Towards an Expression of Uncertainty in Accelerator Alignment

IWAA2024 SLAC

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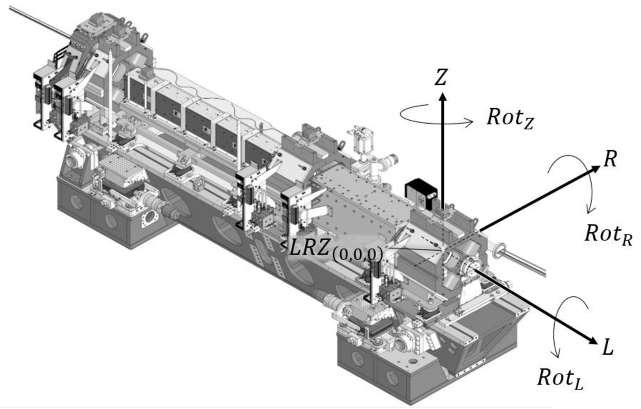
THE PROBLEM – HOW TO KNOW IF TOLERANCES ARE RESPECTED

When we are asked to align something in an accelerator, on a beamline or in a detector, there is always a desired tolerance associated with the alignment. Typically, this tolerance describes how precisely the object, such as a quadrupole magnet should be aligned with respect to another object, for example, the adjacent quadrupole magnet.

ESRF EBS alignment tolerances

Machine	U(L) [µm]	U(R) [µm]	U(Z) [µm]
Long. Varying field dipoles	1000	>100	>100
High gradient quadrupoles, Combined function dipoles	500	60	60
Medium gradient quads	500	100	85
Sextupoles	500	70	50
Octupoles	500	100	100



Maximum permissible error 2.5σ

The problem is, how do we know, or how can we determine if the desired tolerances are respected?

For that matter are we sure what these tolerances even mean?

COMMUNICATION

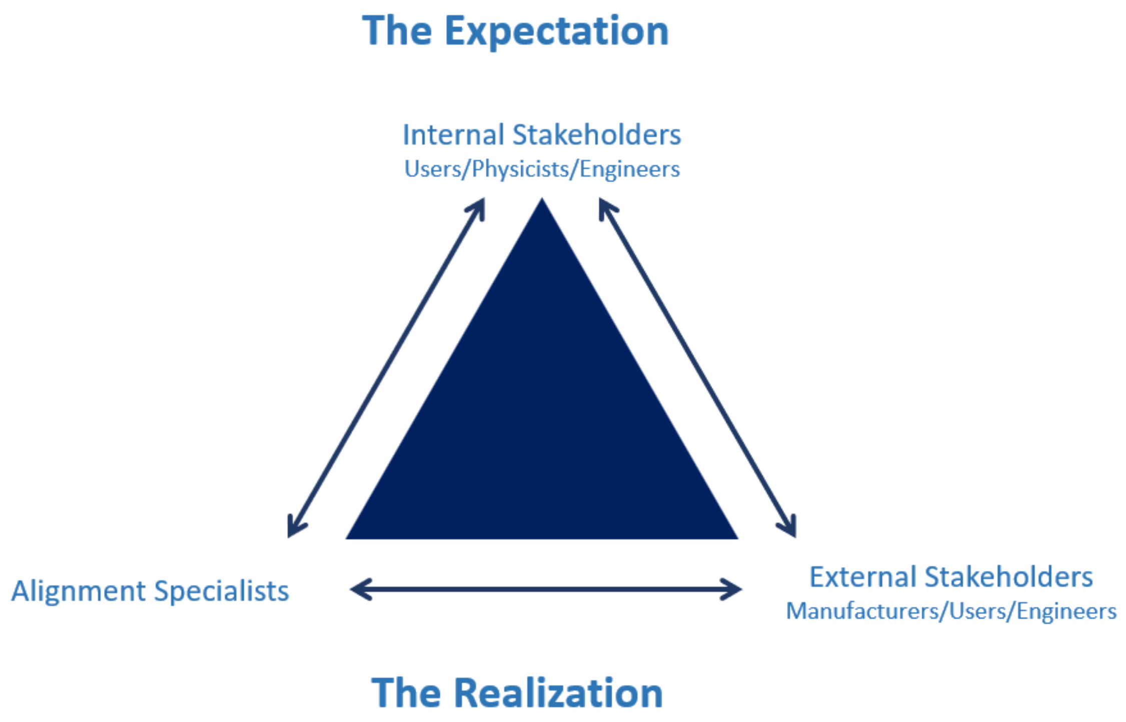
A few years ago I was in Helsinki and walked into a store …

It is very easy to mis-communicate and misunderstand what tolerances mean

COMMUNICATION

There are three problems:

1. What do the tolerances mean?
2. Can you achieve the tolerances?
3. How do you determine if the tolerances have been met?



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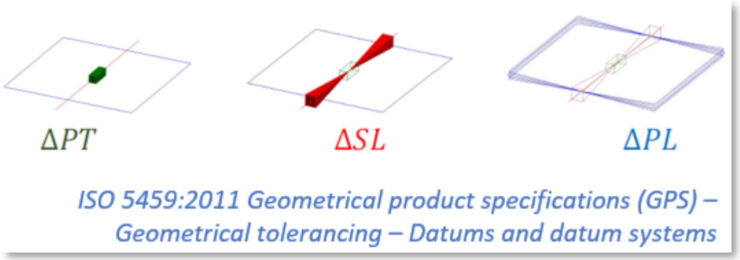
TOLERANCES

Three problems:

1. What do the tolerances mean?
2. Can you achieve the tolerances?
3. How do you determine if the tolerances have been met?

As an aside - a good reference and place to start a discussion about how to define tolerances is Bertrand and Fabien's IWAA 2022 presentation and subsequent paper.



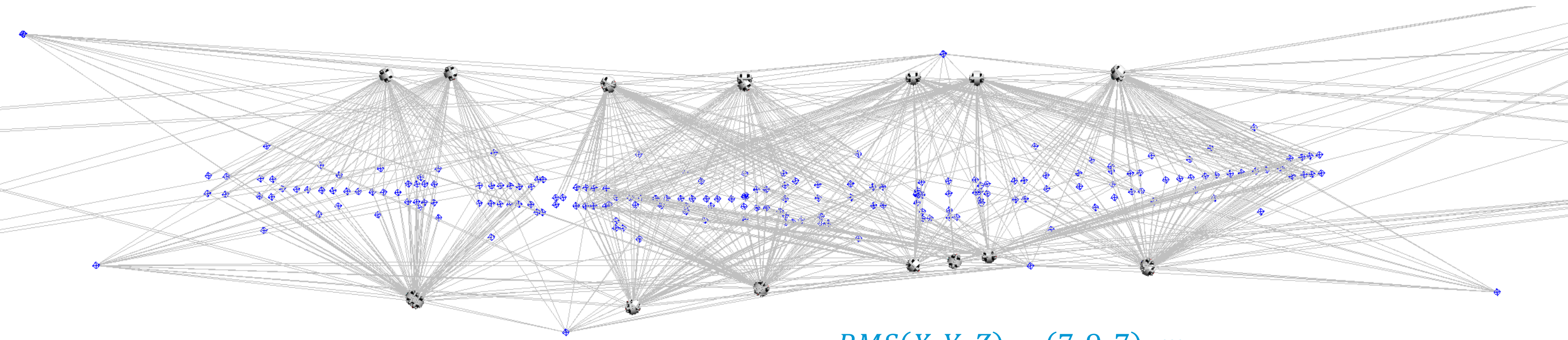
Nicquevert B, Rey. F. (2022). *From Engineering to Alignment - How functional geometrical requirements on equipment are handled and transferred into installation drawings*. Geneva: International Workshop on Accelerator Alignment.

Nicquevert B, Rey. F. (2024). *Handling the Functional Features of Accelerator Components Using ISO GPS Situation Features*. J. Phys.: Conf. Ser. 2687 072028.

Now how do we determine if the tolerances have been met …

ALIGNMENT PRECISION AND UNCERTAINTY

From time to time we see something like the following:

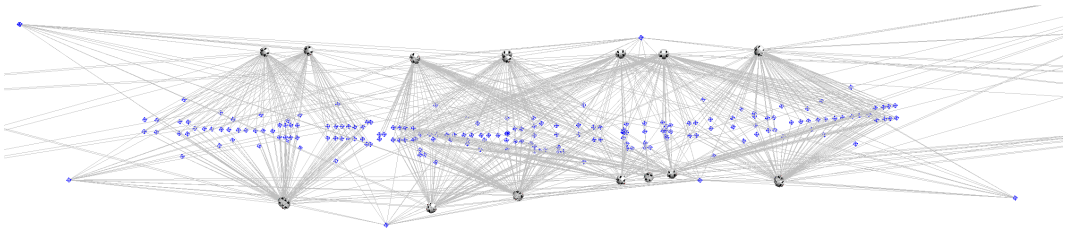


$RMS(X, Y, Z) = (7, 9, 7)\mu m$

The implication being the uncertainty in the alignment is: $X = 7\mu m$; $Y = 9\mu m$ $Z = 7\mu m$

If we were measuring a pile of rocks it might be correct, but saying magnets are aligned to $RMS(X, Y, Z) = (7, 9, 7)\mu m$ is incorrect and misleading …

ALIGNMENT PRECISION AND UNCERTAINTY

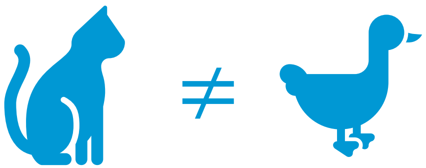


$$RMS(X, Y, Z) = (7, 9, 7)\mu m$$

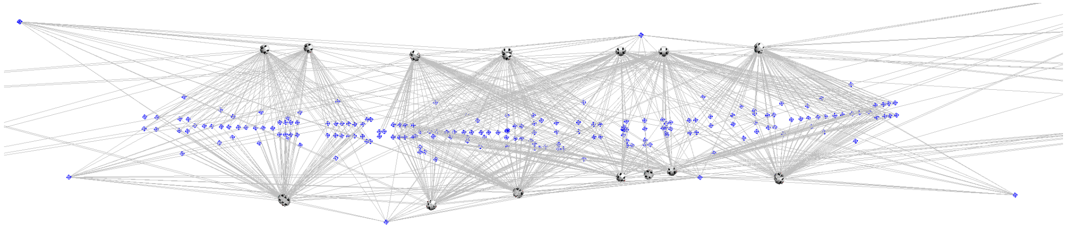
The danger is that decision makers and stakeholders see this type of statement and say:

> *They can align to better than 10 μm in x, y and z at the pile of rocks accelerator, that is what we need for our new spiffy extra brilliant synchrotron radiation source …*

But a simple survey or measurement is not a statement of the uncertainty in the alignment of the accelerator magnets.



ALIGNMENT PRECISION AND UNCERTAINTY

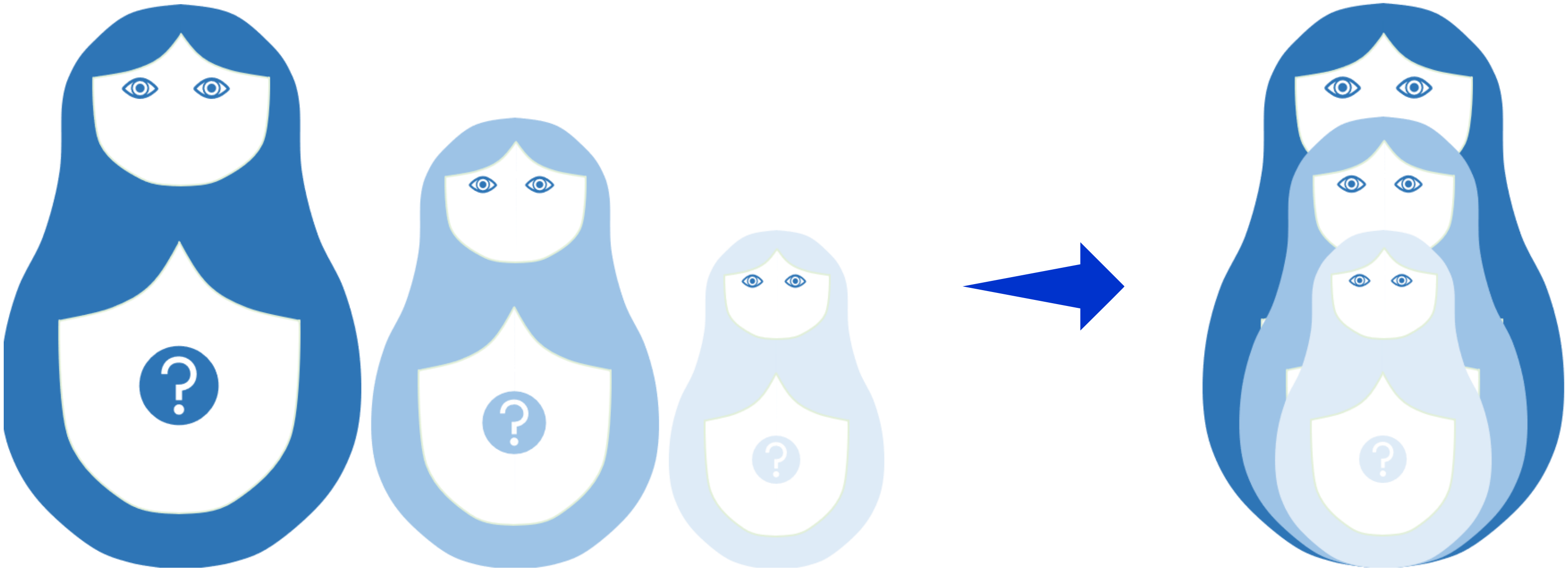


$$RMS(X,Y,Z) = (7,9,7)\mu m$$

There are many error sources in accelerator alignment that a statement of uncertainty should include:

- The fiducialisation of the magnet;
- The preparation of the girder and its reference frame;
- The opening and closing of the magnet, sometimes several times;
- The installation of the magnet on the girder;
- The rectitude of the girder;
- Transport of the girder;
- The effect of bakeout of the vacuum chamber assemblies installed in the magnet;
- The uncertainty of the tunnel reference network used to position the magnet and the girder;
- Instrument errors;
- etc…

A STATEMENT OF UNCERTAINTY



A statement of uncertainty in measurement quantifies the doubt or range of possible values within which the true value of a measured quantity is expected to lie. It communicates the degree of confidence in the accuracy and precision of a measurement by specifying the possible error or variability. It includes all known sources of error and combines them together in a rigorous and well defined way.

In essence, a statement of uncertainty in measurement defines the possible range within which the actual value may lie, allowing for informed decision-making based on the data.

UNCERTAINTY – THE RULES PLAYBOOK

Take a step back and fill in some background.

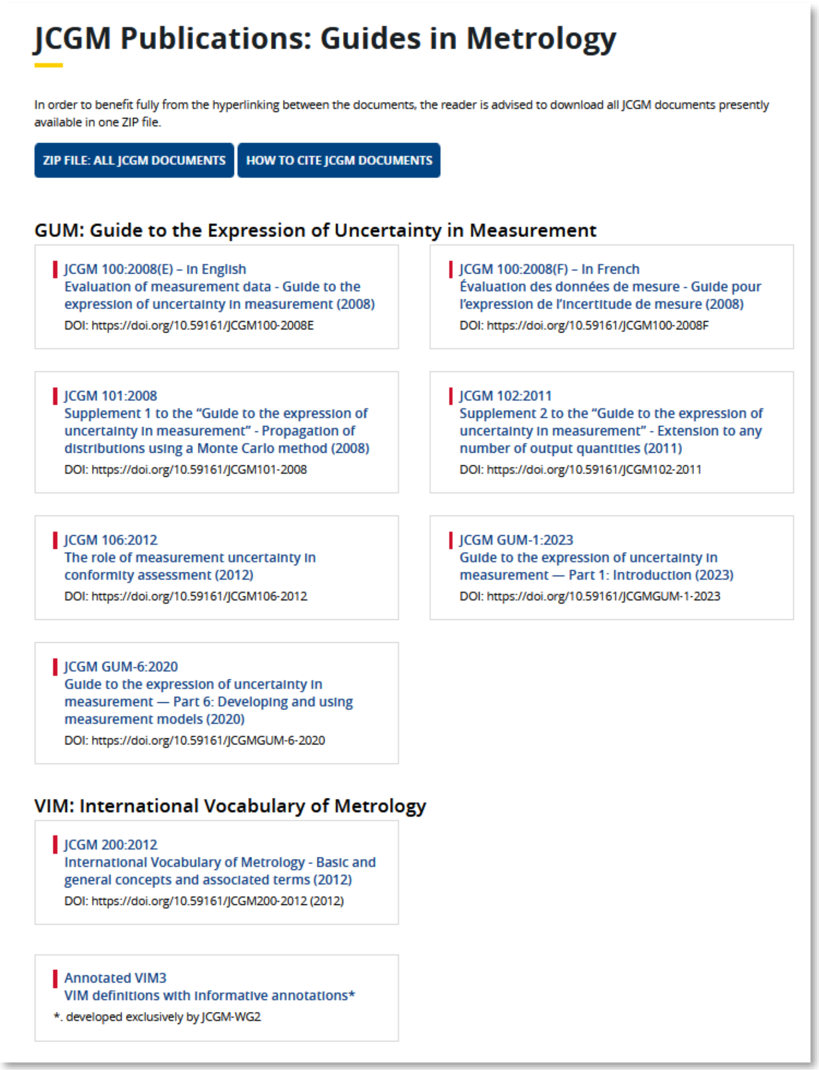
The references for the expression of uncertainty in measurement are the JCGM Publications Guides in Metrology

However, these guides are not light reading for the uninitiated…

Measurement uncertainty is a non-negative parameter characterizing the parameter that characterises the dispersion of the **quantity values**† being attributed to a **measurand**‡ being measured, based on the information used.

*† The **quantity values** refer to what is being measured, for example the distance between two points*
*‡ The **measurand** is the quantity e.g. distance intended to be measured.*

This is not word salad



JCGM Publications: Guides in Metrology

In order to benefit fully from the hyperlinking between the documents, the reader is advised to download all JCGM documents presently available in one ZIP file.

ZIP FILE: ALL JCGM DOCUMENTS | HOW TO CITE JCGM DOCUMENTS

GUM: Guide to the Expression of Uncertainty in Measurement

JCGM 100:2008(E) – In English
Evaluation of measurement data - Guide to the expression of uncertainty in measurement (2008)
DOI: https://doi.org/10.59161/JCGM100-2008E

JCGM 100:2008(F) – In French
Évaluation des données de mesure - Guide pour l'expression de l'incertitude de mesure (2008)
DOI: https://doi.org/10.59161/JCGM100-2008F

JCGM 101:2008
Supplement 1 to the "Guide to the expression of uncertainty in measurement" - Propagation of distributions using a Monte Carlo method (2008)
DOI: https://doi.org/10.59161/JCGM101-2008

JCGM 102:2011
Supplement 2 to the "Guide to the expression of uncertainty in measurement" - Extension to any number of output quantities (2011)
DOI: https://doi.org/10.59161/JCGM102-2011

JCGM 106:2012
The role of measurement uncertainty in conformity assessment (2012)
DOI: https://doi.org/10.59161/JCGM106-2012

JCGM GUM-1:2023
Guide to the expression of uncertainty in measurement — Part 1: Introduction (2023)
DOI: https://doi.org/10.59161/JCGMGUM-1-2023

JCGM GUM-6:2020
Guide to the expression of uncertainty in measurement — Part 6: Developing and using measurement models (2020)
DOI: https://doi.org/10.59161/JCGMGUM-6-2020

VIM: International Vocabulary of Metrology

JCGM 200:2012
International Vocabulary of Metrology - Basic and general concepts and associated terms (2012)
DOI: https://doi.org/10.59161/JCGM200-2012 (2012)

Annotated VIM3
VIM definitions with informative annotations*
*. developed exclusively by JCGM-WG2

https://www.bipm.org/en/committees/jc/jcgm/publications

UNCERTAINTY SIMPLE EXAMPLE

Start with a simple example …

Say we measure a distance 5 times with a TDA5000 with the following values:

12499.933, 12500.152, 12500.036, 12499.997, and 12500.036

The mean value is the best estimate of the distance, and the standard deviation represents the measurement uncertainty.

An expression of uncertainty has four elements:

- a value;
- a unit (e.g., mm);
- an uncertainty; and
- a coverage factor, designated as k.

$k = 1$ *means the uncertainty covers one standard deviation* (1σ),
$k = 2$ *means the uncertainty covers two standard deviations* (2σ).

So the best estimate of the distance is: $12500.031\ mm \pm 0.080\ mm;\ k = 1$

TYPE *A* AND TYPE *B* UNCERTAINTIES

Type A Uncertainty
measurement series 1
measurement series 2
⋮
measurement series n

Type B Uncertainty
previous measurement data
experience
manufacturer's specifications
calibration certificates
handbooks

measurement uncertainty
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

$$U = \sqrt{Type\ A^2 + Type\ B^2}$$

Type A
12499.933
12500.152
12500.036
12499.997
12500.036
…

There are Type B contributions to the uncertainty of these measured distances.
For example:

- The manufacturer’s quoted instrument precision
- Temperature, pressure and humidity conditions at the time of measurement
- The stability of the instrument and reflector supports over the time the measurement was taken
- etc.

A MORE DEVELOPED EXAMPLE OF A STATEMENT OF UNCERTAINTY

B_{d1}: the manufacturer's instrument precision for the TDA5005 is 1 mm + 2 ppm at 1σ over the full measurement range. The uncertainty of a measurement of 12500.052 mm is:

$$1 + 2 \times 12500.052 \,/\, 10^6 = 1 + 0.025 = 1.025\ mm$$

B_{d2}: The stability of 0.010 mm between the instrument and reflector supports is derived from operator experience.

B_{d3}: we use the following formula that is derived from the Barrel-Sears formula and provided by the manufacturer Leica:

$$C = 281.8 - \left[\frac{0.29065P}{1 + \frac{T}{273.16}} - \frac{4.126 \times 10^4 H}{1 + \frac{T}{273.16}} \times 10^{\frac{7.5\,T}{237.3+T}+0.7857}\right]$$

Which gives us the following coefficients:

$$dc/dp = 0.2708;\ dc/dt = 0.9390;\ dc/dh = 0.0090$$

with uncertainties of 1 hPa for pressure, 0.5 °C for temperature and 10% for the humidity giving:

$$U(C) = \sqrt{(0.2708 \times 1)^2 + (0.9390 \times 0.5)^2 + (0.0090 \times 10)^2}$$
$$= 0.55 \times 10^{-6} D_{dist}$$

So, for the distance 12500.052 mm the uncertainty due to temperature, pressure and humidity conditions is:

$$12500.052 \times 0.55^{-6} 0.55 = 0.007\ mm$$

Ref	***Quantity***	***σ***
B_{d1}	Instrument manufacture's uncertainty	1.025 mm
B_{d2}	Uncertainty in the instrument and reflector support	0.010 mm
B_{d3}	Uncertainty in the correction of the distance due to temperature, pressure and humidity conditions: Δp = ± 1 hPa Δt = ± 0.5 °C Δh = ± 3 %	0.007 mm

Recall the Type A contributions is: $U(A) = 0.080$ mm

The combined uncertainty for the Type B contributions is: $U(B) = \sqrt{1.025^2 + 0.007^2 + 0.010^2} = 1.025$ mm

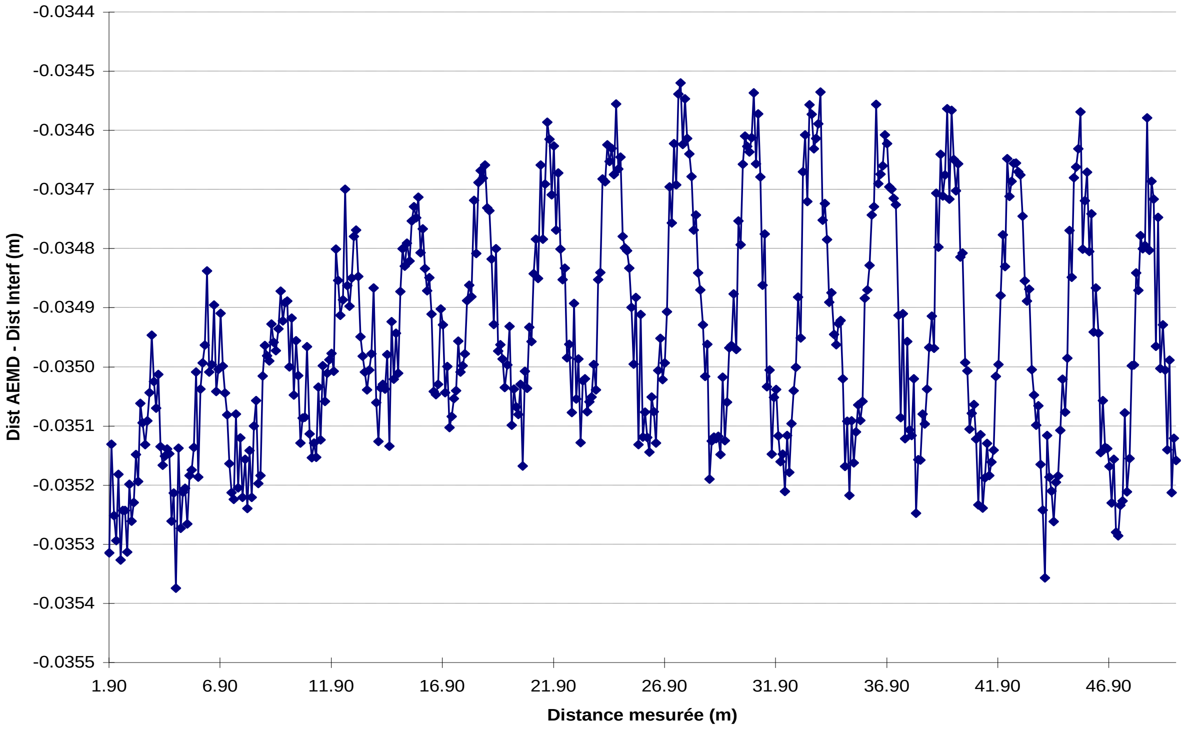
The combined Type A and Type B uncertainties is given by: $U(C) = \sqrt{0.080^2 + 1.025^2} = 1.069$ mm

A MORE DEVELOPED EXAMPLE OF A STATEMENT OF UNCERTAINTY

So we can say the distance that was measured is:

(12500.03 ± 1.07) mm at k=1; or,
(12500.03 ± 2.14) mm at k=2.

However, we know the TDA5000 has a cyclic error that can be calibrated and the measurements significantly improved



The calibration curve for TDA5005 serial number 438122 issued from calibration certificate 10102045DC-1 made on 3 February 2005 (Chaine Nationale d'Etalonnage BNM-COFRAC Métrologie Dimensionnelle Laboratoire D'Etalonnage Accrédité Accréditation N° 2-1508)

A MORE DEVELOPED EXAMPLE OF A STATEMENT OF UNCERTAINTY

Ref	*Quantity*	*σ*
B_{d1}	Instrument uncertainty	0.105 mm
B_{d2}	Uncertainty in the instrument and reflector support	0.010 mm
B_{d3}	Uncertainty in the correction of the distance due to temperature, pressure and humidity conditions: $\Delta p = \pm 1$ hPa $\Delta t = \pm 0.5$ °C $\Delta h = \pm 3$ %	0.007 mm

Recall the Type A contributions is: $U(A) = 0.080$ mm

The combined uncertainty for the Type B contributions is: $U(B) = \sqrt{0.105^2 + 0.007^2 + 0.010^2} = 0.106$ mm

The combined Type A and Type B uncertainties is given by: $U(C) = \sqrt{0.080^2 + 0.106^2} = 0.132$ mm

So we can say the distance that was measured is:

(12500.03 ± 0.13) mm at k=1; or,
(12500.03 ± 0.26) mm at k=2.

Compared to:

(12500.03 ± 1.07) mm at k=1; or,
(12500.03 ± 2.14) mm at k=2.

KEY TAKEAWAYS

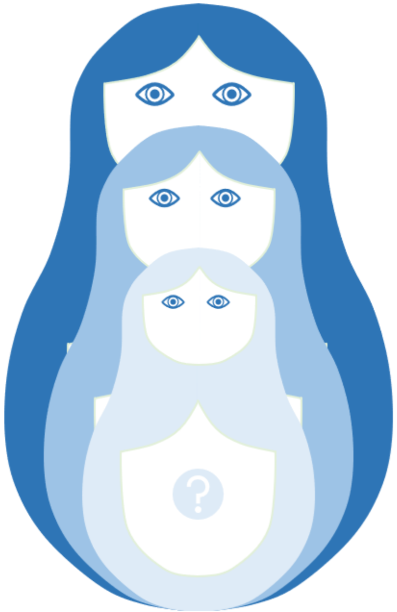
1. A statement of uncertainty must include all sources of error.
2. You can improve uncertainty with increased knowledge.
3. Large contributions to the statement of uncertainty make disproportionately large contributions to the overall statement of uncertainty.

$$U(B) = \sqrt{\boxed{0.105^2} + 0.007^2 + 0.010^2} = \boxed{0.106 \text{ mm}}$$

You might be tempted to not include the contributions from the instrument and reflector support stability (0.010 mm) or the temperature, pressure and humidity (0.007 mm), but these are well known error contributions and if they are not included it could lead to:
what about …, or *why didn't you include …* type questions.

HOW DO WE APPLY THIS CONCEPT TO ACCELERATOR ALIGNMENT?

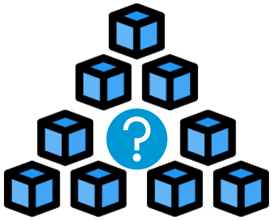
Recall, there are many error sources in accelerator alignment that a statement of uncertainty should include:



a) The fiducialisation of the magnet;
b) The preparation of the girder and its reference frame;
c) The opening and closing of the magnet, sometimes several times;
d) The installation of the magnet on the girder;
e) The rectitude of the girder;
f) Transport of the girder;
g) The effect of bakeout of the vacuum chamber assemblies installed in the magnet;
h) The uncertainty of the tunnel reference network used to position the magnet and the girder;
i) Instrument errors;
j) etc…

We can start by combining these different contributions…

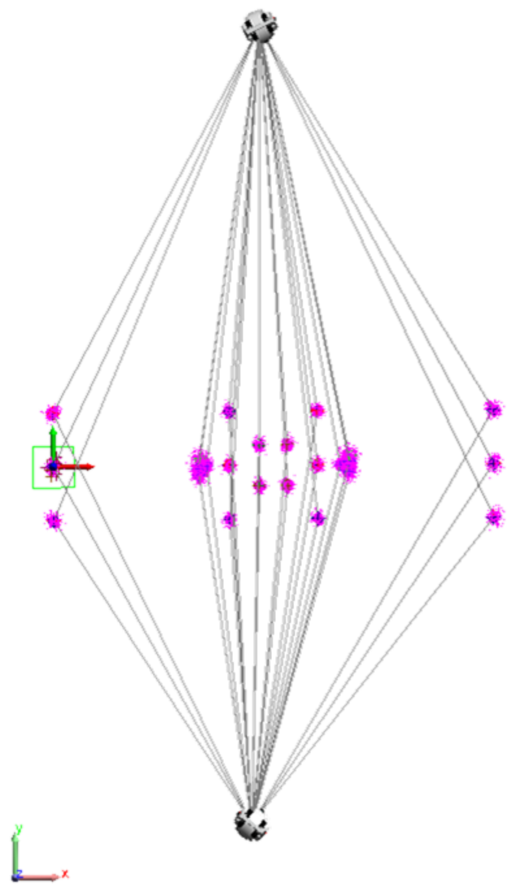
Important note in the following discussion, the coverage factor is k = 1, or 1 standard deviation i.e.1σ

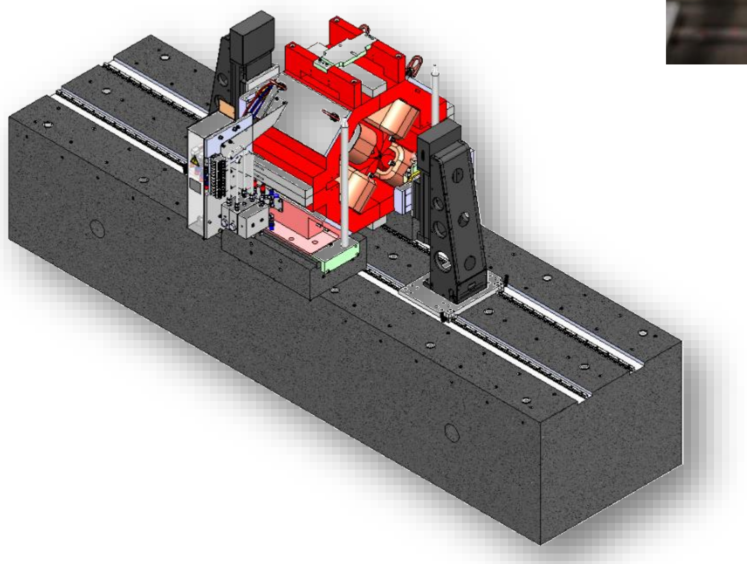


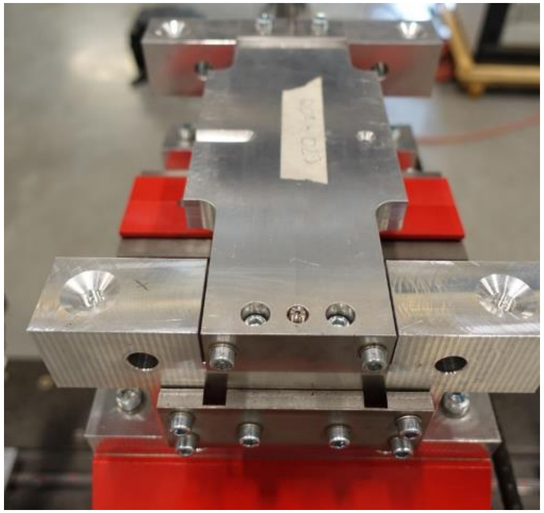
$$\rightarrow \quad \sqrt{a^2 + b^2 + c^2 + d^2 + \cdots}$$

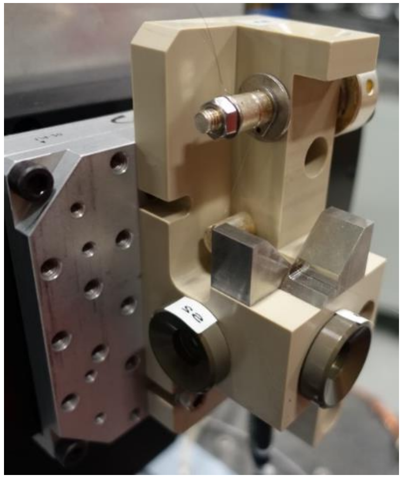
FIDUCIALISATION – AT THE ESRF

The magnet reference points were determined from two laser tracker stations.









MAGNET FIDUCIALISATION

Ref	Quantity	U(x) [µm]	U(y) [µm]	U(z) [µm]
$B_{fidBench1}$	Magnet measurements		4	4
$B_{fidBench2}$	Shim determination			29†
B_{fidLT1}	Wire block reference repeatability	5	5	5
B_{fidLT2}	Wire position determination repeatability	20	20	24
B_{fidLT3}	Measurement	9	10	9
B_{fidLT4}	Repeatability	3	3	12

†Low gradient quadrupoles, octupoles and sextupoles use shims for the vertical alignment. This contribution reflects that the whole fiducialisation procedure needs to be done twice

$B_{fidbench1}$: the 4µm uncertainty of a magnet measurement using the ESRF magnet measuring bench is discussed in detail in (Le Bec G, 2019).

Reference: G. Le Bec, J. Chavanne, L. Lefebvre, D. Martin, and C. Penel, "Magnetic Measurements and Fiducialisation of the ESRF-EBS Magnets", in Proc. 11th Int. Particle Accelerator Conf. (IPAC'20), Caen, France, May 2020, paper THVIR09, pp. XX-XX

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†Low gradient quadrupoles, octupoles and sextupoles use shims for the vertical alignment. This contribution reflects that the whole fiducialisation procedure needs to be done twice

$B_{fidbench2}$: Low gradient quadrupoles, octupoles and sextupoles use shims for vertical alignment. The entire fiducialisation process is performed twice, which means that an additional vertical alignment contribution is included for the second fiducialisation i.e. 29 µm.

we'll come back to this at the end …

MAGNET FIDUCIALISATION

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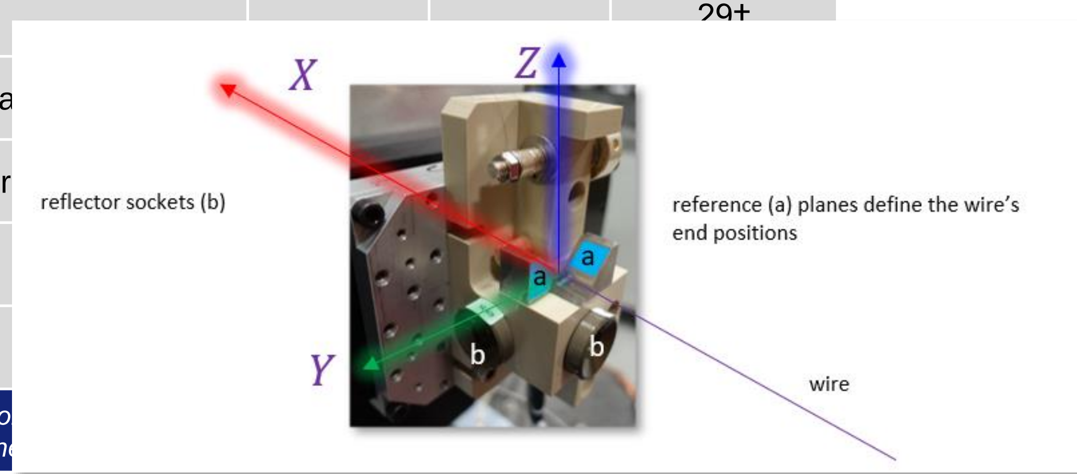

B_{fidLT1}: During the fiducialisation process, the positions of the two ends of the wire are measured in two independent steps. First, the positions of the four reflector sockets (with two visible in this picture) are determined with respect to the plane surfaces that define the wire's position.
To facilitate rapid measurement, the planes defining the wire end positions were not measured during every fiducialisation. Instead, four easily measurable reference sockets were used for the fiducialisation. Periodically, the planes were remeasured using an AT40x laser tracker to re-determine the reflector socket positions.

MAGNET FIDUCIALISATION

Ref	Quantity	U(x) [µm]	U(y) [µm]	U(z) [µm]
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B_{fidLT1}	Wire block reference repeatability	5	5	5
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B_{fidLT3}	Measurement	9	10	9
B_{fidLT4}	Repeatability	3	3	12

†Low gradient quadrupoles, octupoles and sextupoles use shims for the vertical alignment. This contribution reflects that the whole fiducialisation procedure needs to be done twice

B_{fidLT2}: All of the reference points on the benches were measured periodically to provide an estimate of the repeatability of the determination of the wire end points. This is the standard deviation $U(x), U(y), U(z)$ of the 11-determinations made on Bench 3 and Bench 4 i.e. a total of 22 determinations, between July 2017 and May 2018.

Note these values have been revised from earlier publications (e.g. (Martin D, 2022) where the values used $U(x) = 13\ \mu m, U(y) = 15\ \mu m, U(z) = 18\ \mu m$ were based on fewer determinations. You can improve uncertainty with increased knowledge

MAGNET FIDUCIALISATION

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$B_{fidBench2}$	Shim determination			
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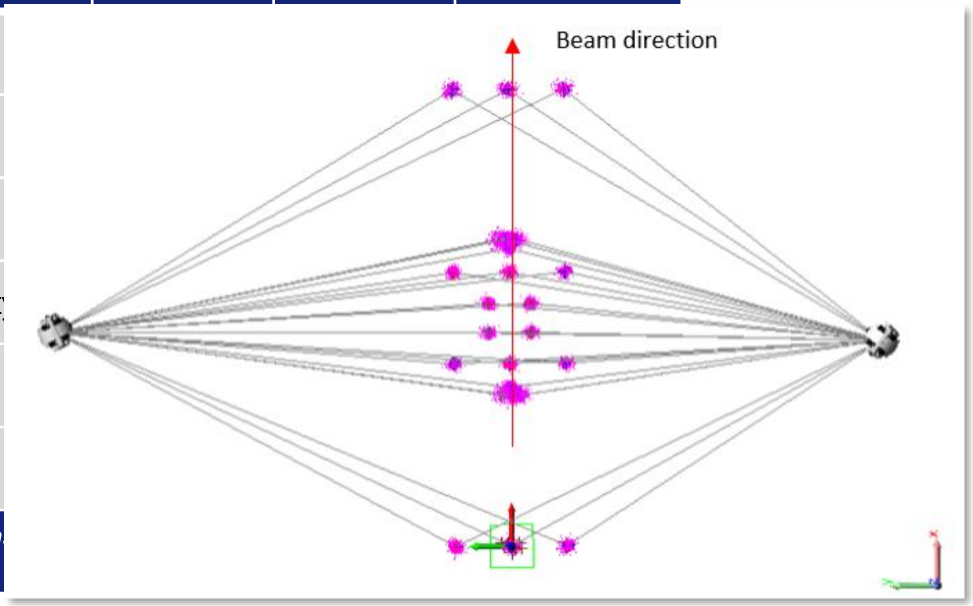

B_{fidLT3}: The uncertainties come from the results of a typical Spatial Analyser (SA) USMN fiducialisation calculation.

MAGNET FIDUCIALISATION

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B_{fidLT4}: The repeatability comes from six independent fiducialisations of the same magnet on the same bench over two-day period. This is essentially the repeatability of the B_{fidLT2} contributions.

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MAGNET FIDUCIALISATION

The combined uncertainties for the Type B contributions for magnet fiducialisation are:

$$u_x = \sqrt{5^2 + 20^2 + 9^2 + 3^2} = 23\ \mu\text{m}$$

$$u_y = \sqrt{4^2 + 5^2 + 20^2 + 10^2 + 3^2} = 24\ \mu\text{m}$$

$$u_z = \sqrt{4^2 + 5^2 + 24^2 + 9^2 + 12^2} = 29\ \mu\text{m}$$

$$u_{z\_shimmed} = \sqrt{4^2 + 29^2 + 5^2 + 24^2 + 9^2 + 12^2} = 41\ \mu\text{m}$$

This is the first of several contributions to the overall alignment uncertainty.

We’re not going to do this for every contribution - they are discussed in detail in the paper. They were also discussed in the last IWAA.
Note once again values have evolved as more information has become available …

FINAL UNCERTAINTY

Ref	Quantity	U(x) [µm]	U(y) [µm]	U(z) [µm]	U(z)† [µm]
B_{final1}	Fiducialisation	23	24	29	41
B_{final2}	Assembly	126	29	32	33
B_{final3}	Transport and bakeout	42	17	20	20
B_{final4}	Tunnel alignment	6	6	19	19
B_{final5}	Girder smoothing	219	39	36	36

†Low gradient quadrupoles, octupoles and sextupoles use shims for the vertical alignment. This means the girder rectitude must be also included.

Assembly contributions: magnet opening and closing, girder rectitude (for shims), laser tracker survey measurements, overall positional differences with respect to the expected/nominal position.
Transport and Bakeout: surveys made in the tunnel after transport and after bakeout were transformed onto the positions measured immediately after assembly.
Tunnel Alignment: The relative error ellipsoids $U(x)$, $U(y)$ and $U(z)$ issued from the least squares calculation.
Smoothing: the residuals between the actual girder positions and a smooth curve representing an ideal position of the girder.

FINAL UNCERTAINTY

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B_{final4}	Tunnel alignment	6	6	19	19
B_{final5}	Girder smoothing	219	39	36	36

†Low gradient quadrupoles, octupoles and sextupoles use shims for the vertical alignment. This means the girder rectitude must be also included.

The combined uncertainties for the Type B contributions are:

$$u_x = \sqrt{23^2 + 126^2 + 42^2 + 4^2 + 219^2} = 257\ \mu\text{m}$$

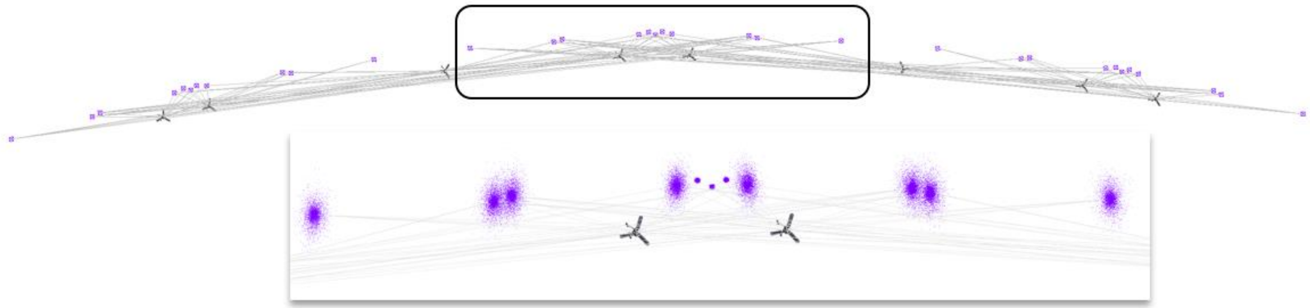
$$u_y = \sqrt{24^2 + 29^2 + 17^2 + 6^2 + 39^2} = 57\ \mu\text{m}$$

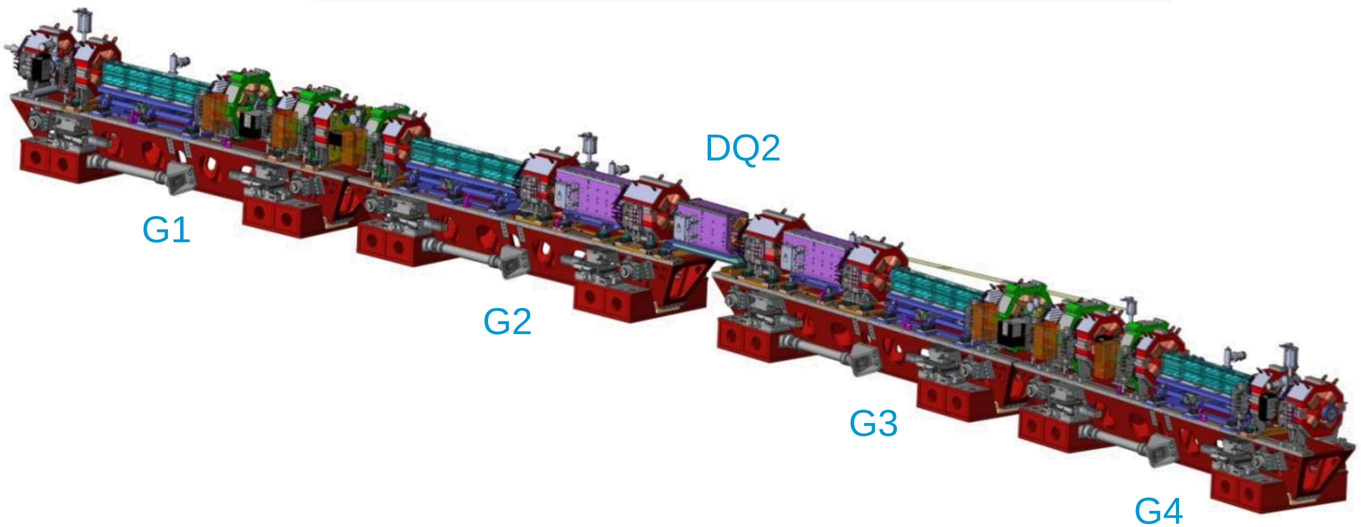
$$u_z = \sqrt{29^2 + 32^2 + 20^2 + 19^2 + 36^2} = 63\ \mu\text{m}$$

$$u_{z\_shimmed} = \sqrt{41^2 + 33^2 + 20^2 + 19^2 + 36^2} = 69\ \mu\text{m}$$

FINAL UNCERTAINTY

This is a general uncertainty statement. There are some intricacies†, with the tunnel alignment and smoothing that are discussed in the paper.





†variations dependent on the position of the magnets in the tunnel.

FINAL ALIGNMENT BY MAGNET

Taking into account these issues we end up with an uncertainty per magnet:

Magnet	Magnet type	Nominal $U(y)$[μm]	Measured $U(y)$[μm]	Nominal $U(z)$[μm]	Measured $U(z)$ [μm]	
QF1A	Med. Grad. Quad.	100	67	85	71	↑
QD2A	Med. Grad. Quad.	100	67	85	71	.
QD3A	Med. Grad. Quad.	100	67	85	71	.
SD1A	Sextupole	70	58	*50*	*68*	G1
QF4A	Med. Grad. Quad.	100	67	85	71	
SF2A	Sextupole	70	58	*50*	*68*	.
QF4B	Med. Grad. Quad.	100	67	85	71	.
OF1B	Octupole	100	61	100	65	↓
SD1B	Sextupole	70	58	*50*	*68*	↑
QD3A	Med. Grad. Quad.	100	67	85	71	.
QF6B	High Grad. Quad.	60	48	60	58	G2
DQ1B	Dipole-Quadrupole	60	48	60	58	.
QF8B	High Grad. Quad.	60	48	60	58	↓
DQ2C	Dipole-Quadrupole	60	48	60	58	DQ2
Symmetric moving back up the table for in the order DQ2 exit, G3 and G4 girders …						

All the magnets are within tolerance with the exception of the $U(z)$ for the sextupoles. Part, but not all of the problem, is the shimming.

“It is seen that the alignment of the storage ring ranges from 22 to 42 µm in the horizontal plane and from 22 to 54 µm in the vertical plane.”

Raimondi P, et al (2021, Nov). Commissioning of the hybrid multibend achromat lattice at the European Synchrotron Radiation Facility. Phys. Rev. Accel. Beams, 24(11).

This was the estimate for the EBS SR alignment uncertainty based on orbit measurements, and therefore mainly quadrupole alignment uncertainties, determined during the machine commissioning. It is an independent and direct assessment of the alignment uncertainty. It is also more (slightly) optimistic than what we have calculated in the previous table.

22 to 42 µm ↔ 48 to 67 µm for quadrupoles in the horizontal direction

22 to 54 µm ↔ 58 to 71 µm for quadrupoles in the vertical direction

Neither estimate is wrong. They are just determined differently and independently.

If we adhere strictly to the GUM this is similar to an interlaboratory comparison and the final uncertainty would be the square root of the quadratic sum of the two determinations.
But, we won’t do that here …

SUMMARY

The only way to know whether tolerances have been achieved is to make measurements. However, all measurements have uncertainty.

Today there is not a commonly accepted way to express uncertainty in measurement in accelerator alignment; a way to know whether or not tolerances have been achieved.

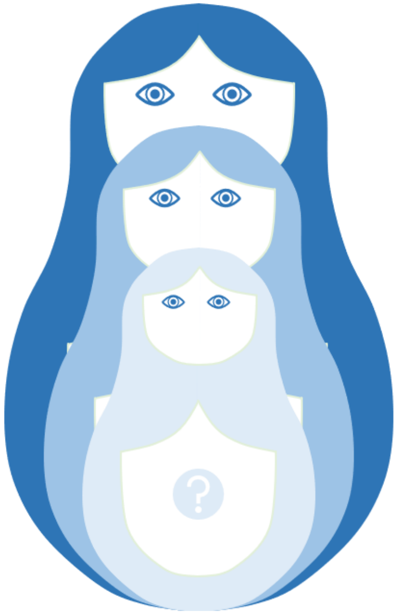
At the ESRF we decided to use the approach proposed in the GUM that considers all major sources of error: fiducialisation, assembly, transportation and installation; and combines each of these contributions into a final statement of uncertainty.

This provides an easy way to compare what is done in different accelerators that use a similar approach.

An uncertainty calculation like the one here provides an easily interpretable baseline for everyone impacted by the results of accelerator alignment. It provides clarity that decision makers need to evaluate if something is or it isn't achievable.

CONCLUSION

The key point is that we are not interested in the smallest possible estimate, but rather the most correct estimate of accelerator alignment uncertainty.



Thank you for your attention…