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National Synchrotron Radiation Laboratory

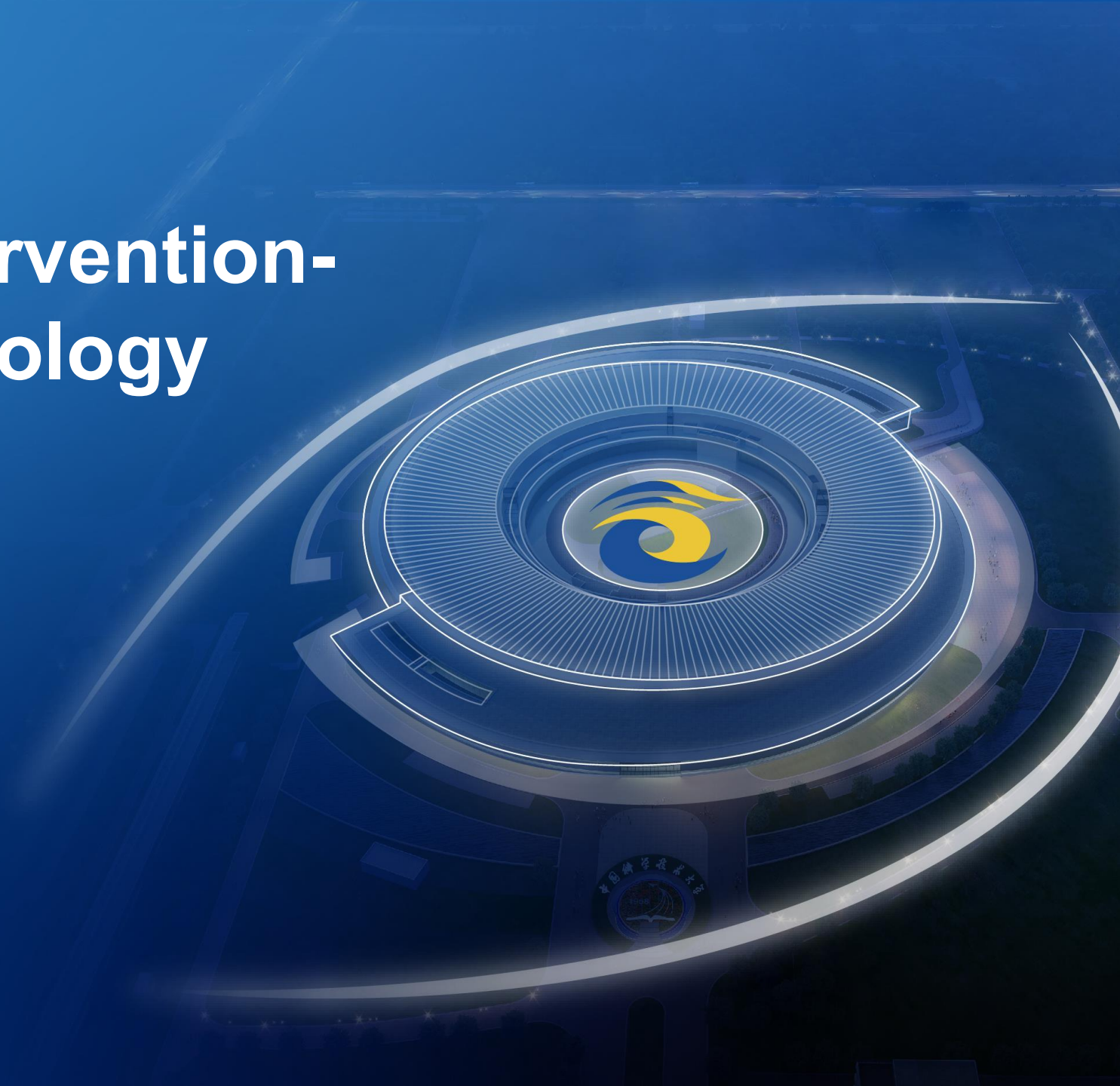
Task-Specific, Intervention-Aware Virtual Metrology

Pre-measurement evaluation of
engineering actions
for accelerator magnet alignment

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OUTLINE

Can we determine whether a measurement plan is adequate, and which engineering action is worth taking, before the survey begins?

01 Current capability



02 Model check



03 Station study



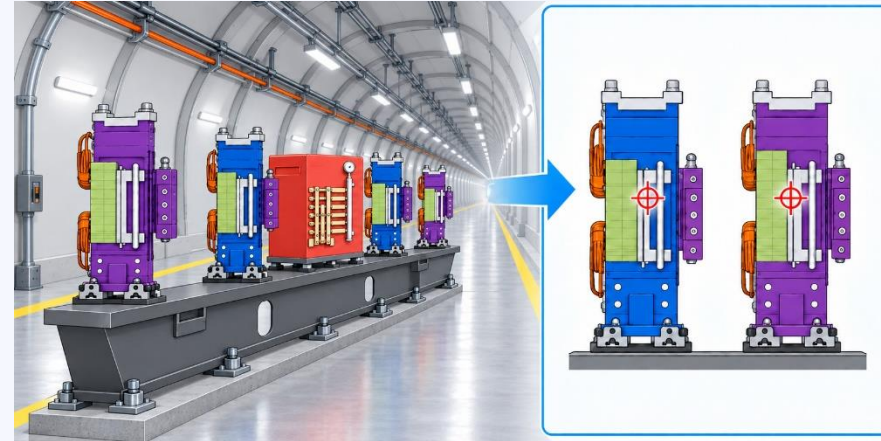
04 Two-face study



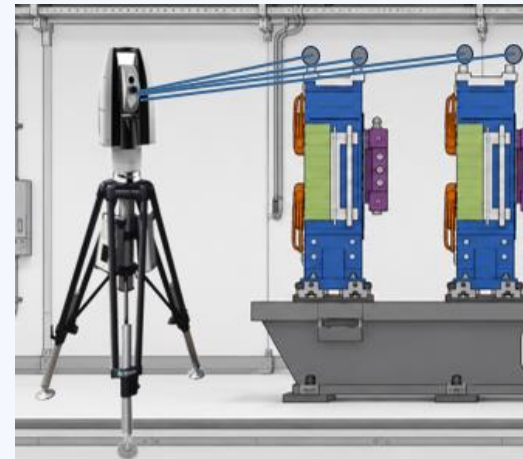
05 Decision support



- Accelerator magnets must be aligned through their magnetic centers.

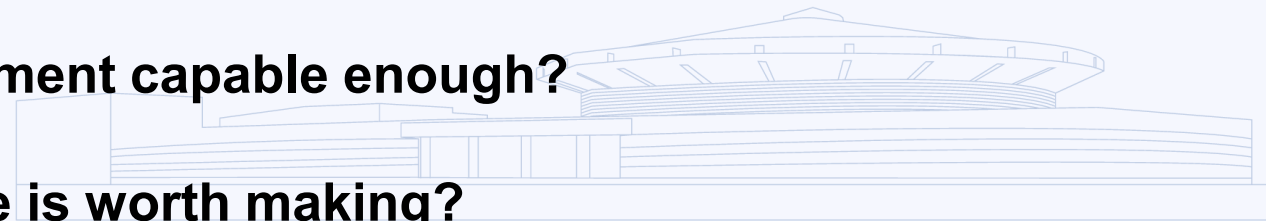


- A laser tracker measures external fiducials.



Is the planned measurement capable enough?

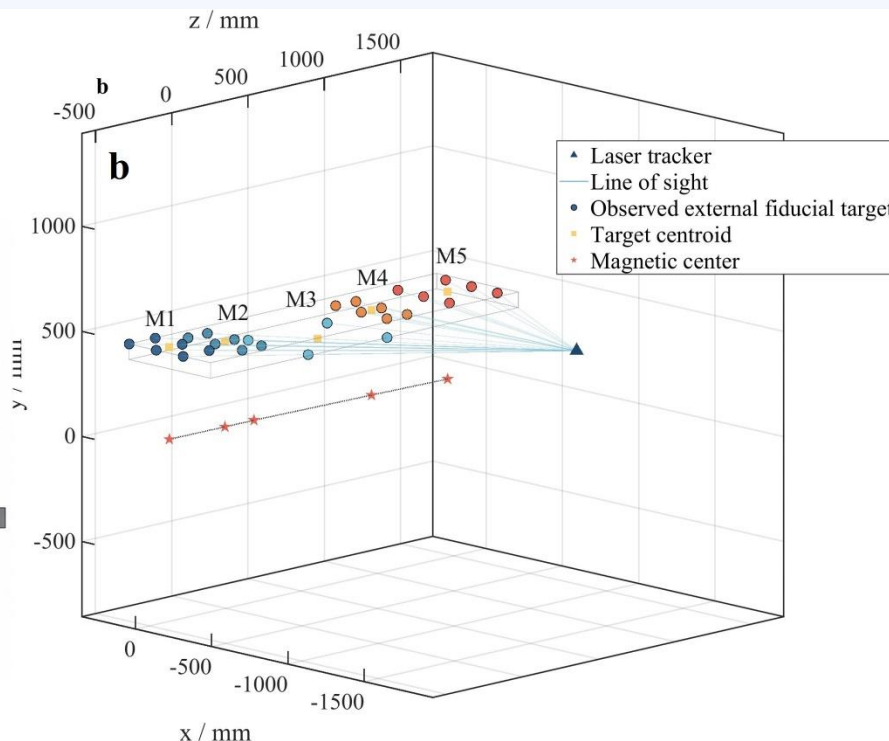
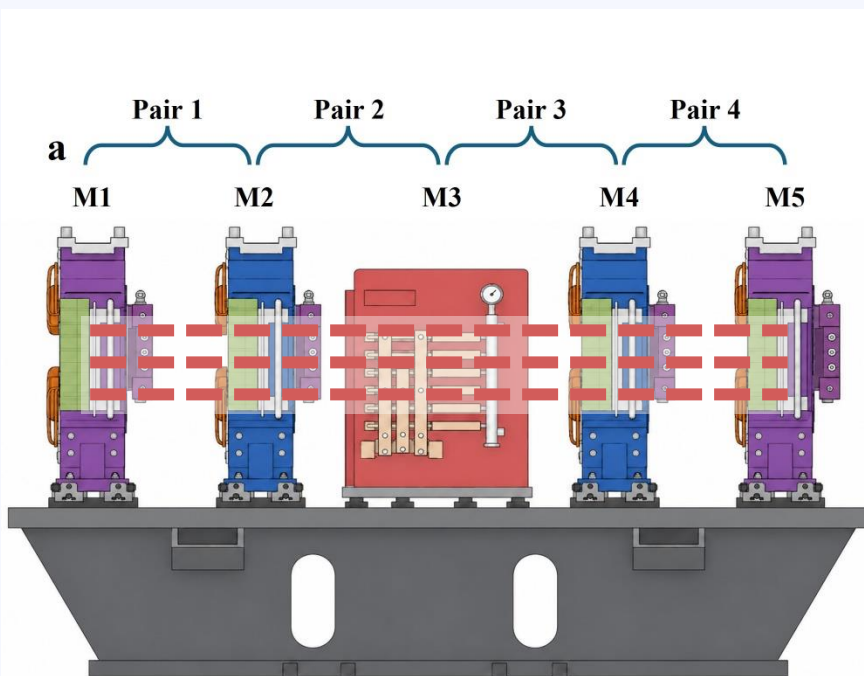
If not, which change is worth making?



The engineering task is to control the transverse relative alignment of adjacent magnetic centers.

Task definition

- Five magnets form four adjacent magnet pairs.
- Each pair contributes one horizontal and one vertical relative-position measurand.
- The case study therefore contains eight transverse relative-position measurands.



Alignment requirement

- Each transverse measurand has a tolerance interval of $[-30, +30] \mu\text{m}$.
- The corresponding tolerance width used for capability evaluation is $T = 60 \mu\text{m}$.

References: JCGM 106:2012;

From Observation to Task

Tracker measurements → Fiducial coordinates → Rigid-body pose estimation →
Magnetic-center positions → Final measurands

Step1

$$u_{task} = \sqrt{u_{local}^2 + u_{fid}^2 + u_{orientation}^2}$$

- u_{local} Tracker measurements propagated through the station-to-target geometry
- u_{fid} Uncertainty in the calibrated relation between external fiducials and the magnetic centre
- $u_{orientation}$ Uncertainty introduced by work-frame orientation

References: JCGM 100:2008 (GUM); JCGM 106:2012.

Step 2

Obtain an approximate 95% interval width

$$U_{95}^{proxy} = k u_{task}, k \approx 2$$

Approximate 95% half-width: U_{95}^{proxy}

Full interval width: W_{95}^{proxy}

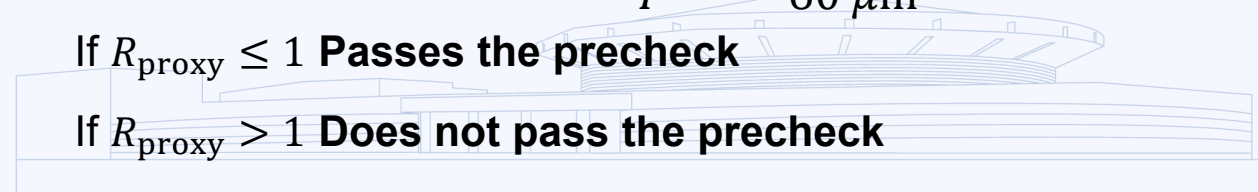
$$W_{95}^{proxy} = 2U_{95}^{proxy} \approx 4u_{task}$$

Under a normal approximation, $k \approx 2$ gives an approximately 95% interval.

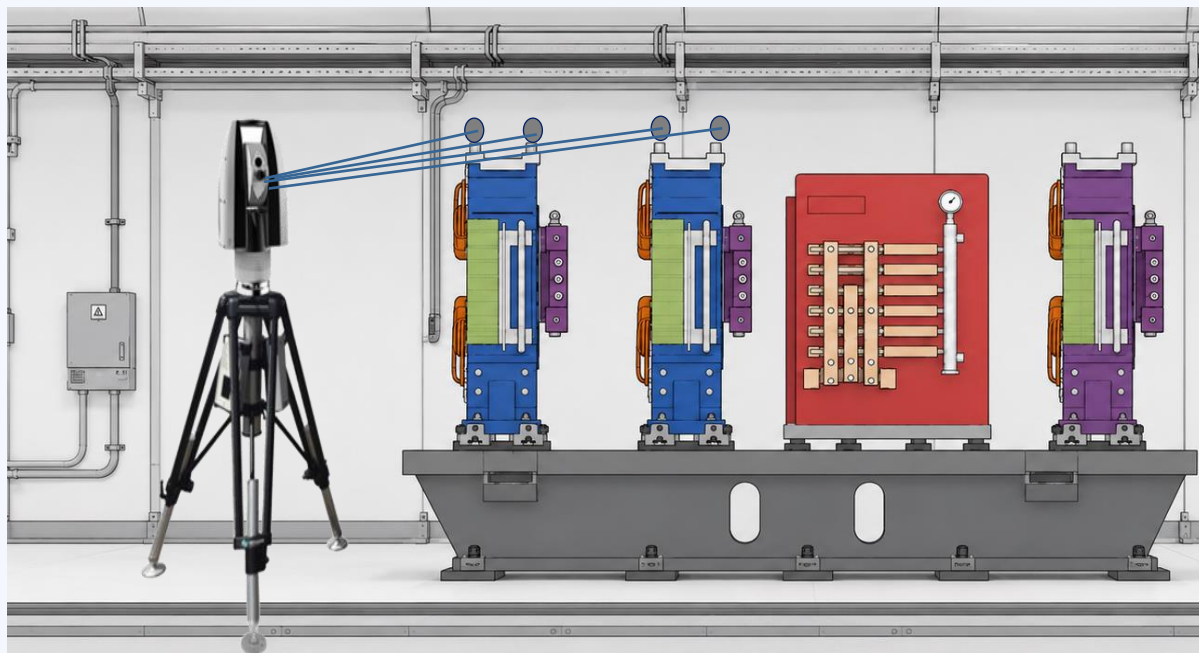
$$R_{proxy} = \frac{W_{95}^{proxy}}{T} = \frac{4u_{task}}{60 \mu m}$$

If $R_{proxy} \leq 1$ **Passes the precheck**

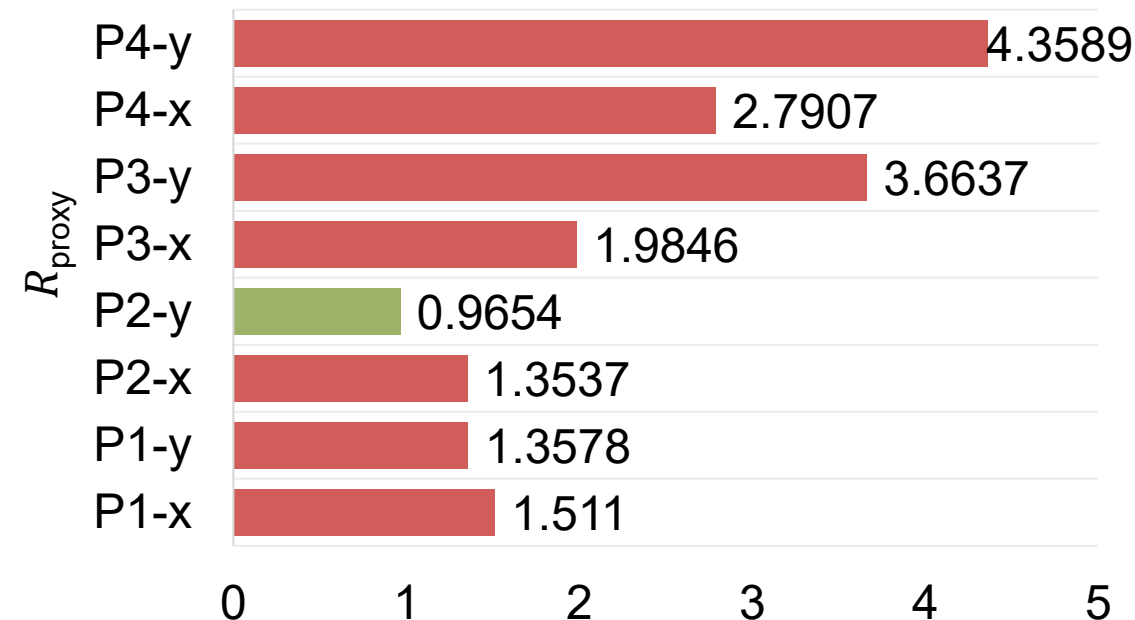
If $R_{proxy} > 1$ **Does not pass the precheck**



Single-station measurement schematic



Task-Specific Capability Ratio (R_{proxy})



- Real single-station measurements provide an empirical check of the station-dependent uncertainty model.
- For the current station, only one of the eight measurands passes the capability precheck. This result motivates the evaluation of practical measurement interventions.

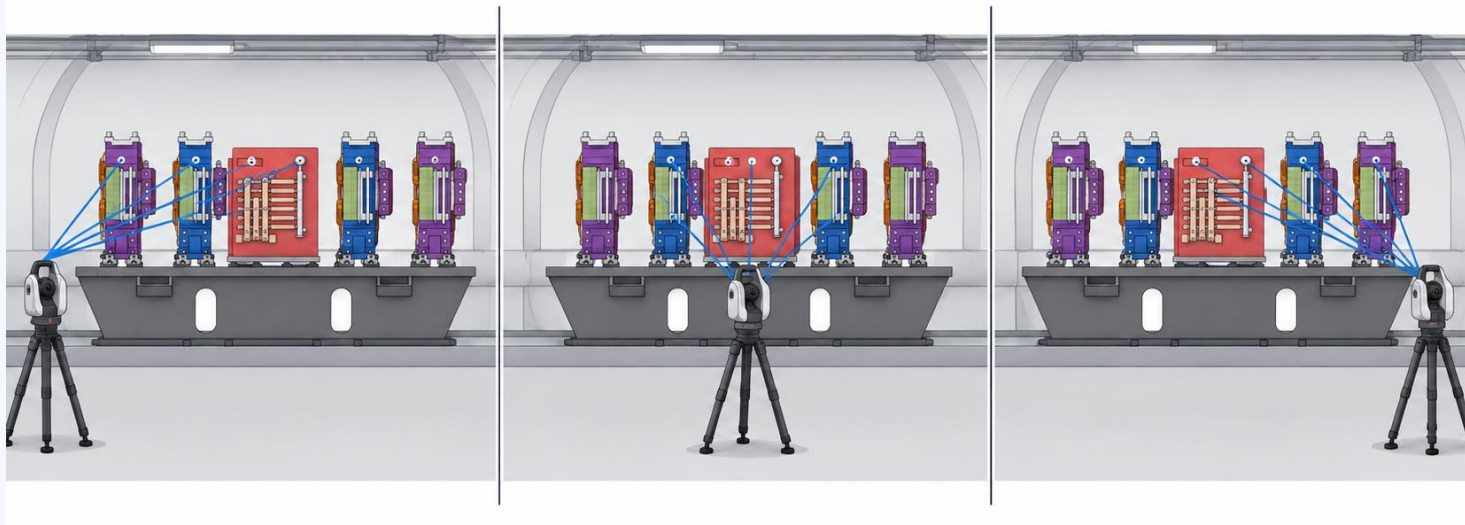
Station relocation Changes the station-to-target geometry

Two-face measurement Changes the measurement procedure

Intervention 1: Single-station relocation



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- Research question
Can a feasible change in tracker position improve the capability of the final relative magnetic-center measurands?

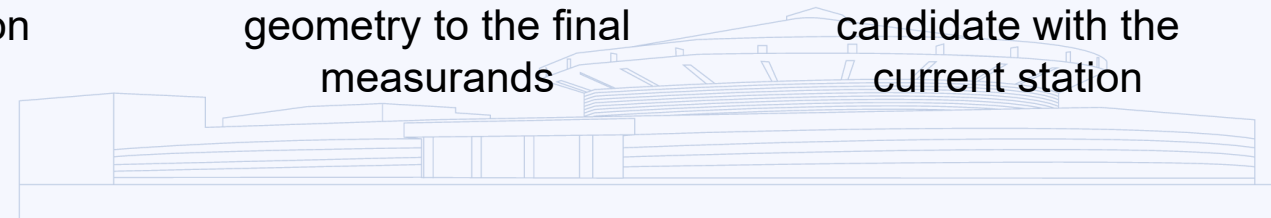
01 Measured data — 02 Candidate stations — 03 Propagation — 04 Comparison

Check the station-dependent model using real single-station measurements

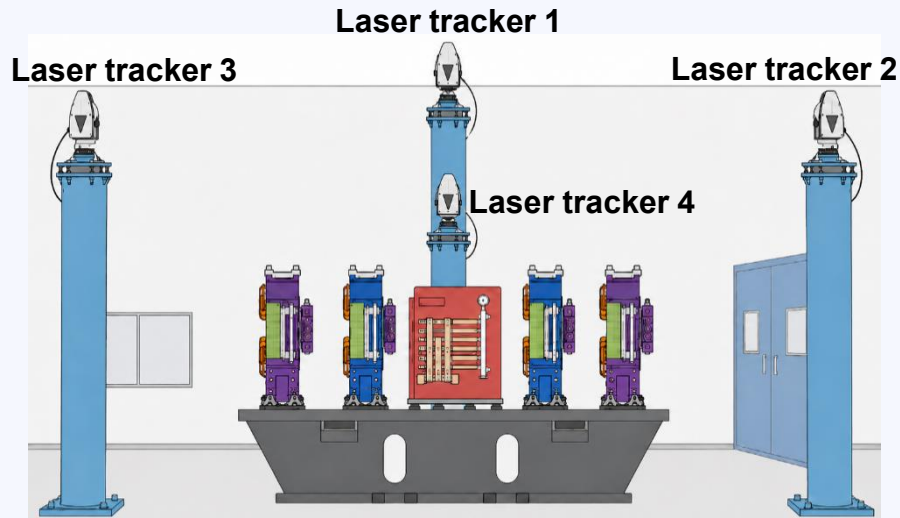
Define the current, upstream and downstream station positions

Propagate each station geometry to the final measurands

Compare each candidate with the current station



Measured datasets



- Four real single-station data sets S1–S4
- Six pairs × eight measurands = 48 comparisons

Observed difference between stations a and b

Predicted standard uncertainty of that difference

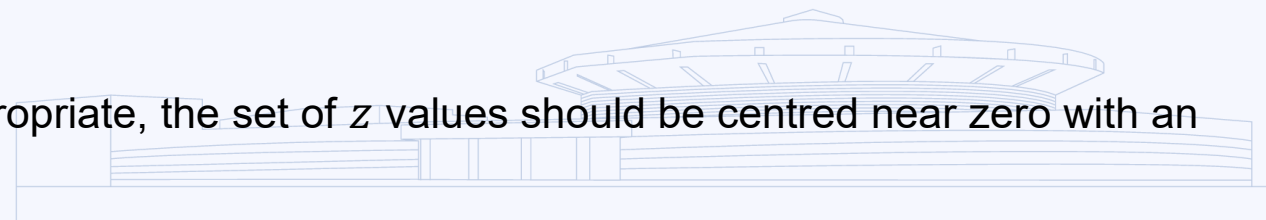
$$z = \frac{\Delta r_{obs}}{\sqrt{u_a^2 + u_b^2}}$$

If the predicted uncertainty scale is appropriate, the set of z values should be centred near zero with an RMS close to one.

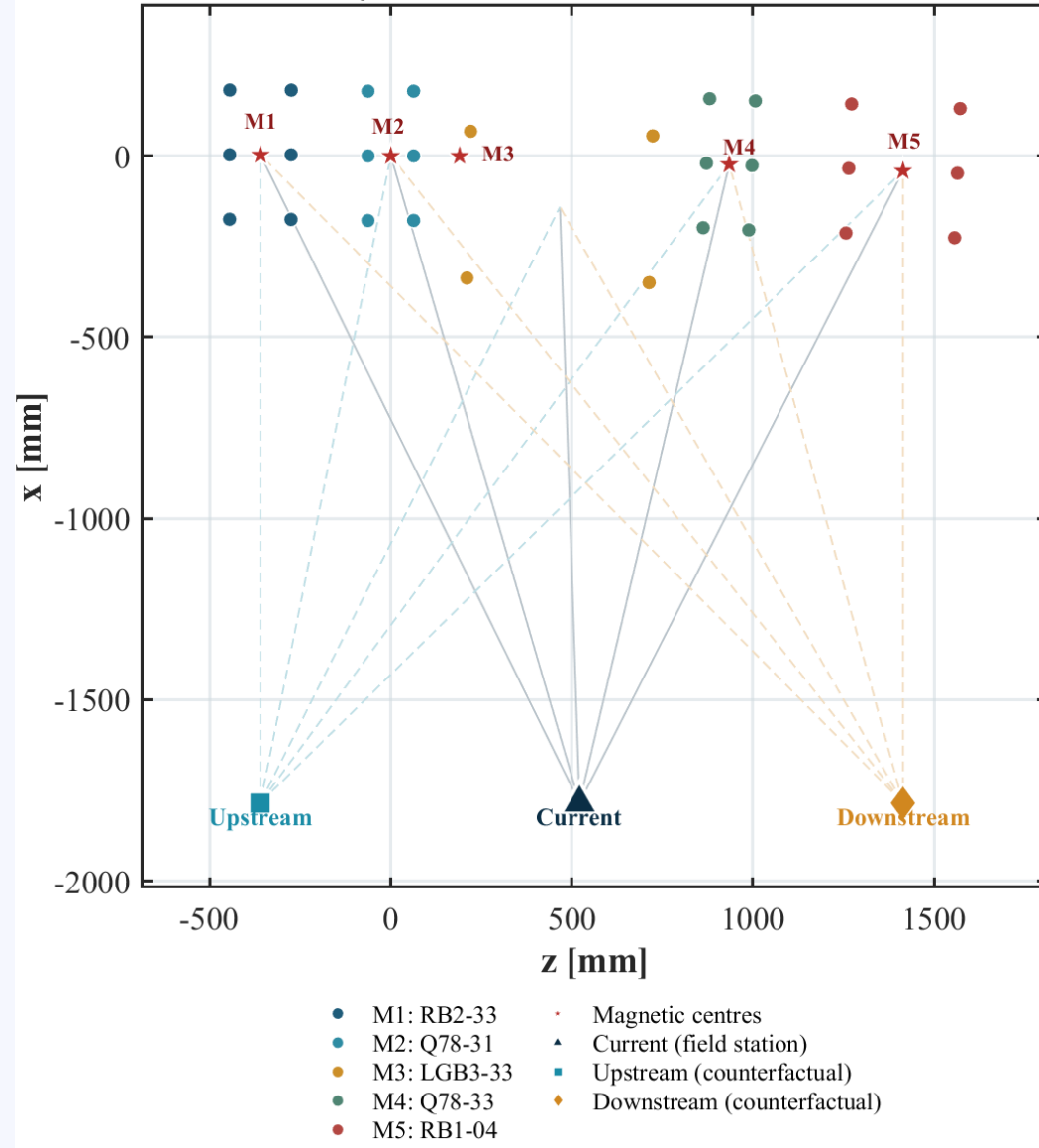
Result

- $z_{RMS} = 0.91$
- 46/48 comparisons satisfy $|z| \leq 2$

The measured station-to-station variation agrees with the uncertainty scale predicted by the model.



GD04 layout and station-relocation scenarios



1. Calculate the observation geometry

Station and fiducial coordinates $\rightarrow (\rho, h, \zeta)$

- ρ : slope distance
- h : horizontal angle
- ζ : zenith angle

2. Assign observation uncertainty

$$u(\rho) = 7.62 + 2.5\rho [\mu\text{m}], \rho \text{ in m}$$

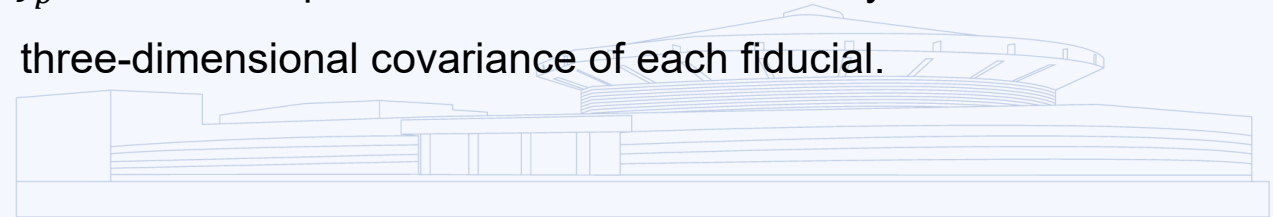
$$u(h)=u(\zeta)=1''$$

3. Propagate to fiducial coordinates

$$\Sigma_{\text{obs}} = \text{diag}[u^2, (\rho), u^2(h)u^2(\zeta)]$$

$$\Sigma_p = J_p \Sigma_{\text{obs}} J_p^T$$

J_p transforms spherical-coordinate uncertainty into the three-dimensional covariance of each fiducial.



Best case: Upstream station, P1-y

Station-dependent uncertainty

$$u_{\text{local}}: 17.42 \rightarrow 15.78 \mu\text{m}$$

9.4% reduction

Capability ratio

$$R_{\text{proxy}}: 1.358 \rightarrow 1.266$$

6.8% reduction, but the measurand remains above the threshold

Other uncertainty contributions reduce the effect of the local geometrical improvement on the final capability ratio.

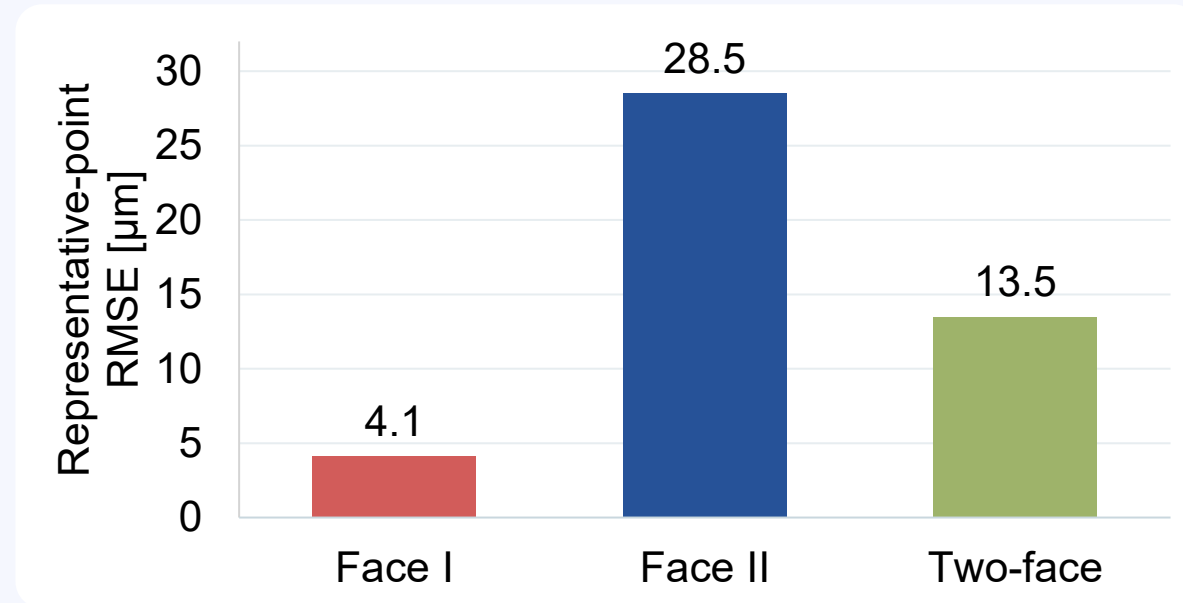
Candidate	Improved	Degraded	Best change	Largest deterioration
Upstream	2/8	6/8	P1-y: +6.8%	P4-y: -22.3%
Downstream	2/8	6/8	P4-x: +2.8%	P1-y: -19.7%

- No previously failing measurand is brought below $R_{\text{proxy}} = 1$.
- The Downstream candidate causes P2-y to move above the threshold.

Station relocation improves selected measurands, but neither candidate improves the capability of the measurement set as a whole.

This limited overall benefit motivates the evaluation of two-face measurement.

Motivation from an independent reference experiment



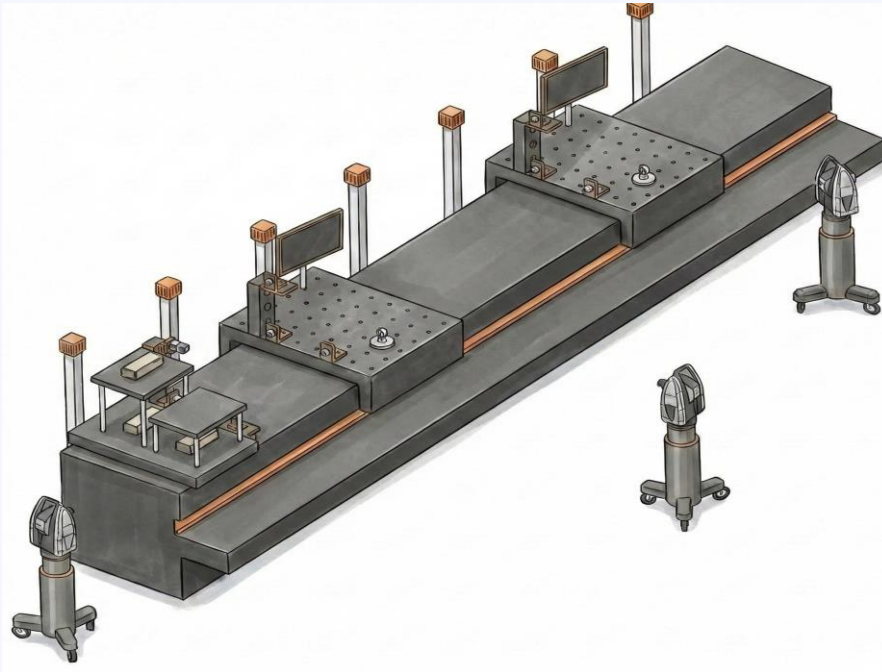
$$p_{\text{two-face}} = \frac{1}{2} [p_{\text{Face I}} + p_{\text{Face II}}]$$

The two-face result reduced the effect of an unfavourable face, although it did not outperform the better face.

Reference Y. Lin et al., *Measurement* 291 (2026) 123080.

Can two-face measurement reduce face sensitivity in the final magnetic-centre measurands?

Schematic of the Measurement Setup

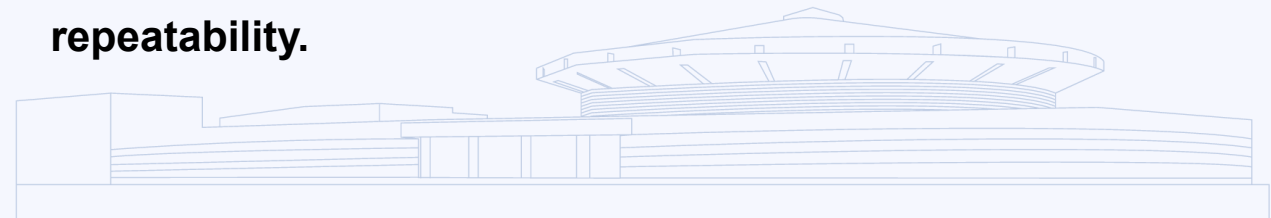


Three stations measured targets along an interferometer-referenced rail. Each setup was repeatedly measured in both Face I and Face II.

- 49 unique station-to-target configurations
- 10 paired repetitions per configuration
- 490 Face I/Face II pairs (980 individual observations)

Observation	Within-face repeatability	Face difference SD	Ratio
Distance	2.49 μ m	11.15 μ m	4.48
Horizontal angle	0.37"	1.21"	3.31
Zenith angle	0.39"	1.26"	3.22

Changing the tracker face introduces a measurable component that is substantially larger than ordinary repeatability.



Measured Face I/Face II differences provide empirical inputs for the magnet-specific measurement model.

Empirical face input

$$\mathbf{f}_g = \frac{1}{2} \begin{bmatrix} \Delta\rho_g \\ \Delta h_g \\ \Delta\zeta_g \end{bmatrix}$$

- Half of the paired difference represents the face-dependent deviation from the Face I/Face II midpoint.
- Distance and angular components are sampled together to preserve their measured relationship.

Empirical face input → 28 fiducial observations → Fiducial coordinates → Magnet pose estimation → Magnetic centers → Relative magnetic-centre measurands



$$Q_{0.95}(|\delta r_q|)$$

The 95th percentile of the absolute face-sensitive shift for each final measurand.

The reference experiment supplies measured face-sensitive inputs, while the magnet-specific model determines their effects on the final measurands.

➤ Result

Measurand	P1-x	P1-y	P2-x	P2-y	P3-x	P3-y	P4-x	P4-y
Face-sensitive shift P95 (μm)	27.3	29.0	26.3	16.9	49.7	90.4	68.3	109.0

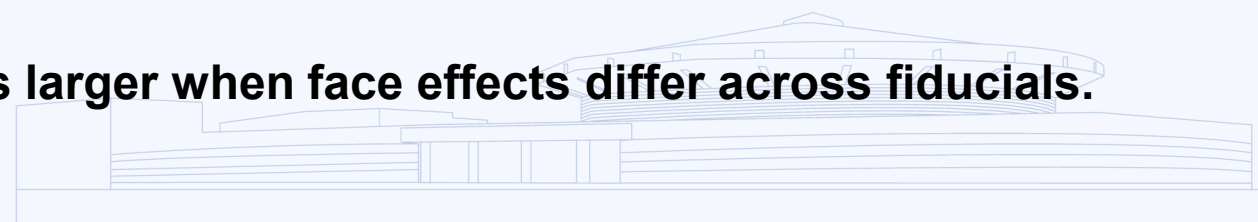
Under separate sampling across fiducials, P3-y, P4-x and P4-y show the largest face-sensitive shifts.

➤ Take P4-y as a representative example

Assumption	How the effect is shared	P4-y shift P95
Separate effects	Each fiducial receives a separately sampled effect	109.0 μm
Shared within each magnet	All fiducials on one magnet share the same effect	17.8 μm
Shared across the network	All 28 fiducials share the same effect	2.1 μm

- Different effects across fiducials change their relative geometry and can affect the estimated magnet poses.
- Shared effects cause less relative distortion and therefore cancel more strongly in the final relative positions.

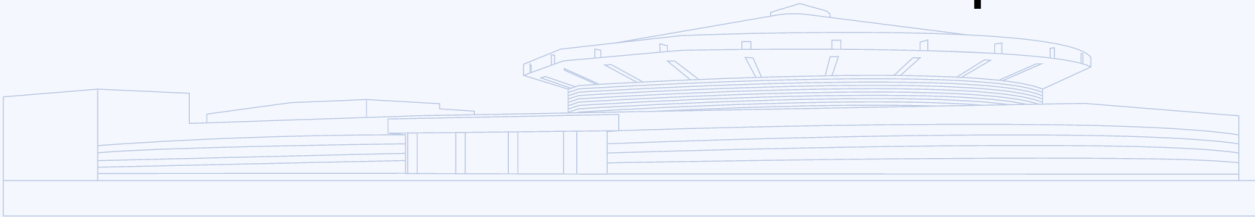
The potential benefit of two-face averaging is larger when face effects differ across fiducials.



The two interventions differ in predicted task-level benefit and supporting evidence.

	Relocate the single station	Use two-face observations
What changes	Tracker position, target ranges and lines of sight	Face I and Face II acquisition followed by coordinate averaging
Evidence available	Four measured single-station datasets support the station-dependent uncertainty scale	Paired Face I/Face II measurements demonstrate measurable face sensitivity
Result for this case	Only 2 of 8 measurands improve for each candidate station, while 6 degrade	Some final measurands show strong sensitivity to differences between Face I and Face II
Representative result	Best case: R_{proxy} decreases from 1.3578 to 1.2660, but remains above 1	P4-y shift P95 ranges from 2.1 to 109.0 μm across the tested sharing patterns
What remains to be verified	Candidate stations have not been tested in the field	The way face effects vary across the complete fiducial network has not been measured
Current assessment	Limited overall benefit from further longitudinal relocation	Stronger candidate for a targeted field experiment

Virtual measurement helps rank engineering actions before additional field measurements are performed.



The present study evaluates station relocation and two-face observation.

The same framework can support a broader range of measurement actions

LLM-assisted interface

Engineer

Measurement goal and field constraints



LLM-assisted interface

Interpret the request and select verified tools



Virtual metrology tools

Uncertainty propagation and intervention simulation



Decision support

Expected effect, trade-offs and supporting evidence

Additional actions to be evaluated

- Add or reposition fiducials
- Combine observations from multiple stations
- Adjust the number of repetitions ...





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THANKS!

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