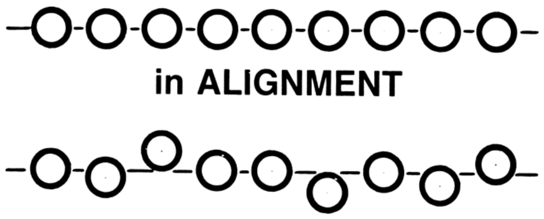
Metrology, fiducialisation & alignment

Patrick Bestmann

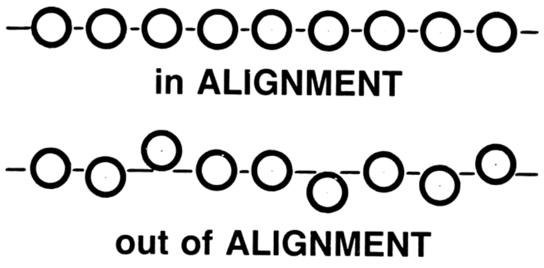
Thank you to all colleagues for their valuable contributions

Outlook



- **What is Metrology?**
  - And how we use metrology at CERN?
- **What do we actually align?**
  - Technically we align the targets on the components
  - But how do they relate to the magnetic axis, the field, the mechanical axis?
- **Fiducialisation**
  - What it is and what it does
  - Geometrical references for fiducialisation
  - Different types of fiducialisation measurements

Outlook

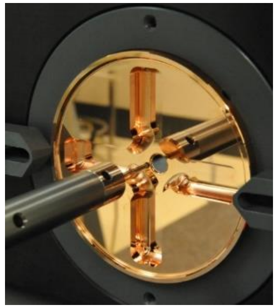


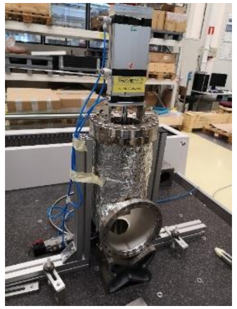
- **Alignment**
  - Reasons for alignment
  - A typical sequence
  - Absolute alignment vs. smoothing
- **Alignment and supporting systems**
  - Requirements
  - Available systems
- **Internal monitoring**
  - Do we know what happens to our magnets inside the vacuum vessels?
- **Conclusions**

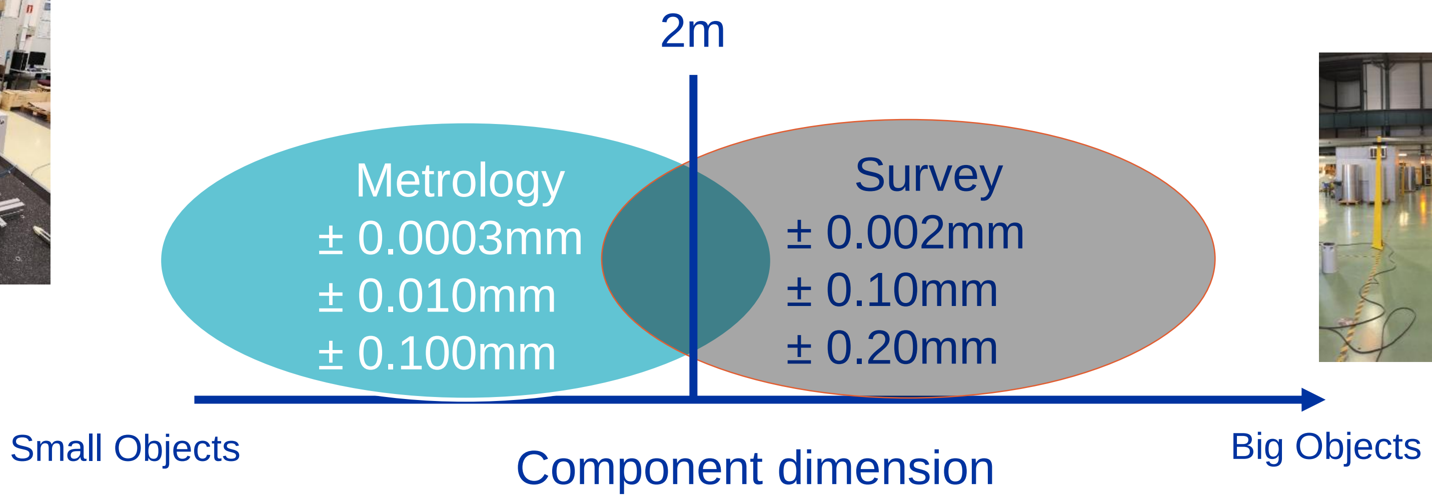
Metrology & Large Scale Metrology

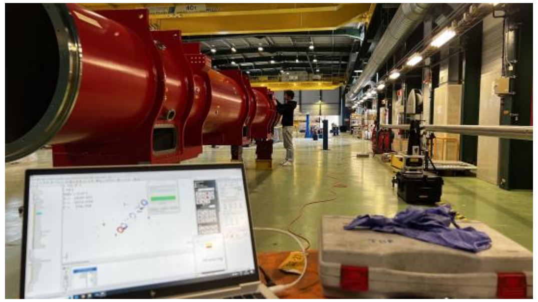
- **Definition of metrology:**
  - International vocabulary of metrology - Basic and general concepts and associated terms (VIM)
  - Science of measurement and its application
    - *NOTE Metrology includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.*
  - Applied, technical or industrial metrology is covering the application of measurement to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration and quality control.

Metrology & Large Scale Metrology

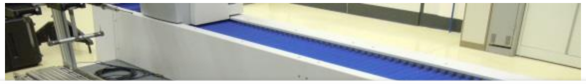








Metrology




T
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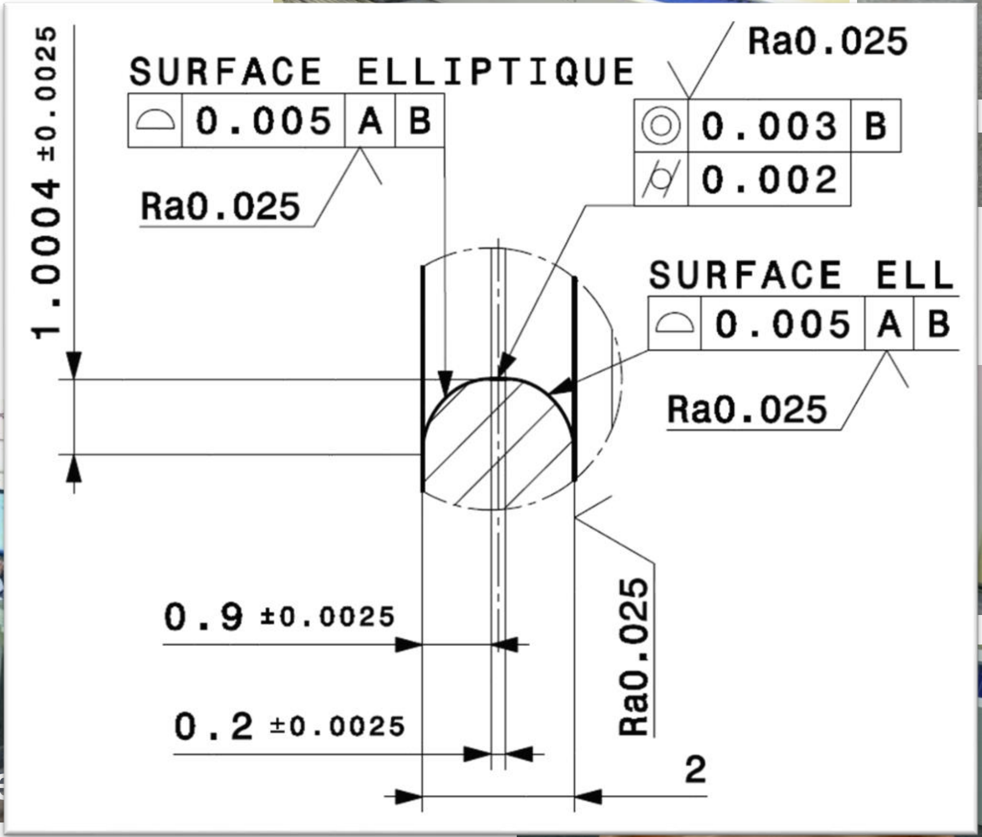
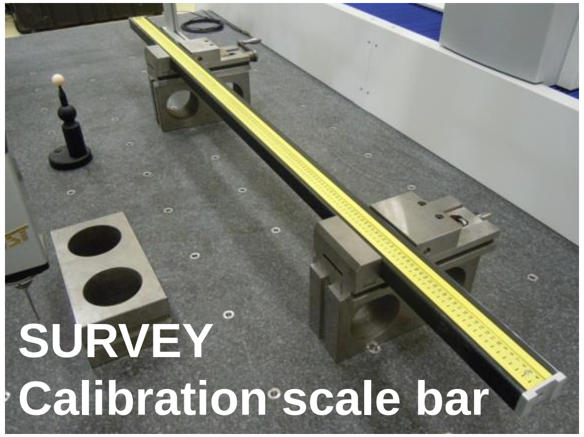
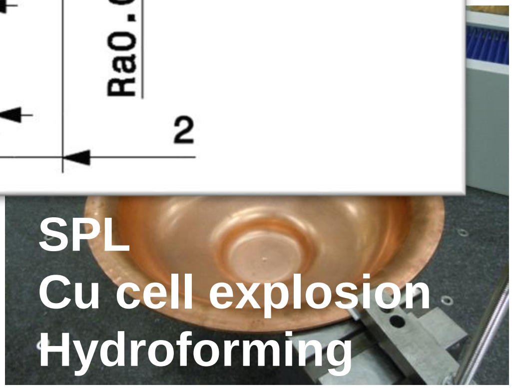
LINAC 4
Y chamber


SURFACE ELLIPTIQUE
0.005 A B
Ra0.025
Ra0.025
0.003 B
0.002
SURFACE ELL
0.005 A B
Ra0.025
1.0004 ±0.0025
0.9 ±0.0025
0.2 ±0.0025
Ra0.025
2


CLIC
Module


SURVEY
Calibration scale bar


LHC
BGV Stainless steel chamber


SPL
Cu cell explosion
Hydroforming


SPL
Cu Cavity

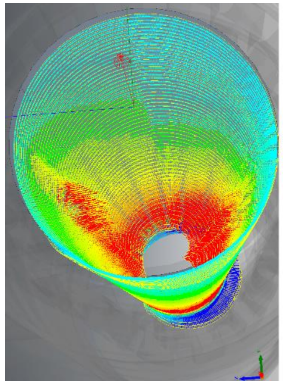

SPL
Nb Cavity

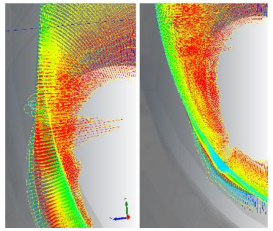
Metrology

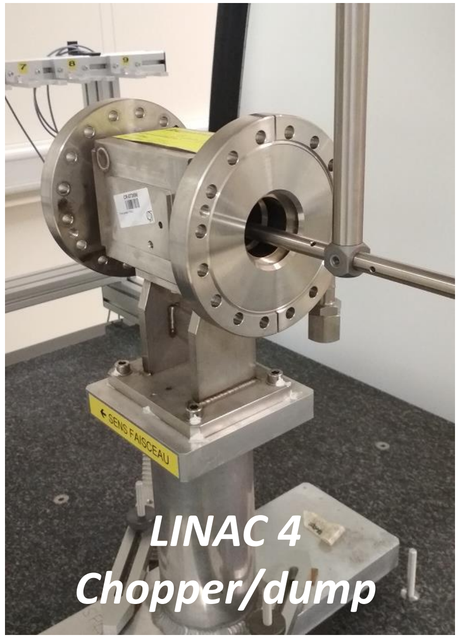
- Leitz PPM-C Infinity

Measuring room specifications :
Class 1
20°C
0.1 K / Meter
0.2 K / Hour
0.4 K / Day
Humidity 50% ±5%

Measuring Range	
10.12.7	1200 x 1000 x 700 mm^3
Accuracy (according to ISO 10360)	
MPE E	**0.3 + L/1000 µm**
MPE P	**0.4 µm**
MPE THP	1.2 µm / 59s

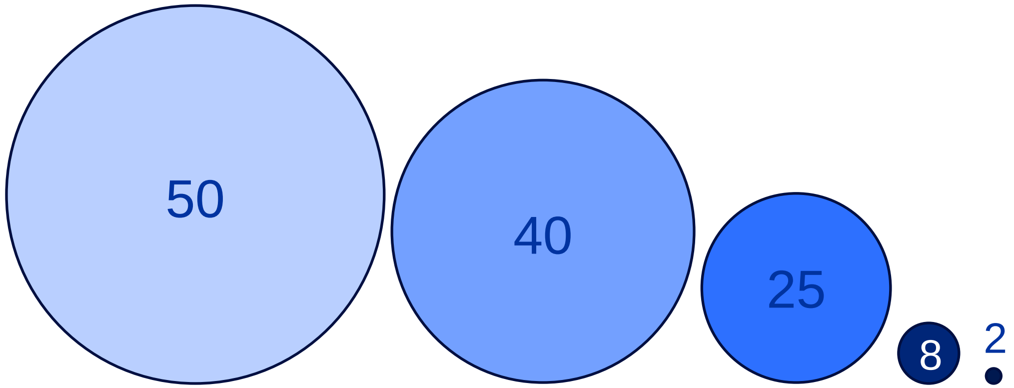






Metrology

- Highly accurate and precise measurements are directly linked to the environment!
- When considering microns, everything gets important:
  - Temperature air/workpiece
  - Instrument warmup
  - Vibrations
  - Direct sunlight
  - Humidity



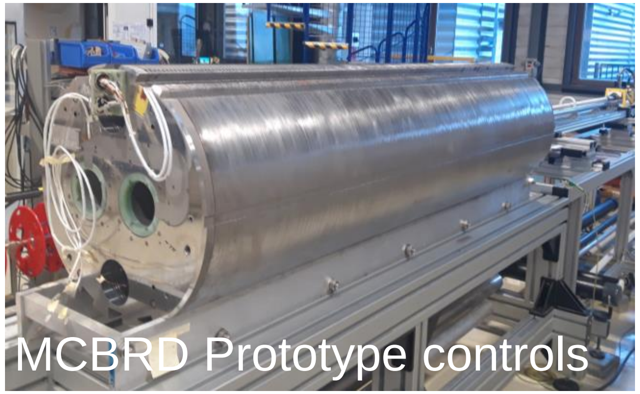
50 Microns – Human Hair
40 Microns – Human Eye lower visibility limit
25 Microns – White Blood Cells
8 Microns – Red Blood Cells
2 Microns – Bacteria

Metrology in practice

- There are manufacturing controls all along the production process
  - For the tooling
  - For the laminations
  - For the coils & magnets
  - The endcovers, feets, flanges…..
- Up to the finished coldmass this is usually covered by industrial and classic metrology
- From the coldmass onwards the objects are usually too big for the classical methods
- This is where the large scale Metrology takes over, mainly using Laser Trackers and Photogrammetry

Fabrication Metrology


Straightness control of coil mandrel


MCBRD Prototype controls


Fabrication control of Vacuum Vessel


Deformation after loading

Assembly Metrology

Position & Shape control @ cryostating


Assembly of bottom tray


Alignment of coldbore tubes

Definitions

- In the engineering domain terms like error, precision, accuracy, tolerance and uncertainty are frequently used and occasionally interchanged
- *Precision and Accuracy*
- Both express how close you are to a target!
- Accuracy evaluates how close you are to the true value of the measurement
- Precision shows how close the measured values are to one another.

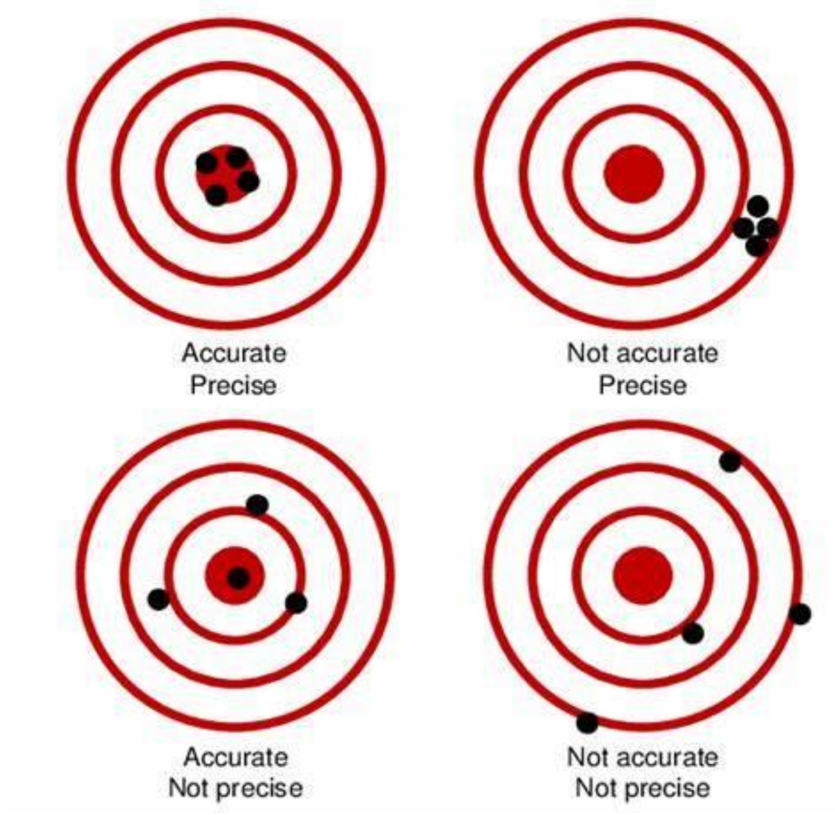
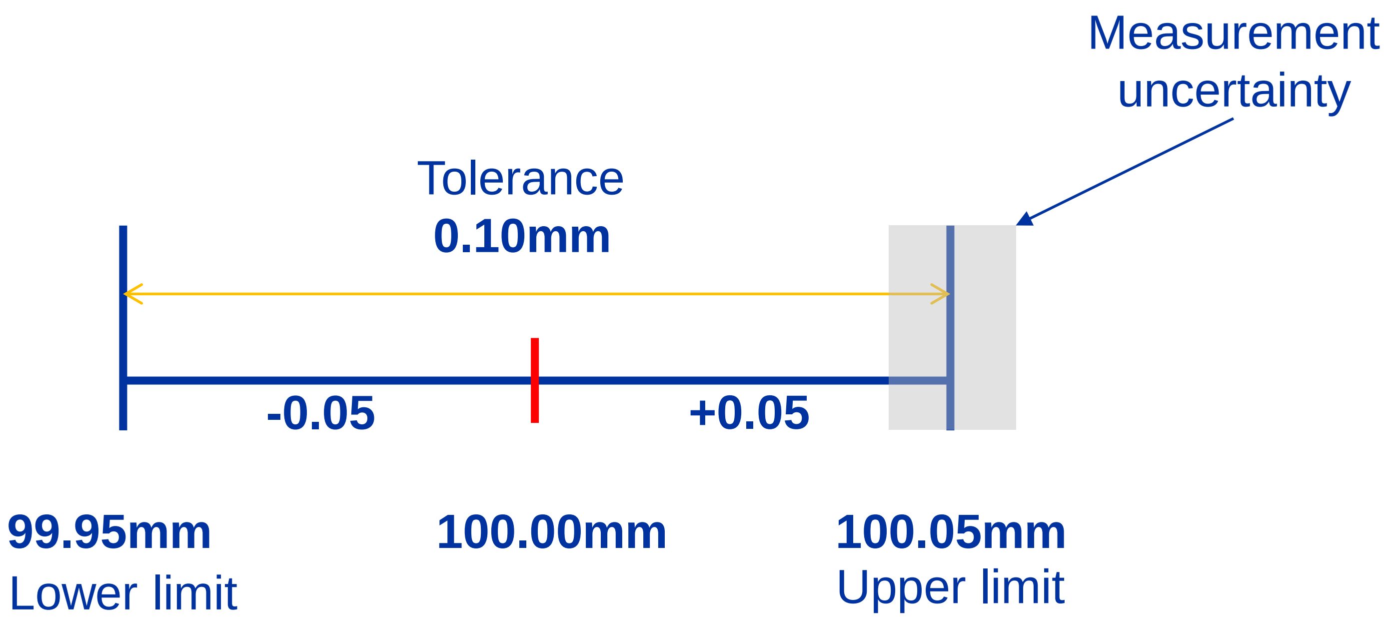


Image: researchgate.net

Definitions

- *A Tolerance in engineering and manufacturing is the extent by which a value is permitted to vary. Specifying a tolerance defines the acceptable limits of variance required for a particular project, part, a dimension or even an alignment.*



For more details refer to the Guide to the Expression of Uncertainty in Measurement (GUM)

Instruments

- The measurement instrument needs to be adapted to the task
  - Factor 2 is the last line of defence
- In our case, the majority of measurements are done using Laser Trackers
- In small volumes, measurement arms and CMMs are more adapted and accurate!
- Sometimes calipers and micrometers do the job perfectly

	MPE_p	MPEe
8312	8 µm	5 + L/40 ≤ 18 µm
8512	6 µm	5 + L/65 ≤ 15 µm

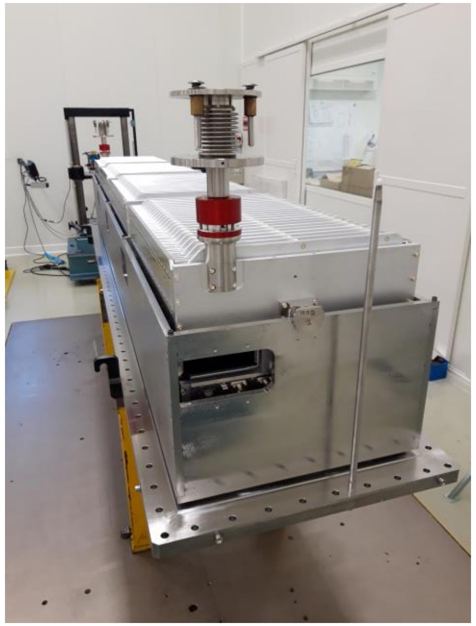
	MPE values
Angle Performance Angular accuracy	± 15 µm + 6 µm/m
Distance Performance ADM Accuracy	± 10 µm
Interferometer Accuracy	± 0.4 µm + 0.3 µm/m

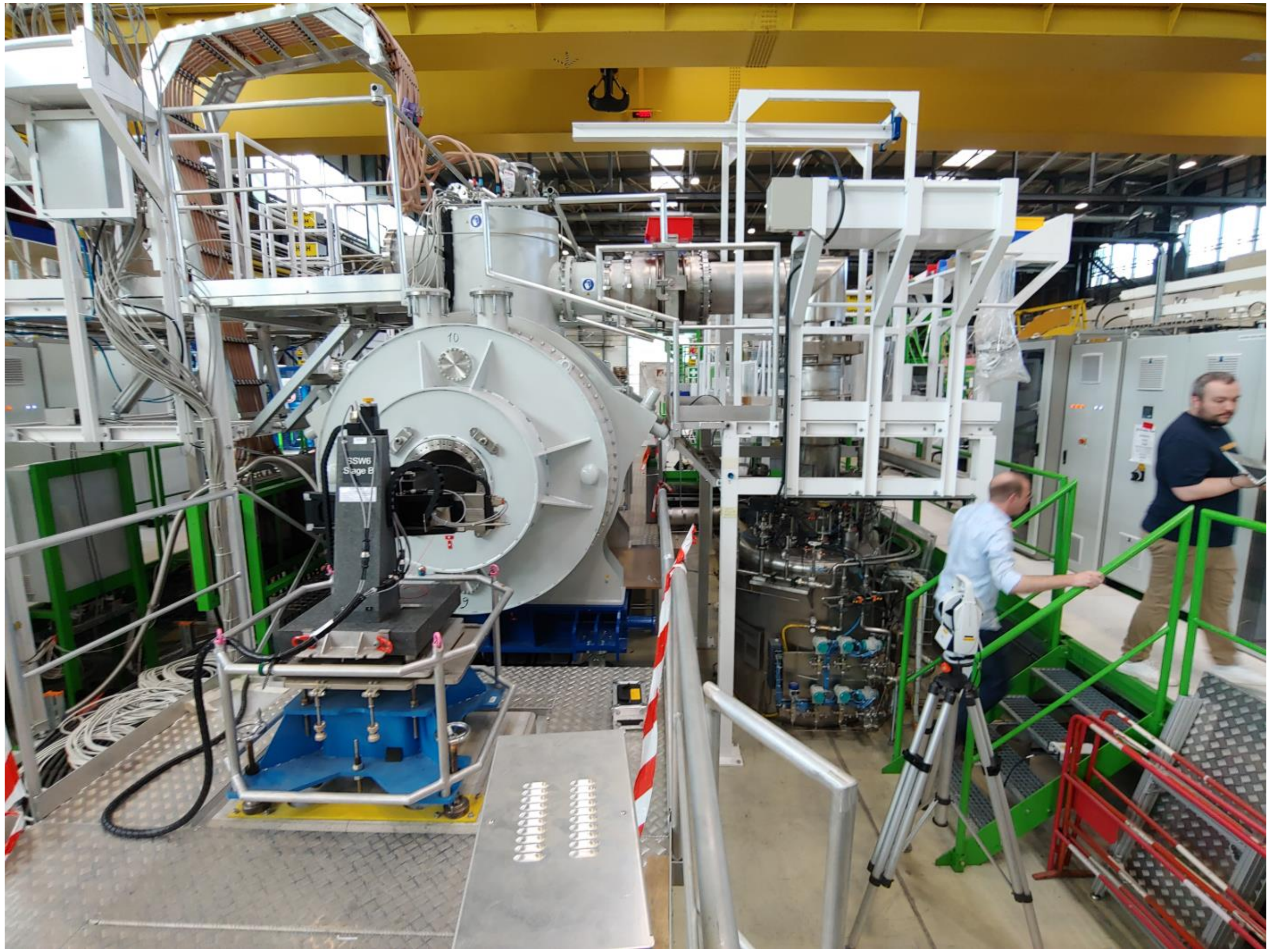
Not as exact as possible, but as accurate as needed

Uncertainty budget / error propagation

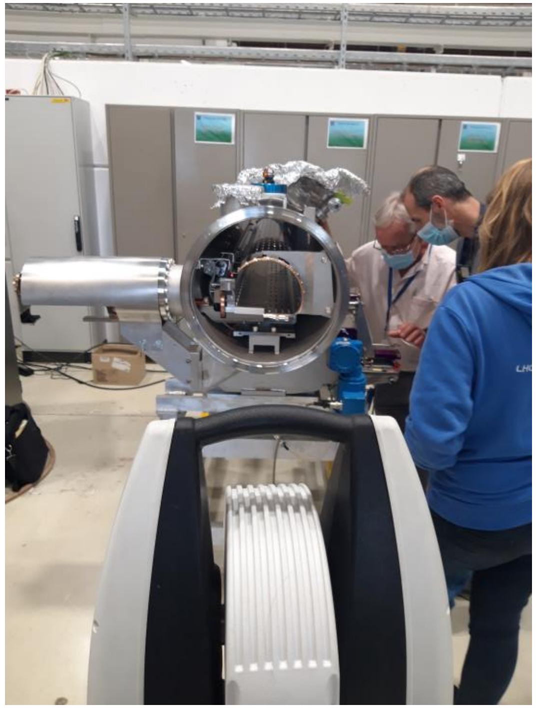
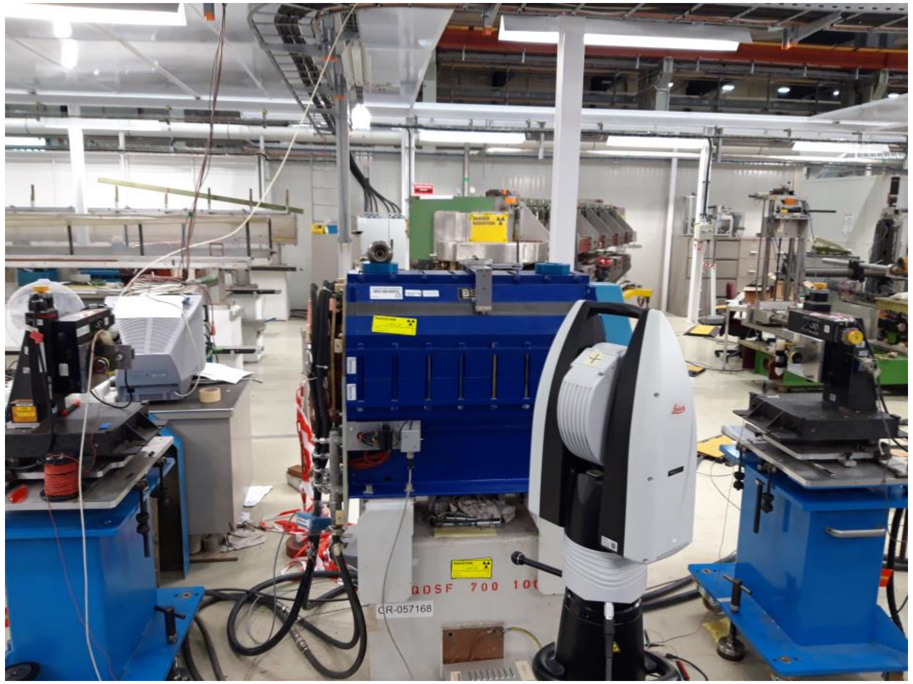
- **The final result of the alignment depends on a chain of uncertainties along the whole process**
  - Manufacturing tolerances
  - Assembly tolerances
  - Fiducialisation uncertainty
  - Alignment tolerance + uncertainty
  - Movements due to vacuum forces and cooldown
  - Or simply multiple measurement epochs
- **A full error propagation is not really possible**
  - But one should use realistic estimates, class them as systematic or random effects and sum them up accordingly!
- **Not an easy and fun exercise, but absolutely mandatory!**

Fiducialisation



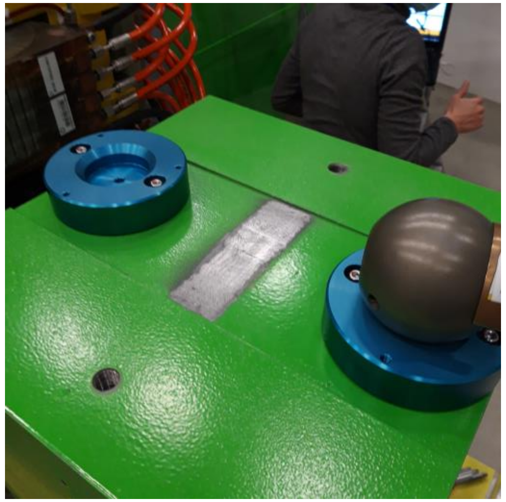


Fiducialisation

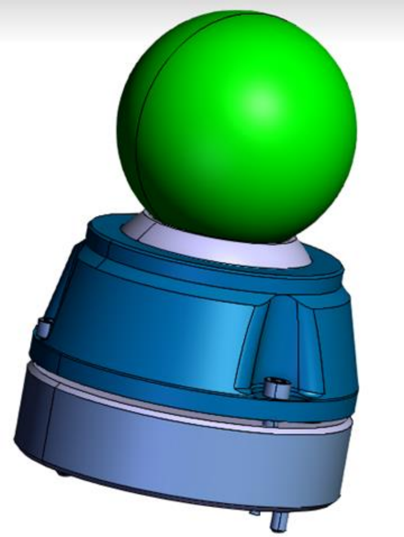





Fiducialisation

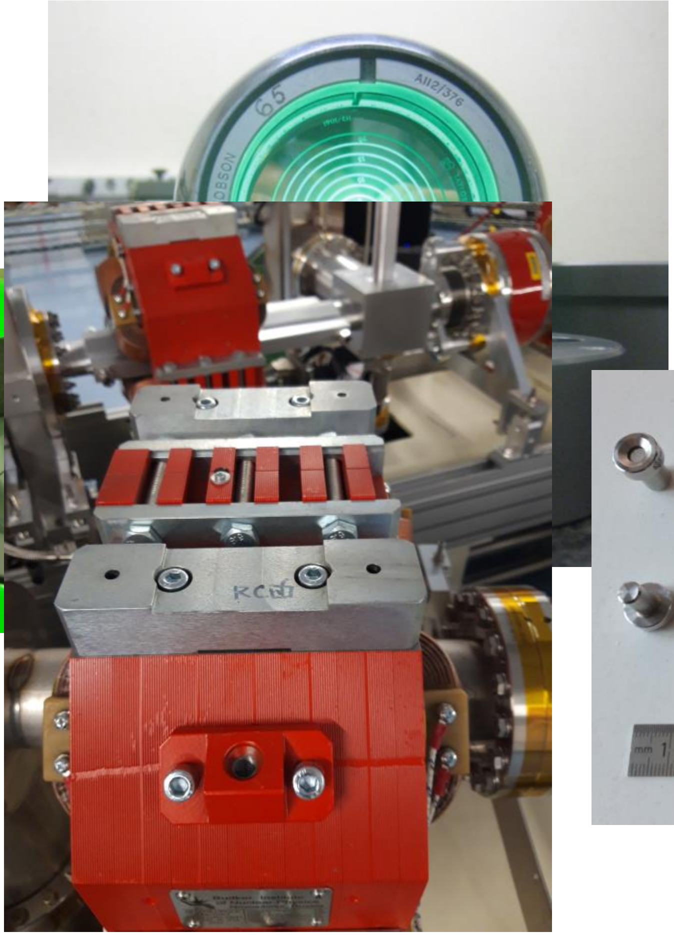
- **A fiducial marker should be stable, reliable and protected reference**
- **Representative for the component and covering the whole object**
- **The number of fiducials is depending on**
  - The seize of the component
  - The deformation of the component
  - The accessibility of the fiducials for later measurements
- **The type of fiducials are adapted as function of**
  - The environment
  - The measurement systems
  - The measurement frequency

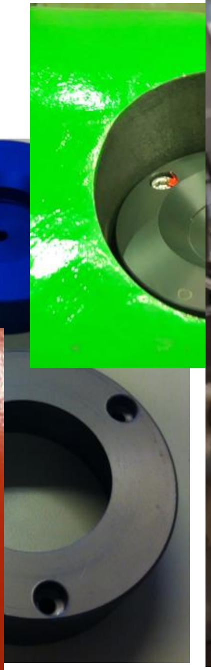


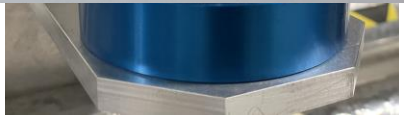
Fiducials



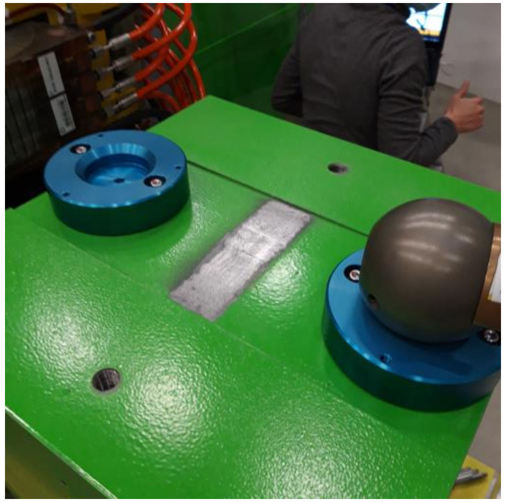
- A fiducial is a fixed and stable reference, accessible on the outside of a magnet
- Usually compatible with 3.5” Taylor Hobson sphere
- Also 1.5” and 0.5” SMR or CCRs



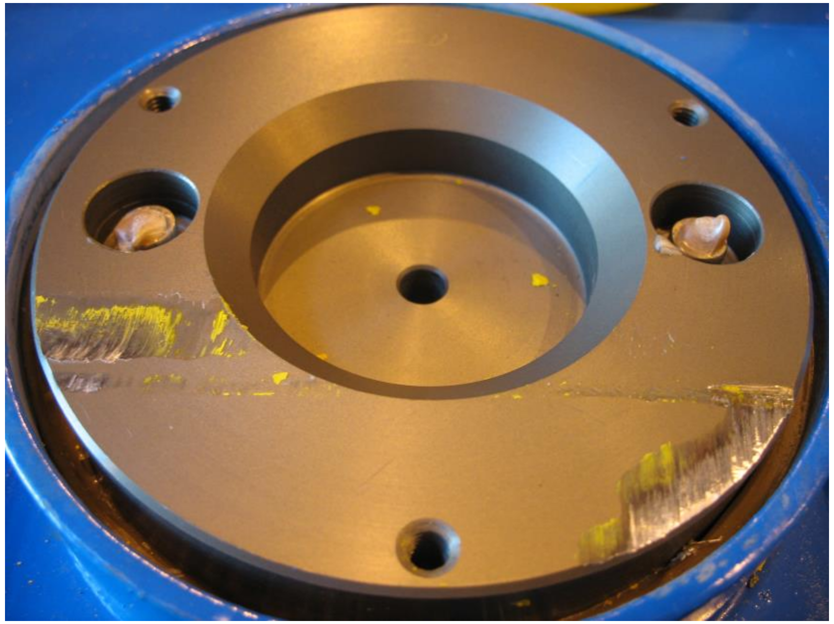




Fiducials

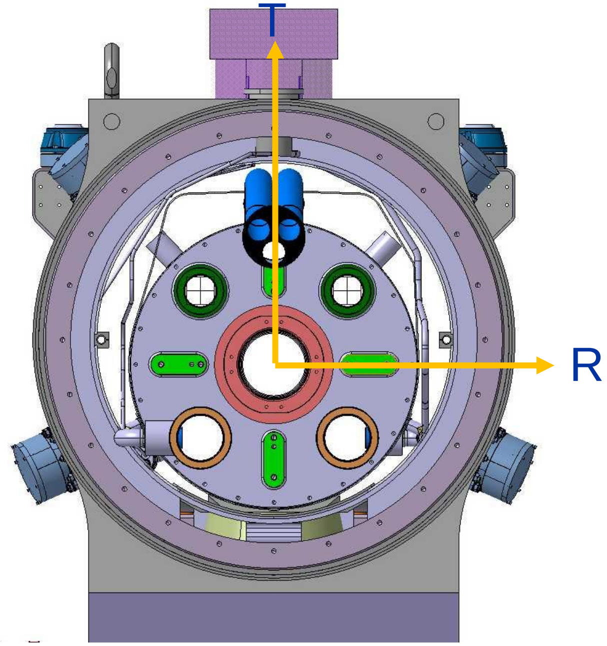


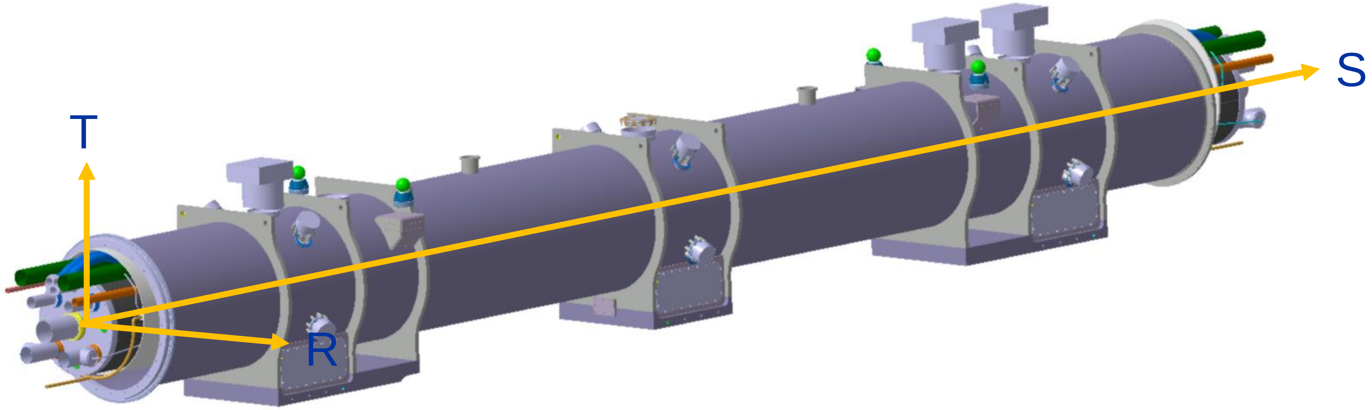
- **Symmetry is an advantage**
  - For the measurement & network layout
  - And for the component itself
  - For any best fit transformation
  - Attention for perfect symmetry
- **Integrity and validity**
  - Redundancy is key here
  - Protect the fiducials
  - Check integrity of fiducials
  - Check validity of fiducialisation



Fiducialisation

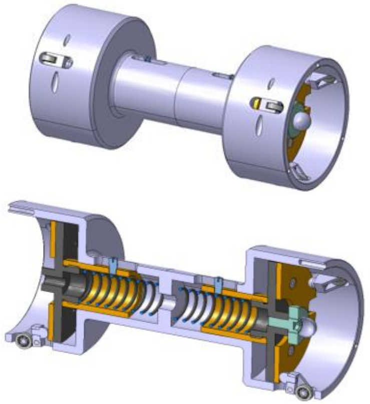
- **The fiducialisation is a transfer measurement**
  - Giving the relation between the future beam-axis of the magnet and the fiducials accessible from the outside
  - Defining the relation between the functional surfaces, the physical magnet -as build- and the theoretical object
  - The fiducialisation is an adaptation of the “real world” object to the theoretical magnet model

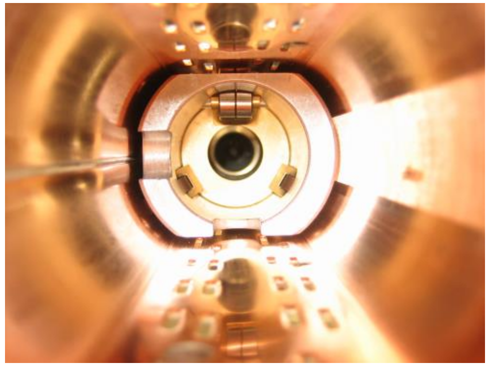




Fiducialisation example

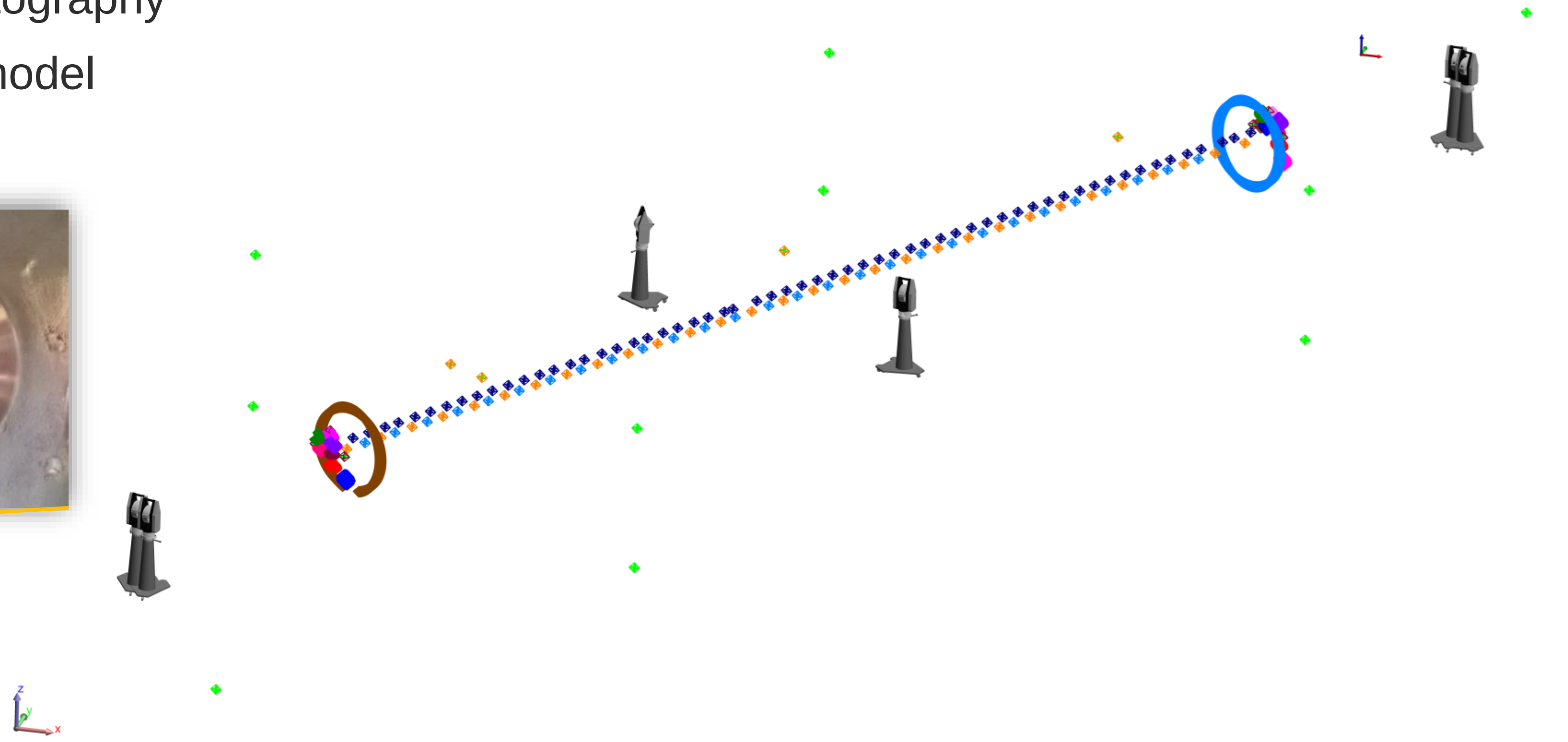
- **Superconducting LHC dipole**
  - Cryostated assembly
  - Twin aperture, curved shape
  - Full cartography of extremities
  - Rather big objects





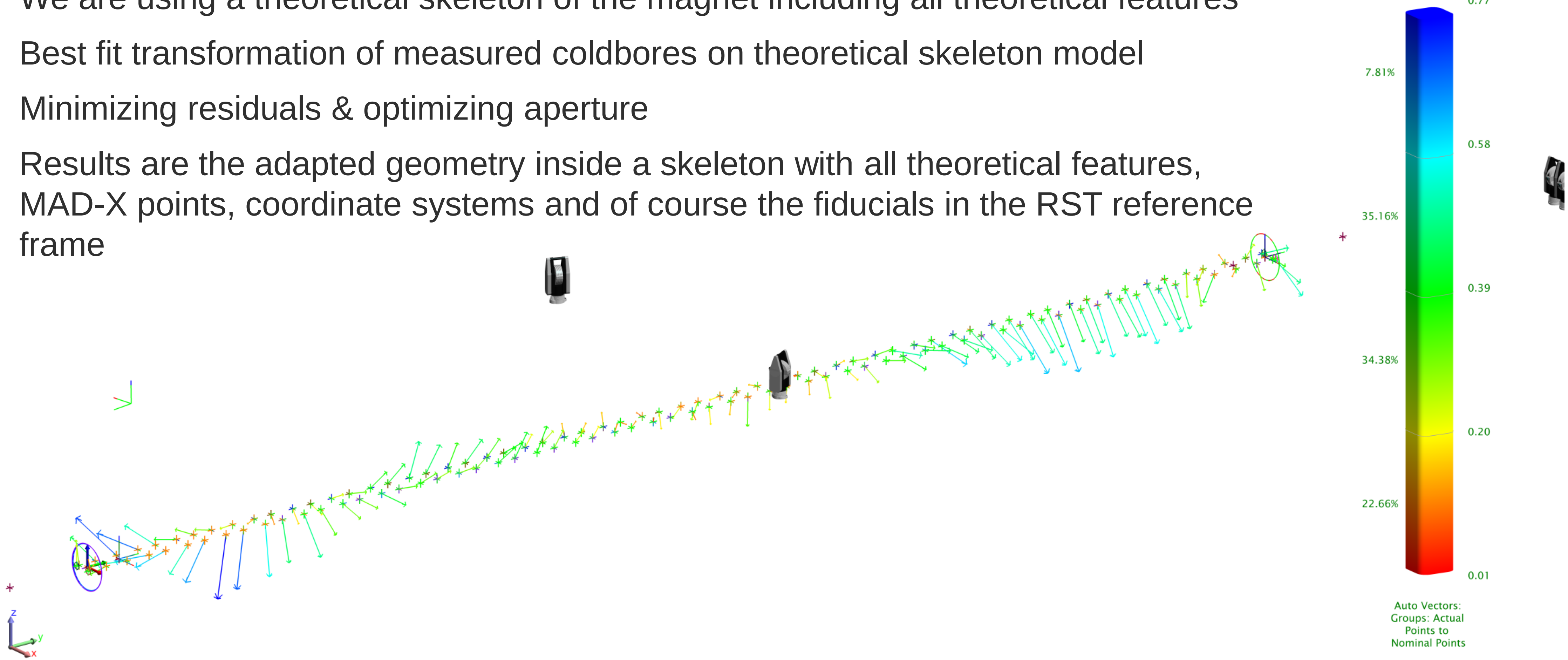
Fiducialisation basics

- **Measurement of the magnet coldbore profiles using a probe**
  - Both coldbore tubes, redundant from both extremities
  - Endvovers, fiducials and cartography
  - Giving the as build magnet model



Fiducialisation basics

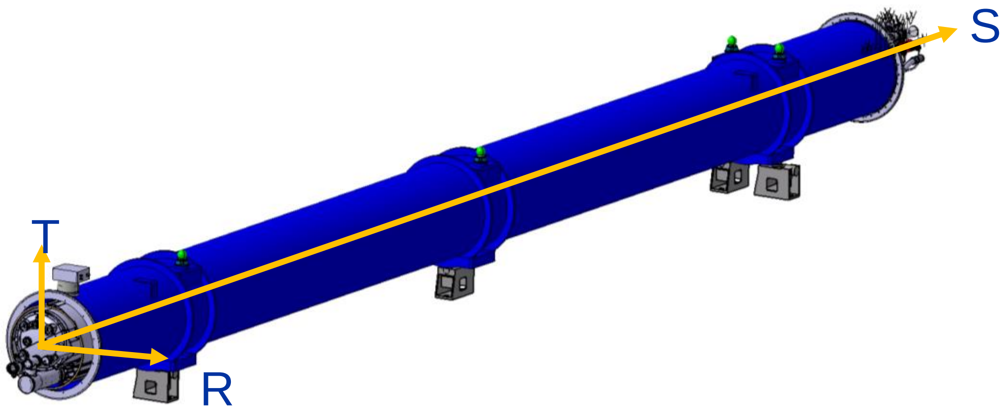
- **The construction of the RST reference frame**
  - We are using a theoretical skeleton of the magnet including all theoretical features
  - Best fit transformation of measured coldbores on theoretical skeleton model
  - Minimizing residuals & optimizing aperture
  - Results are the adapted geometry inside a skeleton with all theoretical features, MAD-X points, coordinate systems and of course the fiducials in the RST reference frame



Fiducialisation results

Fiducials in RST Frame

Id	R	S	T	RMS R	RMS S	RMS T	Total RMS
Mire_E	266.25	1771.71	417.89	-0.03	0.02	0.01	0.04
Mire_M	267.06	7171.29	416.13	0	0.01	0.01	0.01
Mire_S	266.19	12571.6	418.23	-0.02	0.01	0	0.02
Mire_T	-262.5	12572.51	418	-0.03	0.01	0.02	0.04

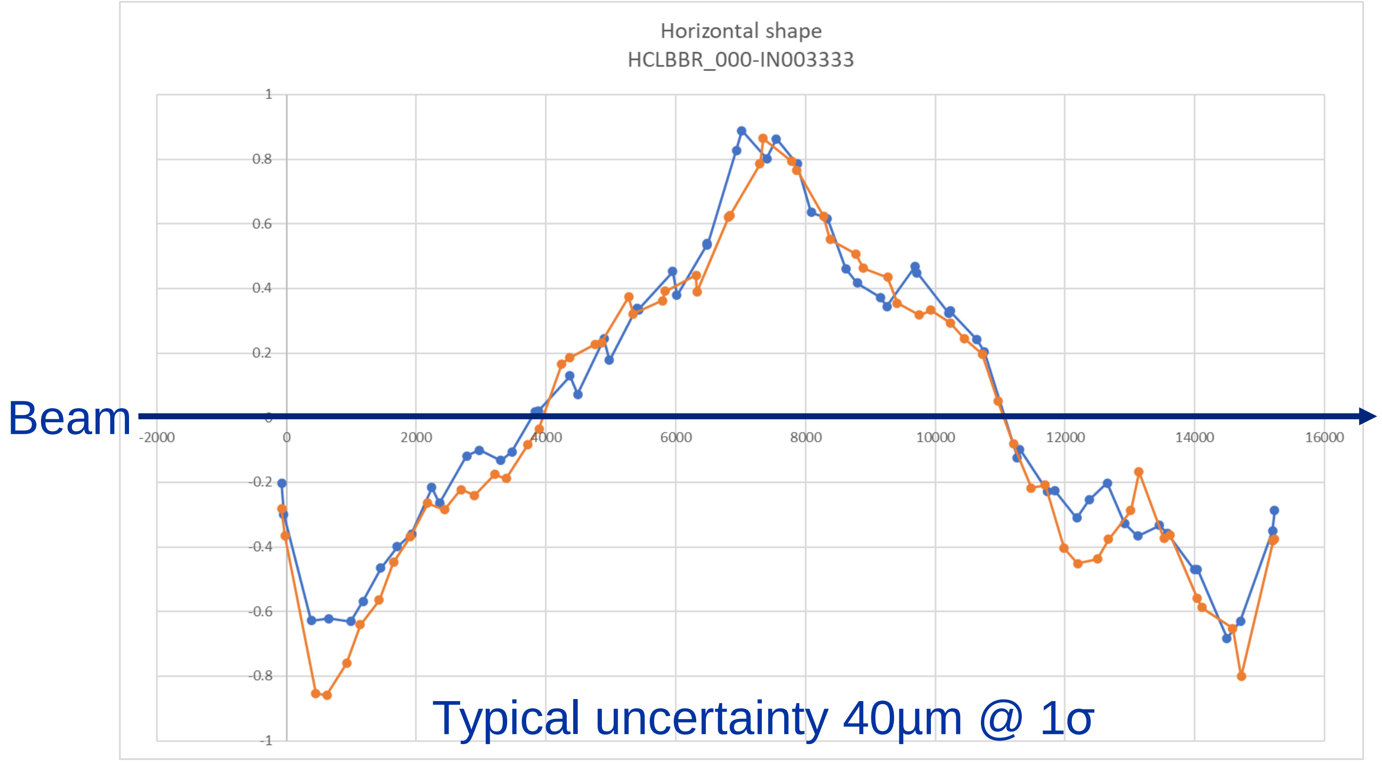


Cold mass tilt (mrad)	-0.34
Fiducials tilt (mrad)	0.10

Cartography in local extremity frames

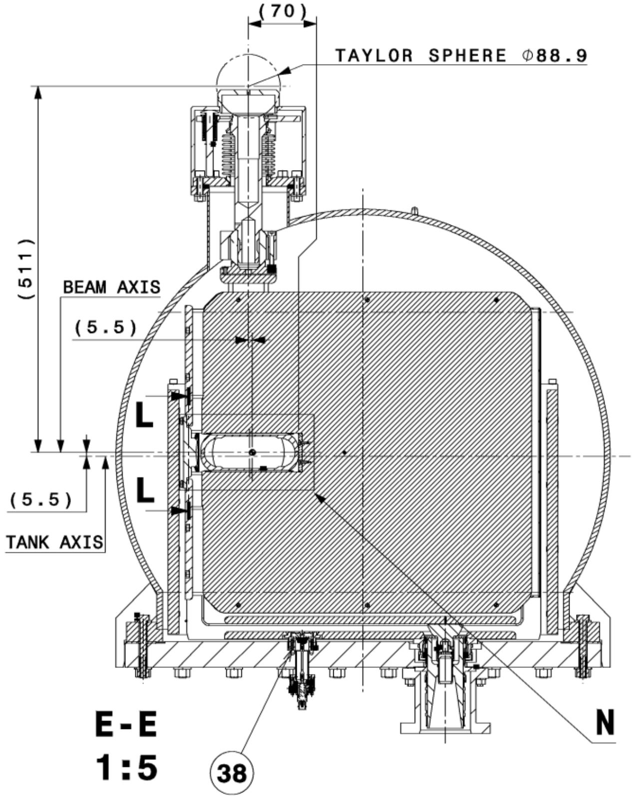
Point	X (mm)				Z (mm)			
	Measured	Theo	Delta	Tolerance	Measured	Theo	Delta	Tolerance
Centre_E	-269.33	-270.00	0.67	±2	-290.47	-290.00	-0.47	±2
Centre_M1	-140.28	-140.00	-0.28	±1.15	145.16	145.00	0.16	±1.15
Centre_M2	139.47	140.00	-0.53	±1.15	145.28	145.00	0.28	±1.15
Centre_M3	-145.29	-145.00	-0.29	±1.15	-144.64	-145.00	0.36	±1.15
Centre_N	309.90	310.00	-0.10	±2	-70.56	-70.00	-0.56	±2
Centre_W (cryostat)	1.28	0.80	0.48	±2	-80.26	-80.00	-0.26	±2
Centre_X	-0.77	0.00	-0.77	±1.15	180.51	180.00	0.51	±1.15

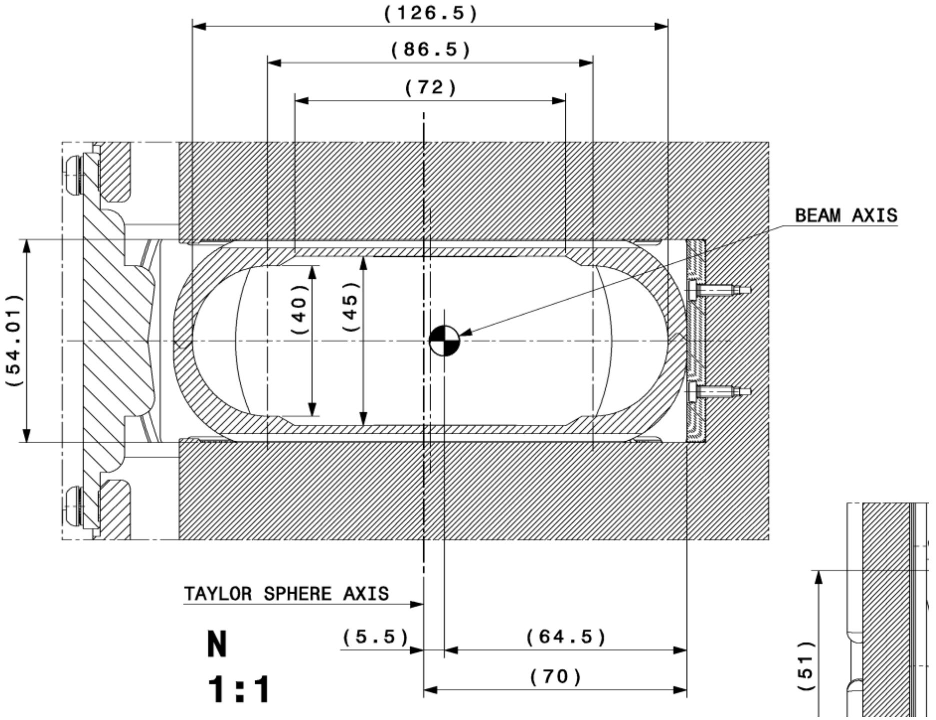
Point	X (mm)				Z (mm)			
	Measured	Theo	Delta	Tolerance	Measured	Theo	Delta	Tolerance
Centre_E	-269.32	-270.00	0.68	±2	-290.80	-290.00	-0.80	±2
Centre_M1	-140.35	-140.00	-0.35	±1.15	144.80	145.00	-0.20	±1.15
Centre_M2	139.54	140.00	-0.46	±1.15	145.26	145.00	0.26	±1.15
Centre_M3	-145.34	-145.00	-0.34	±1.15	-145.07	-145.00	-0.07	±1.15
Centre_W (cryostat)	2.33	0.80	1.53	±2	-80.21	-80.00	-0.21	±2
Centre_X	-0.45	0.00	-0.45	±1.15	180.19	180.00	0.19	±1.15



Geometrical / functional references

- Very clear for the cryomagnets: Center of coldbore tubes as geometrical reference
- Less evident for other components



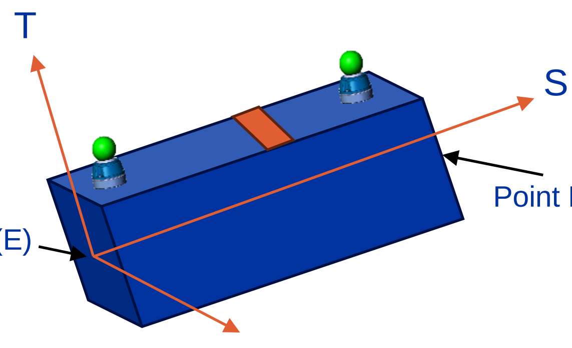


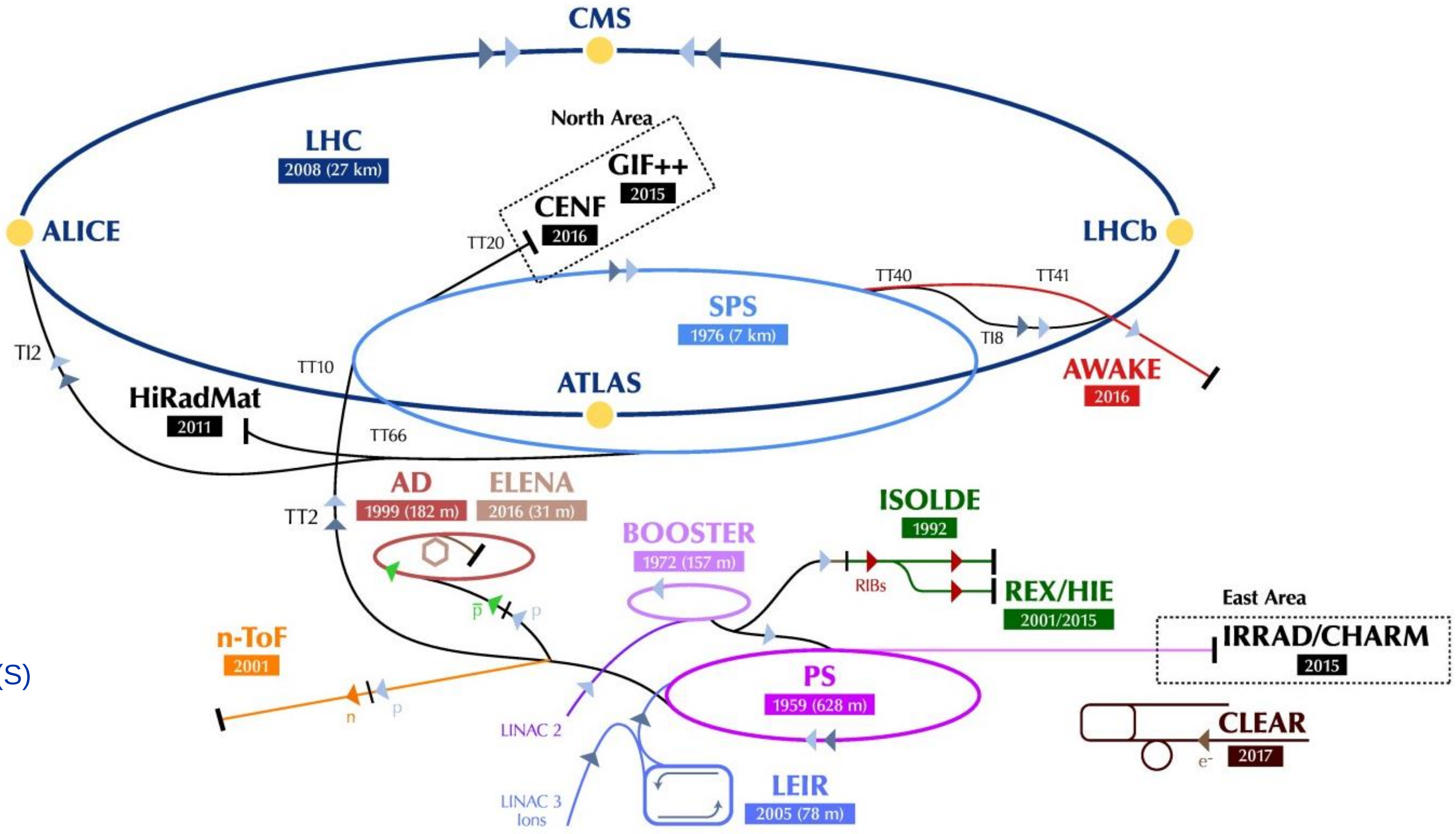
Magnetic axis

- **In some cases, the reference axis should be the magnetic axis and the field direction**
  - No way to measure this geometrically, there is no representative feature
  - Single-Stretched-Wire measurements as presented by Lucio
  - A simple transfer measurement
  - Internally controlled
    - *Measurement process and layout are done in a redundant way to ensure that errors can be detected*
    - *A non-redundant measurement with no uncertainty is:*

Alignment

We are placing our principal MAD-X points defined at the fiducialisation onto the theoretical Beam entry and exit points inside the machine

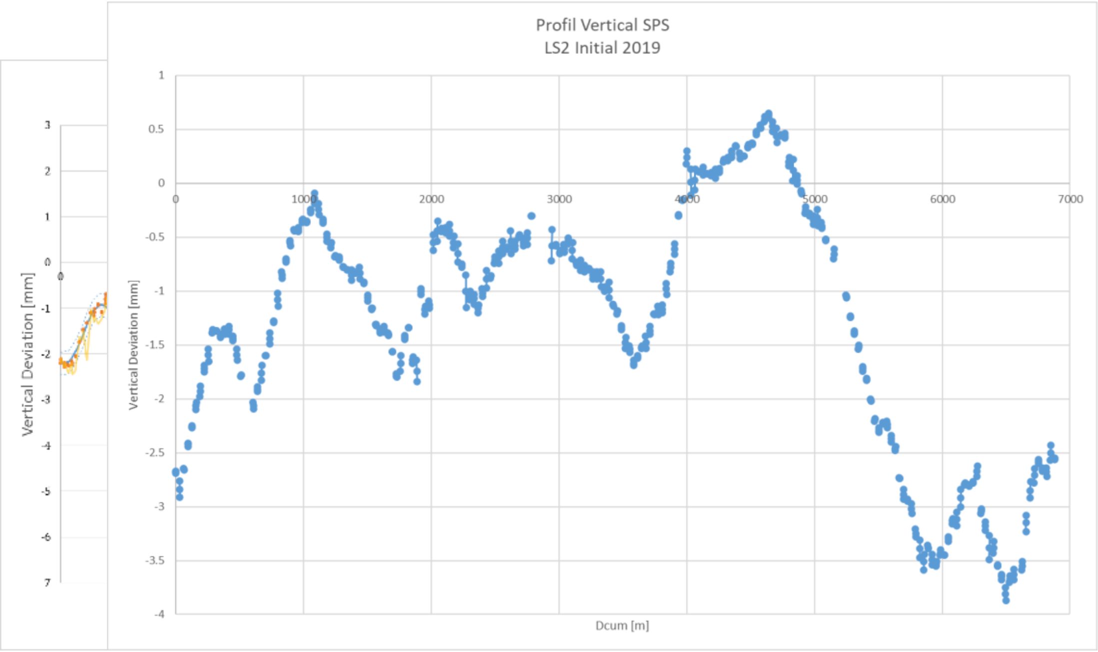


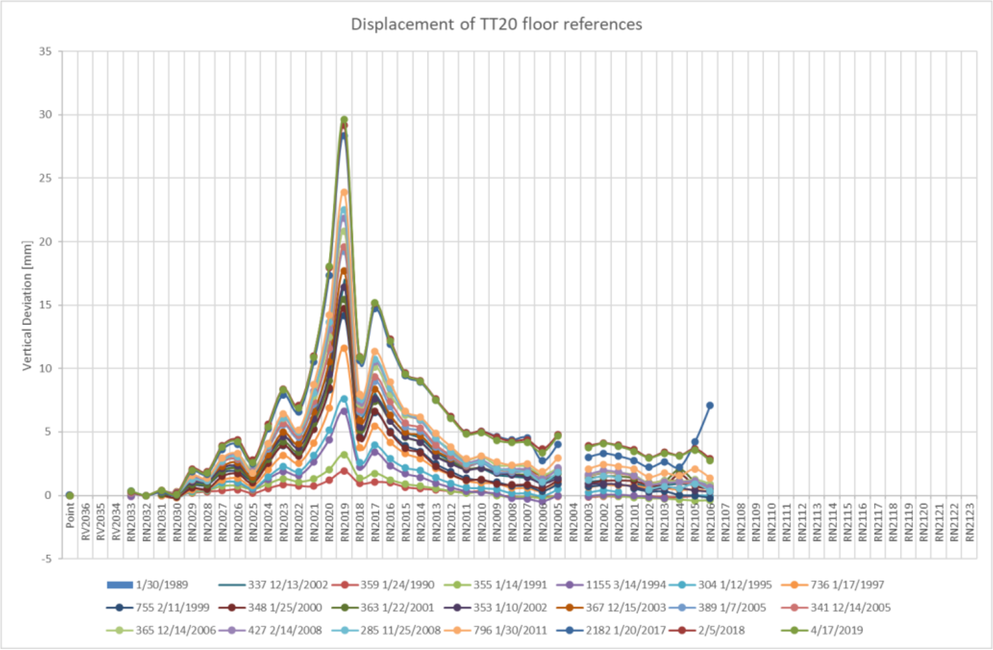


- The sequence file (MAD-X) provides the parameters of components along with the positions of the principal MAD-X points inside the accelerator
- The fiducialised component is allocated to its functional position
- The CCS coordinates of the fiducials are calculated, ready for alignment !

Alignment

- Initial installation of an accelerator
- Installation or exchange of individual accelerator components
- Ground movements are one of the big sources for movements inside an accelerator and will trigger regular realignment campaigns

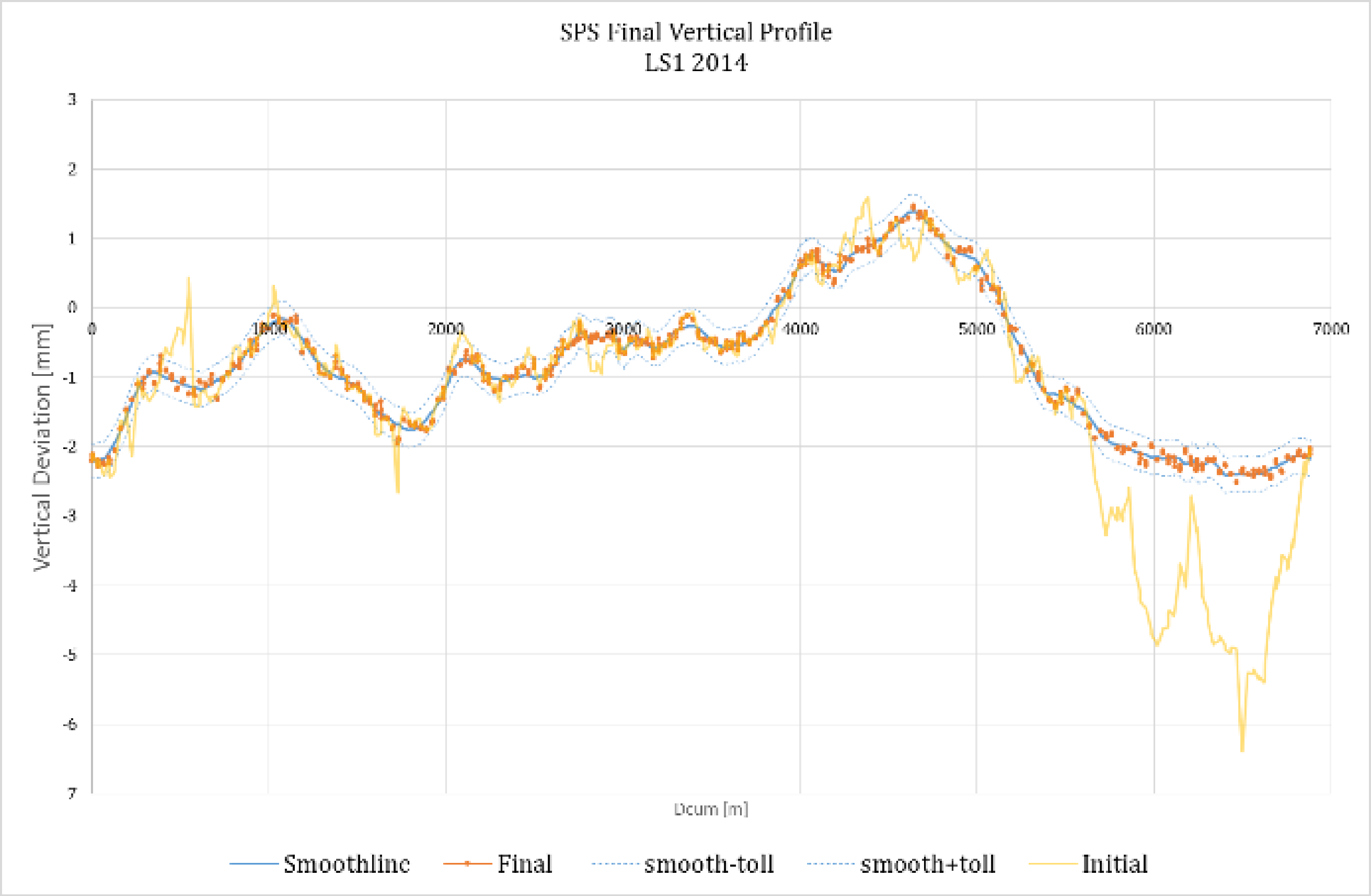




Alignment sequence

- Basis is a common coordinate system (CernCoordinateSystem)
  - Represented by the underground geodetic Network inside the whole complex (monuments)
- Tracing on the floor
  - Marking the vertical projection of beamline and components on the floor (±2mm)
- Positioning of jacks
  - Alignment of the jacks to keep the maximum stroke for future operation (±1mm)
- Initial alignment
  - First alignment of the components with respect to the underground geodetic network (±0.2mm)
- Smoothing of the beamline
  - Smoothing, once the magnets are connected, under vacuum and cold. This ensures the precise relative alignment over a sliding window of 200m within ±0.15mm

Regular smoothing

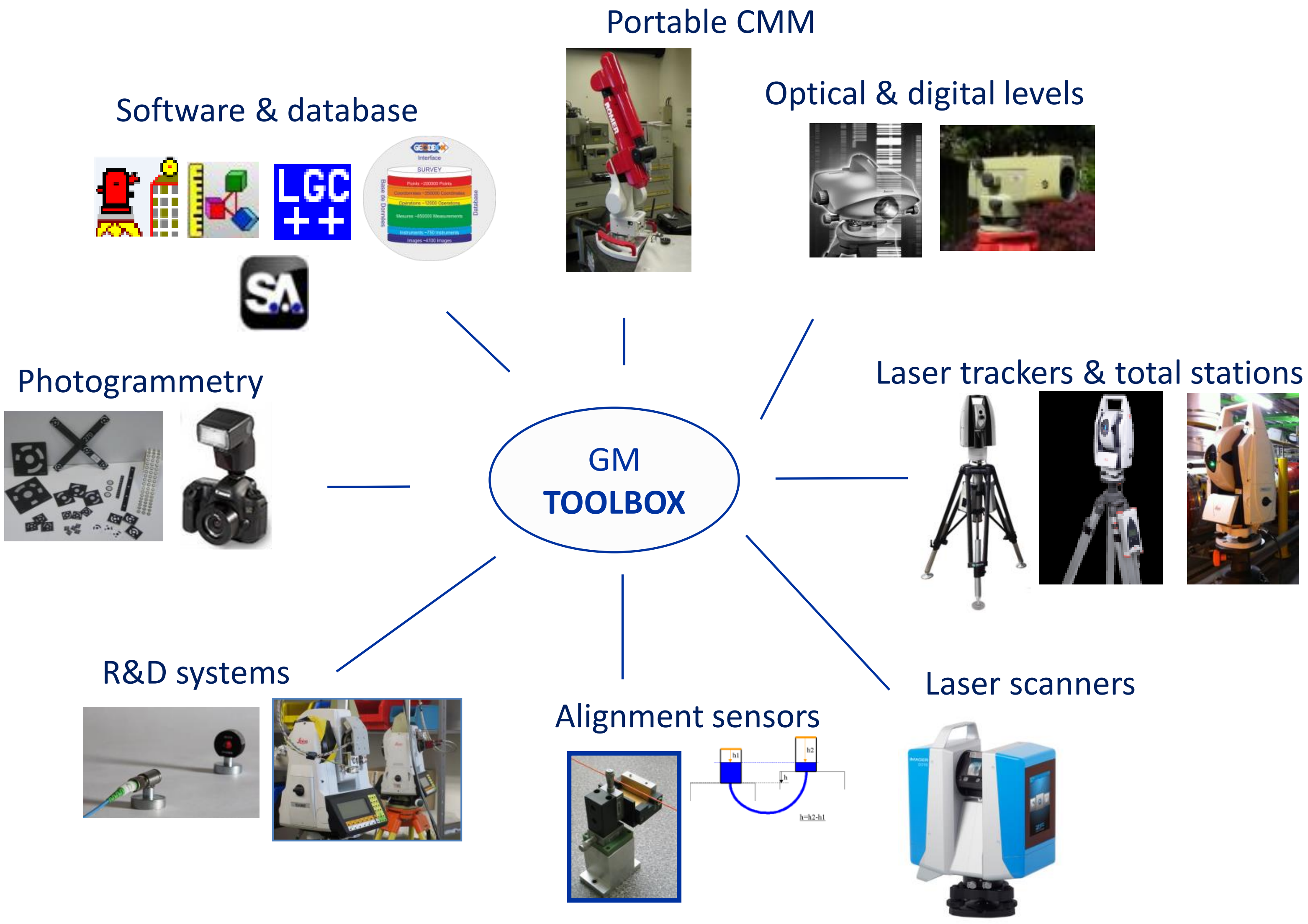


Our Survey toolkit

- **Instruments**
  - Standard
  - Specific
  - Maintenance, Calibration, Validation

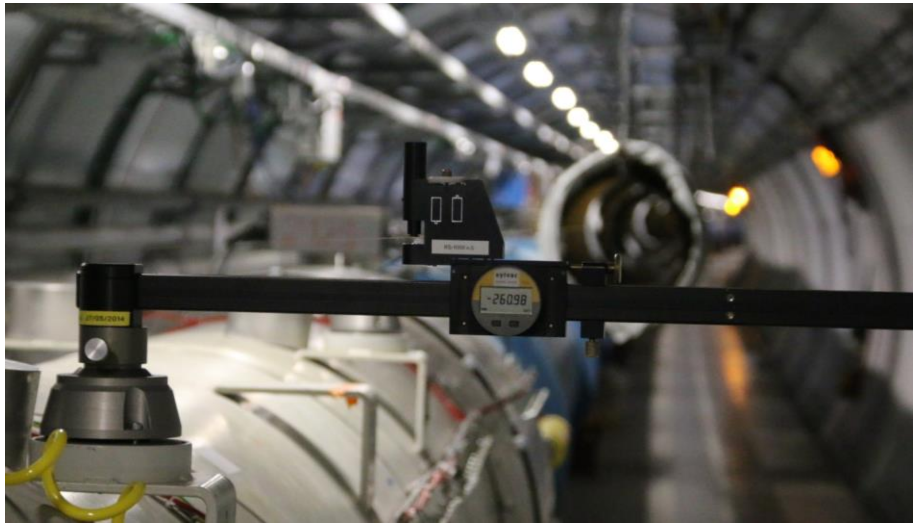
- **Sensors**
  - Permanent monitoring

- **Software & Database**
  - Commercial applications
    - Spatial Analyser
    - Aicon 3D Studio
    - Scan : ZF, Could Compare
  - In-house developments
  - DB SURVEY



Wire offset measurements

- **Radial measurements**
- CERN development (1960s)
  - Avoiding the refraction problems linked to optical methods
  - Speed up the optical methods
  - Simplify the calculations (60 years ago, no portable computers...!)
- Still used today to stabilize the geometry over long distances



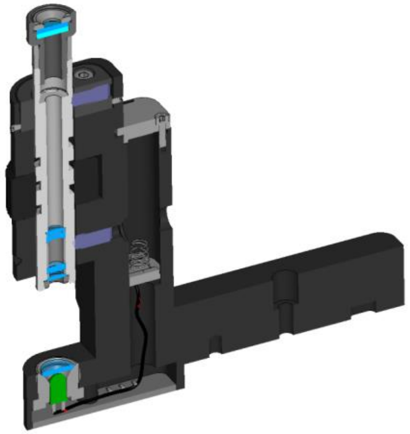
Manual device accuracy < 0.06mm

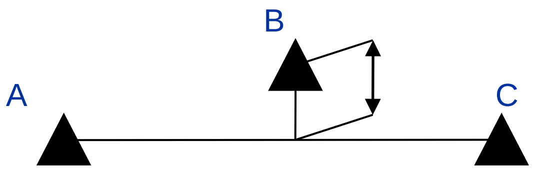
The wire need to be stretched

Automatic device

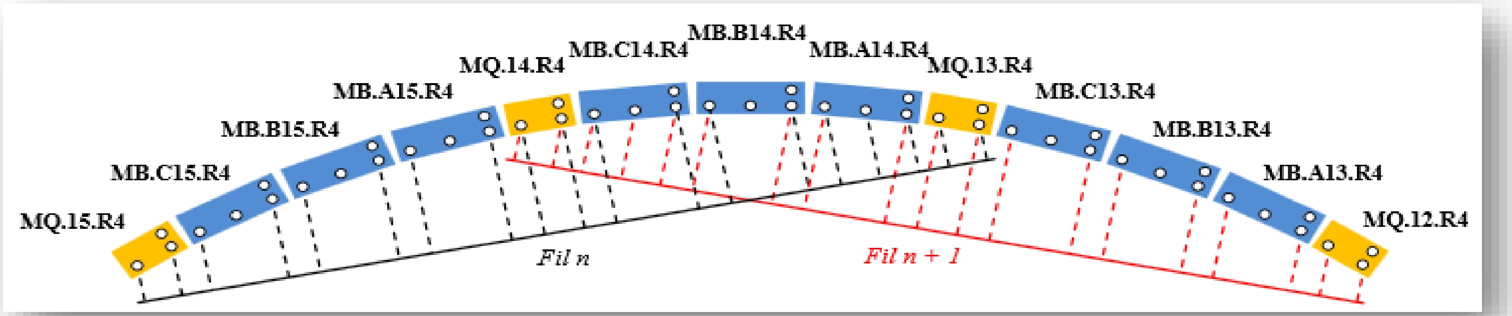
Offset device - Wire offset measurements

- The stretched wire [AC] is used as a common reference, ~ 120 m
- Measurement of the perpendicular distance between a point and the line [AC]
- Very sensitive to systematic :
  - Stability of the wire extremity
  - Air flow / ventilation
- 50% overlap of wires for redundancy
- Precision is almost independant of the wire length





Offset measurement



Alignment systems

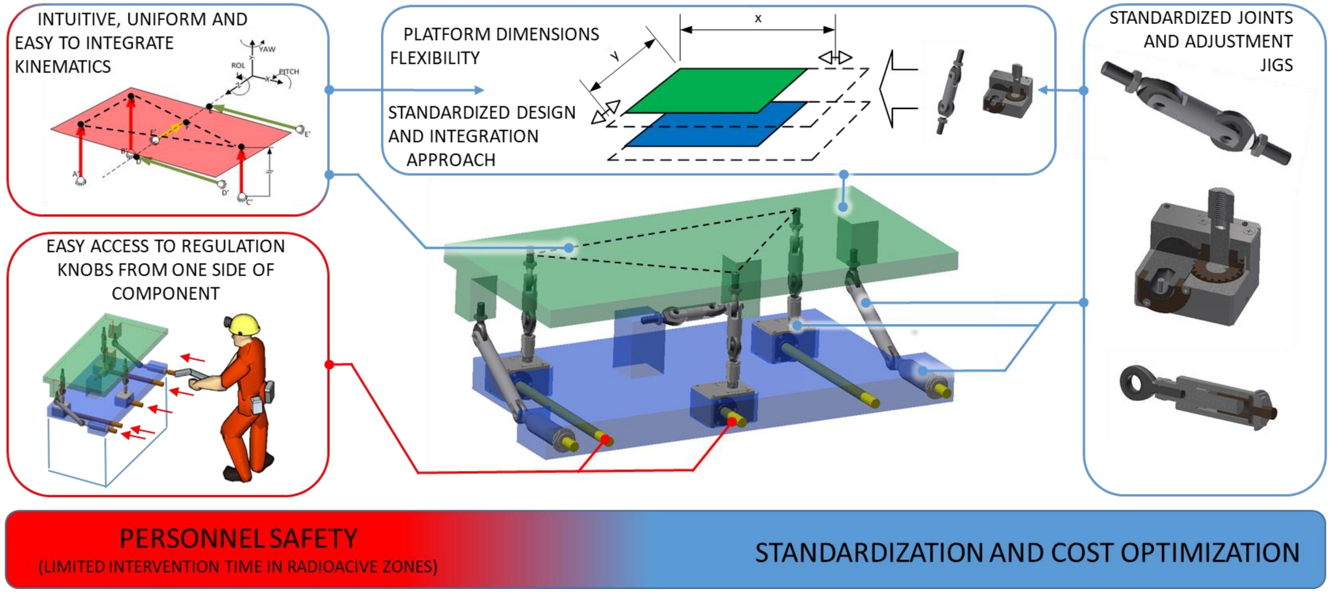
- A good system is supporting the component isostatic
- Rigid and stable, able to cope with the initial load and additional vacuum forces
- Independent movements for the 6 degrees of freedom
- Easily accessible
- Usable with a reasonable force

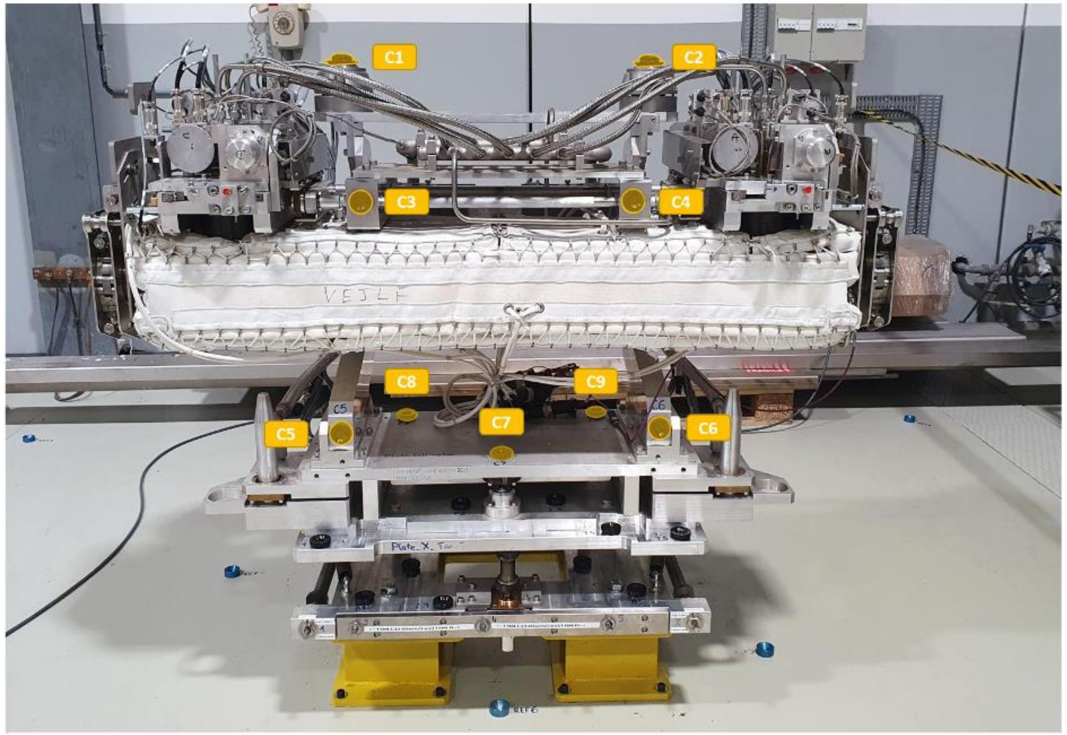
Alignment systems

- A large palette of systems available, good and bad ones!

Alignment systems

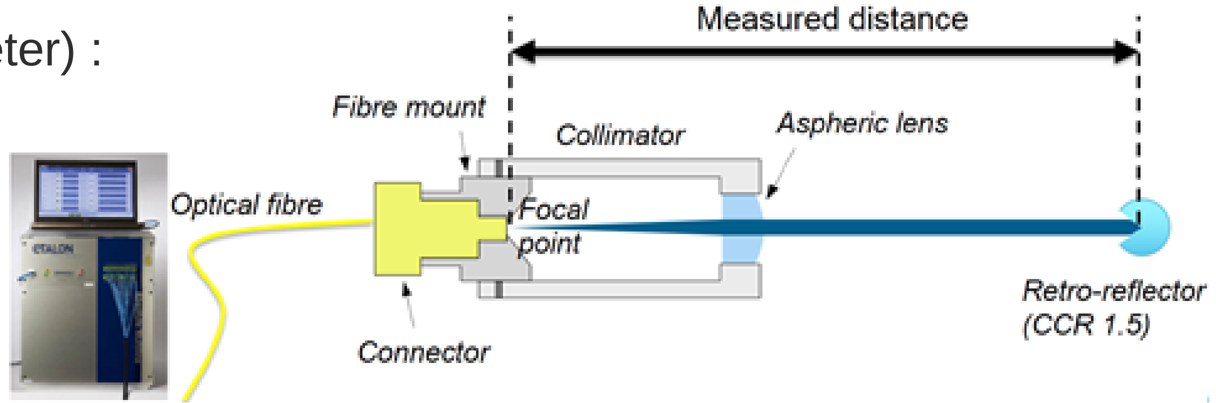
- A new approach is the universal alignment platform UAP
  - All adjustment knobs on one site, universal interface for motorisation
  - Free of backlash
  - +-10mm range with 50µm adjustment precision





Internal monitoring

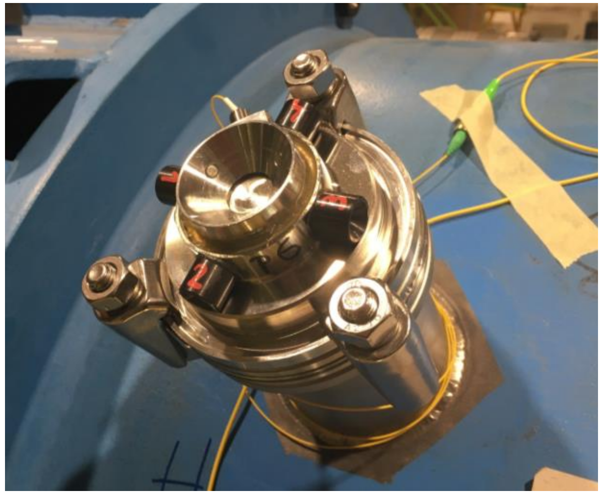
- **HL-LHC triplets will be equipped with an internal monitoring system**
- **FSI : Frequency Scanning Interferometry**
  - Allows absolute distance measurement (interferometer) :
  - With high accuracy (µm level)
  - With no contact
  - Uncertainty (95%) = 0.5 µm/m
  - Measurement distance: 0.2 – 20 m



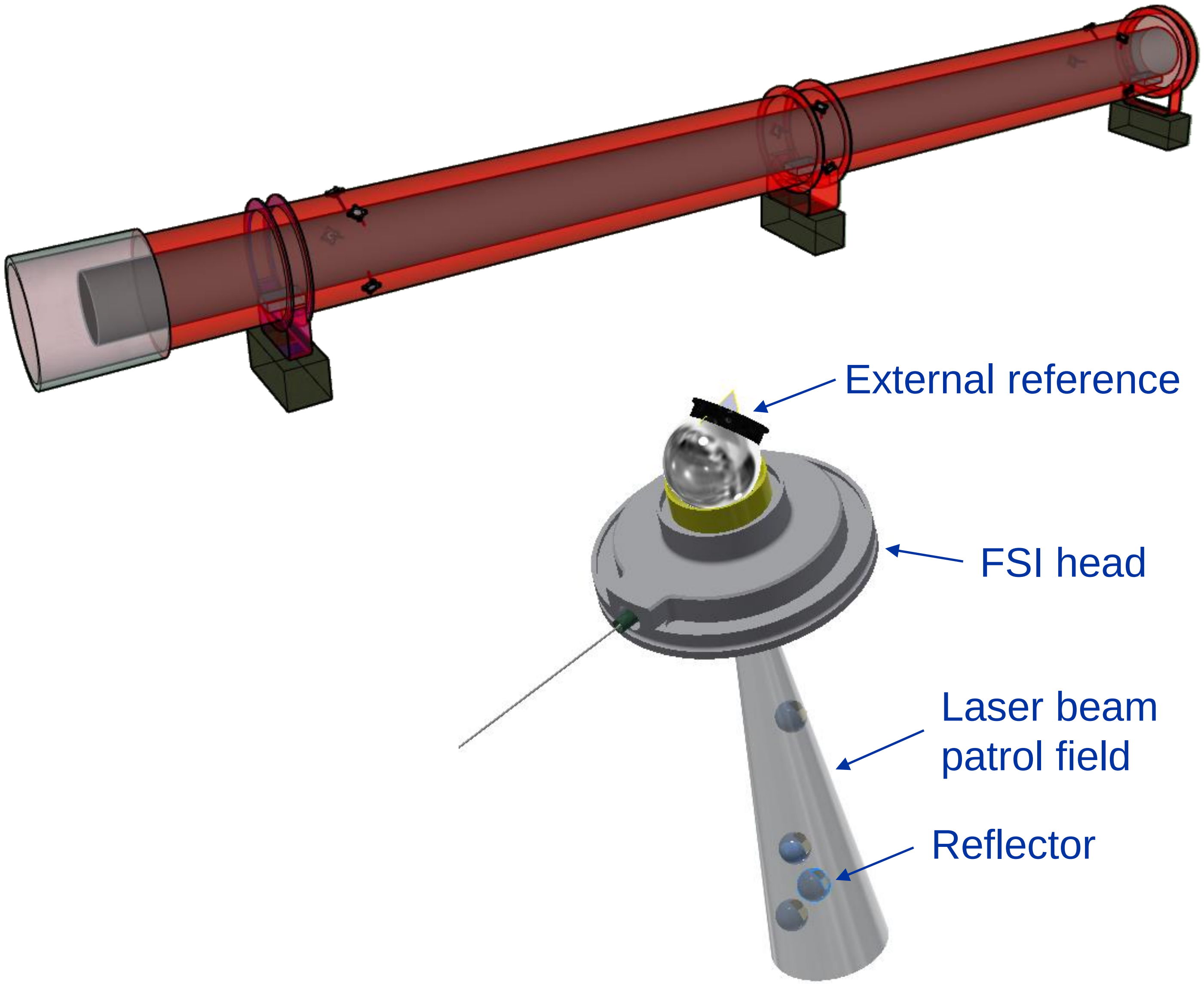
- **Multi-target FSI** : New approach to FSI signal analysis
  - Fourier based distance calculation from detected beat frequencies
  - Allows for measurements of absolute distance to multiple targets
  - Possible to use with the collimated and divergent beams
  - Measurement uncertainty <5 µm (single laser configuration, no vibrations)
  - Collimated and divergent beams compatible

Internal monitoring

Feedthrough
on Vacuum vessel



Reflecting target
(glass sphere)
on cold mass



External reference

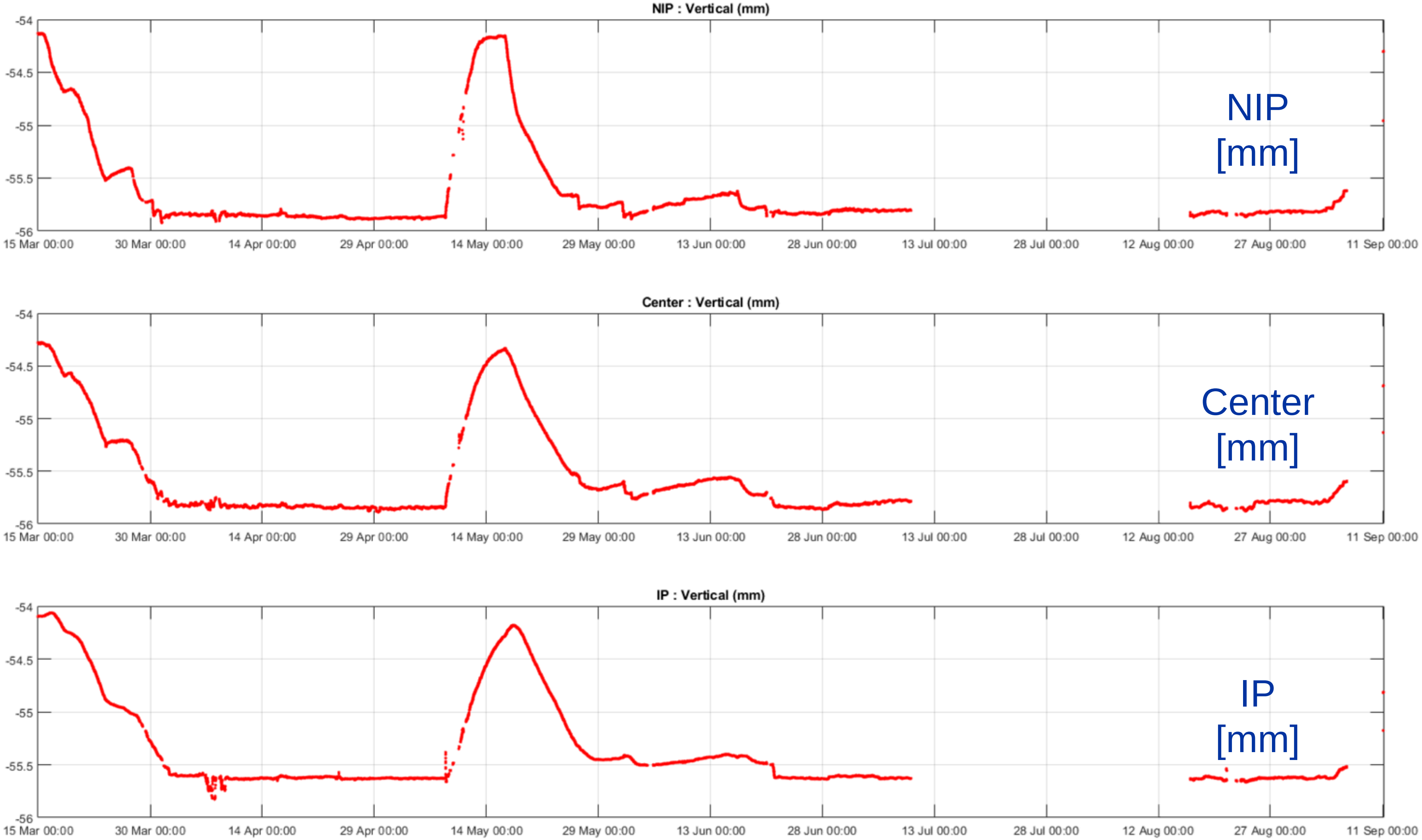
FSI head

Laser beam
patrol field

Reflector

Courtesy Vivien Rude

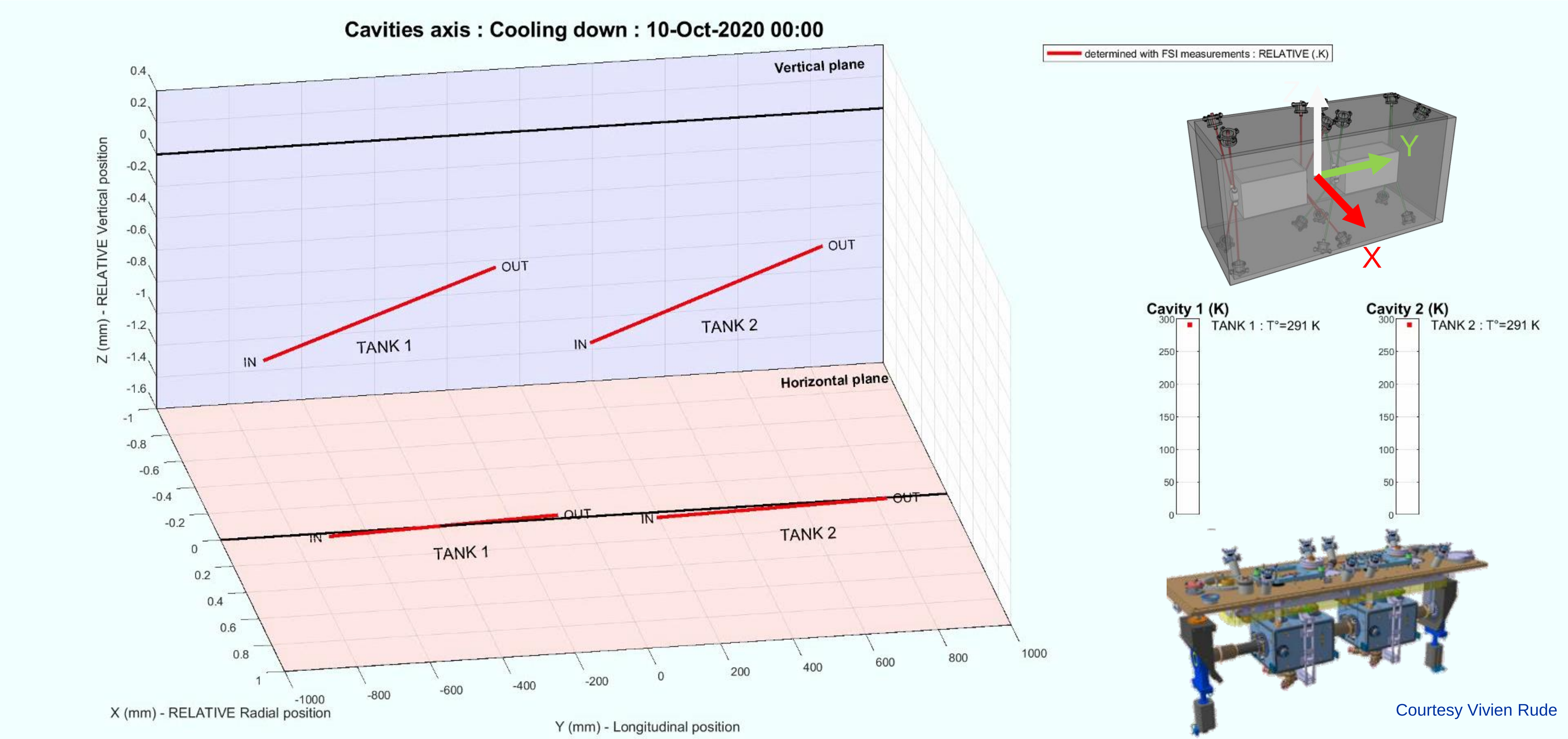
FSI results for Q3 cooldown



First Q3 Assembly @ FNAL

Courtesy Vivien Rude

Crab cavity cooldown in SPS



Courtesy Vivien Rude

Conclusion

- Many different and complementary measurement methods exist
  - CMM`s portable or stationary, Laser Trackers, Photogrammetry, Scanners, Sensors, magnetic measurements…….
  - But none of them is giving automatically final and controlled results
  - Even the latest and most advanced Instrument needs a competent operator
  - Get in touch with your experts
  - Minimize your grey zones
  - Feel free to combine different technologies

Conclusion

- Metrology, fiducialisation and alignment is about
  - A coherent approach from the design to the final alignment….
  - A joint and multidisciplinary discussion on the requirements
- We need
  - A realistic study of the uncertainty budgets all along the process!
  - The right choice in terms of instrumentation
  - A controlled and redundant measurement setup
  - Reliable and stable references and supports

Very small details can make a huge difference in this domain

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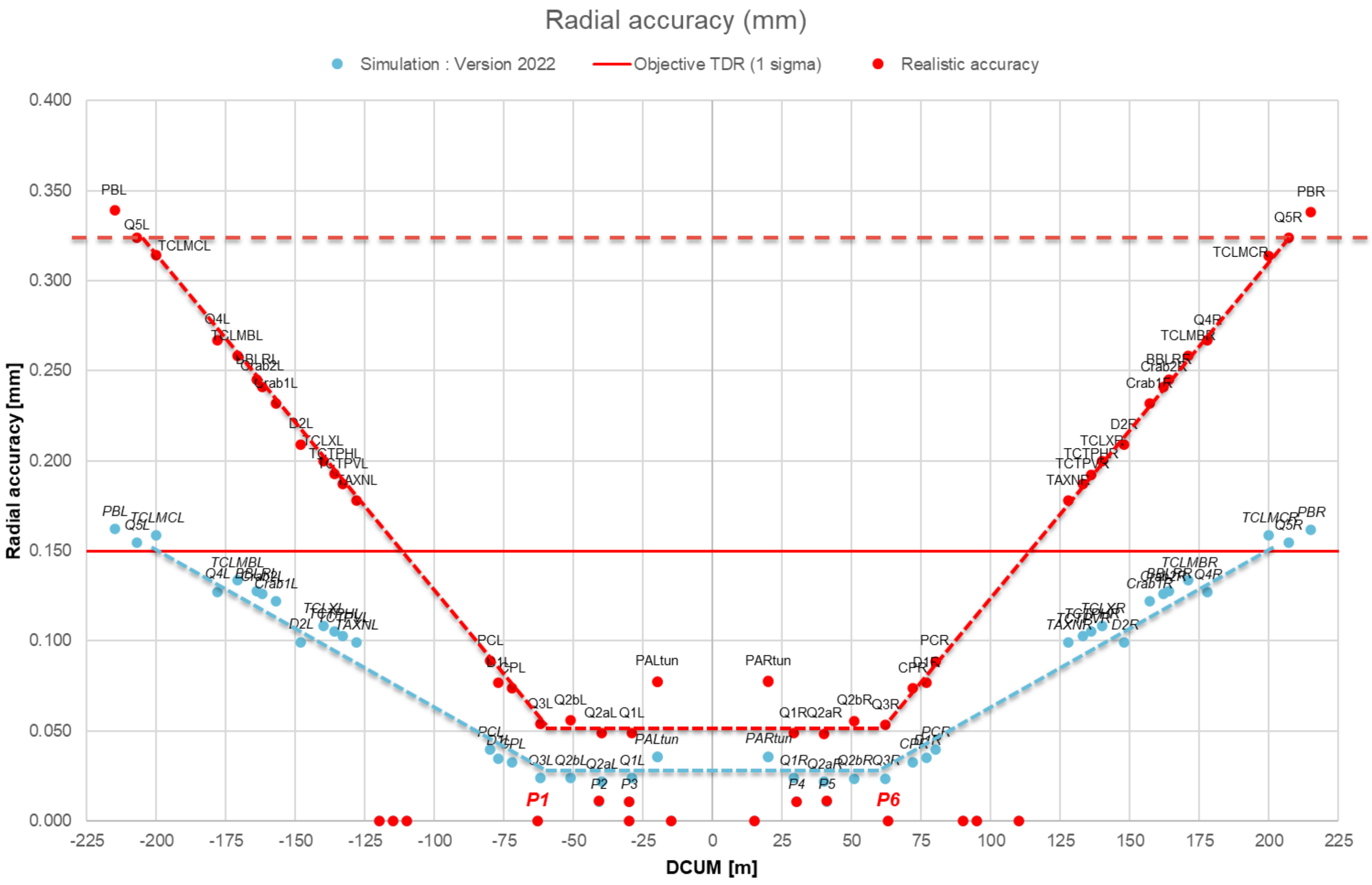
Uncertainty budget / error propagation



25µm change in position uncertainty