Estimation of Magnet Alignment Accuracy for SPring-8 Upgrade using Resonance-Frequency Tracked Vibrating Wire

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1. Introduction
2. Principle
3. Critical Issues and Solution
4. Result
5. Summary

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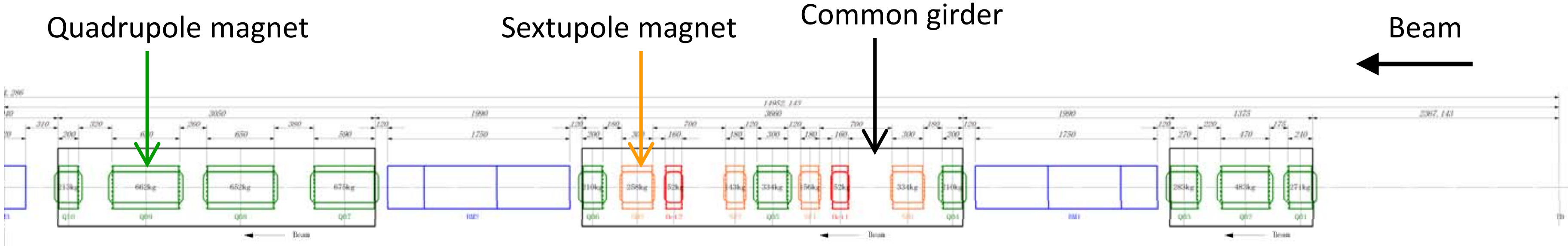
SPring-8 major upgrade (SPring-8-II)

Half-cell lattice (15[m])



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

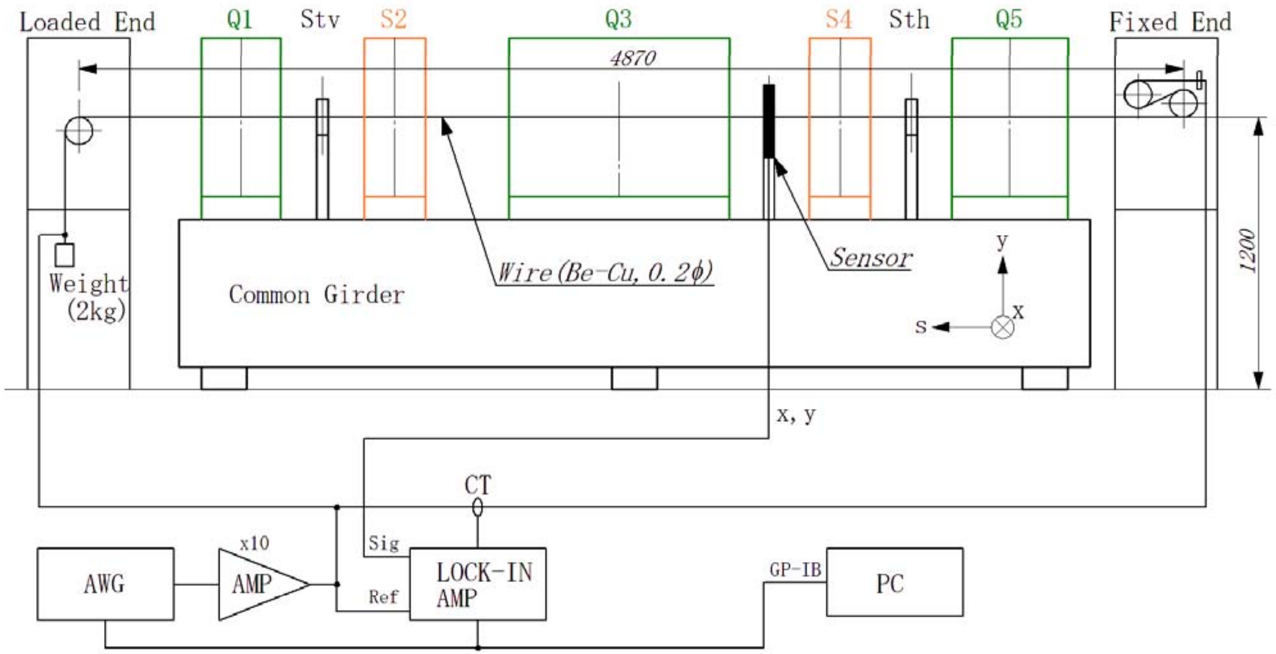
Transverse alignment errors < 25[μm](1σ) on the common girder.
< 50[μm](1σ) between two common girders.

We are planning the alignment on the common girder using VWM out of the machine tunnel.

<u>Our goal is a *in-situ* alignment on the basis of the wire vibration within 10 [μm] !</u>

2. 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.



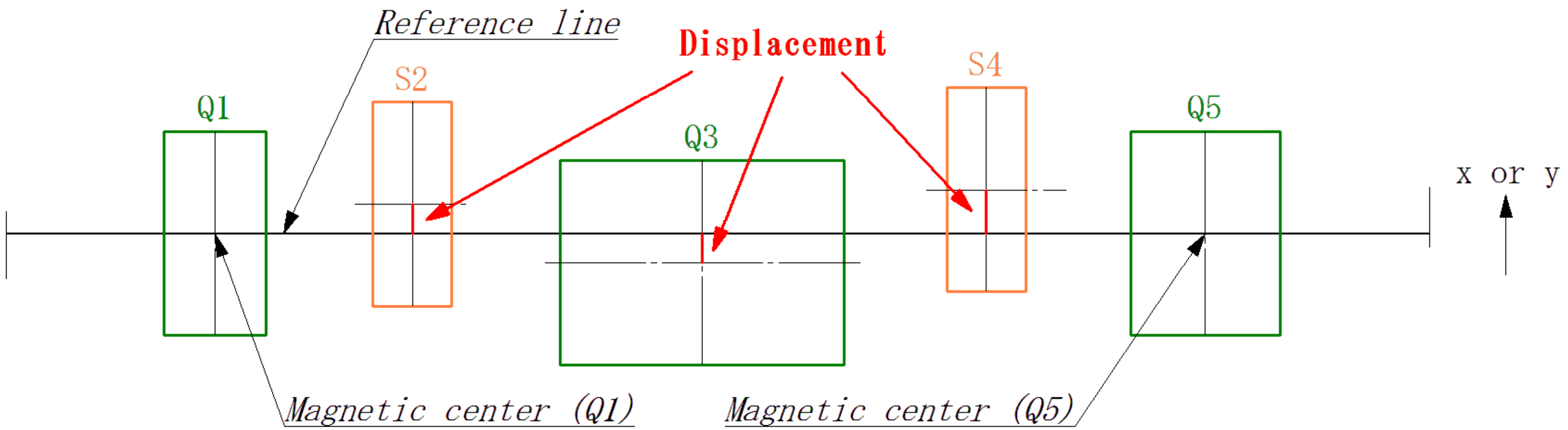
	Bore dia. [mm]	Grad. [T/m] [T/m²]	Length *lp* [mm]
Q1	85	17.0	310
Q3	85	17.6	970
Q5	85	17.4	470
S2	92	420	270
S4	92	420	270

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

Wire length : L=4.87[m] (Be-Cu, 0.2[mm]-ϕ),
Tension : T = 2.0 [kgw], Fundamental resonance : f_1=28.0[Hz]
Maximum sag : S_{max}=390[μm]

2. Principle

A reference line was defined : a straight line passing through two magnetic centers of Q1-Q5
Displacements of the S2, Q3, and S4 were measured.



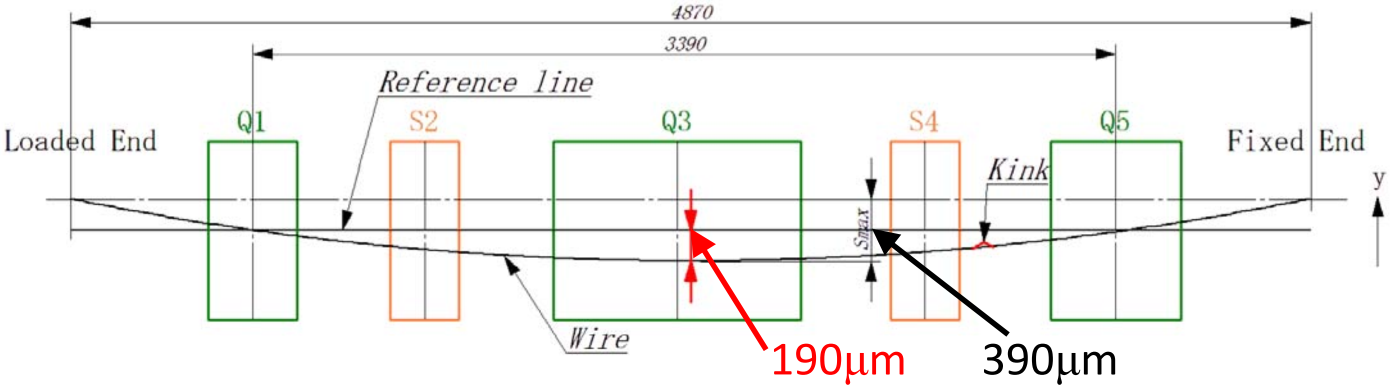
According to our test, resolutions were < 0.1 [μm] for Q-mag, < 1 [μm] for S-mag, but....

Critical issues

(1) Wire sag and kink
(2) Background fields
(geomagnetism, remanent)
(3) Repeatability
(4) Drift of the resonance frequency

→ **Today's talk**

3. Critical issue (1) Wire sag and kink



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

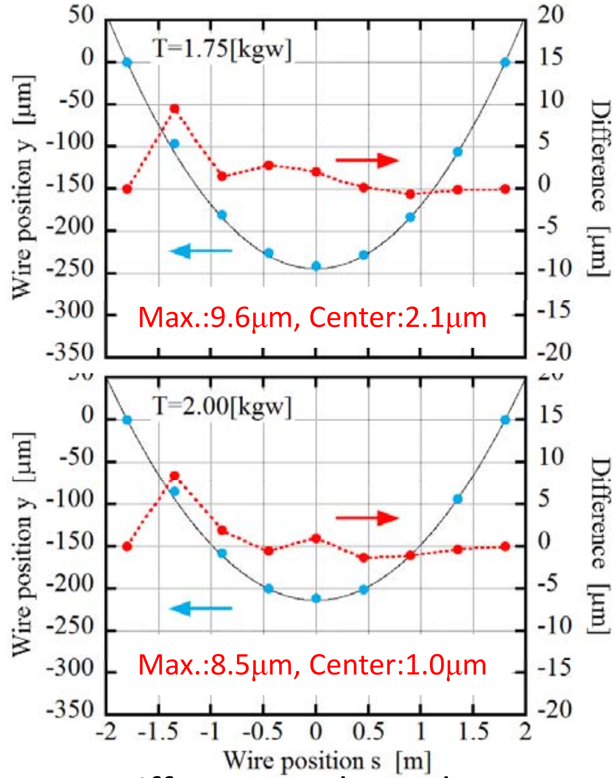
$$S_{\max} = \frac{\rho g}{8T} L^2 = \frac{g}{32 f_1^{\,2}}$$

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

The sag can be corrected by measuring a resonance frequency.

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

We are investigating about an individual differences.



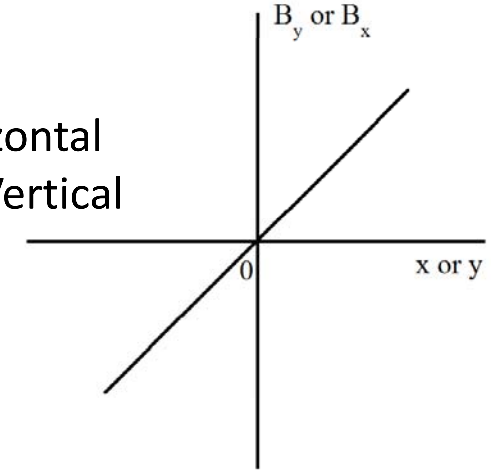
Difference calc. and meas.

3. Critical issue (2) Background field

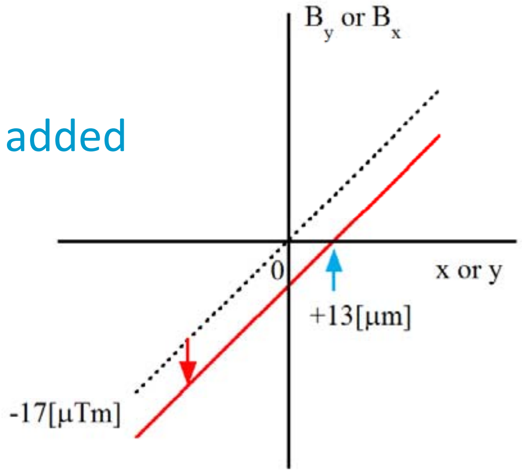
For Q-mag, background fields are not negligible.

$$B_x(y) = G_q y$$
$$B_y(x) = G_q x$$

Horizontal
or Vertical

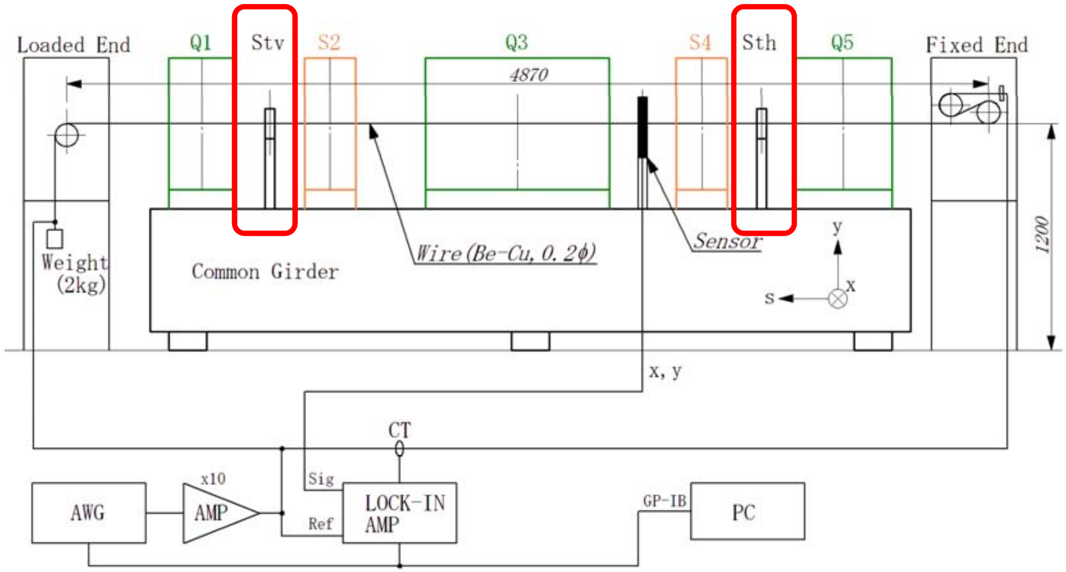


Geomagnetism etc., are added



Counter steerings "*Sth*" and "*Stv*"

	Max. field [mT]	Length *lp* [mm]
Sth	30	50
Stv	30	50



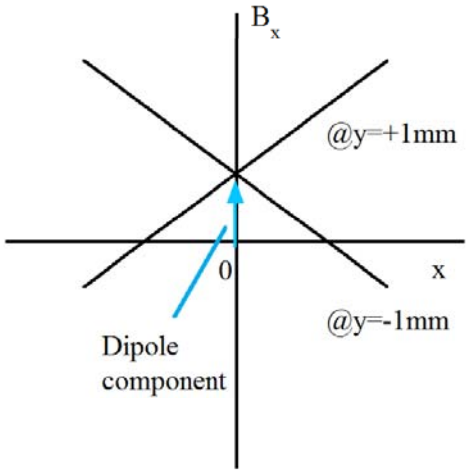
3. Critical issue (2) Background field

For S-mag, Bx components were chosen.

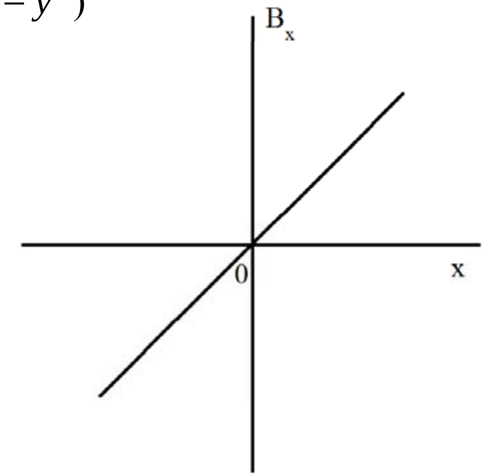
$$B_x(x,y) = G_s xy$$

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

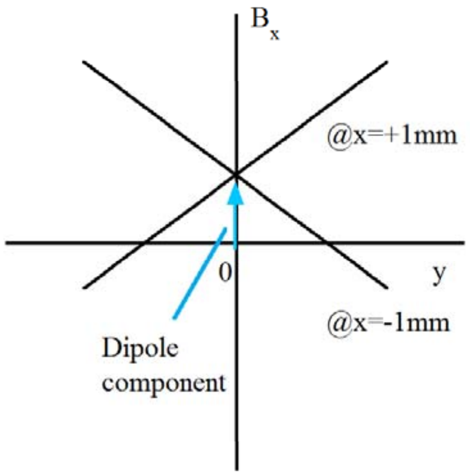
Horizontal



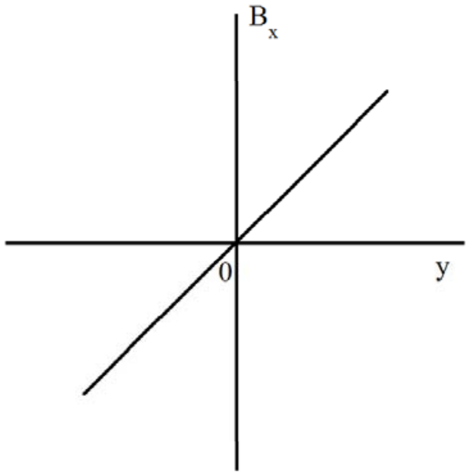
Subtracted



Vertical



Subtracted



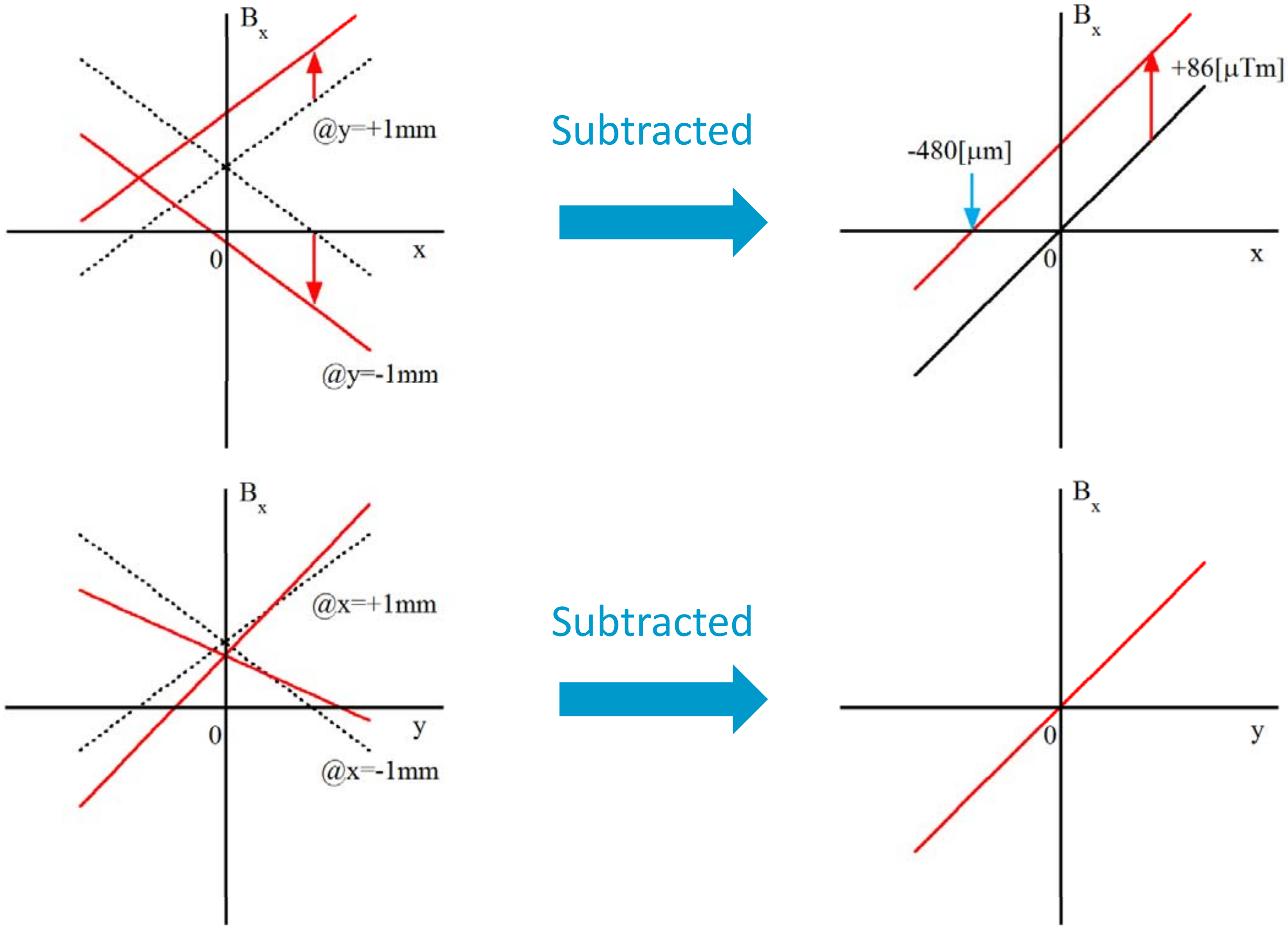
Dipole component, and background field are canceled in principle, but…

3. Critical issue (2) Background field

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

Horizontal

Vertical



Q1 was used as a counter quadrupole.

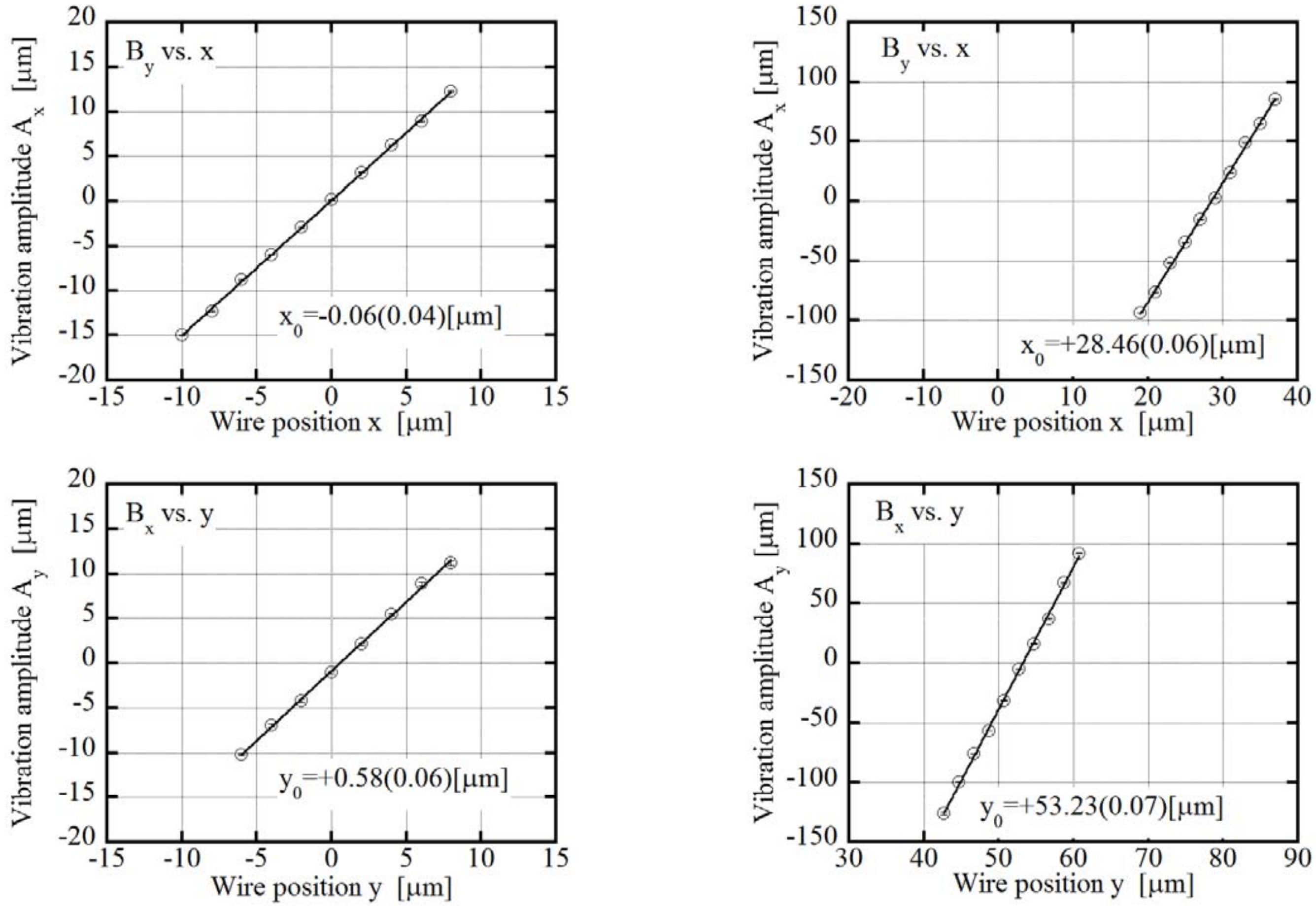
4. Result (Magnetic center of Q-mag)

Q1 (GL=1.31[T])

Q3 (GL=9.13[T])

X

Y

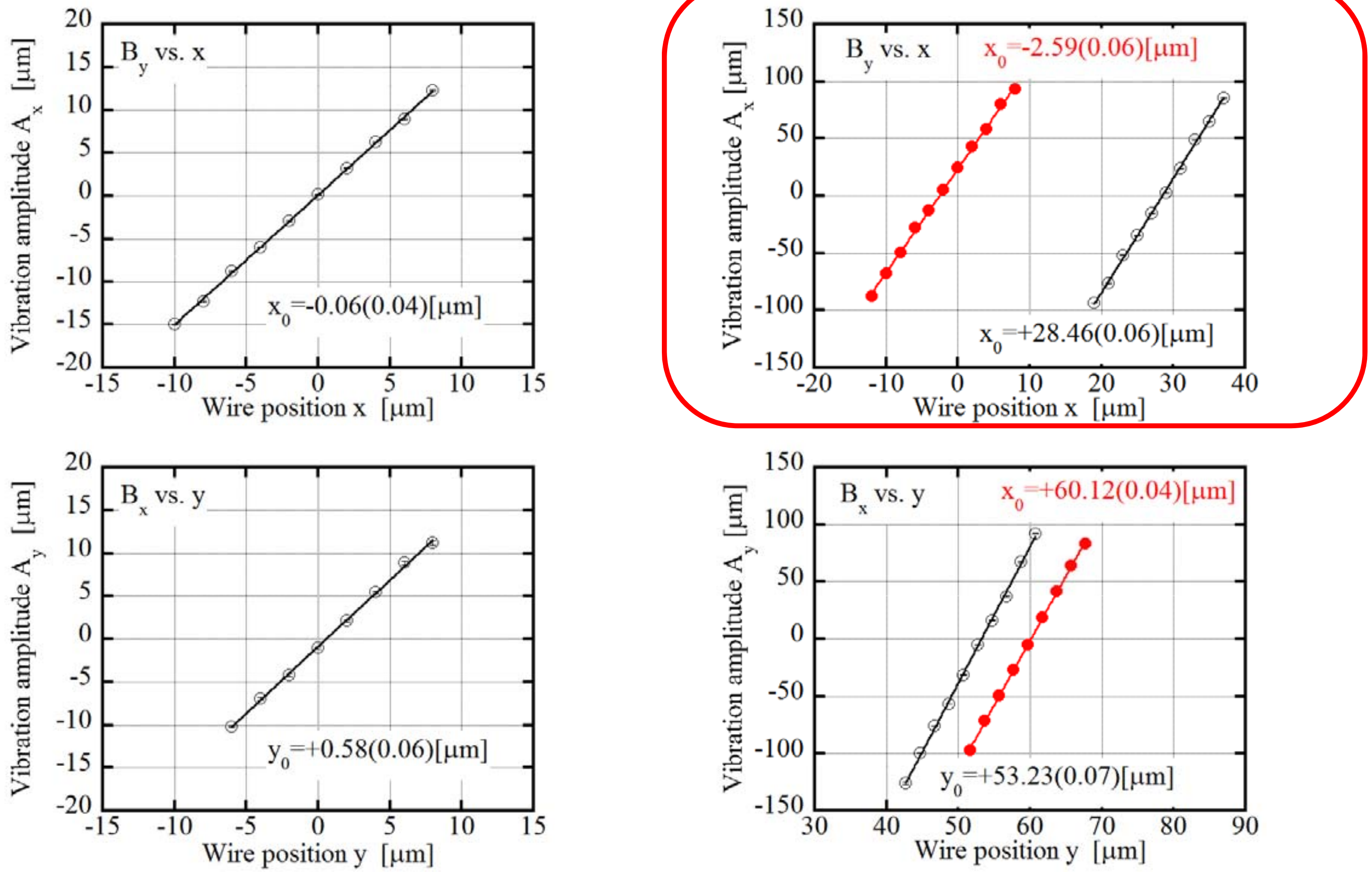


Vibration amplitude versus wire position. Wire current : 98 [mA_{rms}]

4. Result (Adjustment of Q-mag)

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

X / Y



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

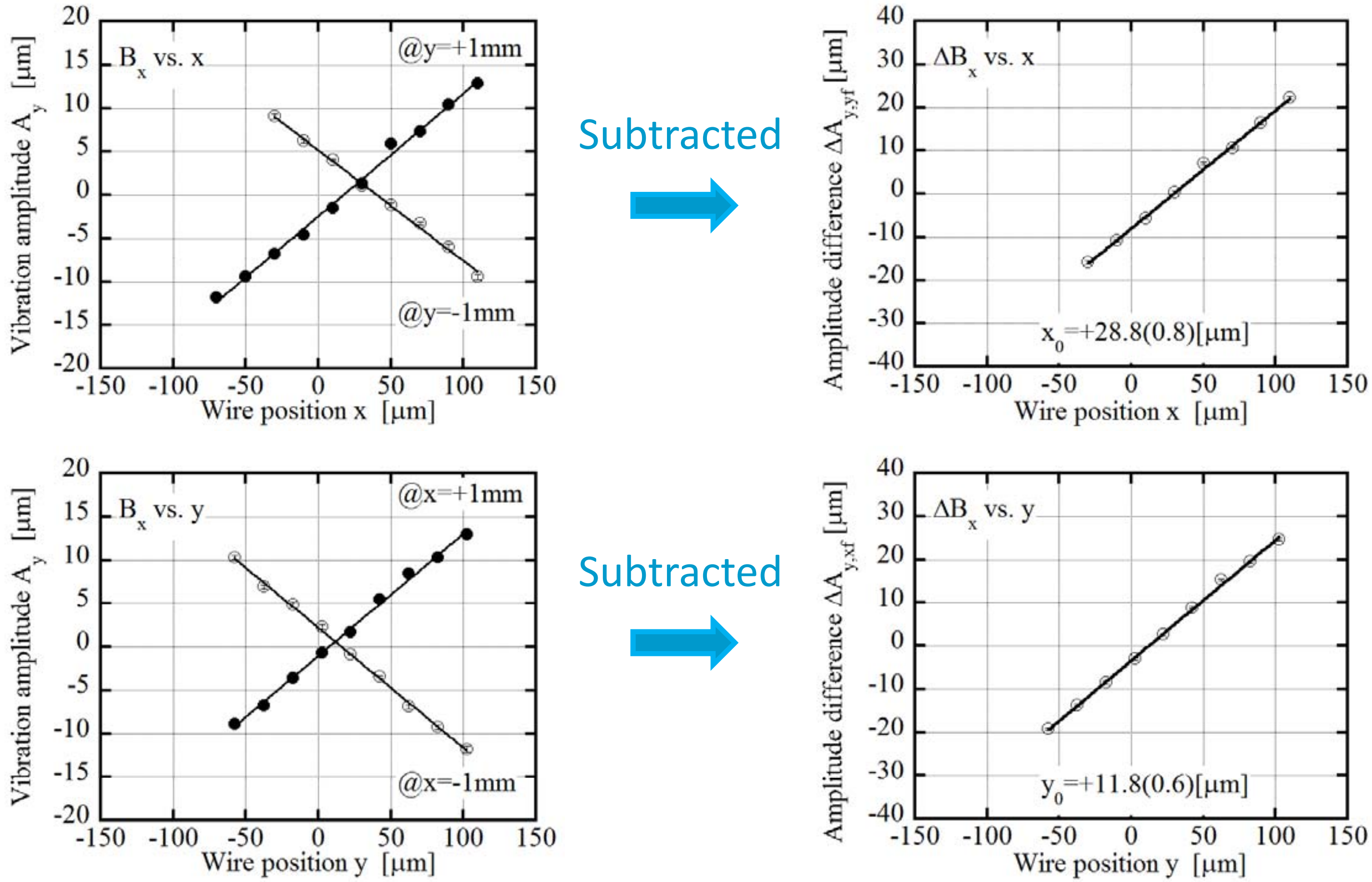
Displacement was successfully suppressed to 2.6 [μm] !

4. Result (Magnetic center of S-mag)

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] !

3. Critical issue (3) Repeatability

Result of the tests for a repeatability

Test item	Difference* [μm]
Using same tension and wire	< fitting errors
Tension was released once, using same wire	< 10
Wire was removed once, using new wire	< 10(in x), Max.=16 (in y) at Q3

* Differences of the displacements between before and after these tests

There is a possibility that the sag was changed.

The source of the change will be figured out.

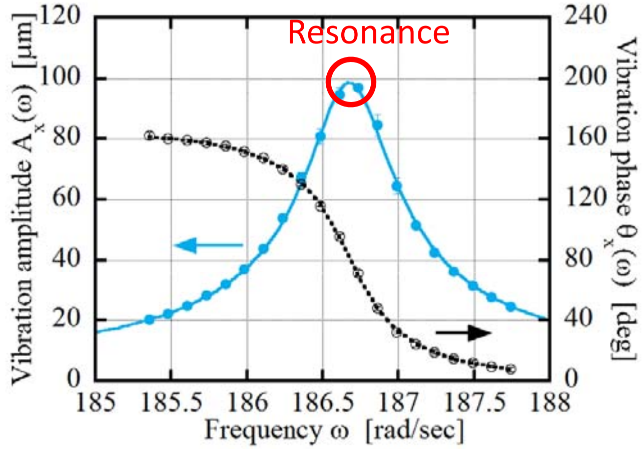
3. Critical issue (4) Drift of the resonance frequency

The resonance frequency easily drifts due to a change in an ambient air temp.

<u>(1) To obtain a temperature dependence on the resonance frequency,</u>

<u>(2) To observe a long-term drift of the magnetic center,</u>

-> Set frequency for the wire was tracked to the resonance.



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

Basic Feedback

Set frequency was tracked to the resonance by measured phase of itself.

Advanced Feedback

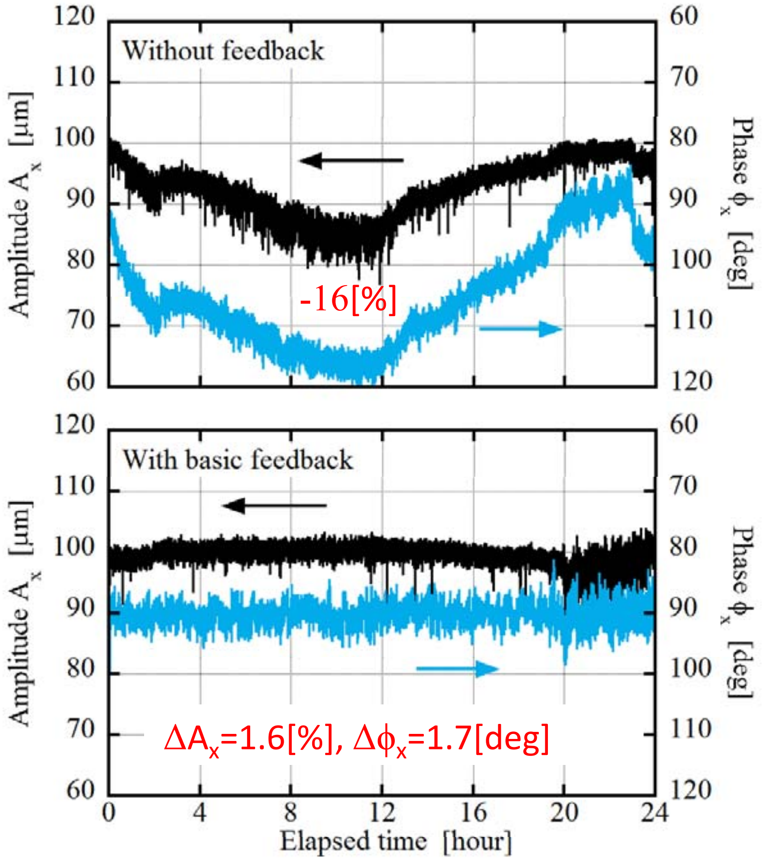
Set frequency was tracked by measured phase of the feedback wire*.

*The second wire (“feedback wire”) was installed in parallel to the “signal wire”.

<u>-> The process is available when the signal wire is placed near the magnetic center.</u>

3. Critical issue (4) Drift of the resonance frequency

In a constant field generated by “Sth” and “Stv”.



Temporal changes in the amplitude and the phase in x-direction.

Phase
Temperature coefficient : -29[deg/K]
(Correlation coefficient = 0.89)

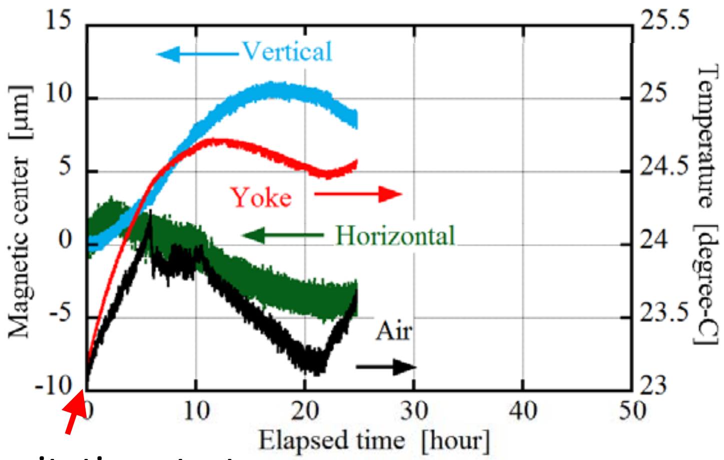
Frequency
Temperature coefficient : -0.02[Hz/K]
(Correlation coefficient = 0.69)

Error of the magnetic center < 1 [μm] / air temperature change ΔT=1[K]

The feedback is needed to observe a long-term stability of the magnetic center.

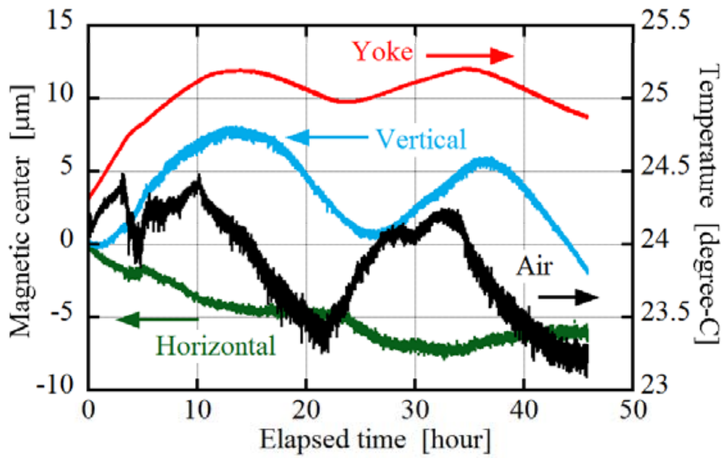
4. Result (Drift of the magnetic center)

Q1 (GL=1.31[T])



Excitation start

Q3 (GL=9.13[T])



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

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

The temporal changes will be observed about all sort of the magnets for the SPring-8-II.
Then, we will determine a timing of magnetic-center measurement
to expect the magnetic center at the machine operation.

5. Summary (Error budget for the SPring-8-II)

Resolution ◎

• Detection limit : < 0.1[μTm], fitting error : < 0.1[μm](for Q-mag), <1[μm](for S-mag).

Any more improvement is not needed.

Systematic error caused by a background gradient ○

In case of the test sextupole magnet, the error is estimated to be -480 [μm] in *x*. This value will reduce to 50 [%] in the SPring-8-II. Still, we must…

• To suppress the gradient less than 1/100 (~3×10^{-5}/Q3, already achieved).

• To monitor the remanent of the quadrupoles.

Repeatability △

• The wire is removed : max. difference exceeded aimed accuracy in *y*.

The source of the change will be figured out.

Drift and change of the magnetic center △

The magnets should be aligned after yoke temperature become stable.

• To stabilize the air temperature within 0.5 [K] (machine tunnel, measurement room).

• To determine the timing for the magnetic-center measurement.

A change caused by a transportation to the machine tunnel and
A drift caused by a deformation after installation will be observed.