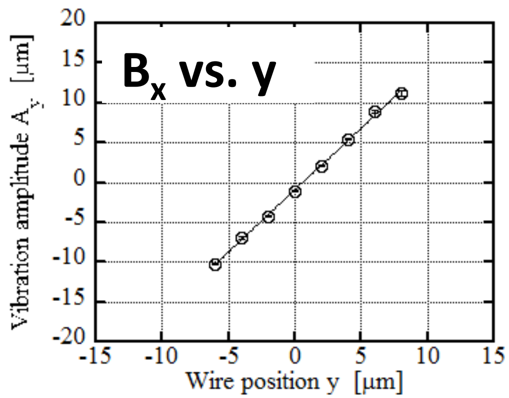
Reference line :

A straight line passing through two magnetic centers of Q1-Q5

Displacements of the S2, Q3, and S4 were successfully measured.







According to our test, resolutions were < 0.1 [μm] for Q-mag, < 1 [μm] for S-mag, but….

Critical Issues

VWM error sources

(1) Wire sag and kink

induces a systematic error.

(2) Background fields

"geomagnetism", and "remanent field" induces a systematic error.

(3) Repeatability

"resolution", and "wire linearity", etc. induces a statistical error.

Magnet stability and repeatability

(4) Change in the magnetic center

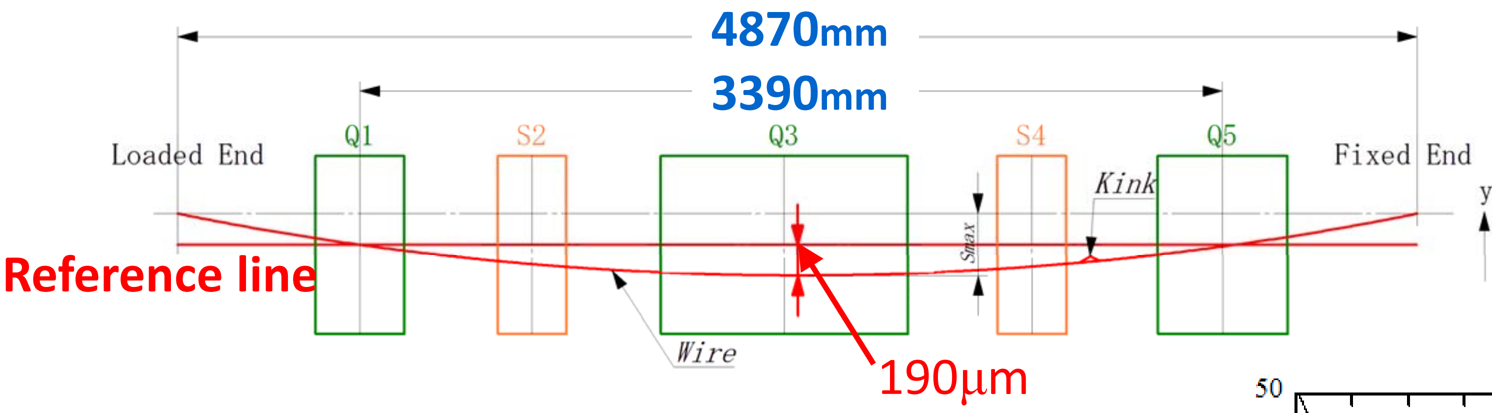
Mechanical repeatability

Change due to the transportation

Drift due to a deformation after the alignment

→ **Show in detail**

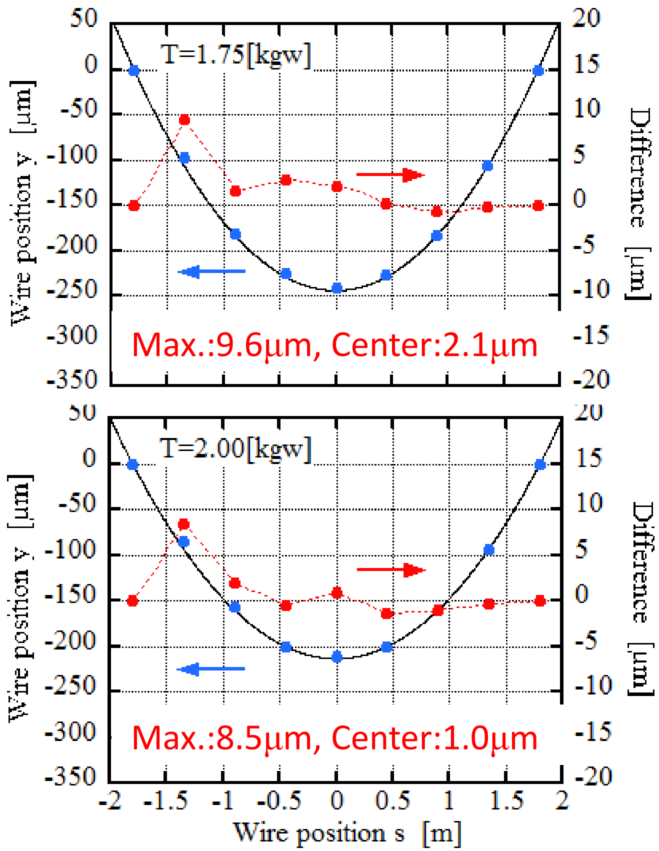
2-(1) Wire sag and kink



Vertical position of a tensioned wire is expressed by a catenary curve. Max. sag is shown as,

$$S_{max} = \frac{\rho g}{8T} L^2 = \frac{g}{32 f_1^2}$$

g : the acceleration due to gravity [m/s²]



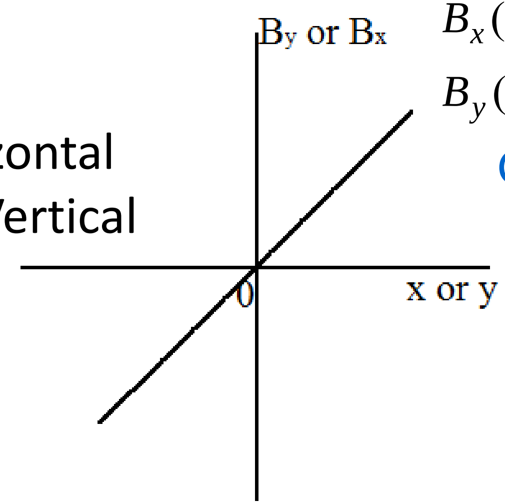
The sag can be corrected by measuring a resonance.

In order to confirm, wire position was measured by "HLS" and "WPS".

We are investigating about an individual differences.

For Q-mag, background fields are not negligible.

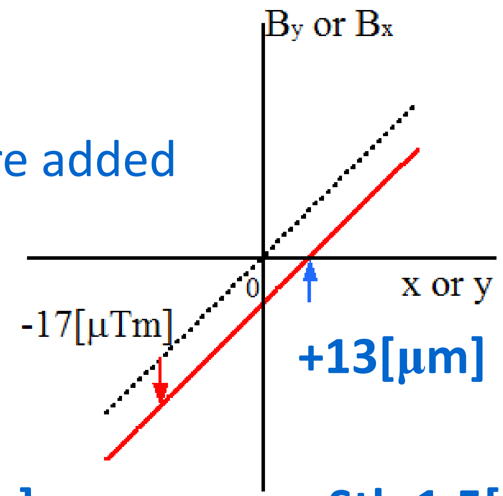
Horizontal
or Vertical



$$B_x(y) = G_q y$$

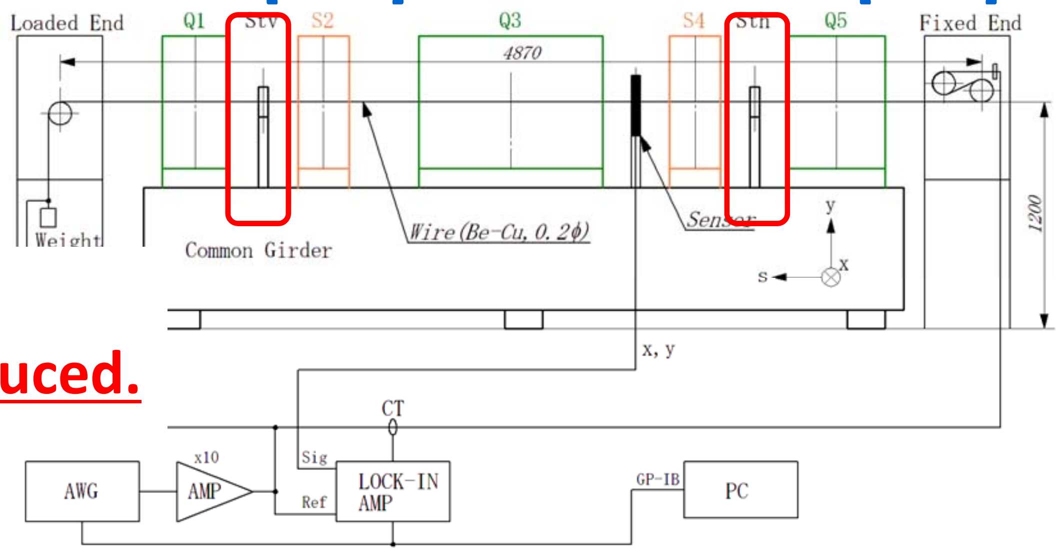
$$B_y(x) = G_q x$$

Geomagnetism etc., are added



Stv:1.5[mTm]

Sth:1.5[mTm]

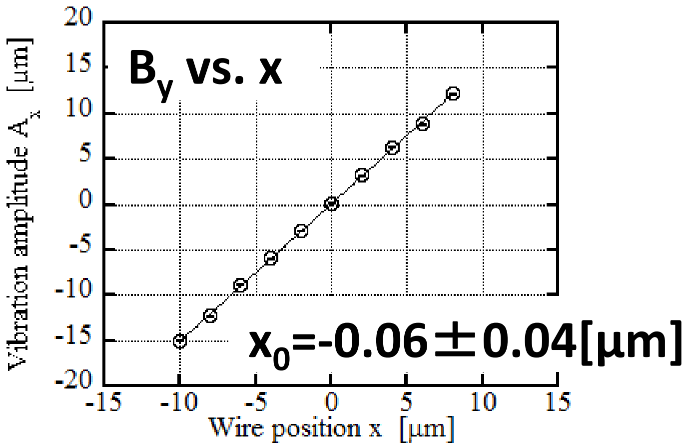


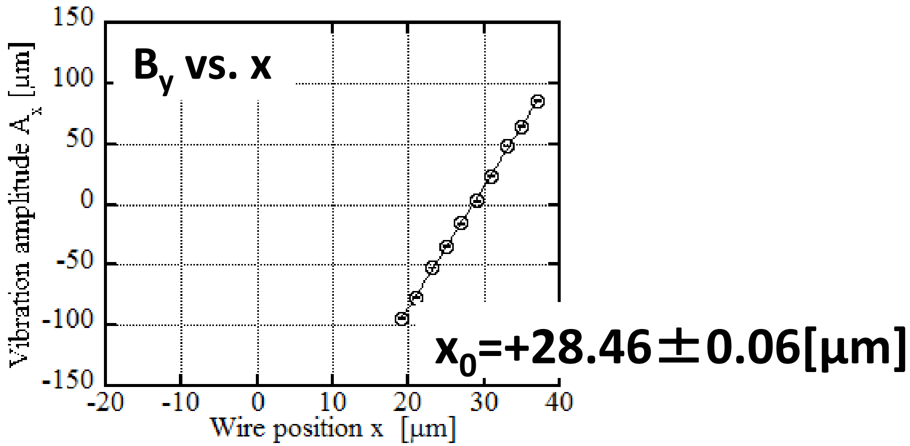
Counter dipoles,
"*Sth*" and "*Stv*" were introduced.

2-(2) Background field

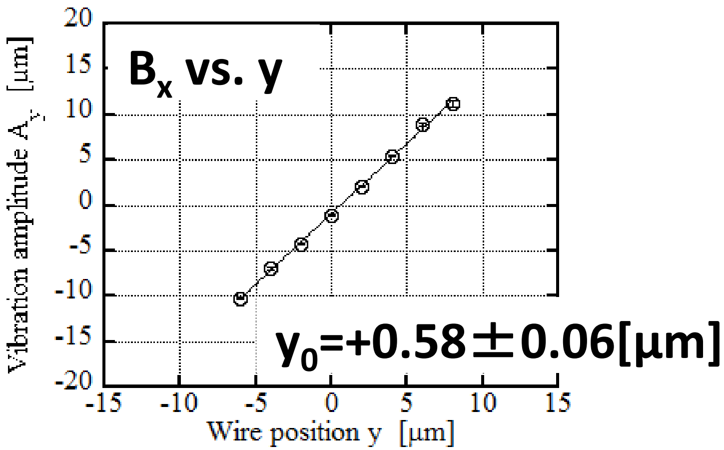
Q1 (GL=1.31[T]) | **Q3** (GL=9.13[T])

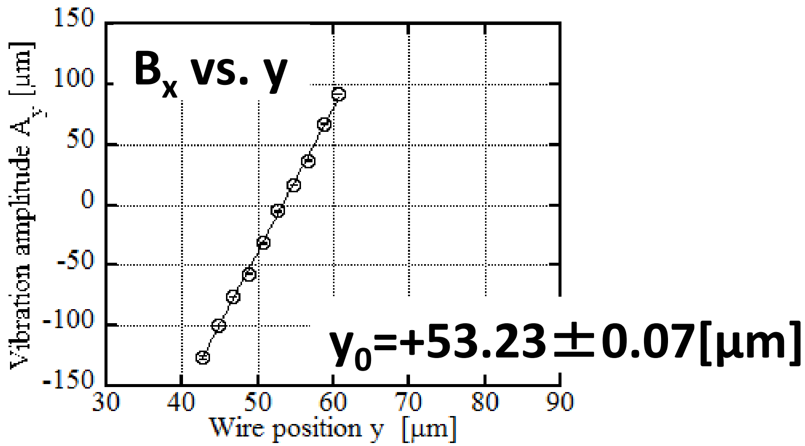
X





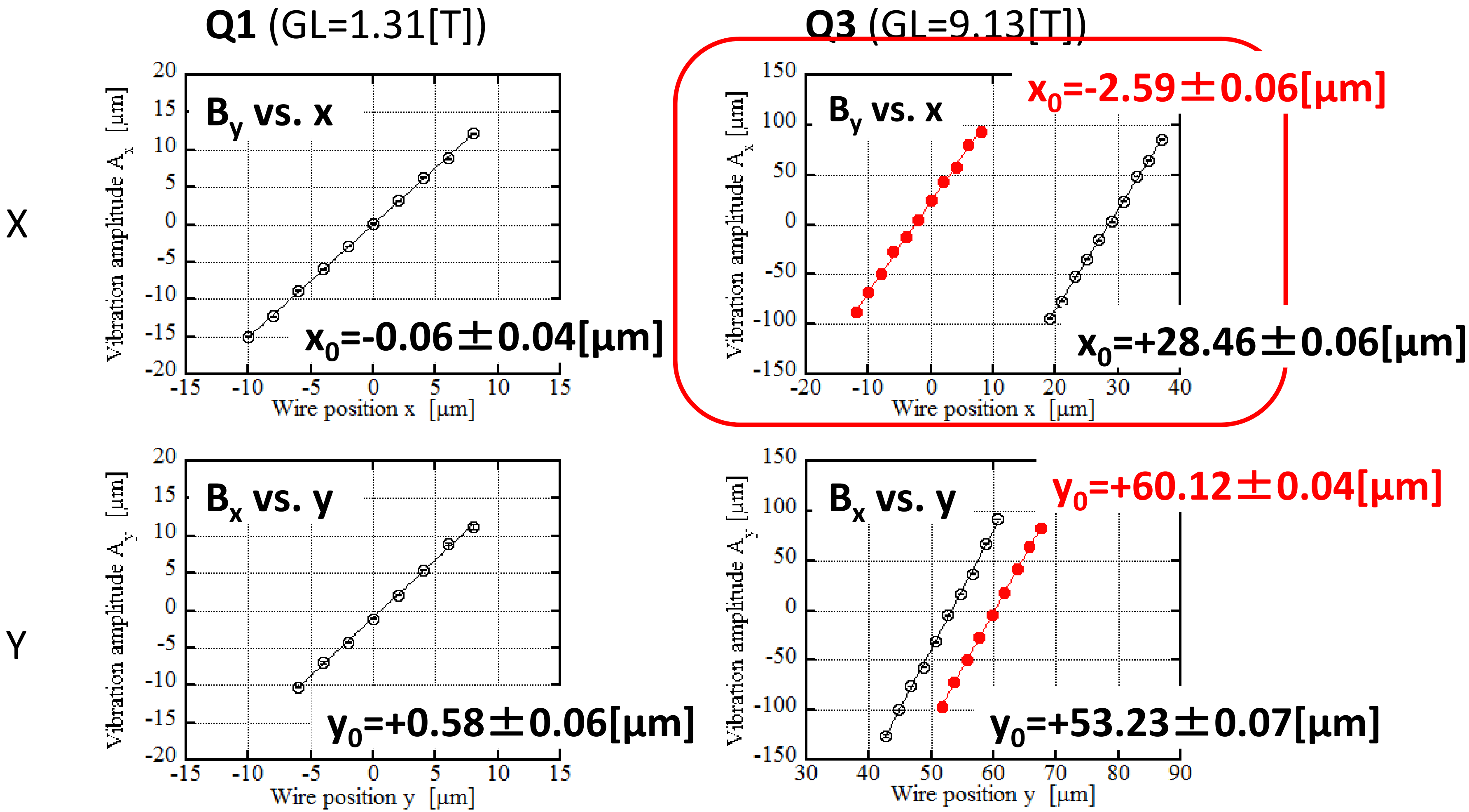
Y





Vibration amplitude versus wire position. Wire current : 98 [mA_{rms}]

2-(2) Background field



Vibration amplitude versus wire position. Wire current : 98 [mA_{rms}]

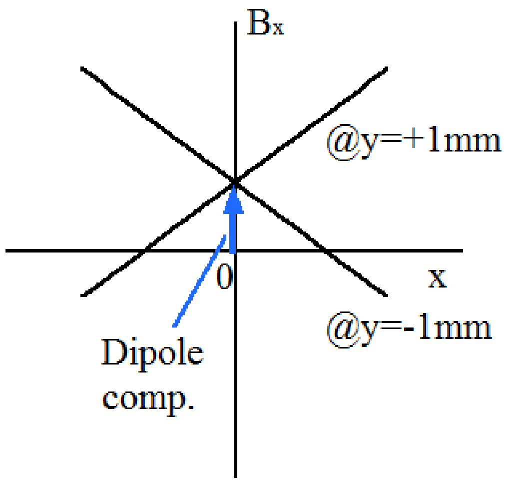
Displacement was successfully suppressed to 2.6 [μm] !

2-(2) Background field

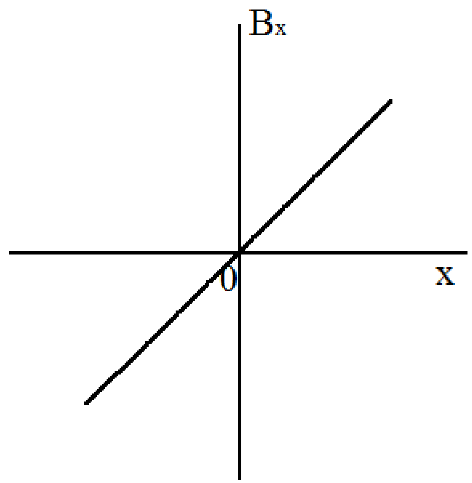
For S-mag, Bx component was chosen.

$B_x(x,y) = G_s xy,$ $B_y(x,y) = \frac{1}{2} G_s (x^2 - y^2)$

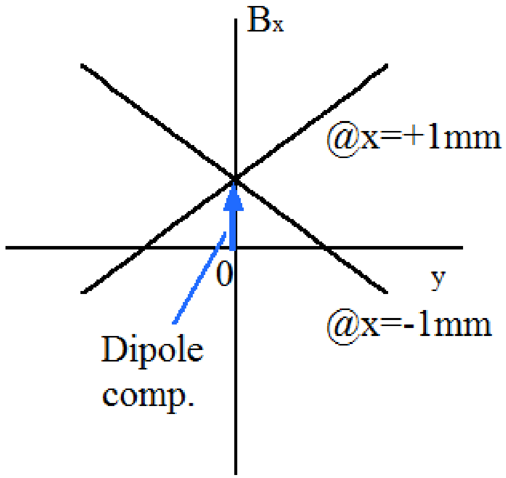
Horizontal



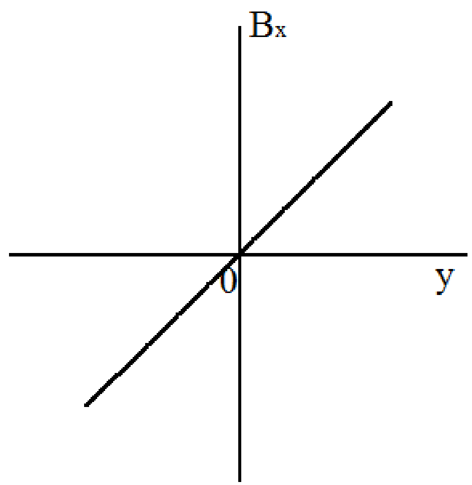
Subtracted



Vertical



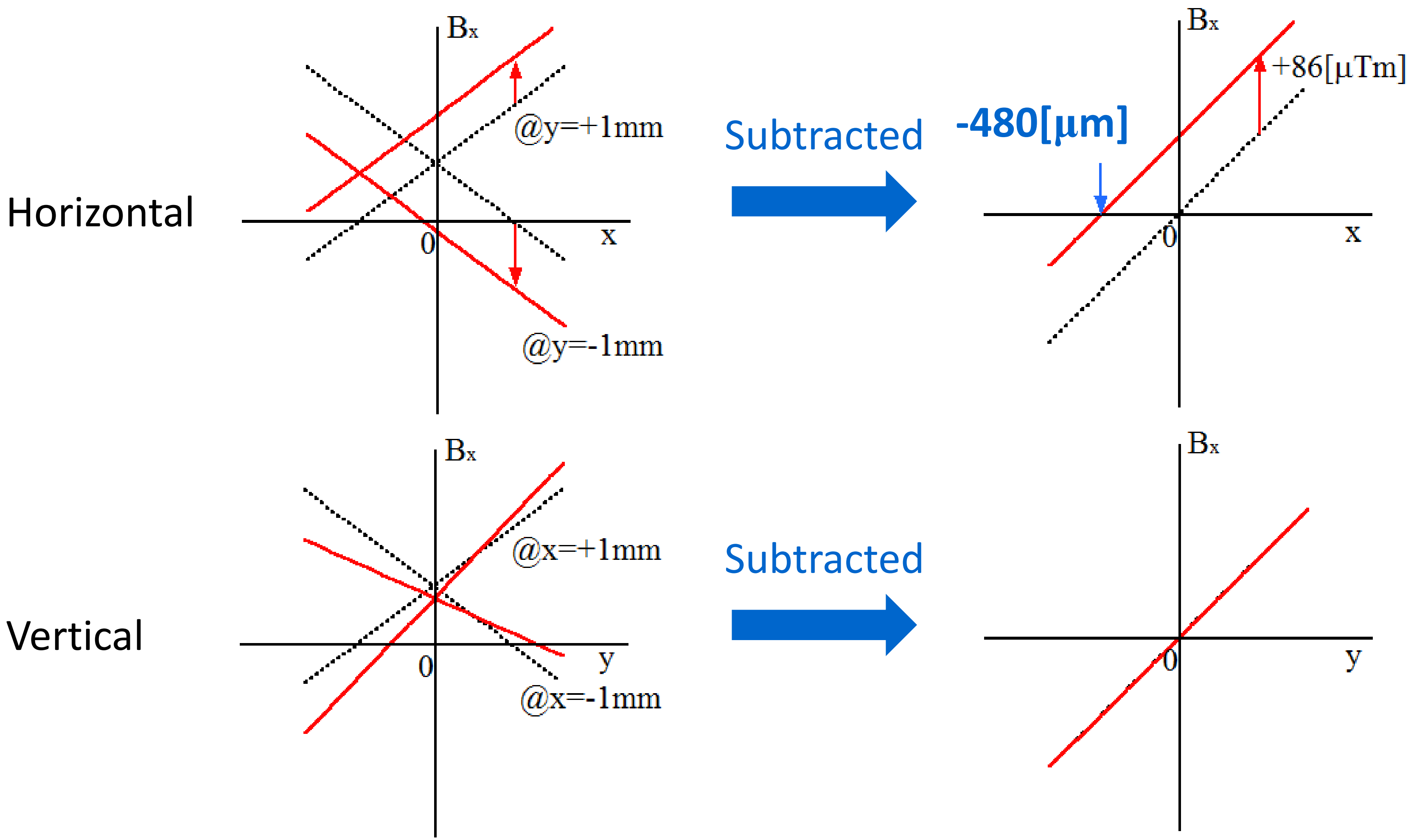
Subtracted



Dipole component, and background field are canceled in principle, but…

2-(2) Background field

Background gradient caused by Q-mag remanent are not negligible.



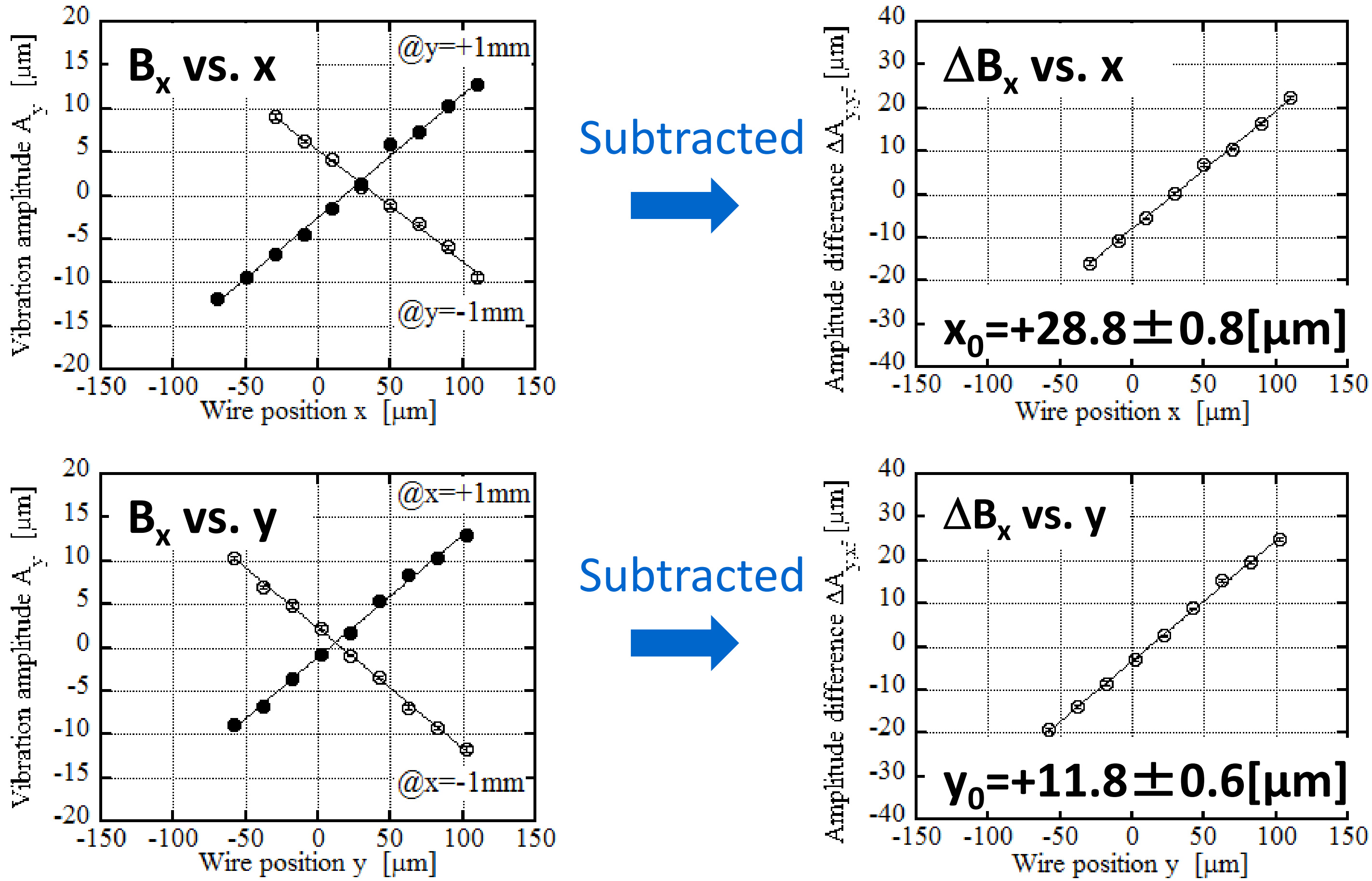
Q1 was used as a counter quadrupole magnet.

2-(2) Background field

S2 (GL=88.6[T/m])

X

Y



Vibration amplitude versus wire position. Wire current : 98 [mA_{rms}]

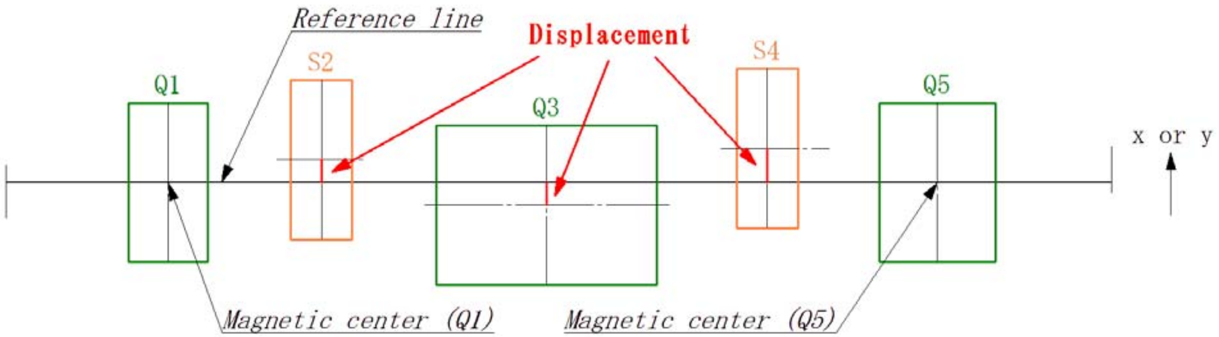
Resolution of the integrated field < 0.1 [μTm].

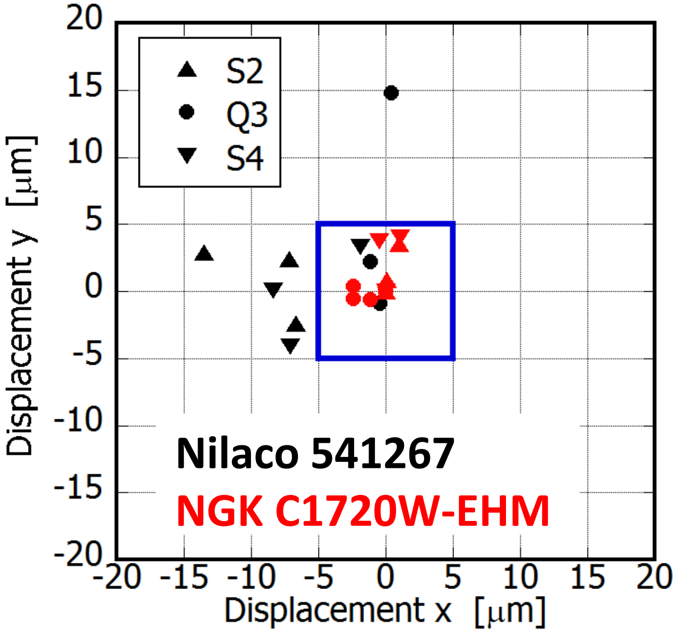
The systematic error caused by the background gradient << 5 [μm] !

2-(3) Repeatability

To estimate **an overall error of the system,**

the displacements were measured **before and after the wire was re-installed.**





Change in the displacement

Error strongly depends on the wire linearity.

Overall random error < 5 [μm] !

(Inc. resolution, linearity, kink and etc.)

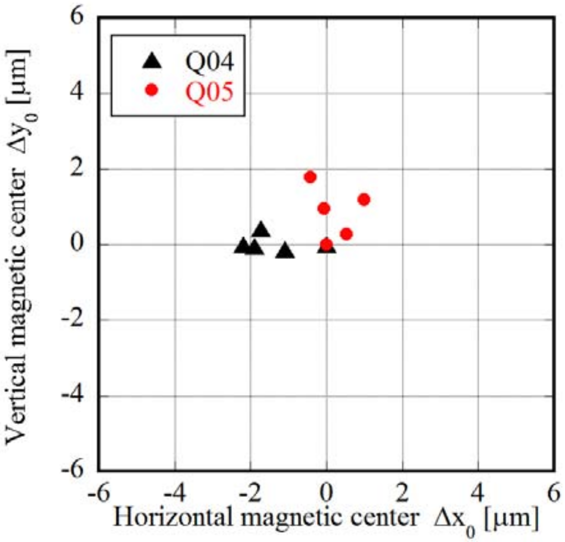
Mechanical Repeatability

After the alignment,
 upside core will be detached.
↓
 Chamber will be installed.
↓
 The core will be attached again.

Mechanical repeatability was observed.
(Test magnets Q04, Q05 for SPring-8-II)

Before and after difference < ±2 [μm]

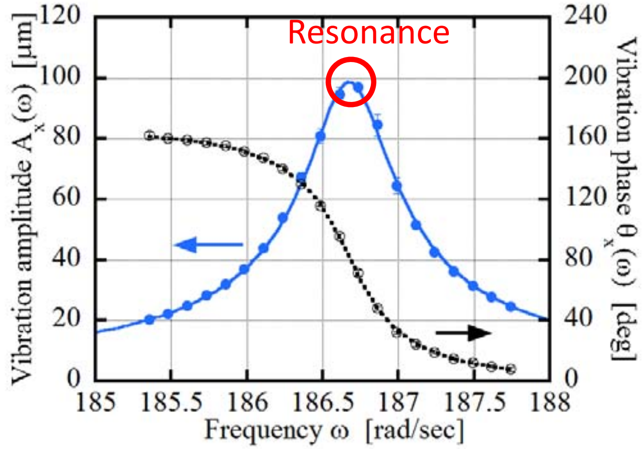
All sort of magnets will be tested.



Change in the magnetic center

Drift due to a deformation

To observe a long-term drift of the magnetic center,
AC current frequency for the wire was tracked
to the resonance.
(Because the resonance drifts by ambient air temp.)



Freq. dependence of amplitude and phase.
(In a constant field)

Basic Feedback

AC current frequency was tracked to the resonance
using measured phase of itself.

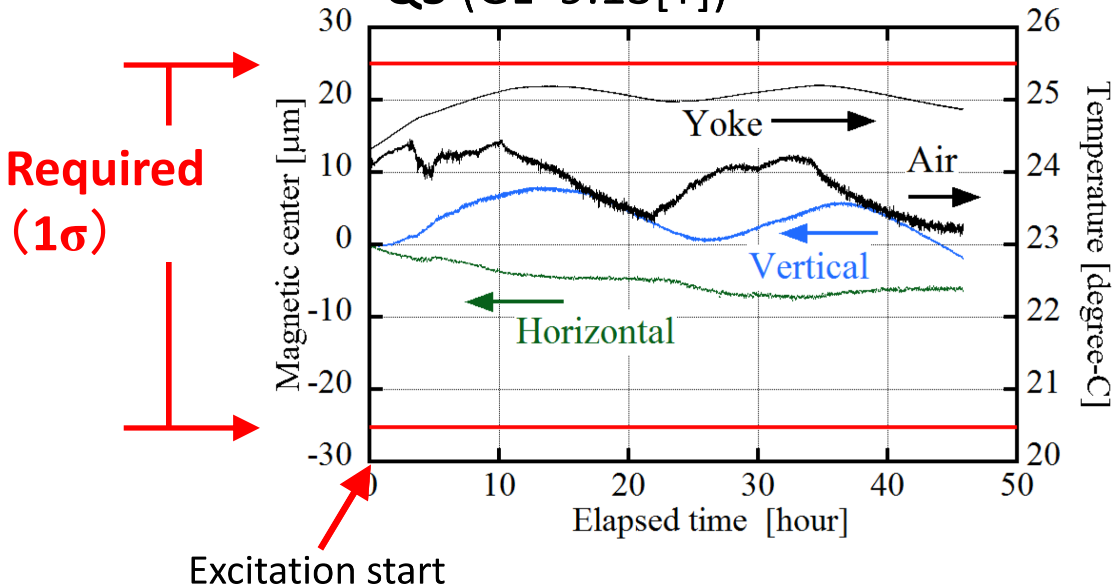
Advanced Feedback

AC current frequency was tracked to the resonance
using measured phase of the feedback wire*.

*The second wire (“feedback wire”) was installed in parallel to the “signal wire”.
-> The process is available when the signal wire is placed near the magnetic center.

Temporal changes in the magnetic center (by the advanced feedback).

Q3 (GL=9.13[T])



The yoke temp. was also changed due to a fluctuation of the ambient air temp.
-> To estimate a time constant of the drift of the magnetic center,
it is necessary to stabilize the air temp.

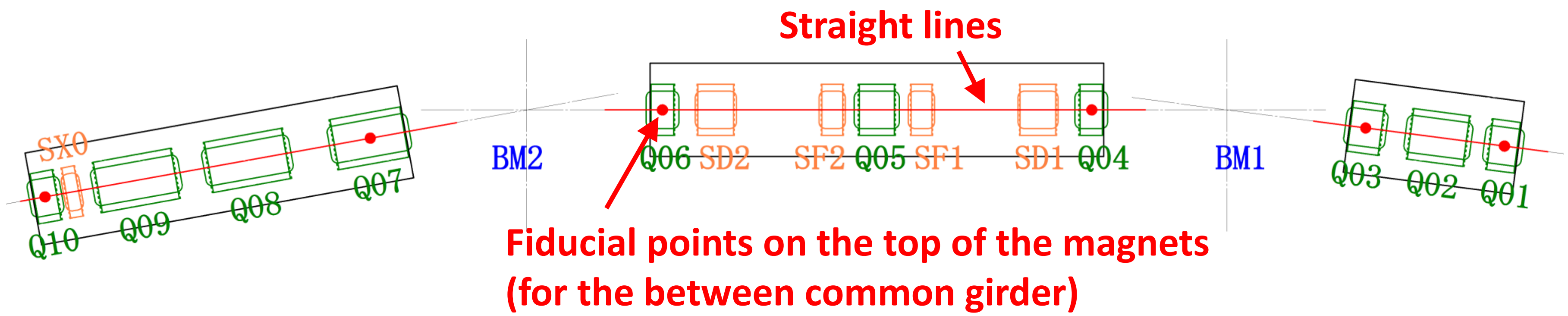
The temporal changes will be observed about all sort of the magnets.
Then, we will determine a timing of magnetic-center measurement
to expect the magnetic center at the machine operation.

Fiducializasion

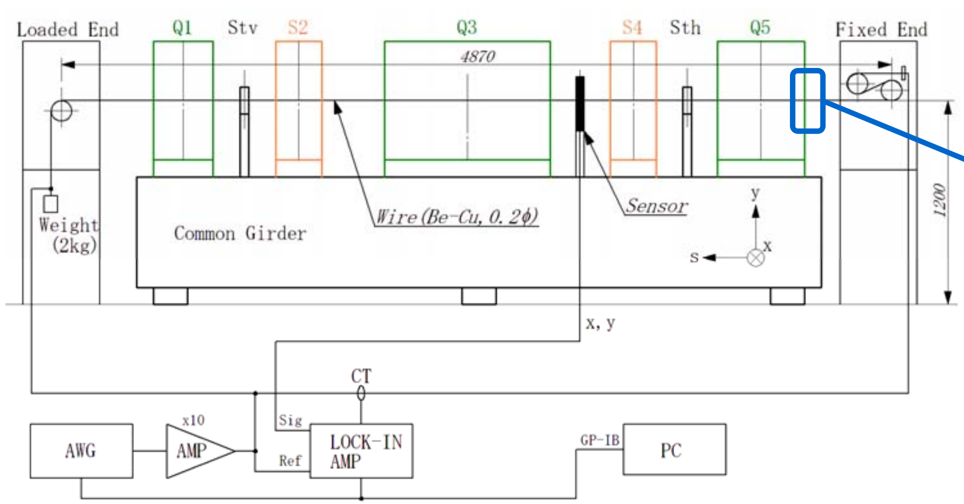
To align common girders,
fiducialization is necessary for magnets placed at both ends of each girder.

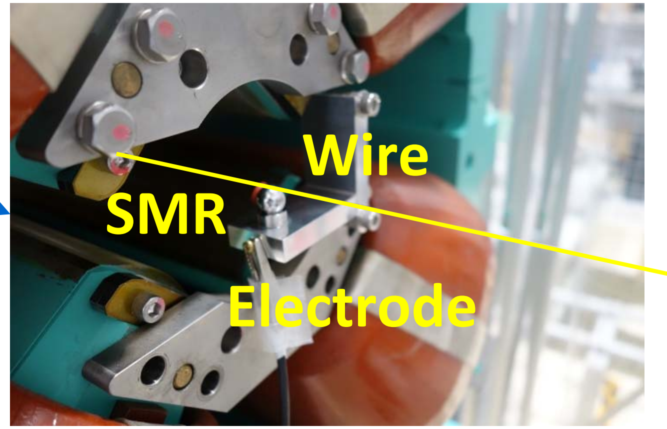
Our proposal :
Wire position is measured by a Laser tracker system.

Method :
SMR targets are attached near the center of QM placed at the both ends.
Contact points (Wire-SMR) are measured by watching electric resistance.
The SMR center is estimated using a least-squares fit.



Fiducialization Test (Using VWM system)





A 0.5”-SMR was attached at Q5.

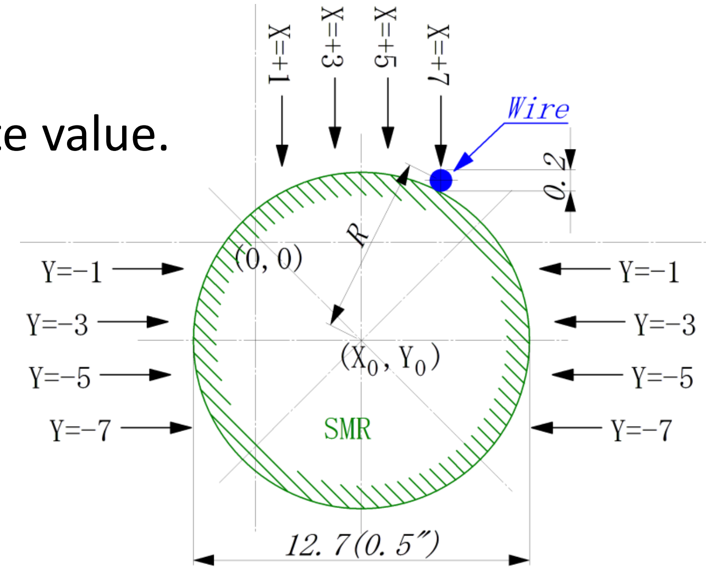
Wire was brought closer to the SMR using x-y stage with 1-μm step until resistance changed to a finite value.

Contact positions were recorded at 12 pts.

-> X_0=4014.3**±0.3μm**, Y_0=-3715.6**±1.5μm**

R=6449.4±0.3μm

The errors are negligibly small !



Magnet alignment on common girders

Error budget :

Statistical error < 5[μm], Systematic error : < **10[μm]**

To further reduce the systematic error, we will investigate,

i) difference between measured sag and calculated one

ii) wire-by-wire difference of linearity (kink)

Sag correction method will be optimized using these data.

Magnet stability and repeatability :

Drifts (caused by a transportation, a deformation, etc) will be observed.

Mechanical repeatability will be observed using this system.

Common girder alignment

For the fiducialization at both ends of girders :

"Wire" – "SMR near the bore center" : Error < 1.5[μm]

"SMR near the center" – "Fiducial point on the top of the magnet" : will be tested.

Other methods (Rotating-coil, Stretched-wire, etc) will be tested.

We plan to align girders based on a conventional network method.