Precise Magnet Alignment for SPring-8-II and Beyond

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1. Alignment Scheme for SPring-8-II using Vibrating Wire Method, VWM
- Introduction
- Demonstration at the New 3GeV Light Source, NanoTerasu
- Magnetic Center vs. Mechanical Bore Center

2. Proposal of a New VWM for Magnet Arrays Containing Permanent Magnets

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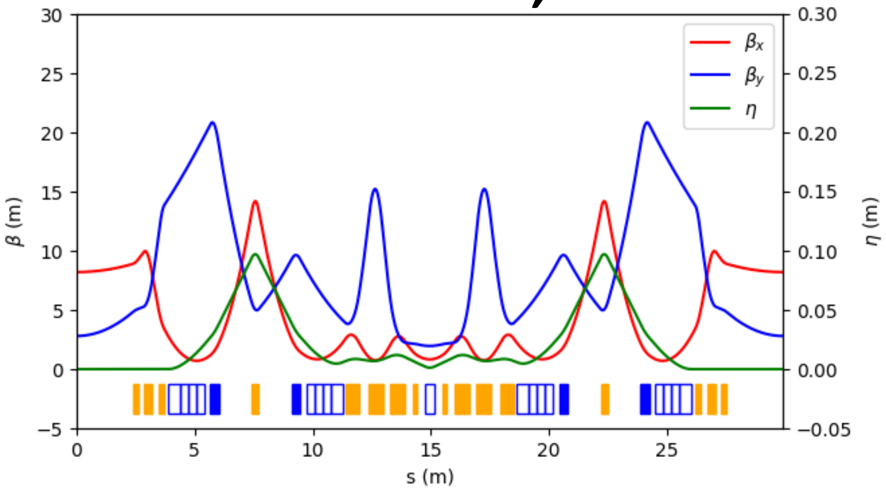
1. Introduction

Major Parameters	SPring-8-II	SPring-8
Energy (GeV)	6	8
Stored current (mA)	200	100
Circumference (m)	1435.43	1435.95
Effect. emittance (pmrad)	110~50 (with DWs)	2,400

5-bend achromat, 48 cells



T. Watanabe, SRI2024, Hamburg, Germany.

The required alignment tolerance: ±50μm
for the multipole magnets in the transverse plane.

Even smaller deviation is preferable
to make the dynamic aperture as large as possible.

Our goal is < ±10μm or better.

1. Introduction

Fiscal year	2017	2018 -2022	2023	2024	2025 -2028
SPring-8-II Design/Development Restarted and Redesigned Magnet Mass Production 4/2025-6/2028 Shutdown Period 7/2027-9/2028				★ Here	
NanoTerasu (3GeV LS in Japan)					

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NanoTerasu (3GeV LS in Japan)					

- Precise magnet alignment based on a VWM has been developed for SPring-8-II.
- The same alignment procedure was applied to NanoTerasu.
- Magnets for SPring-8-II will be aligned from 7/2026 to 6/2028.

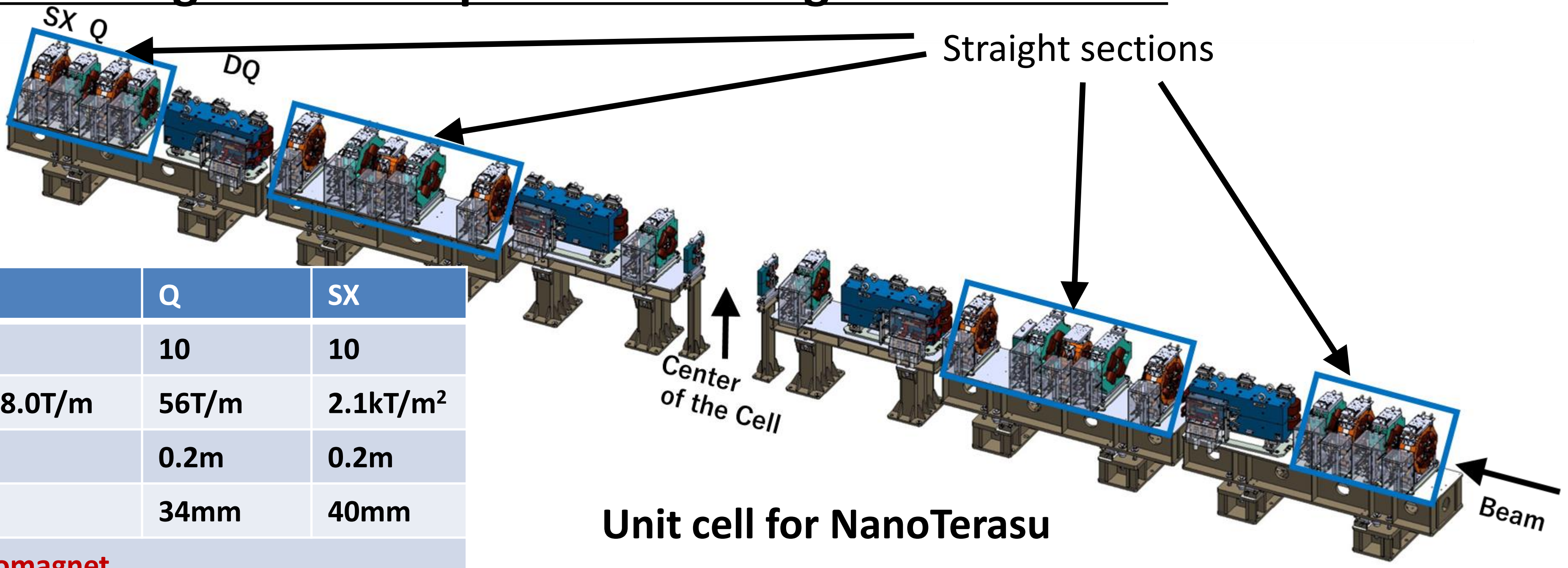
(1) "On-girder alignment" was performed using a VWM out of the accelerator tunnel.

320 multipole magnets (Q and SX) on 96 common girders were aligned for 16 weeks in 4 temperature-controlled vinyl booths.

(2) Girders were transported into the accelerator tunnel.

SMRs on the top of the magnets were measured using a laser tracker to confirm the magnet positions.

(3) Girder-to-girder alignment was performed using a laser tracker.



	DQ	Q	SX
Number/cell	4	10	10
Maximum field	0.98T-8.0T/m	56T/m	2.1kT/m^2
Effective length	1.1m	0.2m	0.2m
Gap/Bore dia.	28mm	34mm	40mm
Type	Electromagnet		

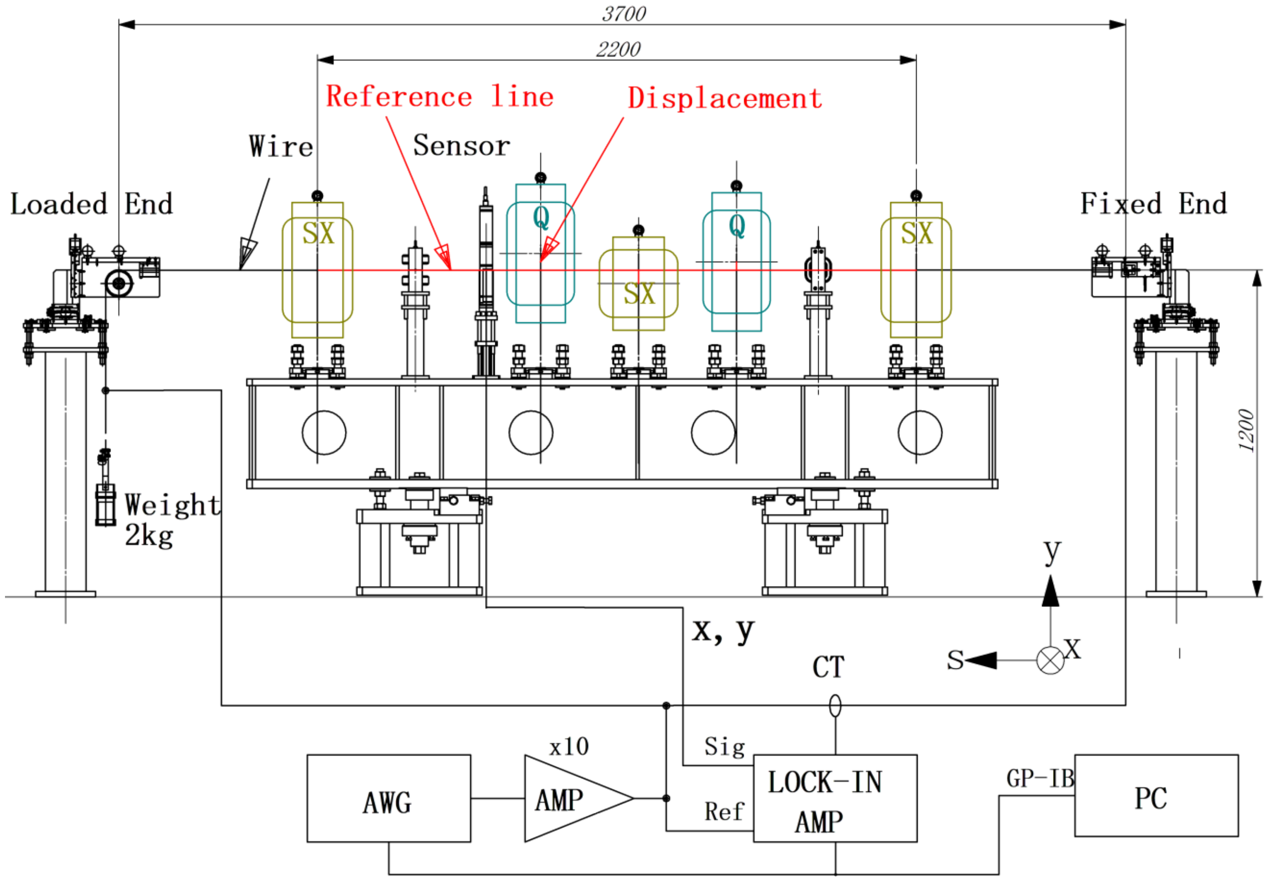
Unit cell for NanoTerasu

1. Demonstration at NanoTerasu

When an AC is applied to a tensioned wire,

the wire vibrates in the presence of a magnetic field.

→ We can determine the magnetic profile of multipole magnets.

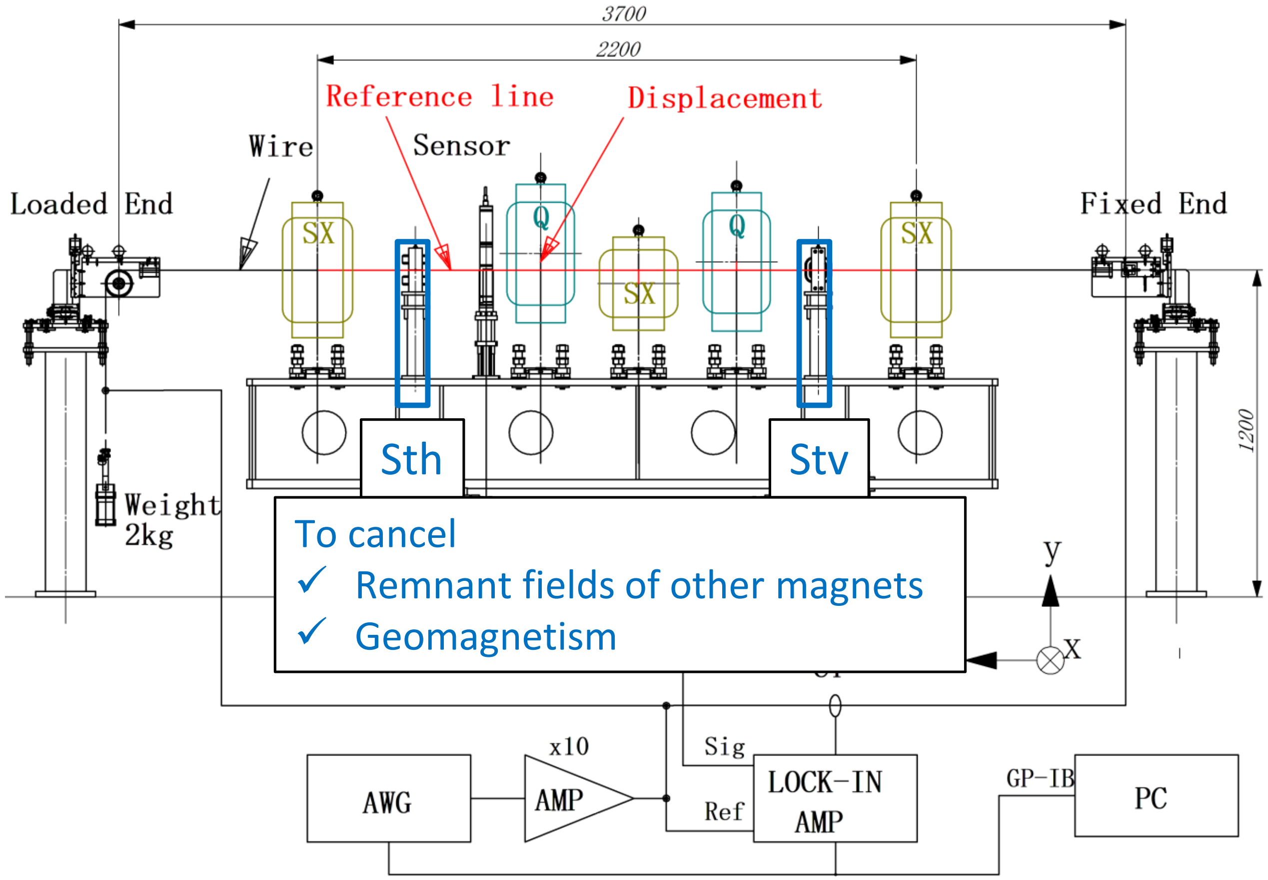


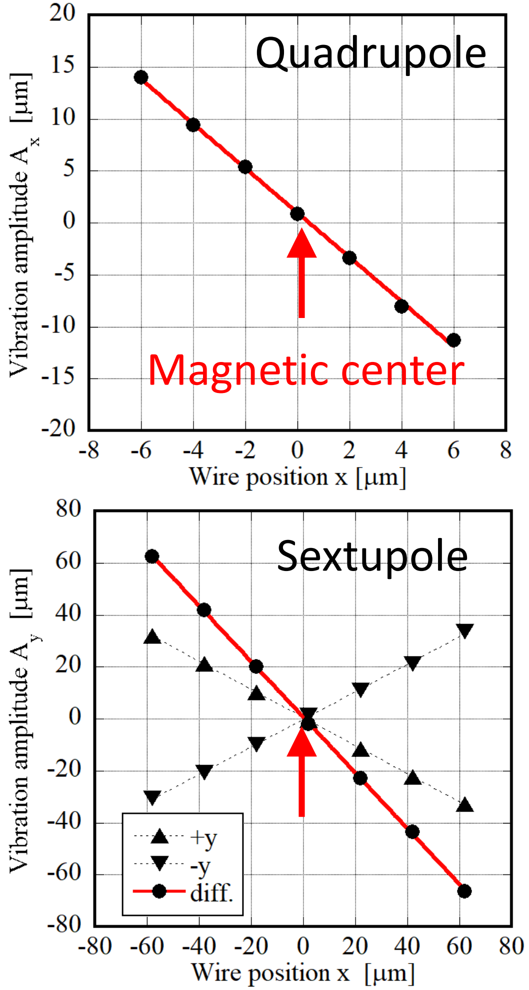
- **Wire :**
  NGK Ltd., C1720W-EHM
  Be-Cu, 0.2[mm]ϕ
- **Tension :**
  $T = 2.0$[kgf]
- **Maximum sag :**
  $S_{max}=0.23$[mm]
- **Resonance:**
  $f_1=36.8$[Hz]

Example of the setup of the on-girder alignment. The wire was scanned using x-y stages.

- ✓ **Only the alignment target magnet was excited in the magnet array.**
- ✓ **A spurious wire oscillation due to an external field was canceled using “Sth” and “Stv”.**

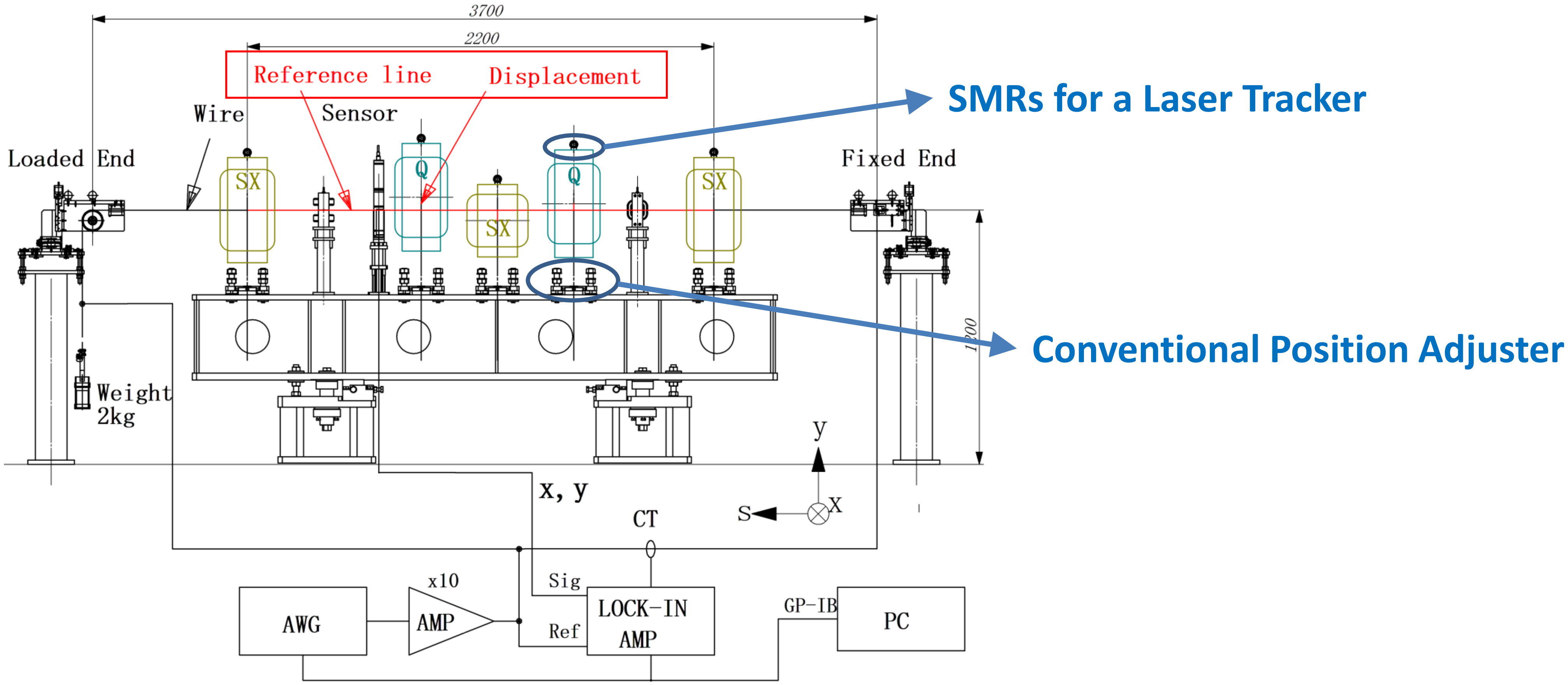
The magnetic center of the target magnet was detected with the resolution < 0.3 µm.





Reference line was defined as a straight line connecting the magnetic centers of two end magnets of a straight section.

Displacements of other magnets between the two end magnets from the reference line were compensated by adjusting the magnet position with a conventional adjuster.



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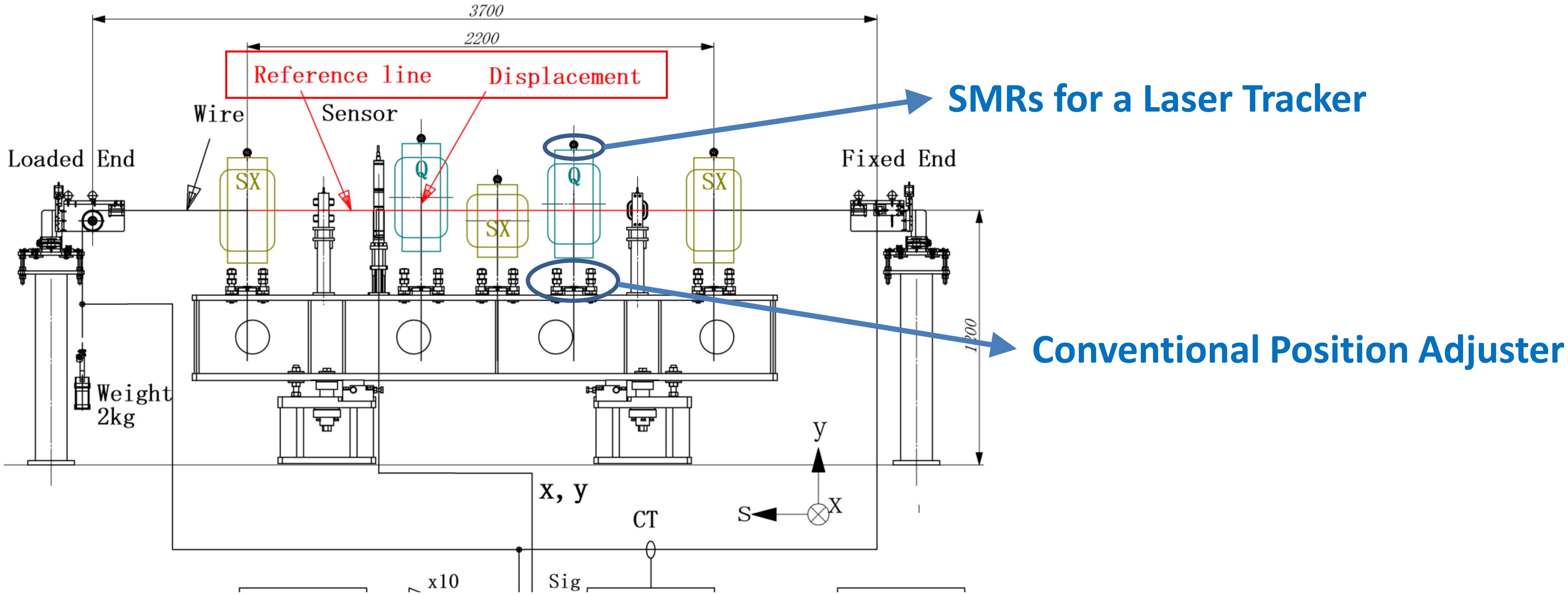
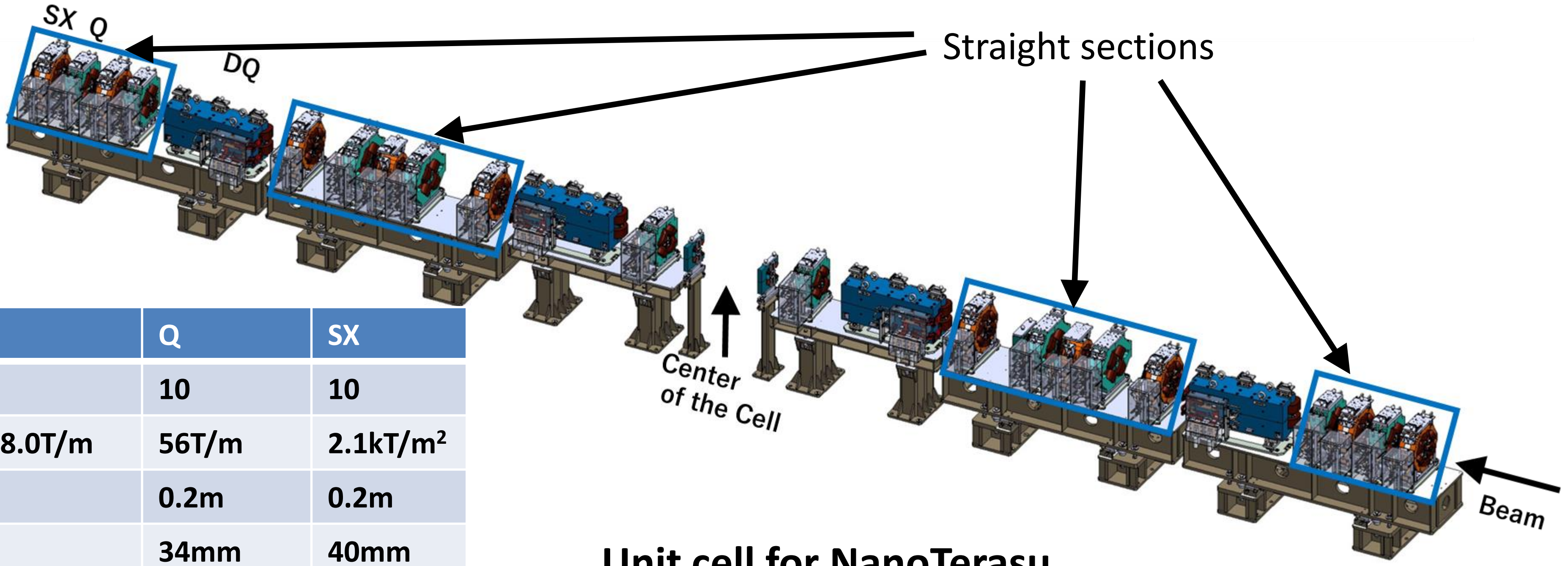


Magnet alignment after the transportation was inspected by measuring the coordinates of the SMRs on the reference plate of the magnets.

(1) Result of on-girder alignment using a VWM out of the tunnel.
(2) Confirmation of the magnet positions after the transportation.
(3) Girder-to-girder alignment was performed using a laser tracker.



Unit cell for NanoTerasu

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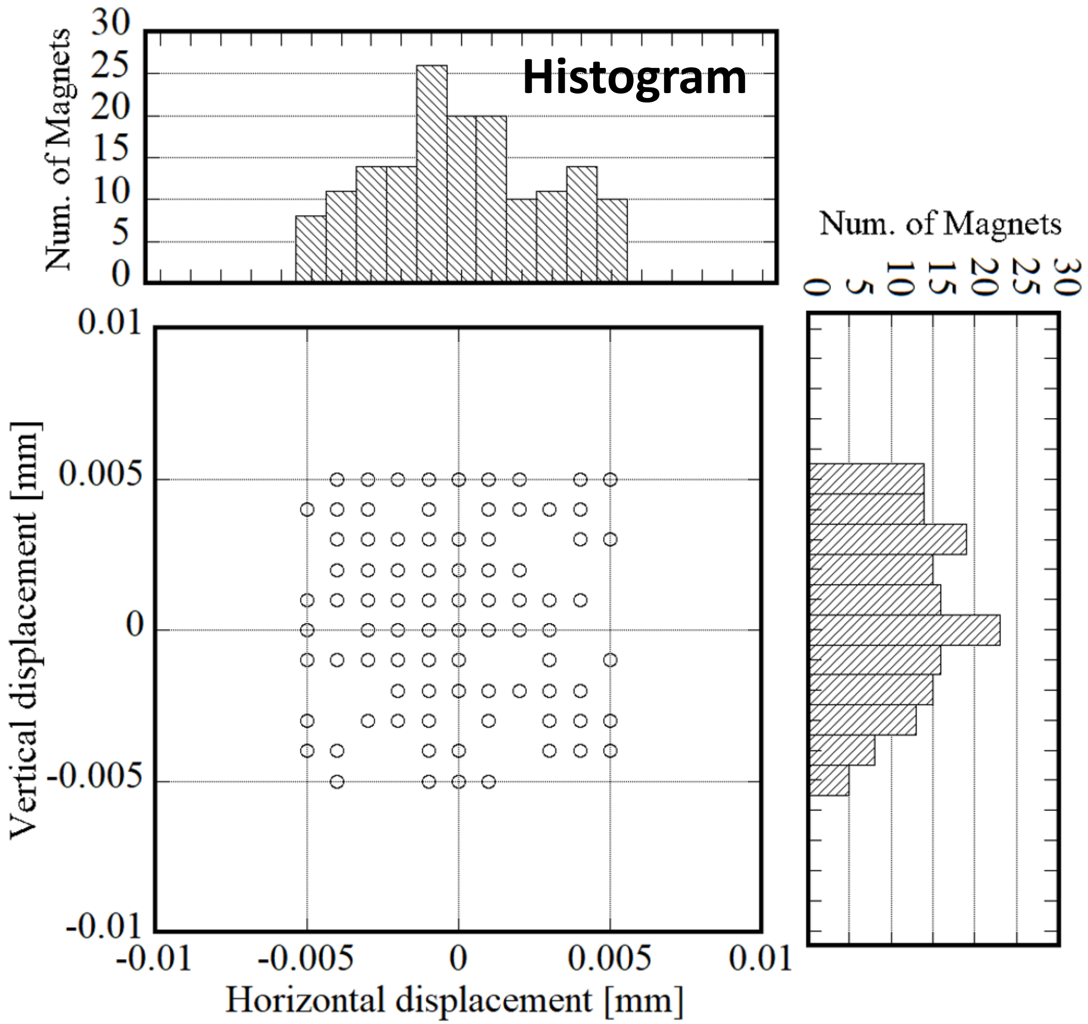
Type	Electromagnet		

(1) Result of on-girder alignment



Displacements of the magnetic centers from the reference line in the transverse plane for the 160 aligned magnets for NanoTerasu.

Displacements of the aligned magnets were successfully suppressed to within ±5μm!

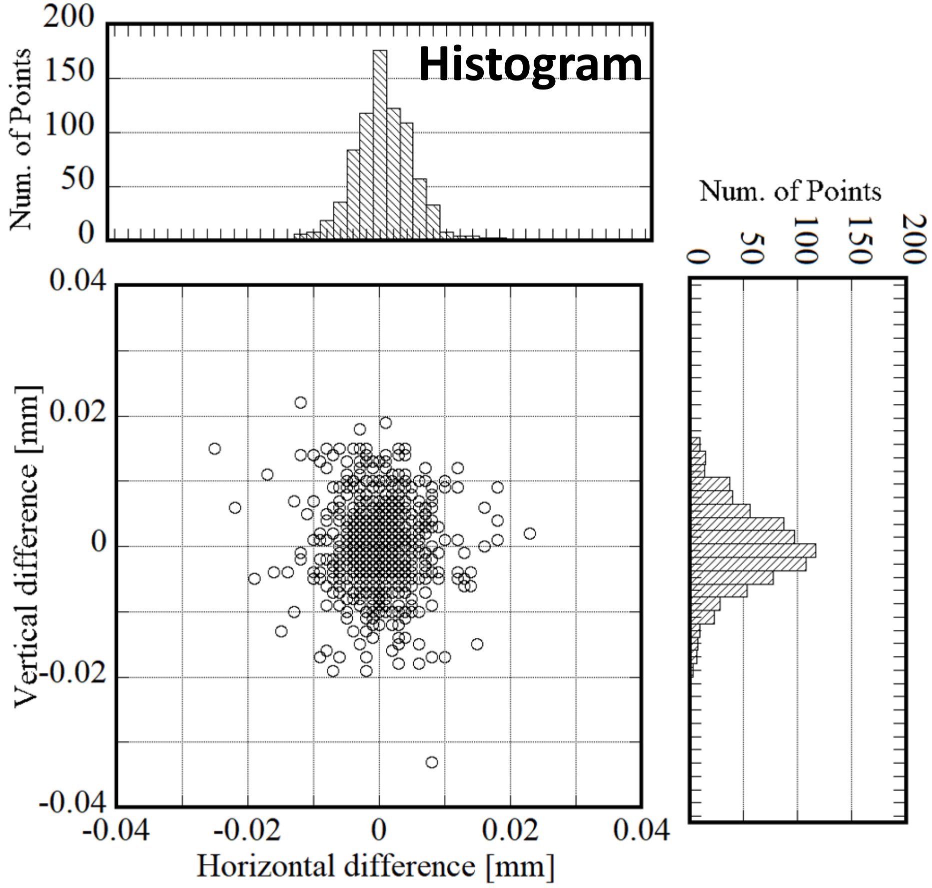
(2) Confirmation of the magnet positions after the transportation

We inspected the magnet alignment by using a laser tracker in the tunnel.

The coordinates of SMRs on the magnet reference plate were compared before and after the transportation.

The differences were all within the alignment tolerance.

→ Re-alignment was not performed even once.



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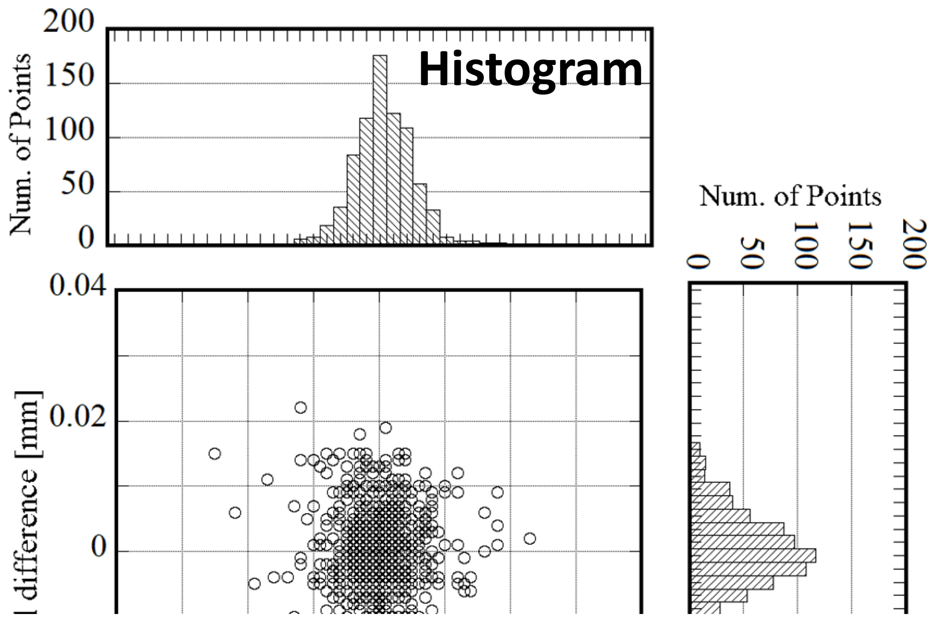


Thanks to the excellent alignment accuracy, the well-suppressed natural COD was obtained.
The root mean squares of the COD were
1.2mm in the horizontal and 0.8mm in the vertical directions without orbit correction*.

*S.Obara et al., doi:10.48550/arXiv.2407.08925

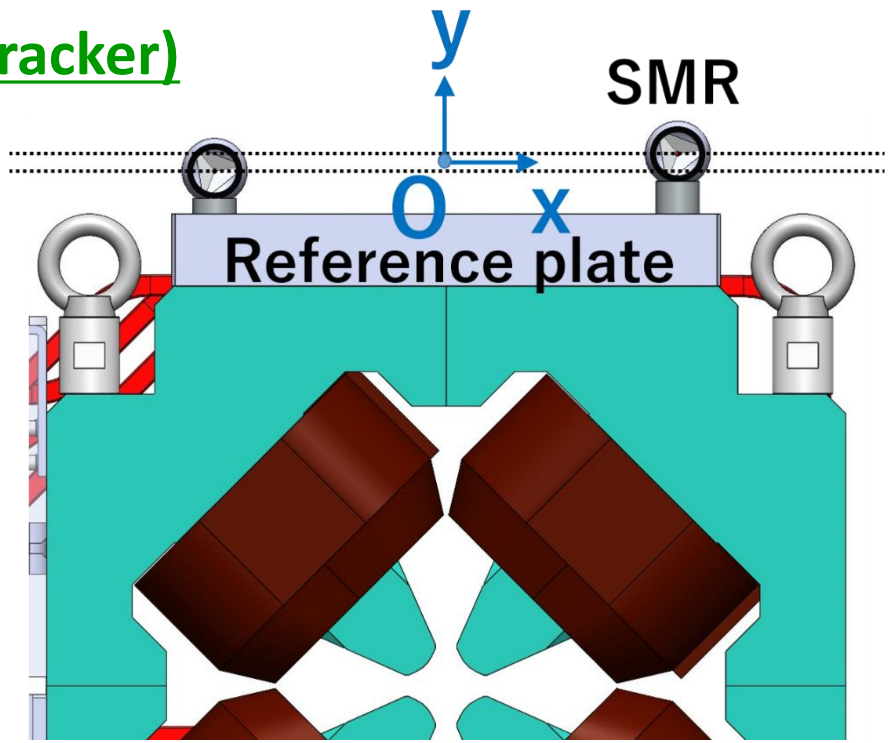
Mechanical Bore Center (measured by using a Coordinate Measuring Machine)

- The center of the two SMRs was defined as the origin of the x-y axes.
- The mechanical bore center was estimated by measuring the pole surfaces at upstream and downstream ends.

Magnetic Center (measured by using the VWM and a Laser Tracker)

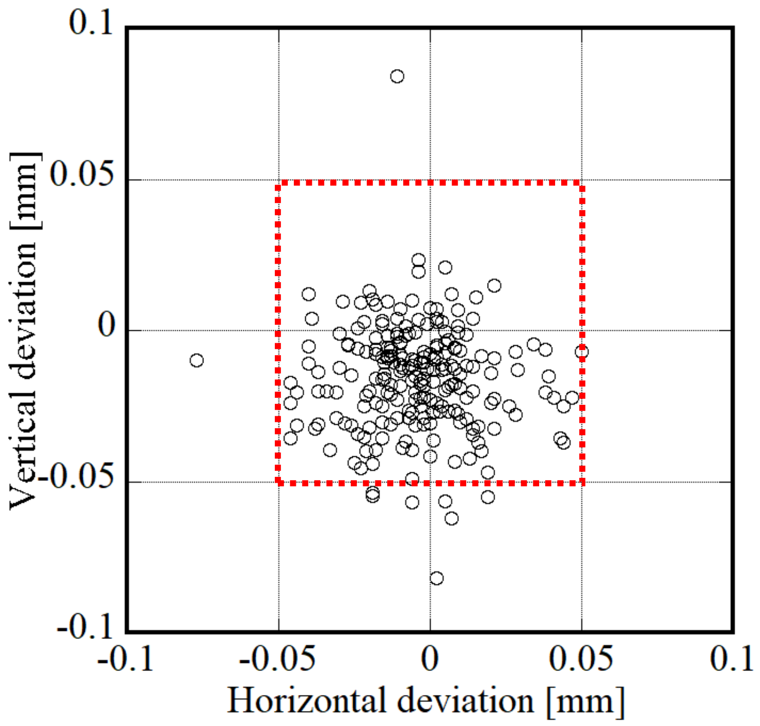
- The wire detected the magnetic center in the VWM.
- The wire position was measured using a laser tracker in the x-y coordinate system*.

* See reference K. Fukami et al., Review of Scientific Instruments, 90, 054703 (2019)



1. Magnetic Center vs. Mechanical Bore Center

The deviations of the mechanical bore center from the magnetic center in 9 examples exceeded the alignment tolerance due to mechanical errors such as a longitudinal undulation of the magnet poles.

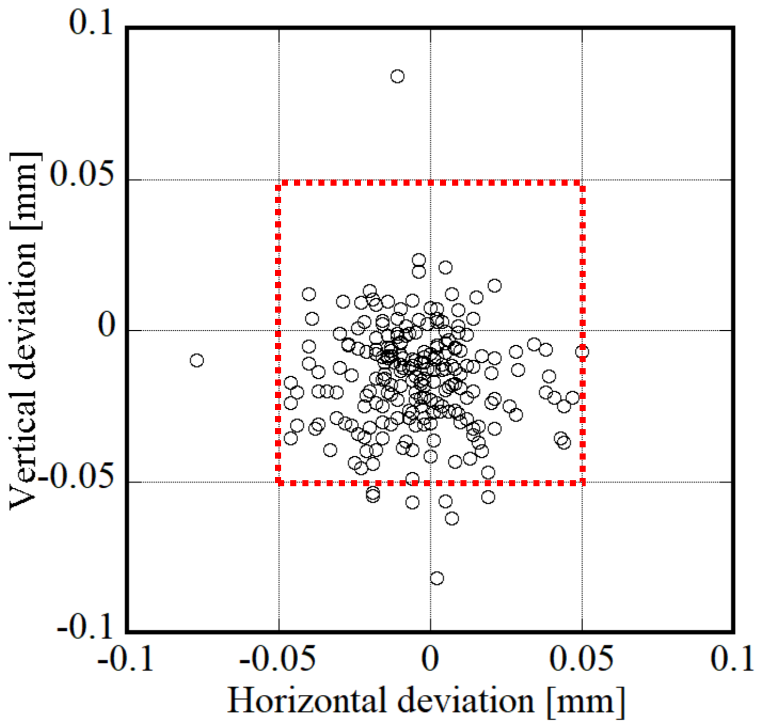


Deviations of the mechanical bore center from the magnetic center of magnets for NanoTerasu.

The deviations of the mechanical bore center from the magnetic center in 9 examples exceeded the alignment tolerance due to mechanical errors such as a longitudinal undulation of the magnet poles.

If we had applied a mechanical bore center-based alignment, the deviation would have contributed to the misalignment of magnets.

We will again apply the VWM, i.e. a magnetic center-based alignment for SPring-8-II.

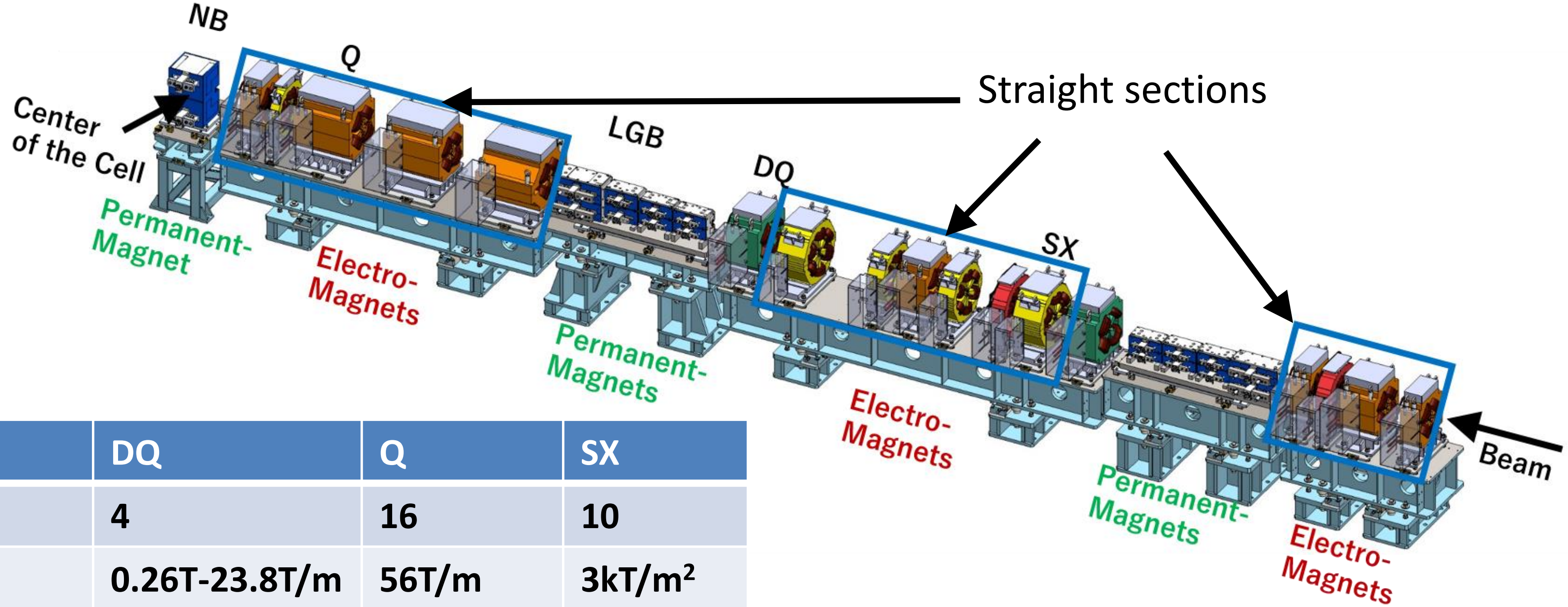


Deviations of the mechanical bore center from the magnetic center of magnets for NanoTerasu.

1. Alignment Scheme for SPring-8-II

The same alignment procedure as we did for NanoTerasu can smoothly be applied to SPring-8-II with the following differences in details;

- **DQ combined function magnets** are aligned by applying a position offset on a wire.
- **Permanent dipole magnets** separately placed on independent girders and aligned by a laser tracker.



The upstream half of a normal cell for SPring-8-II

	LGB	NB	DQ	Q	SX
Number/cell	4	1	4	16	10
Maximum field	0.62T	0.95T	0.26T-23.8T/m	56T/m	3kT/m^2
Effective length	1.55m	0.38m	0.35m	0.2-0.65m	0.1-0.3m
Gap/Bore dia.	25mm	25mm	22mm	34mm	42mm
Type	Permanent magnet		Electromagnet		

Challenge for VWM beyond SPring-8-II

Precise alignment of magnet array involving permanent magnets (PMs).

Disadvantages of conventional VWM

- **Since AC is applied to the wire, any magnetic fields from sources other than the alignment target will add spurious oscillation to the wire and result in the alignment error.**
- **We can subtract the spurious component from the wire oscillation data if the spurious oscillation can be accurately measured with the target turned off. However, when a PM is the target, it is impossible to turn it off.**
- **Including a PM-based DQ magnet in the alignment will result in a significant spurious oscillation that is difficult to subtract correctly.**

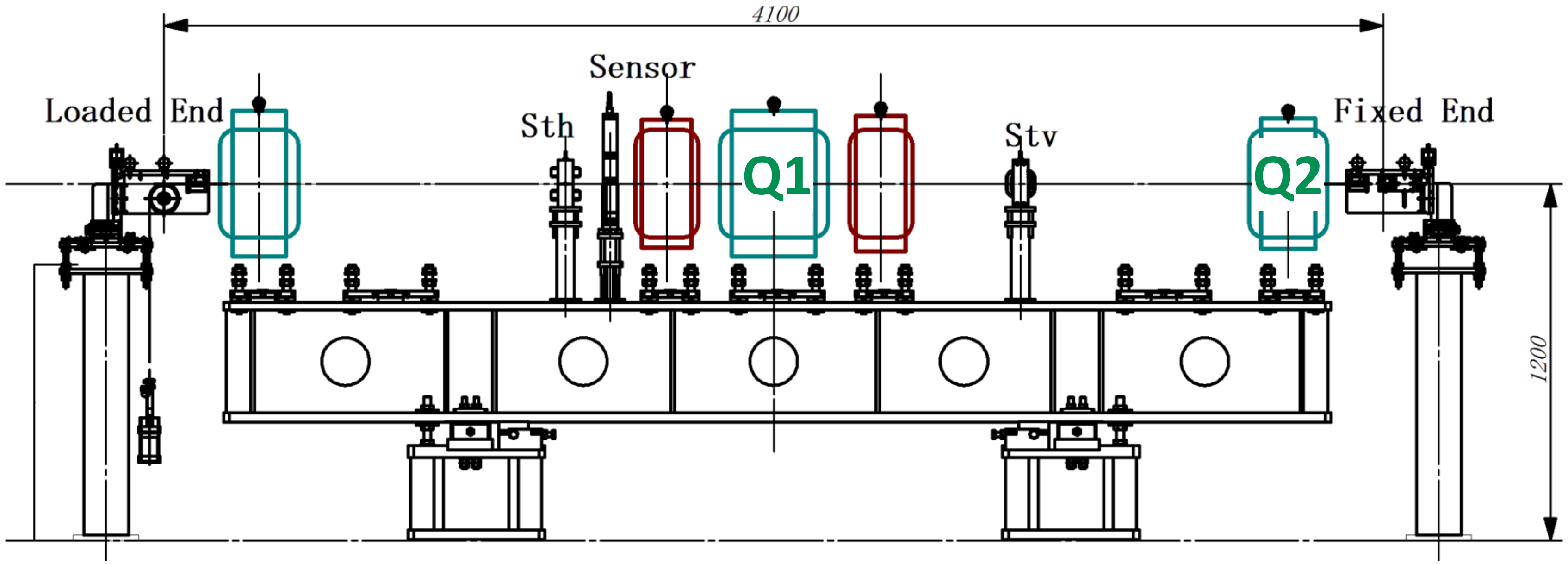
We propose a new VWM that enables a precise magnet alignment in the presence of PMs in the same girder.

Field Modulated VWM (FM-VWM)

- A DC is applied to the tensioned wire.
- The target magnet is excited by an AC with a resonance frequency of wire vibration.

→ An external field does NOT generate a spurious wire oscillation.

1. The FM-VWM can be applied to a group containing permanent magnets.
2. A permanent magnet can also be aligned by adding an extra AC field.



Test magnet array for proof-of-principle experiments for FM-VWM using electromagnets.

Proof-of-principle Experiments

1. Accuracy of magnetic-center measurement

The magnetic center of the target quadrupole magnet was measured with two methods, conventional VWM and FM-VWM.

2. Effect of an external multipole magnetic field

A misaligned extra quadrupole magnet was involved and excited by a DC to simulate a permanent quadrupole magnet.

3. Magnetic center of a simulated permanent magnet.

Alignment target quadrupole magnet was excited by a DC to simulate a permanent quadrupole magnet.

The magnetic center of the target magnet was measured with FM-VWM by superimposing an AC excitation.

1. Accuracy of magnetic-center measurement

FM-VWM:

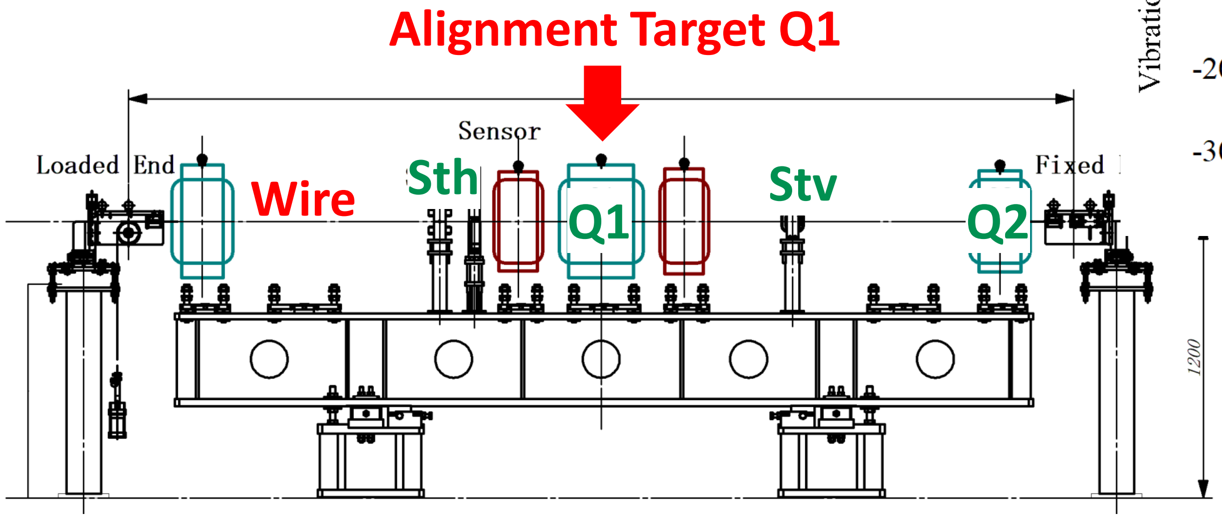
Wire DC0.056A, Q1 AC0.03T_{rms}

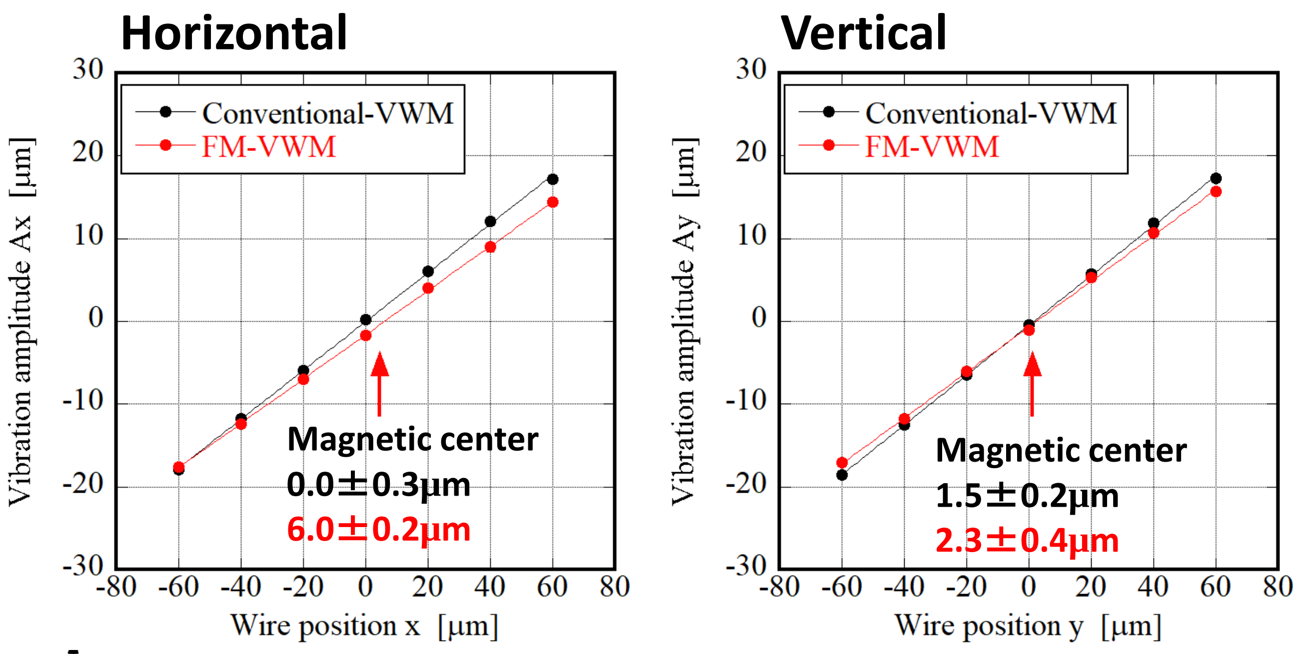
Conventional VWM:

Wire AC0.056A_{rms}, Q1 DC0.03T + Sth, Stv*

*** Spurious wire oscillation (1μm)**

-> Error of magnetic-center (3.7μm)





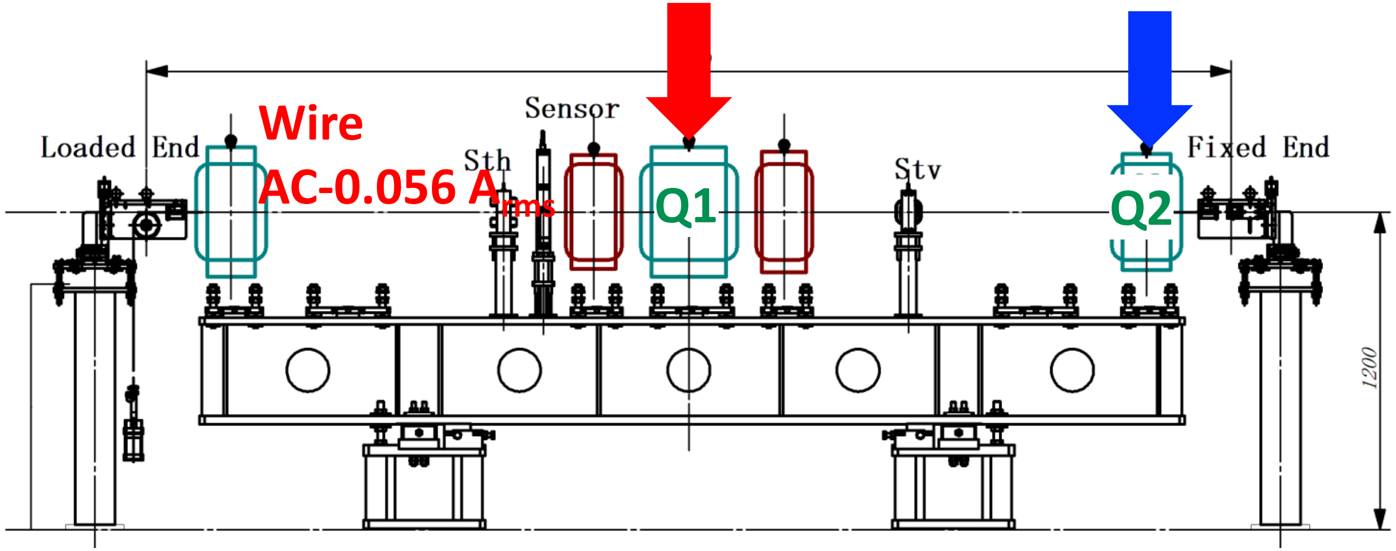
Wire vibration amplitude versus wire position in the transverse plane.

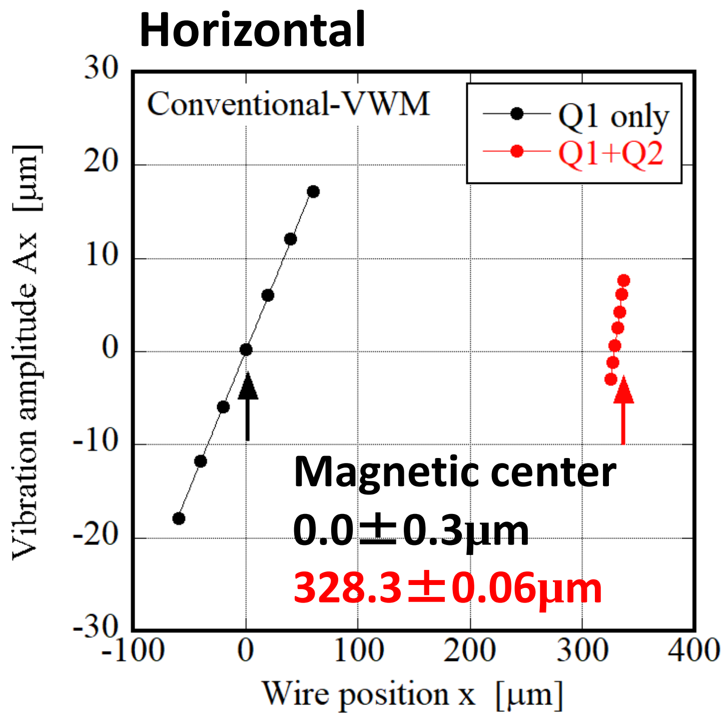
The FM-VWM can detect the magnetic center correctly without canceling spurious wire oscillations that disturbed the conventional VWM.

2. Effect of an external multipole magnetic field

A misaligned extra quadrupole magnet was involved and excited by a DC to simulate a permanent quadrupole magnet.

Conventional VWM



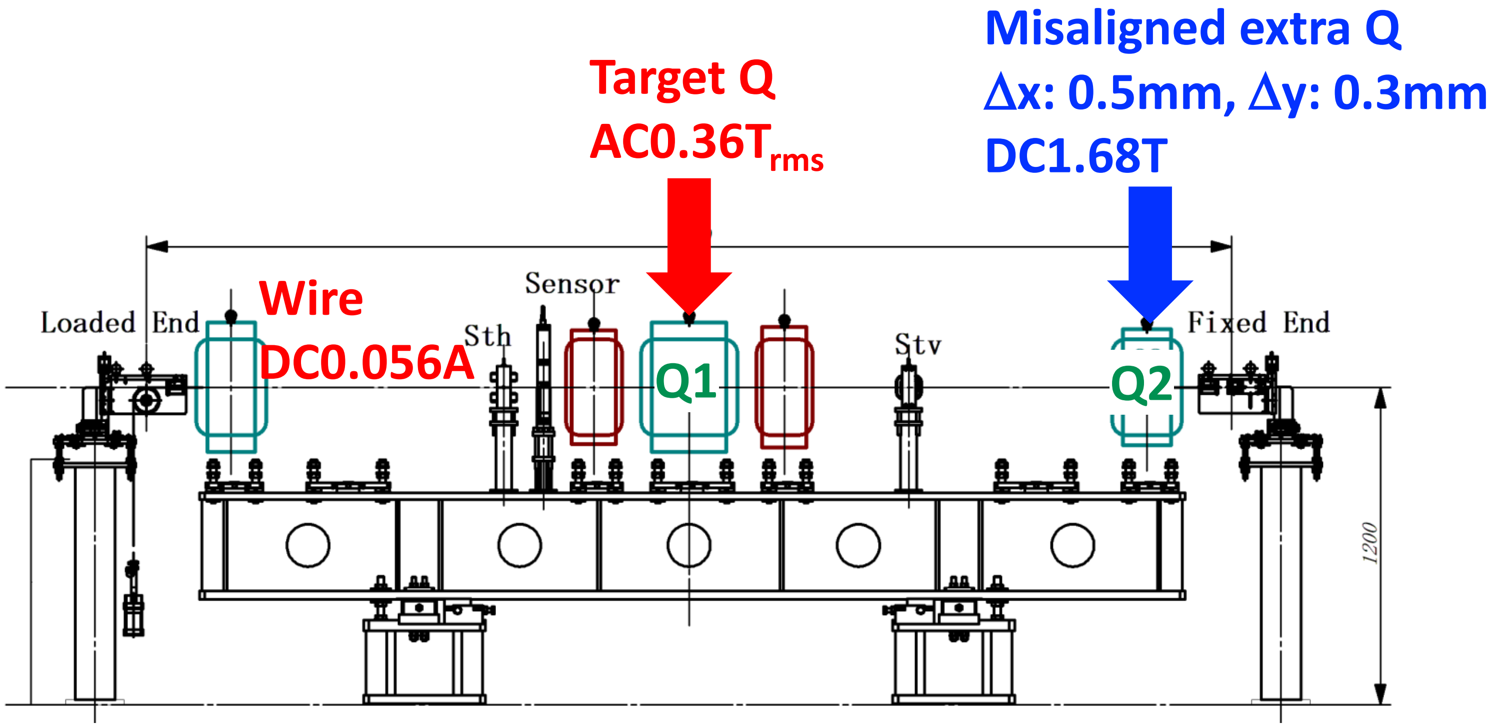


Wire vibration amplitude versus wire position.

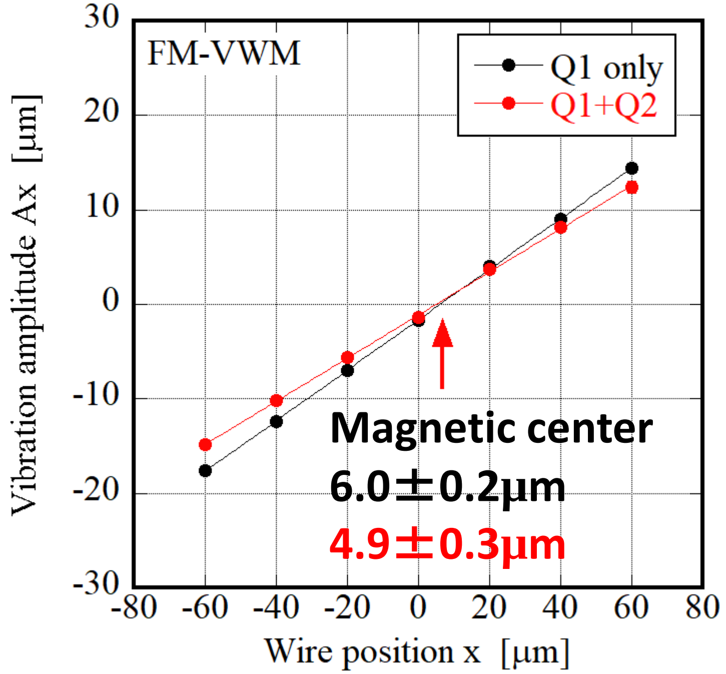
Conventional VWM is useless in the presence of external multipole field, e.g. by permanent quadrupole magnets.

2. Effect of an external multipole magnetic field

FM-VWM



Horizontal

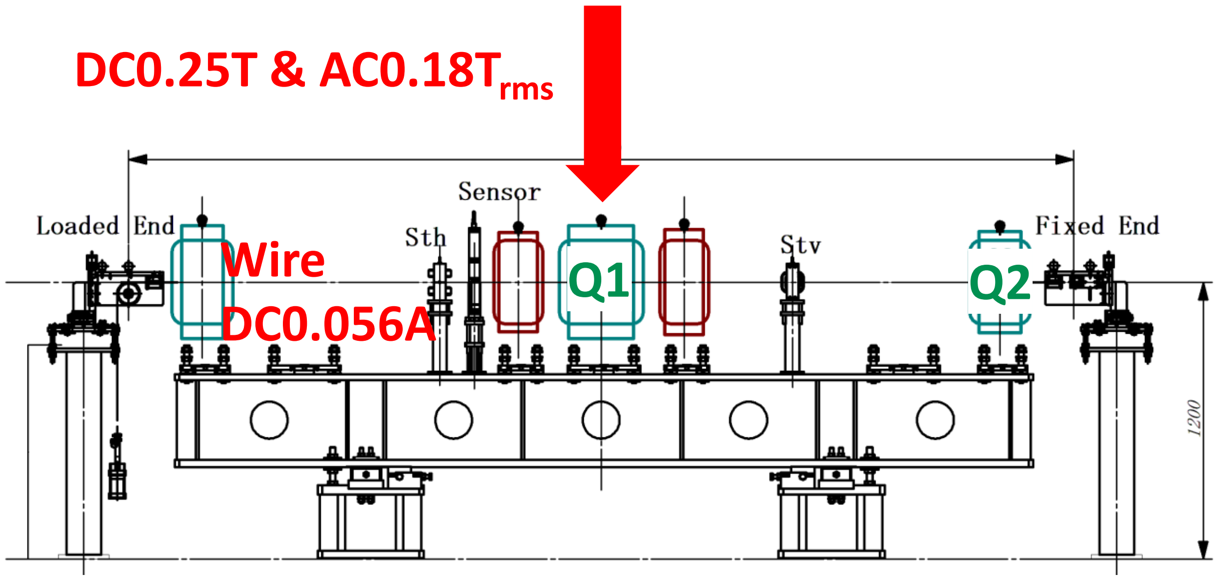


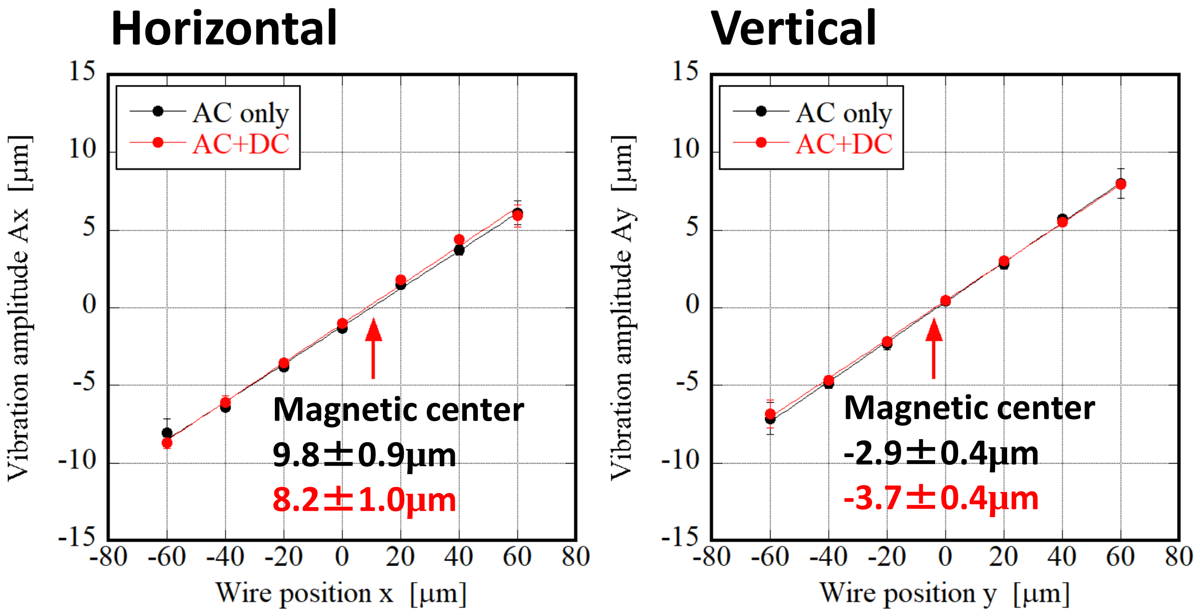
Wire vibration amplitude versus wire position.

The FM-VWM can measure the magnetic center correctly even if there is an external multipole field, e.g., by permanent quadrupole magnets.

3. Magnetic center of a simulated permanent magnet

DC was applied to the target quadrupole magnet to simulate a permanent quadrupole magnet.





Wire vibration amplitude versus wire position in the transverse plane.

The FM-VWM can measure the magnetic center of a permanent quadrupole magnet!

SPring-8

Notes

1: The presence of strong dipole fields, e.g., permanent DQ magnets

The wire moves by Lorentz's force
due to an interaction between a direct current and a static magnetic field.
Correcting the wire movement like a wire sag is necessary when it is not negligible.

2: Frequency dependence of the alignment target magnets

No field attenuation and delay were observed up to 100Hz in the test magnets
because their iron cores are made of a laminated sheet with a thickness of 0.5mm.
We recommend a laminated core for permanent magnets and electromagnets
if FM-VWM is applied.

3. Outlook

Magnet Alignment for SPring-8-II

- Our alignment scheme for SPring-8-II has been successfully applied to NanoTerasu and the adequately precise alignment was verified from the natural COD.
- We will apply it to coming SPring-8-II with some improvements in the detailed procedure.

New VWM

- We propose a new alignment scheme that can precisely align magnet arrays in the presence of permanent magnets along the wire.
- The new VWM we proposed will expand the scope of VWM for future accelerators.