Mini-CAS - Course on Mechanical and Materials Engineering for Accelerators, 6.11.20-22.01.21

METROLOGY

Ahmed CHERIF
EN/MME-MM, CERN - 27th November 2020

Ahmed.Cherif@cern.ch

Outline

1. History of Metrology
2. Introduction to Metrology
3. Metrology equipment
4. Approach to CMM measurement
5. Examples

History of Metrology

- Up to French Revolution, arbitrary standards based on:
  - Local kings or governors such:
    - foot,
    - inch,
    - line: 1/12th of inch,
  - Journal
  - Pint.
- Non decimal System (12th, 60^{th,} 64$^{th...}$)
- But... How to do to understand?
  - Germany: 19 different feet,
  - Europe: 18 others.

Trade and exchanges were difficult, and abuse and scams were frequent

History of Metrology

After the French revolution, the French scientists began to work quickly and define the meter

Charles-Maurice de TALLEYRAND-PÉRIGORD (1754-1838)

- Understandable (comprehensible)
- For all for ever
- Non arbitrary standards

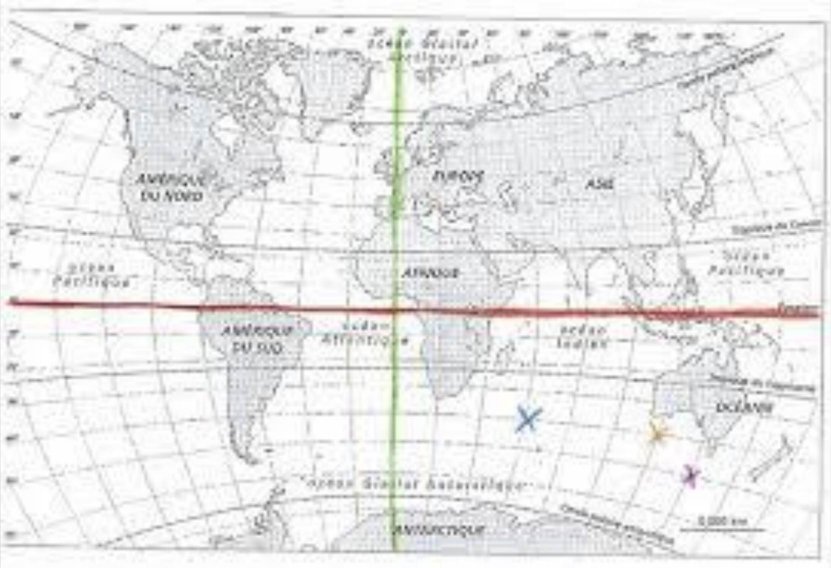
Jean-Baptiste Joseph DELAMBRE (1747-1822)

Pierre-François MECHAIN (1744-1804)

In March 1790, he proposes a

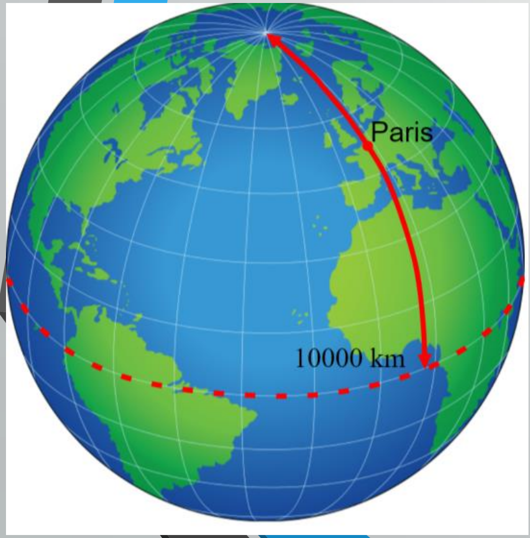
System of Unification of the Measurements

Birth of the Meter



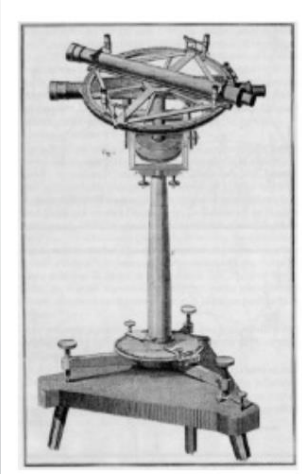
The green meridian

On the 26th of March **1791** define the meter as **1/10 000 000 part of the quarter of the meridian of the earth.**



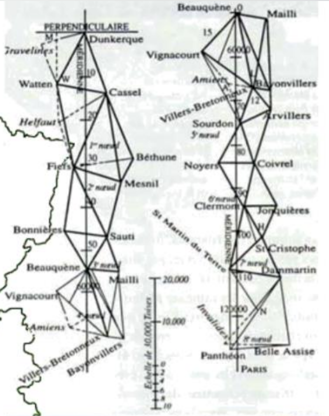
- The idea of the meter is:
  - **Universal unit**
  - **Not linked to a person**

The meter, from Greek "metron"
Which means measurement

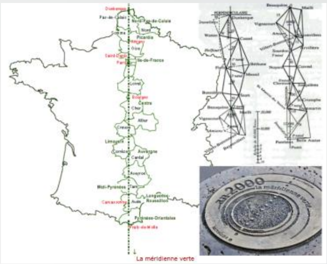


DUNKERQUE

MONTJUIC (BARCELONE)



Evolution of the definition of the Meter



1791 — **1/10 000 000 part of the quarter of the meridian of the earth.**

1796

1797 — Fabrication of 10 standards of the meter in Paris

1889

1960 — The bars were to be made of a special alloy, **90% platinum and 10% iridium**, have a special X-shaped cross section used as an international standard.

1960 — The 11th **General Conference on Weights and Measures (CGPM) redefine the meter as** a length equal to **1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels 2p10 and 5d5 of the krypton 86 atom.**

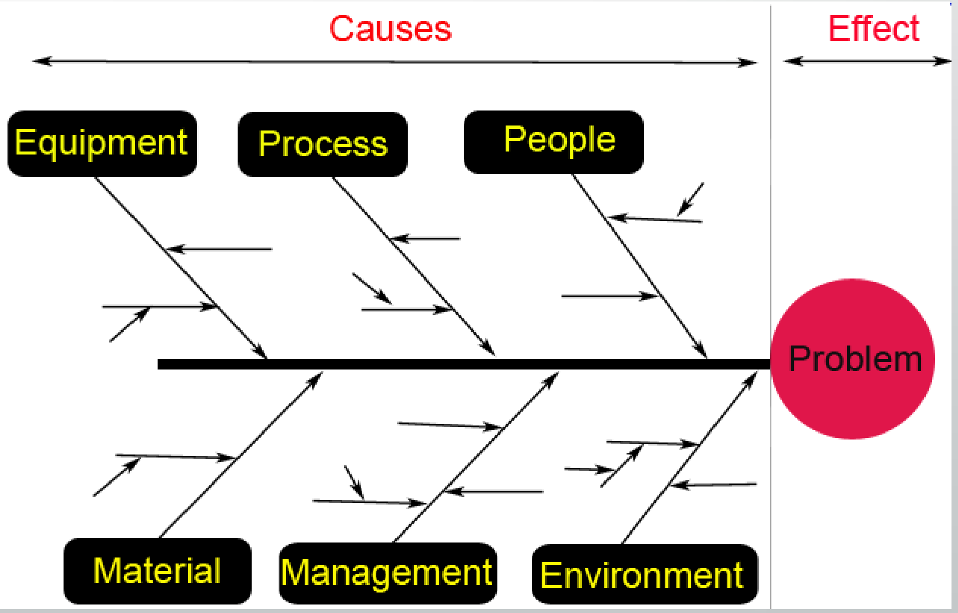
1983 — The 17th CGPM redefine **the meter is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second**

What is the point of measuring ?

- Quantify the physical quantities
- Help for decision (conform, non conform, dangerous ...)

False or erroneous results could lead to serious consequences

- **Hence the need for reliable results**
  - Reliable result minimizes the risk of measurement errors and their consequences
    - **Reliable results can be obtained by the whole process analysis**
      - **A fishbone (ISHIKAWA) diagram could help**



Measurement process

- The measurement can be done :
  - With **measurement instrument**
  - Or with a measurement machine.

  This gives a number or numbers

  - **By comparison** :
    - Length : a graduated ruler,
    - Angles : an angle protractor,
    - Mass: a balance with masses

  - **By transformation** of a physical phenomenon by an electric current.

Most of modern devices work on this principle

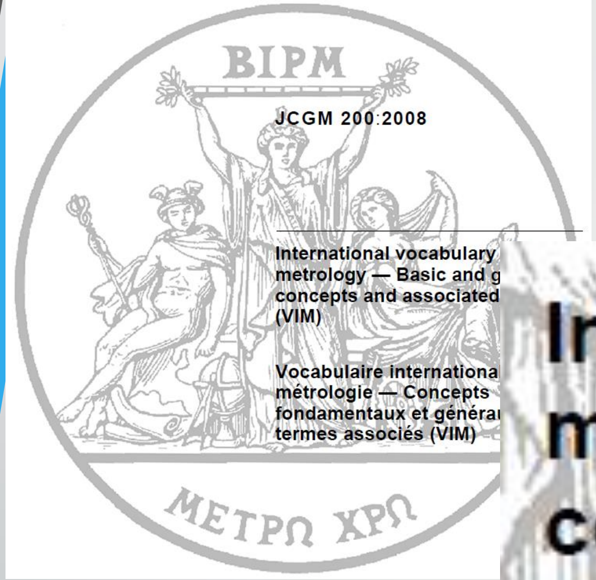
Digital device

Types de Metrology

- Separated in 3 categories
  - Fundamental or scientific metrology
  - Industrial metrology
  - Legal metrology

VIM - International Vocabulary of Metrology

In **1997** the Joint Committee for Guides in Metrology (JCGM) : **International vocabulary of metrology — Basic and general concepts and associated terms (VIM)**



International vocabulary of metrology — Basic and general concepts and associated terms (VIM)

Vocabul
métrolog
fondame
termes a

JCGM 200:2008 (E/F)

4.14
resolution
smallest change in a **quantity** being measured that causes a perceptible change in the corresponding **indication**

NOTE Resolution can depend on, for example, noise (internal or external) or friction. It may also depend on the **value** of a quantity being measured.

4.14
résolution, f
plus petite variation de la **grandeur** mesurée qui produit une variation perceptible de l'**indication** correspondante

NOTE La résolution peut dépendre, par exemple, du bruit (interne ou externe) ou du frottement. Elle peut aussi dépendre de la **valeur** de la grandeur mesurée.

4.15 (5.12)
resolution of a displaying device
smallest difference between displayed **indications** that can be meaningfully distinguished

4.15 (5.12)
résolution d'un dispositif afficheur, f
plus petite différence entre **indications** affichées qui peut être perçue de manière significative

Norms

- ISO 1 - Standard reference temperature for geometrical product specification and verification"
- ISO 286 - *System of limits and fits*
- *ISO 5458 - Positional tolerancing*
- ISO 5459 - *Geometrical tolerancing*
- ISO 2692 - *Maximum material requirement (MMR), least material requirement (LMR) and reciprocity requirement (RPR)*
- ISO 10579 - *Dimensioning and tolerancing -- Non-rigid parts*
- ISO 8015 - *Fundamentals -- Concepts, principles and rules*
- ISO 1101 - *Geometrical tolerancing -- Tolerances of form, orientation, location and run-out*
- ISO 10578 - *Tolerancing of orientation and location -- Projected tolerance zone*
- ISO 3040 - *Dimensioning and tolerancing -- Cones*
- ISO 1302 - *Geometrical Product Specifications (GPS) -- Indication of surface texture in technical product documentation*
- ISO 2768 - *General tolerances*
- ISO 13715 - *Edges of undefined shape*

... and many others

Too many Norms...

but we need all of them !!

ISO 1 - Standard Reference Temperature

- **ISO 1** is a standard
  temperature for g

Material	Linear CTE (x 10^{-6} K^{-1})
Aluminium	24
Copper	17
Austenitic Stainless steel	16
Steel	10.8 to 13
Silicon	2.56
Invar	1.2
Glass-ceramic (Zerodur®)	0,01 - 0,02

CERN ABOUT NEWS SCIENCE

is the first major step in the technical validation of a full-scale portion of the LHC," explained LHC project leader Lyndon Evans.

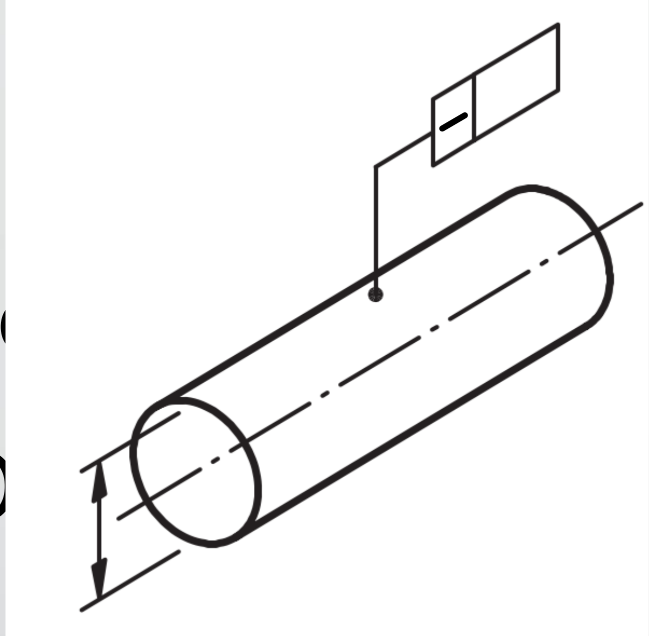
There are three parts to the cool down process, with many tests and intense checking in between. During the first phase, the sector is cooled down to 80 K, slightly above the temperature of liquid nitrogen. At this temperature the material will have seen 90% of the final thermal contraction, a 3 millimetre per metre shrinkage of steel structures. Each of the eight sectors is about 3.3 kilometres long, which means shrinkage of 9.9 metres! To deal with this amount of shrinkage, specific places have been design... ...mpensate for it, including expansion bellows for pipin... ...slack. Tests are done to make sure no h...

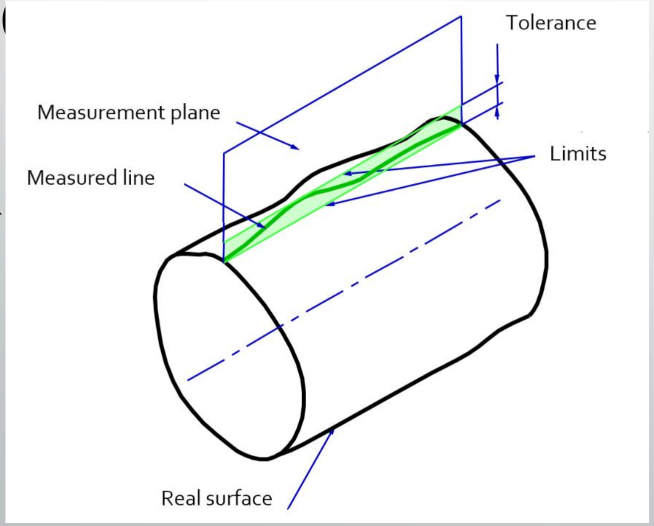
The second phase brings... ...frigerators. Each sector has its own refrigerator and e... ...main magnets is filled with liquid helium, the coolant of choice for the LHC because it is the only element to be in a liquid state at such a low temperature.

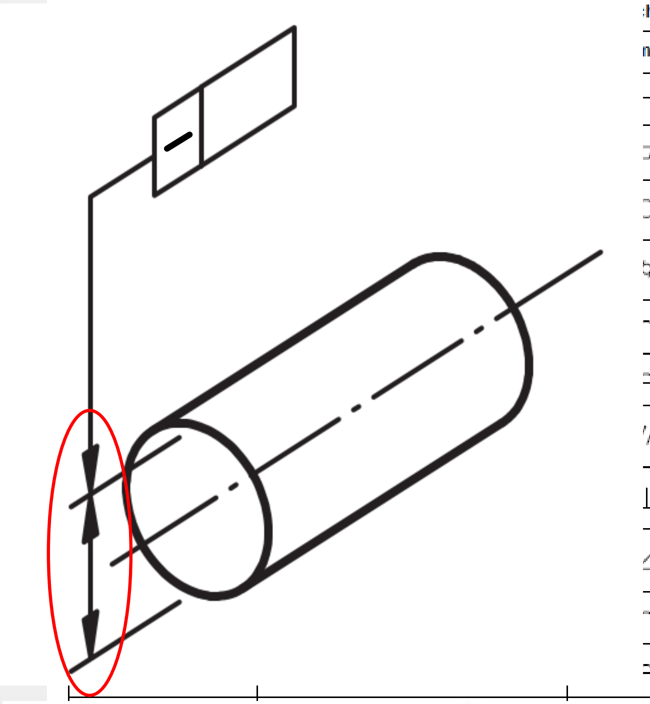
45 mm for the LHC
Cold Mass of 15 meters

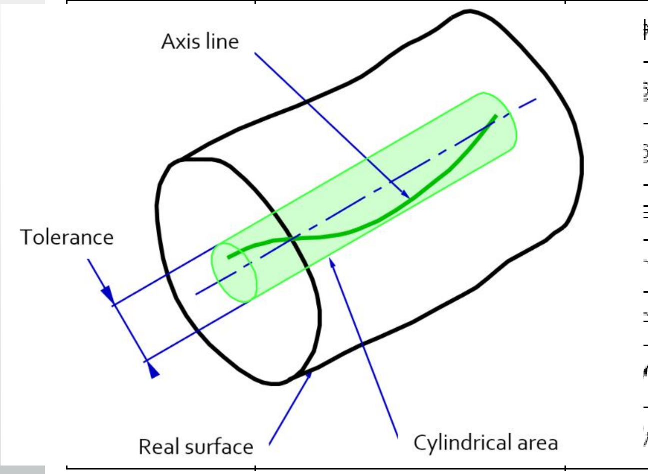
ISO 1101 - (GPS) Geometrical Product Specifications

- F
- O
- L
- R





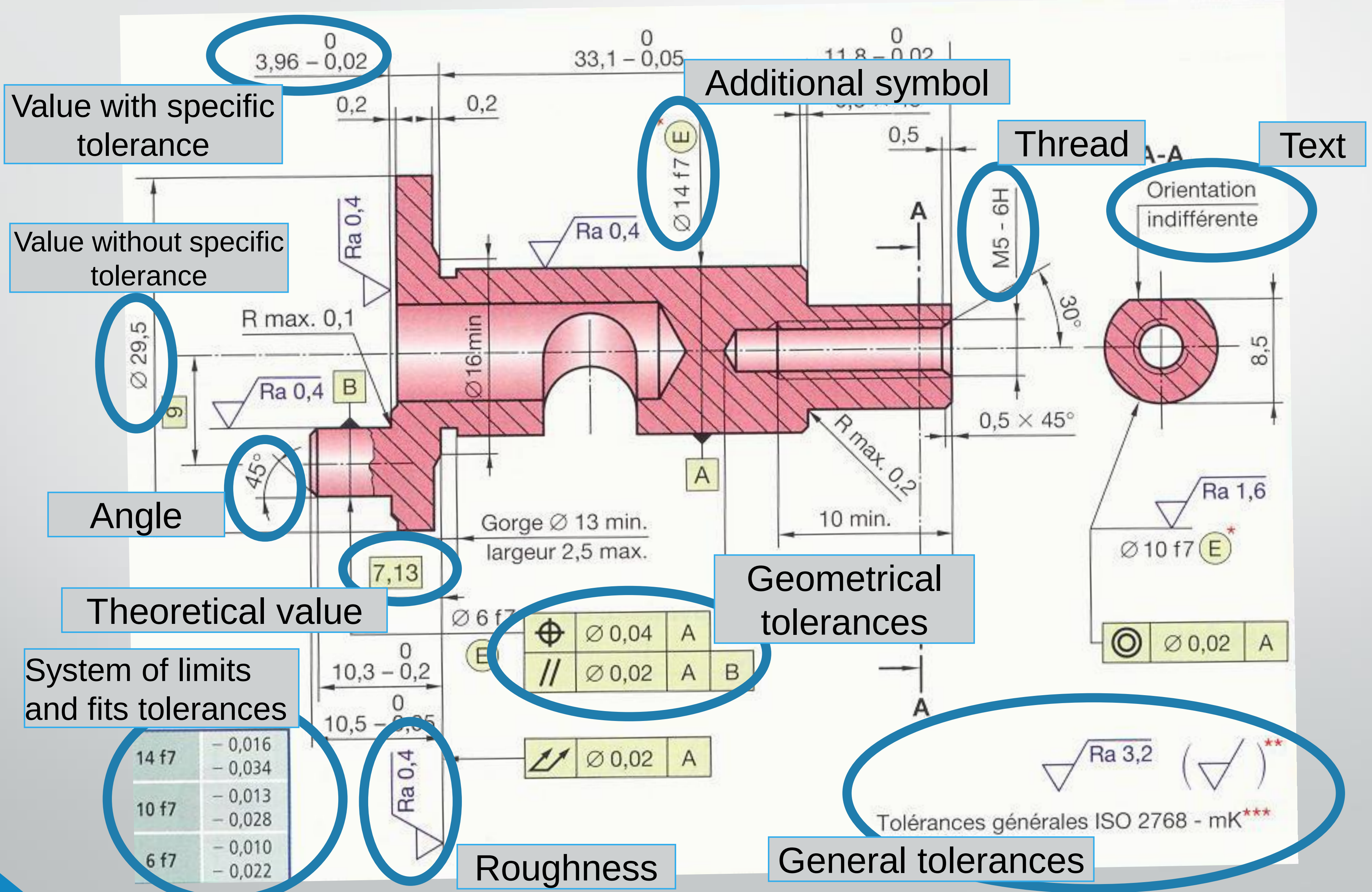




haracteristics

nbol	Datum needed	Subclause
	no	18.1
	no	18.2
	no	18.3
	no	18.4
	no	18.5
	no	18.7
	yes	18.9
	yes	18.10
	yes	18.11
	yes	18.6
	yes	18.8
	yes or no	18.12
	yes	18.13
	yes	18.13
	yes	18.14
	yes	18.6
	yes	18.8
	yes	18.15
	yes	18.16

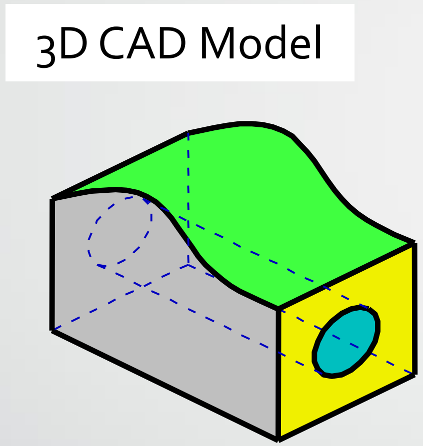
Technical drawings

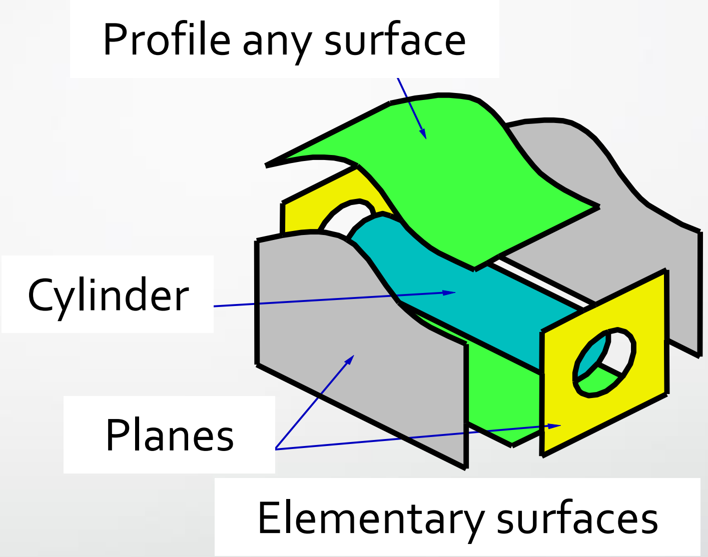


Dimensioning and tolerancing

Geometric model of a part form the design office

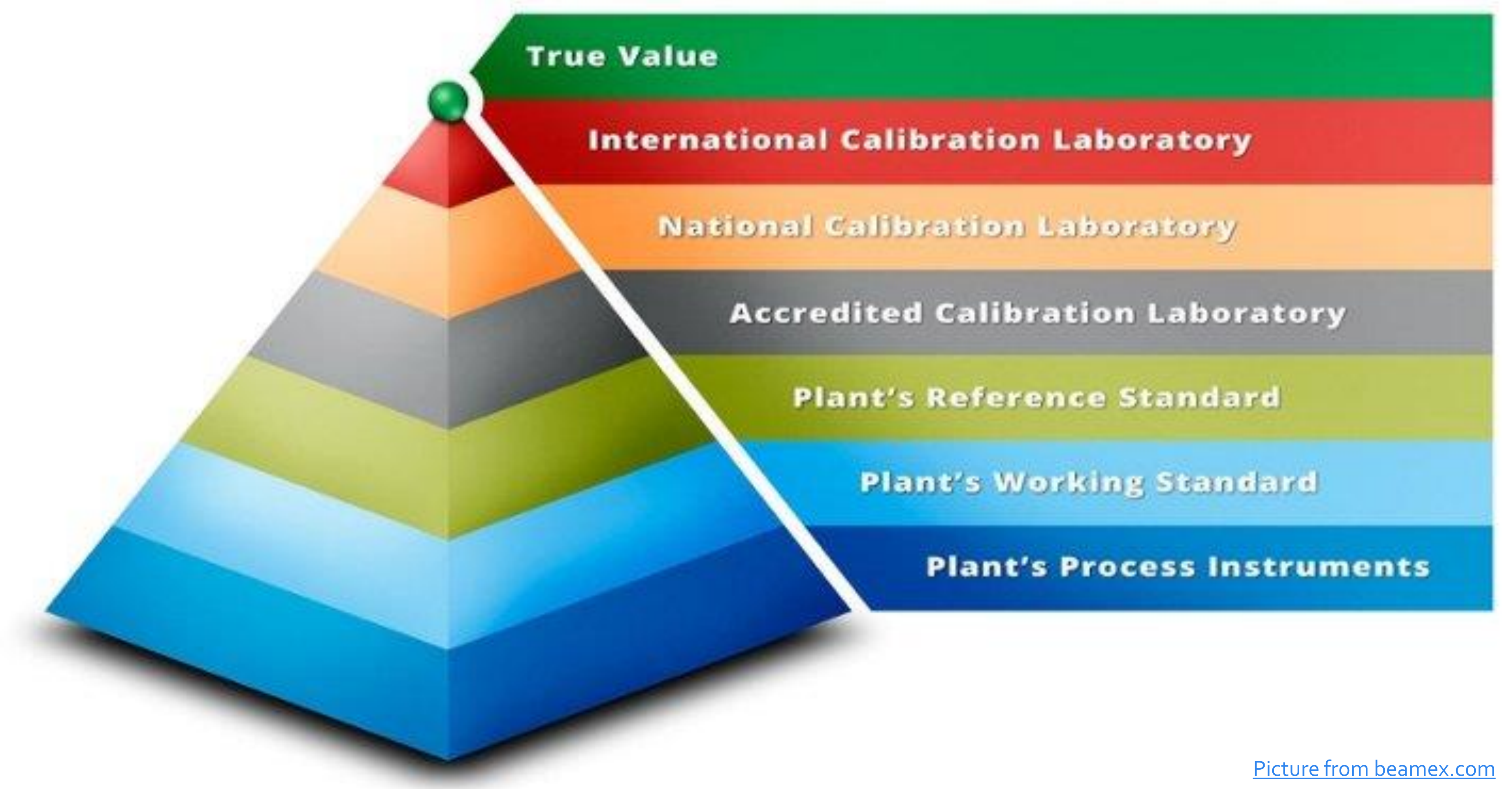
- The part is considered as elementary surfaces.





- **Dimensioning**: To define, by a 2D drawing or a 3D CAD, the shape, the size, the position with respect to other surfaces of all the elementary surfaces of the part.
- **Tolerancing:** To define, with tolerances, the maximum deviations of the reel surfaces with respect to theoretical surfaces (perfect surfaces).

Traceability – Chain of measurements



Picture from beamex.com

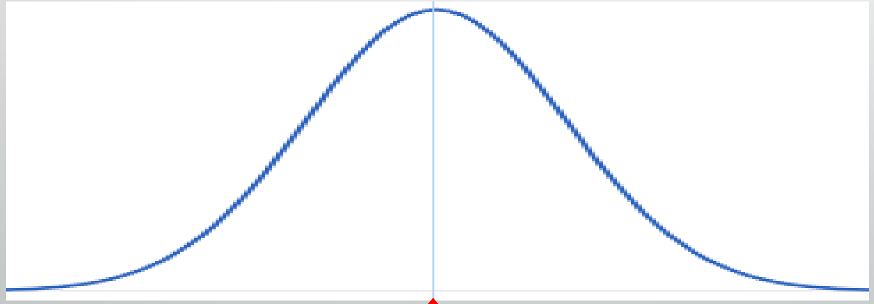
Measurement uncertainty

- The GUM (**Guide to the Expression of Uncertainty in Measurement**) **defines measurement uncertainty** as a "parameter, associated with the result of a **measurement**, that characterizes the dispersion of the values that could reasonably be attributed to the measurand"

L=321.32 ± 0.05 mm

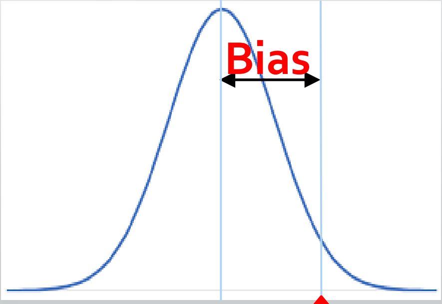
- Measurement ≠ true value
- Deviations are called errors
- 2 sources of errors:

Random errors



True value

Systematic errors



True value

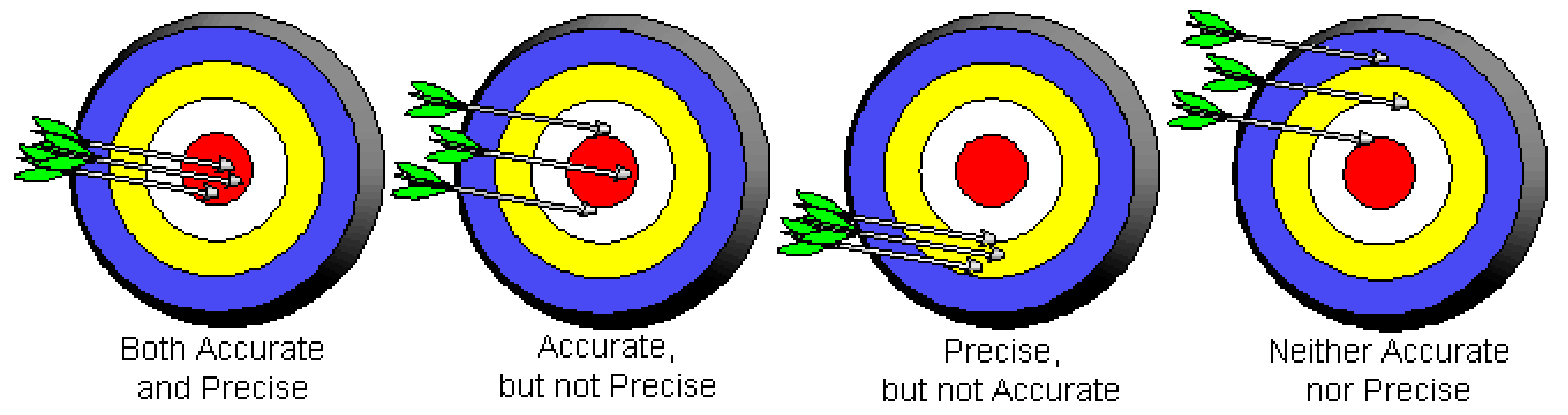
Accuracy vs Precision

Accuracy

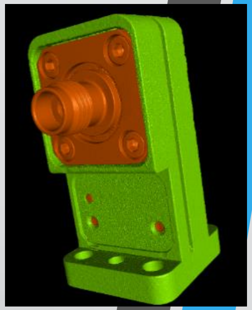
How close are the measurements to the true value.

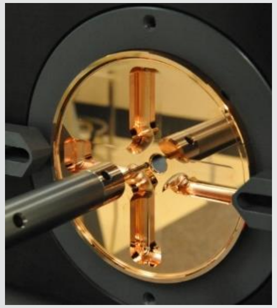
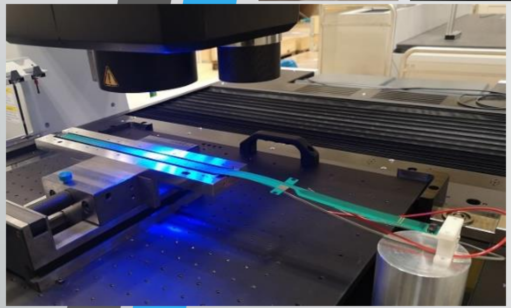
Precision

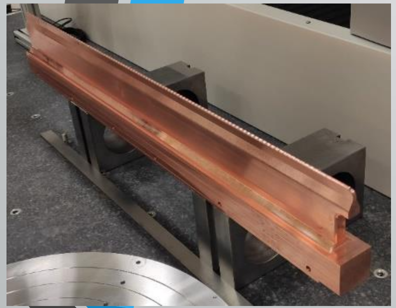
How reproducible are the measurements?

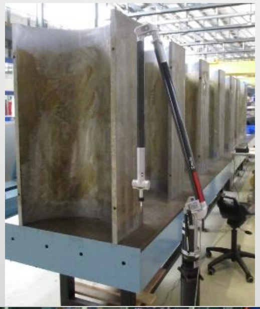


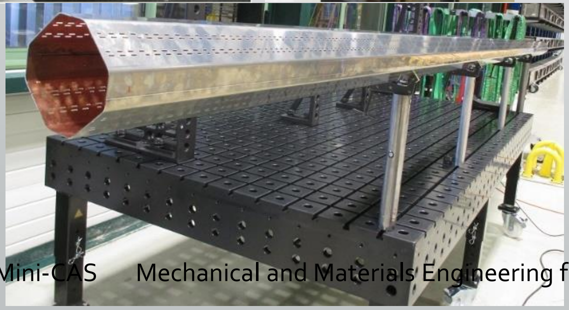
Dimensional measurement at CERN

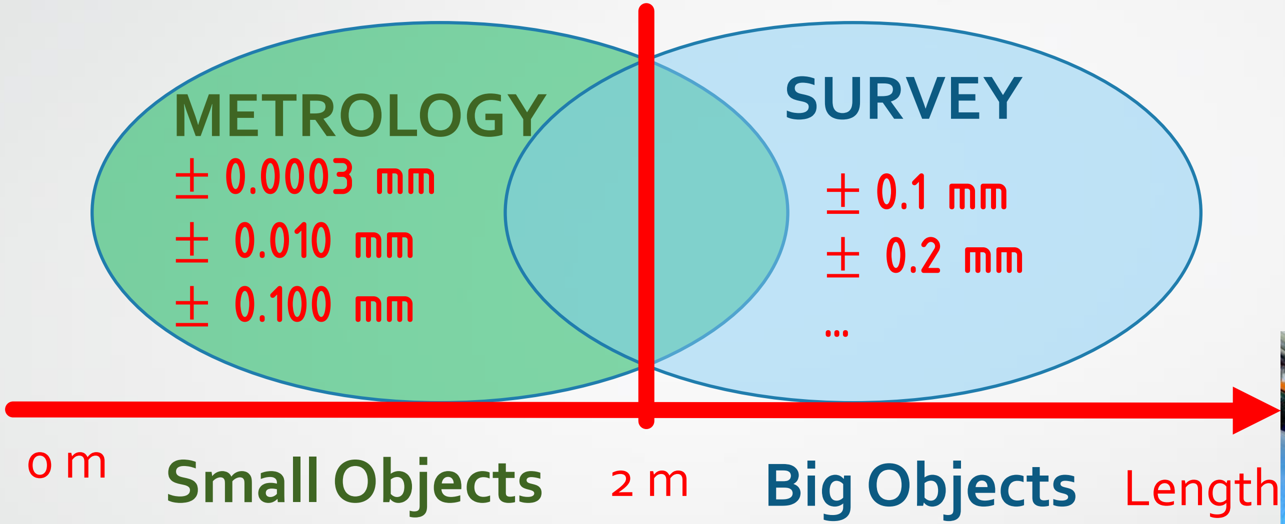


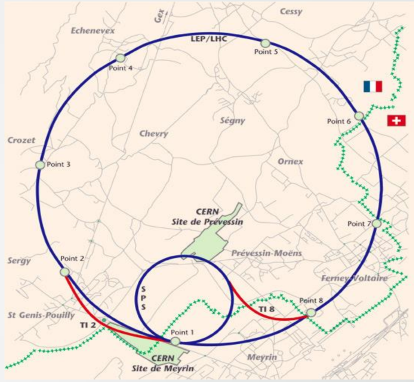
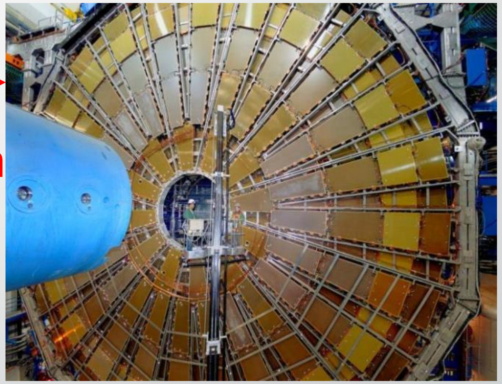



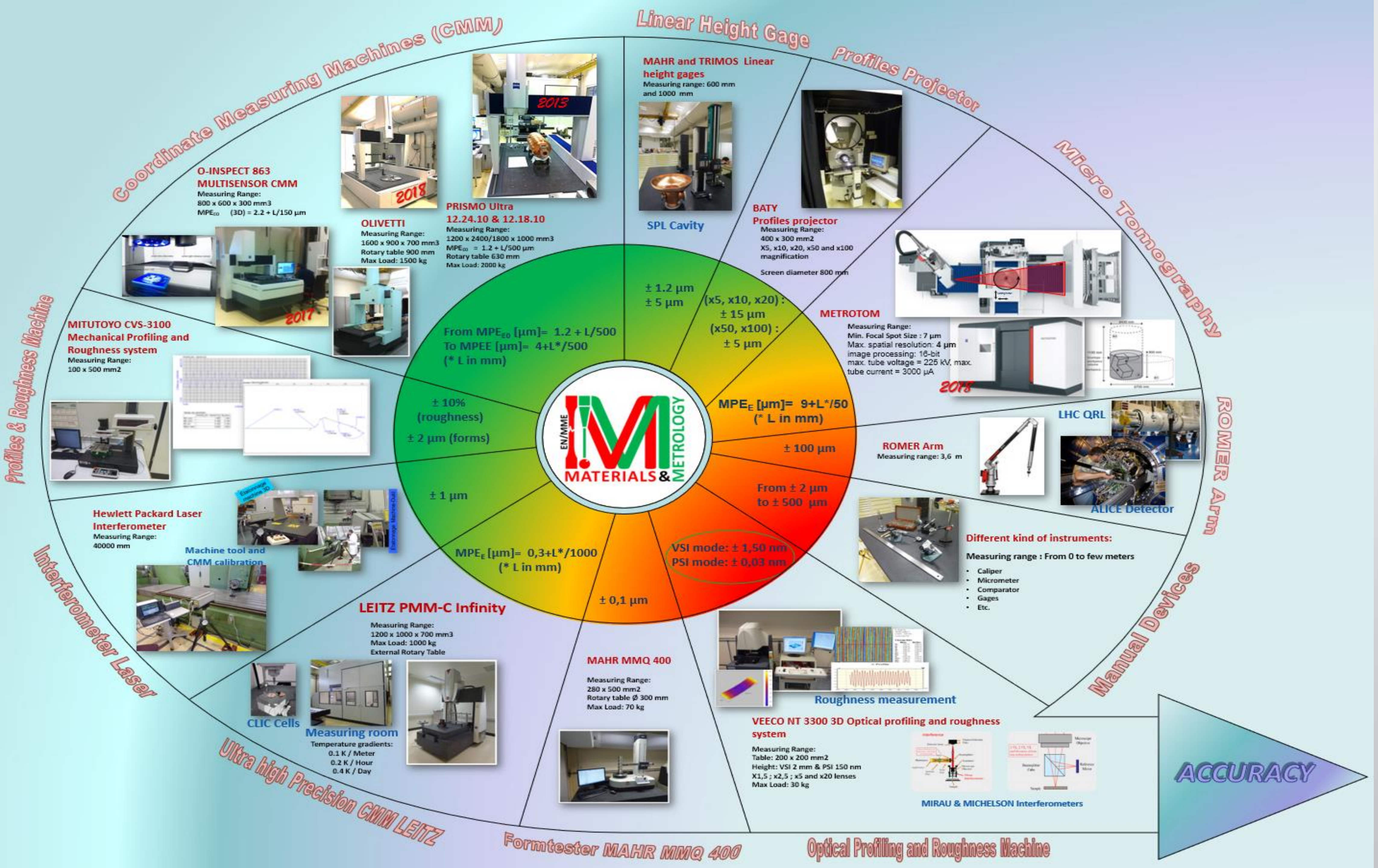








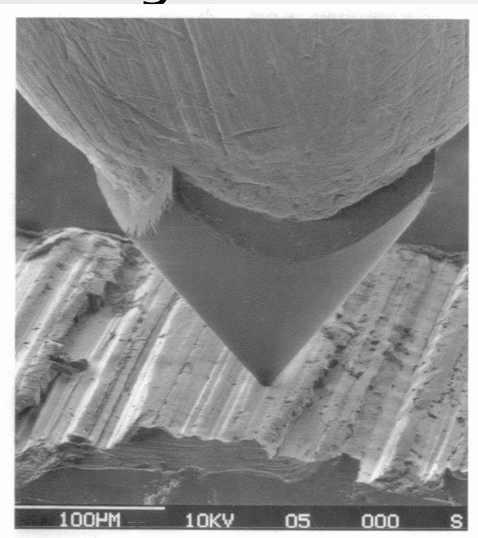



Coordinate Measuring Machines (CMM)
Linear Height Gage
Profiles Projector
Micro Tomography
ROMER Arm
Manual Devices
Optical Profiling and Roughness Machine
Formtester MAHR MMQ 400
Ultra high Precision CMM LEITZ
Interferometer Laser
Profiles & Roughness Machine
O-INSPECT 863 MULTISENSOR CMM
Measuring Range:
800 x 600 x 300 mm3
MPE (3D) = 2.2 + L/150 µm
2017
OLIVETTI
Measuring Range:
1600 x 900 x 700 mm3
Rotary table 900 mm
Max Load: 1500 kg
2018
PRISMO Ultra
12.24.10 & 12.18.10
Measuring Range:
1200 x 2400/1800 x 1000 mm3
MPE = 1.2 + L/500 µm
Rotary table 630 mm
Max Load: 2000 kg
2013
MAHR and TRIMOS Linear height gages
Measuring range: 600 mm and 1000 mm
SPL Cavity
BATY
Profiles projector
Measuring Range:
400 x 300 mm2
X5, x10, x20, x50 and x100 magnification
Screen diameter 800 mm
METROTOM
Measuring Range:
Min. Focal Spot Size : 7 µm
Max. spatial resolution: 4 µm
image processing: 16-bit
max. tube voltage = 225 kV, max. tube current = 3000 µA
2018
LHC QRL
ROMER Arm
Measuring range: 3,6 m
ALICE Detector
Different kind of instruments:
Measuring range : From 0 to few meters
Caliper
Micrometer
Comparator
Gages
Etc.
Roughness measurement
VEECO NT 3300 3D Optical profiling and roughness system
Measuring Range:
Table: 200 x 200 mm2
Height: VSI 2 mm & PSI 150 nm
X1,5 ; x2,5 ; x5 and x20 lenses
Max Load: 30 kg
MIRAU & MICHELSON Interferometers
MAHR MMQ 400
Measuring Range:
280 x 500 mm2
Rotary table Ø 300 mm
Max Load: 70 kg
LEITZ PMM-C Infinity
Measuring Range:
1200 x 1000 x 700 mm3
Max Load: 1000 kg
External Rotary Table
CLIC Cells
Measuring room
Temperature gradients:
0.1 K / Meter
0.2 K / Hour
0.4 K / Day
Hewlett Packard Laser Interferometer
Measuring Range:
40000 mm
Machine tool and CMM calibration
MITUTOYO CVS-3100
Mechanical Profiling and Roughness system
Measuring Range:
100 x 500 mm2
From MPE$_{E0}$ [µm]= 1.2 + L/500
To MPEE [µm]= 4+L*/500
(* L in mm)
± 1.2 µm
± 5 µm
(x5, x10, x20) :
± 15 µm
(x50, x100) :
± 5 µm
MPE$_E$ [µm]= 9+L*/50
(* L in mm)
± 100 µm
From ± 2 µm
to ± 500 µm
VSI mode: ± 1,50 nm
PSI mode: ± 0,03 nm
± 0,1 µm
MPE$_E$ [µm]= 0,3+L*/1000
(* L in mm)
± 1 µm
± 10%
(roughness)
± 2 µm (forms)
EN/MME
MATERIALS & METROLOGY
ACCURACY

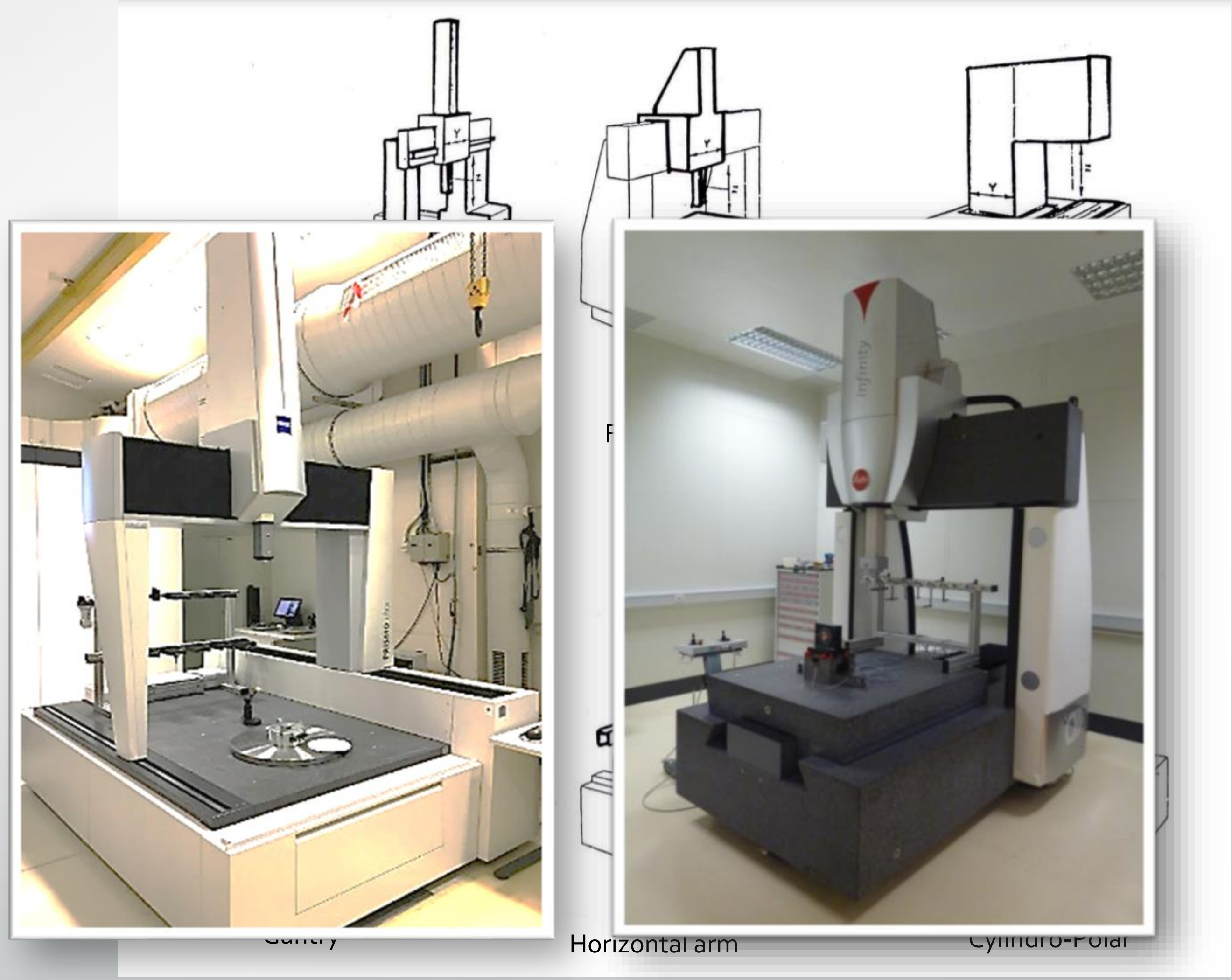
Metrology Equipment Overview

- Conventional measurement instruments
- CMMs (Coordinate Measuring Machines)
- Portable CMMs
  - Polyarticulated arm
  - 3D Scanner
- Contact profiles and roughness devices
- Non contact topog ess c
- Form and shape m es
- Interferometry
- Tomography…



CMM (Coordinate Measuring Machine)

- Architecture of CMMs

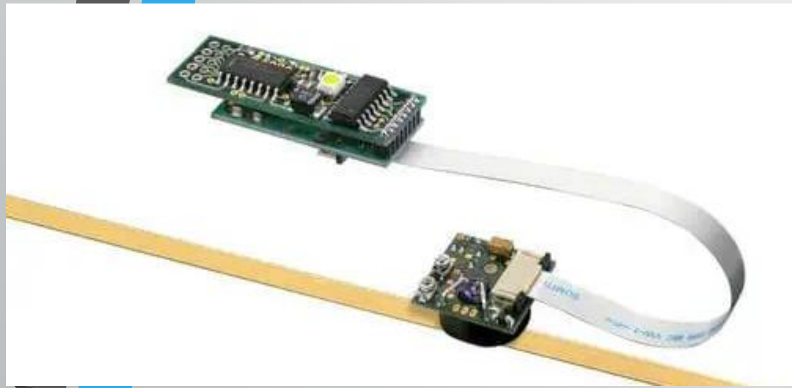


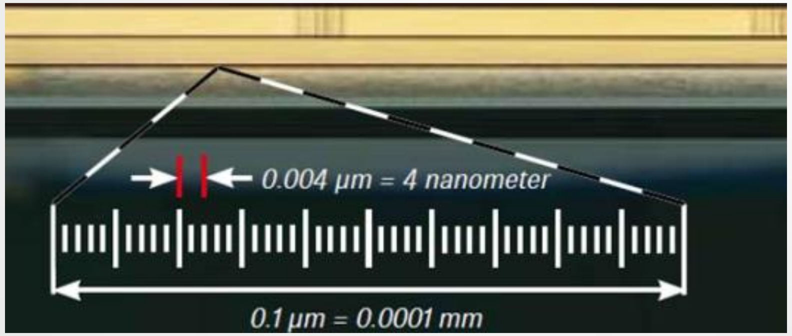
CMM (Coordinate Measuring Machine)

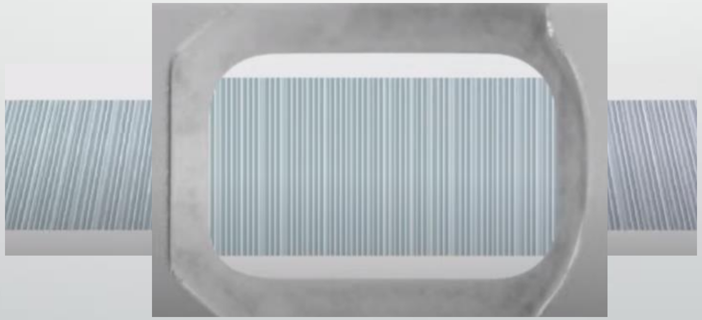
- Architecture of CMMs
- Operation
  - Air bearings

CMM (Coordinate Measuring Machine)

- Architecture of CMMs
- Operation
  - Air bearings
  - Scales bars

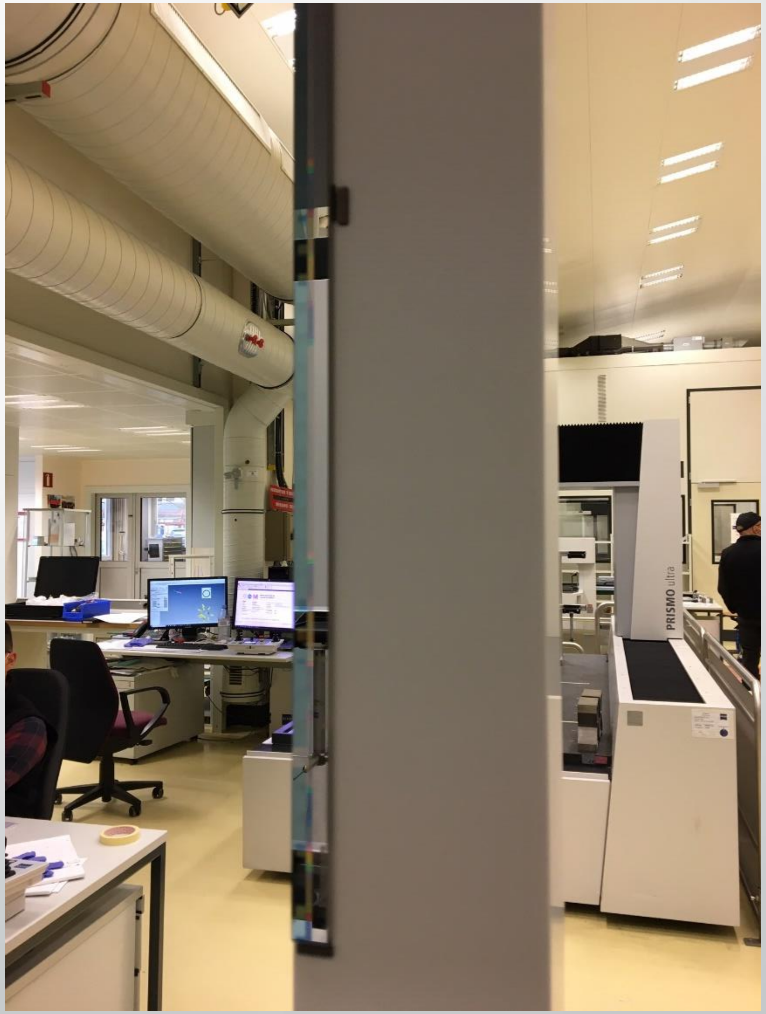






Scale pitch 20 µm

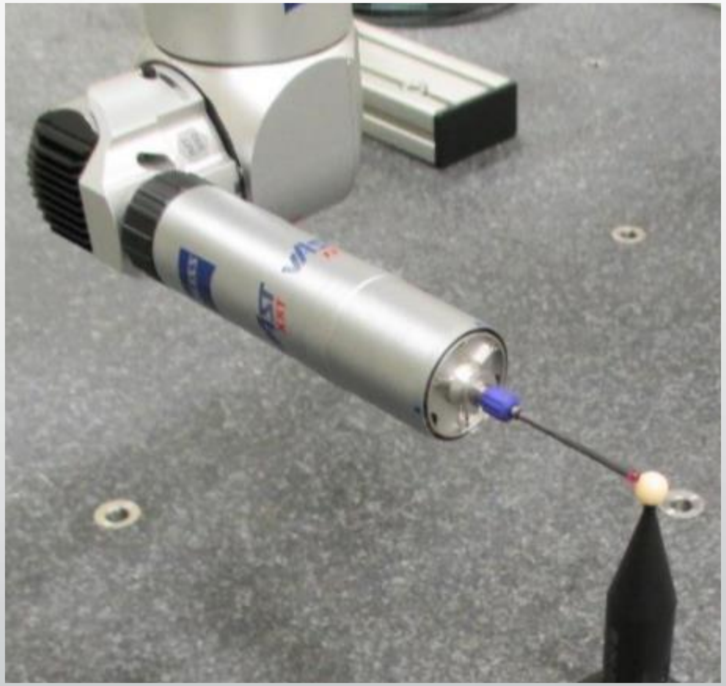
Thermal expansion 0.02 µm/m/K



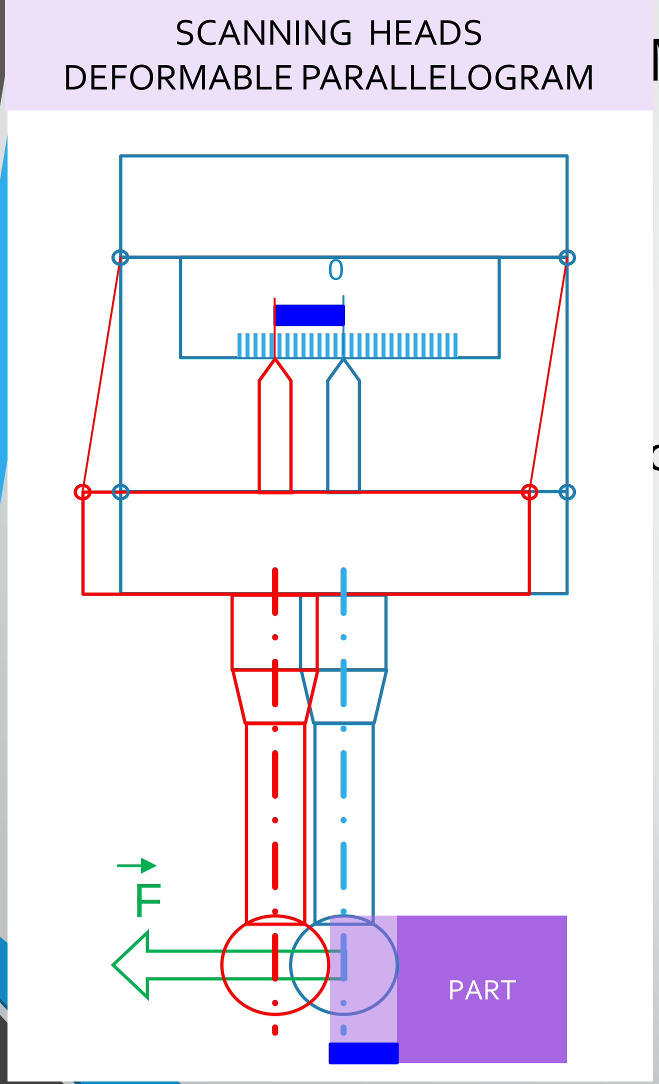
CMM (Coordinate Measuring Machine) Measurement head

- Architecture of CMMs

SCANNING HEADS DEFORMABLE PARALLELOGRAM		POINT BY POINT TRIGGER HEAD
FIXED HEADS	ROTATIVE HEADS	

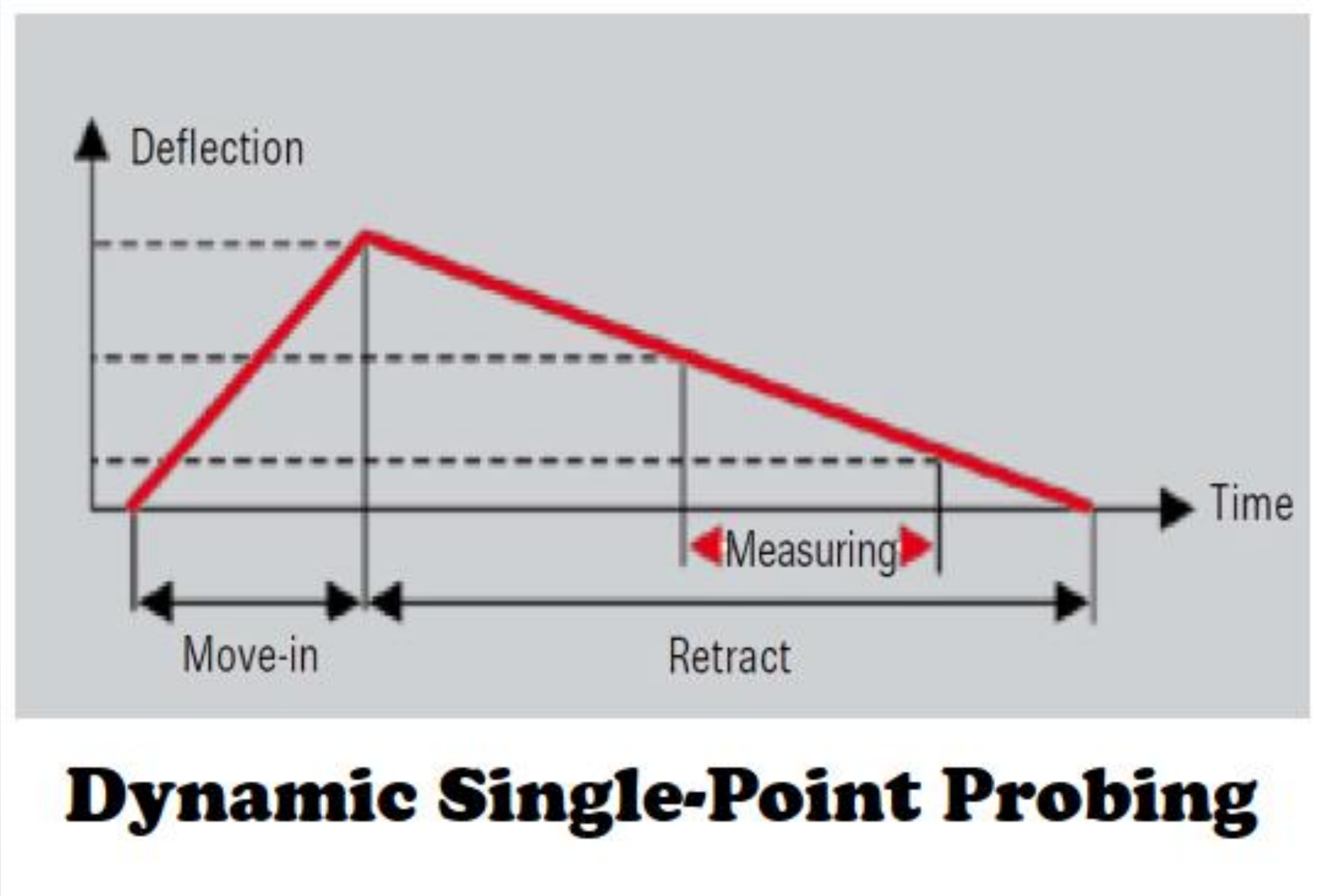


CMM (Coordinate Measuring Machine)
Measurement head



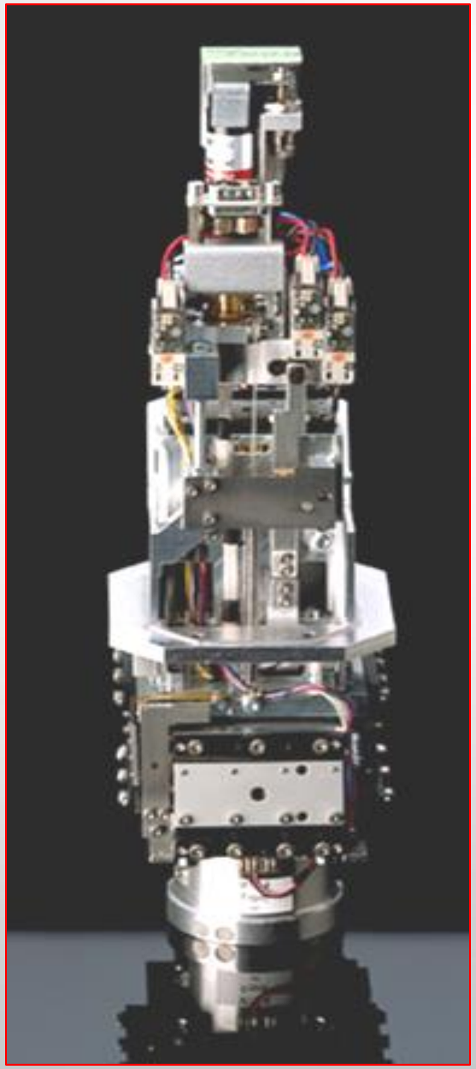
M

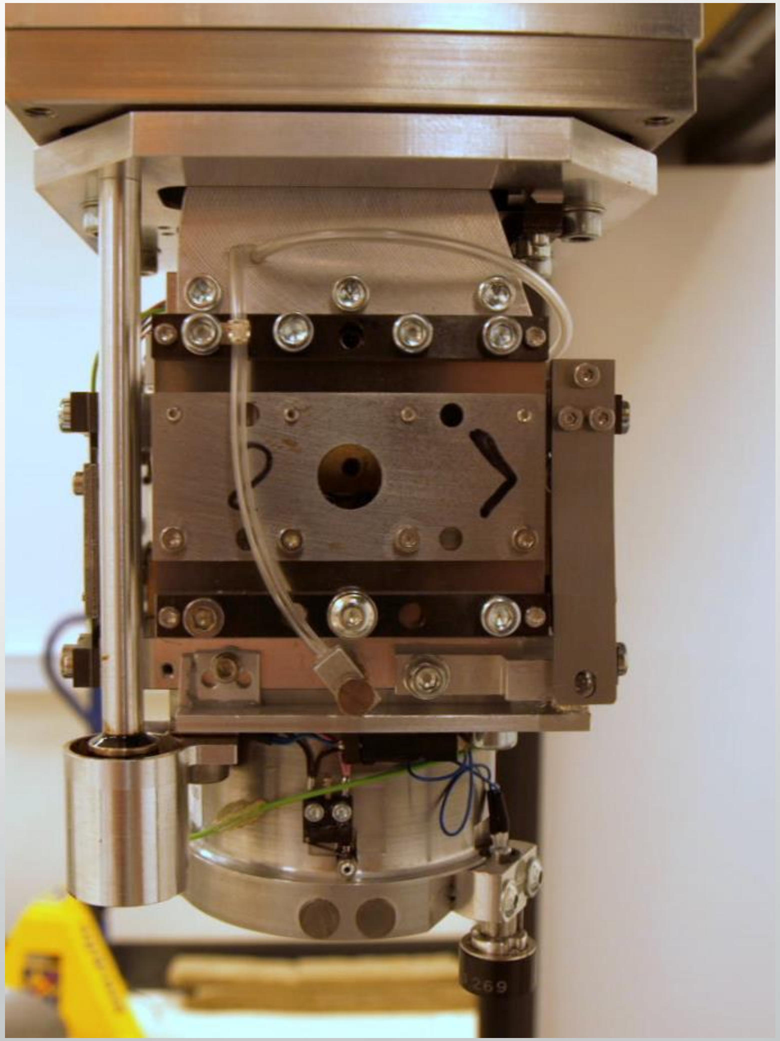
ds



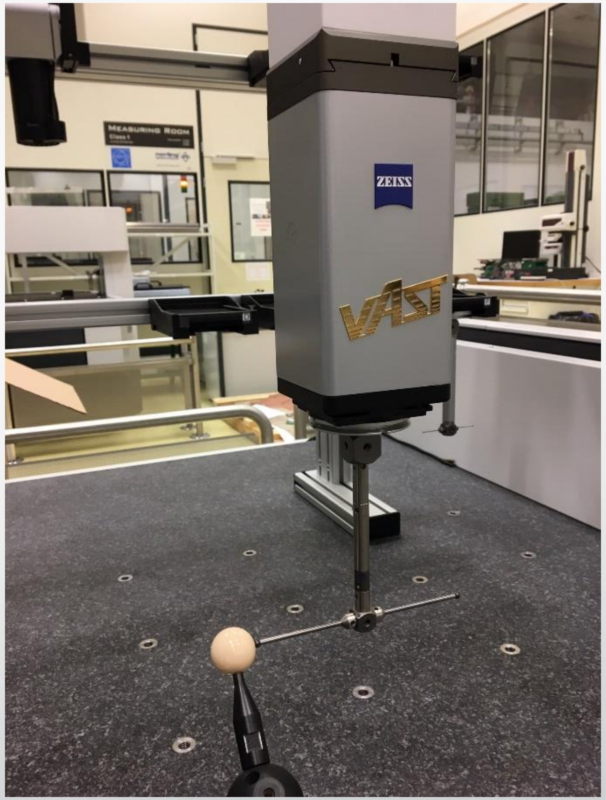
CMM (Coordinate Measuring Machine) Measurement head

- Architecture of CMMs
- Operation

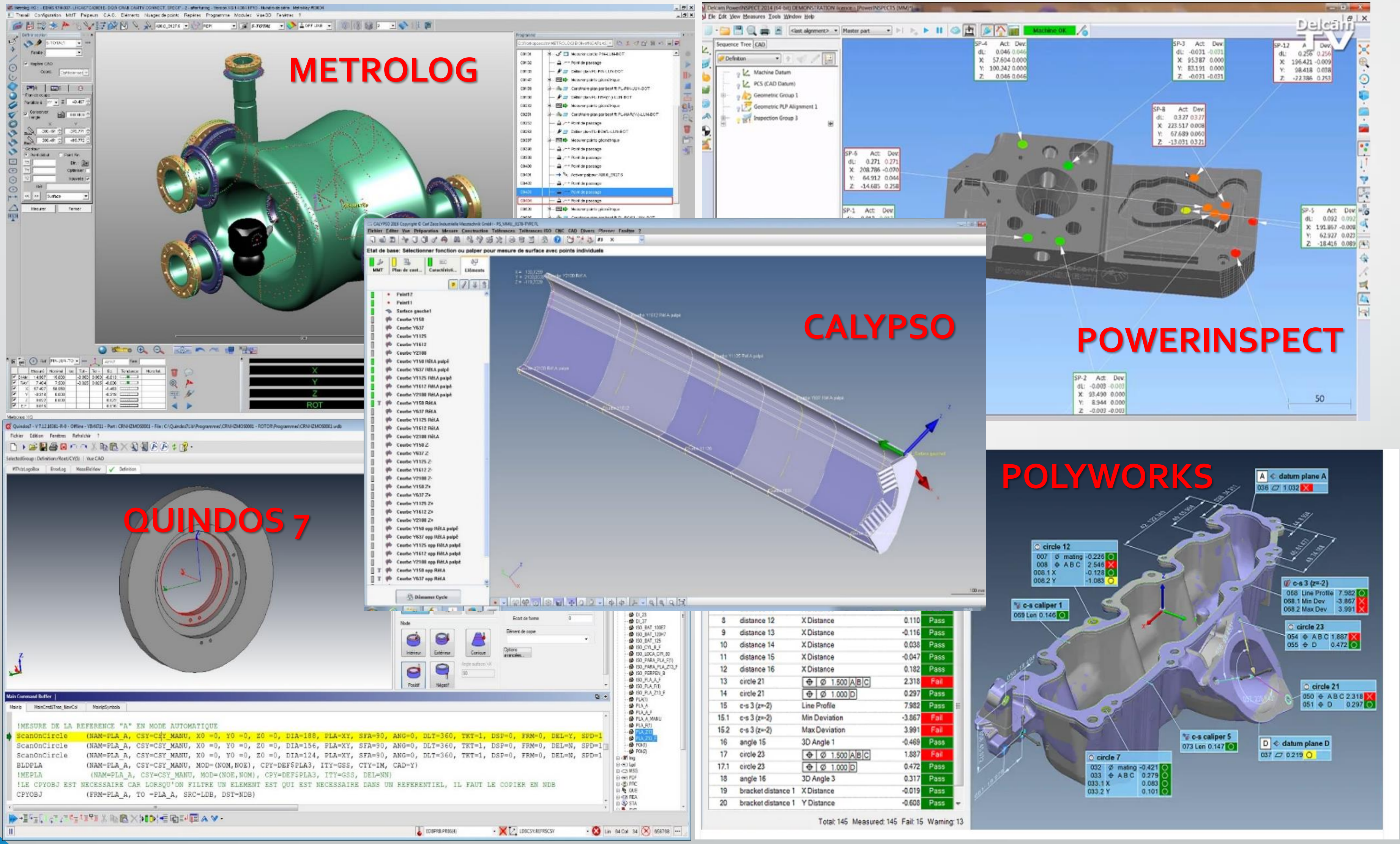




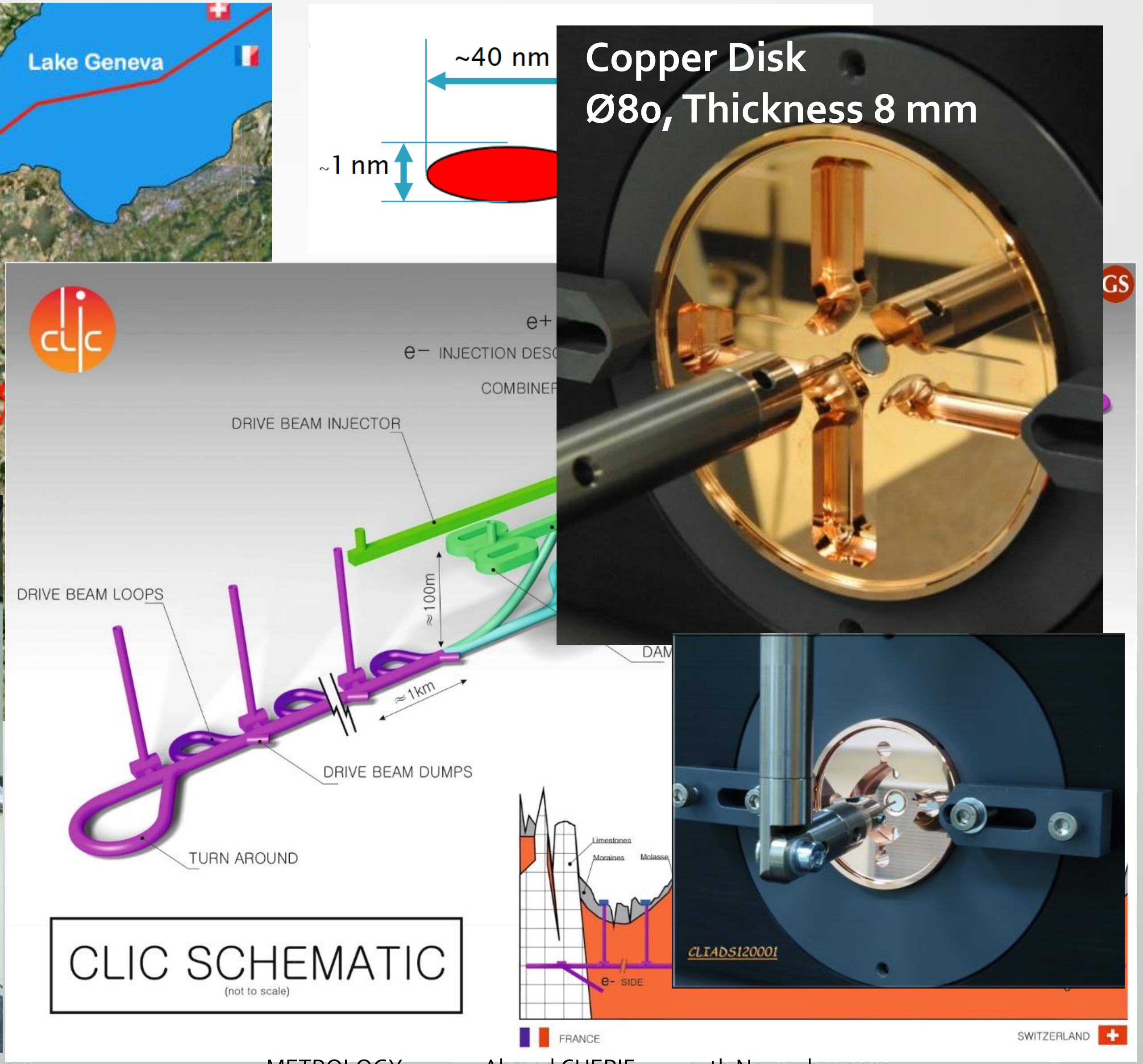
CMM (Coordinate Measuring Machine) Stylus calibration



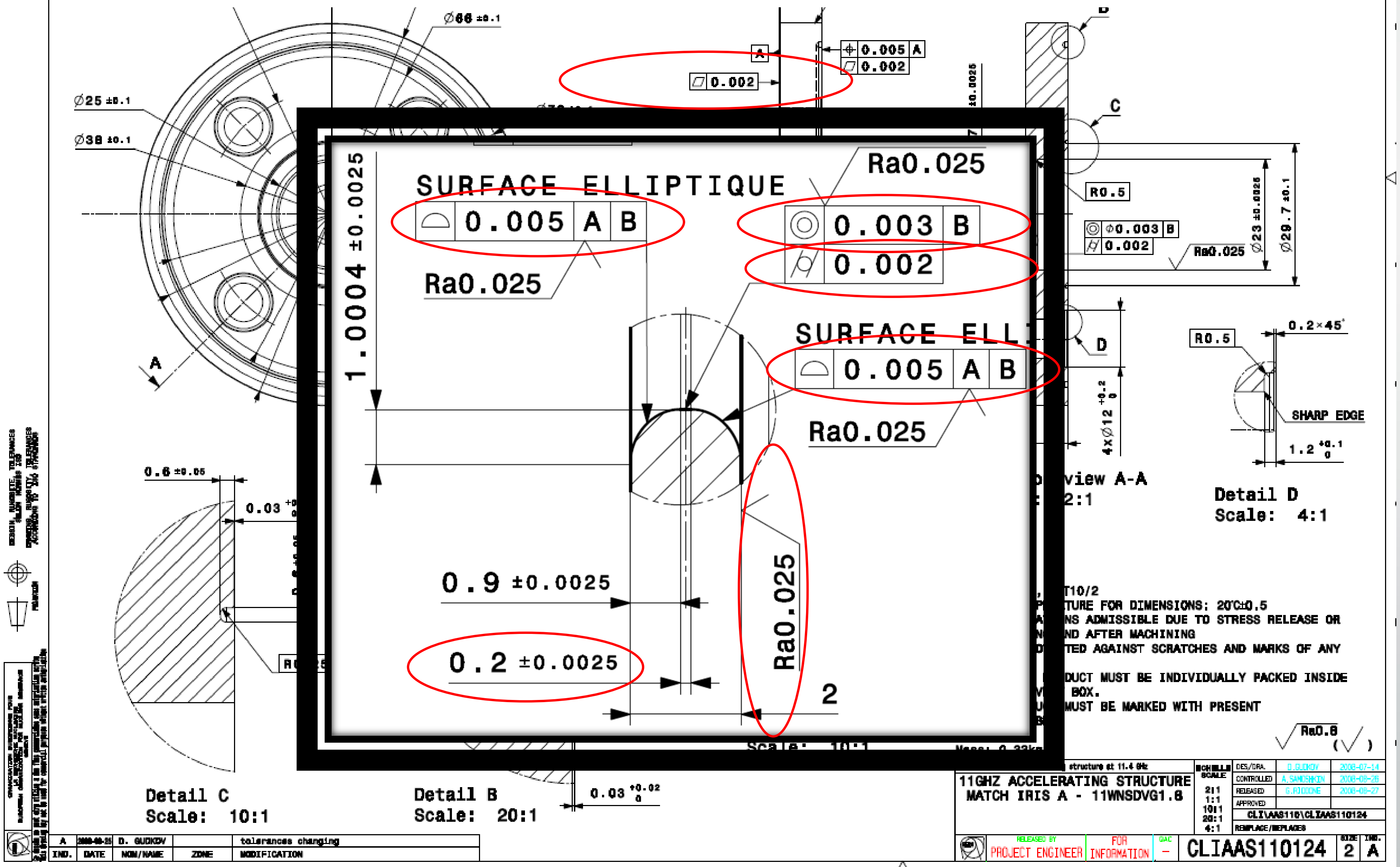
CMM (Coordinate Measuring Machine) Metrology software



CLIC – Compact LInear Collider

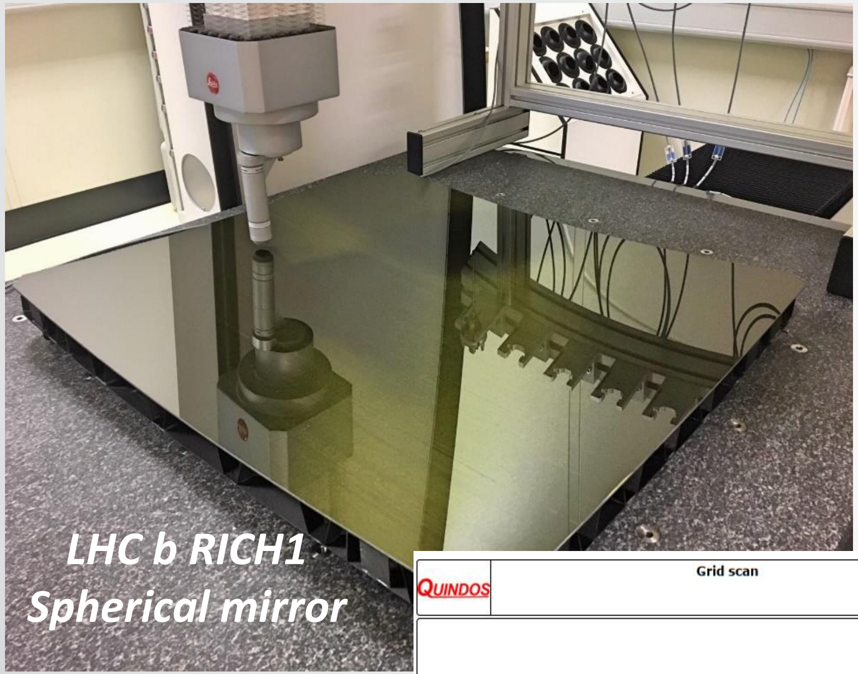


CLIC DISKS TOLERANCES

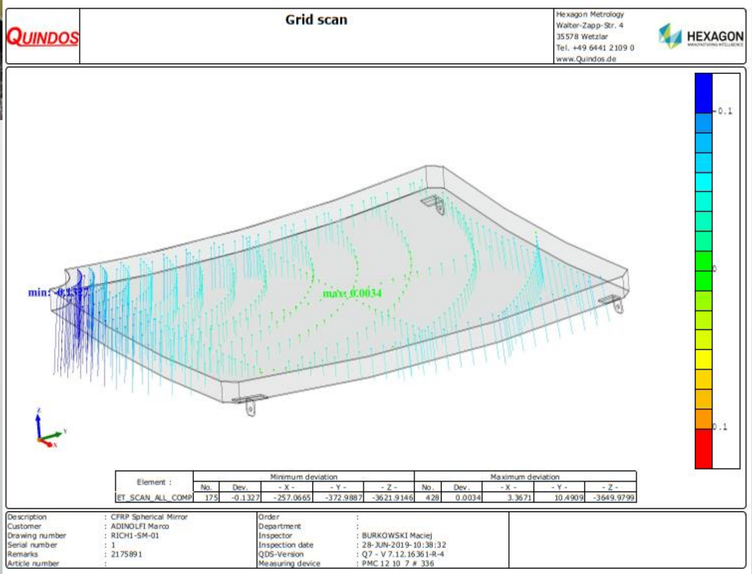


Leitz PMM-C Infinity

Leitz PMM-C Infinity



LHC b RICH1
Spherical mirror

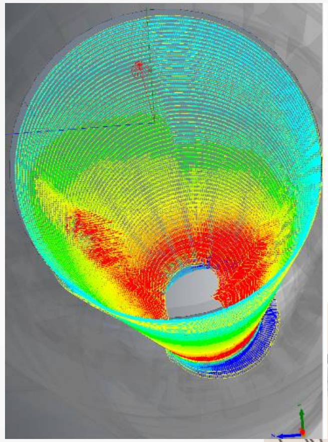


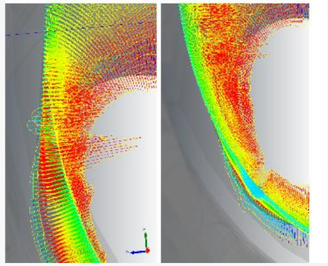
Grid scan

Hexagon Metrology
Walter-Zapp-Str. 4
35578 Wetzlar
Tel. +49 6441 2109 0
www.Quindos.de

Element :	Minimum deviation					Maximum deviation				
	No.	Dev.	- X -	- Y -	- Z -	No.	Dev.	- X -	- Y -	- Z -
ET_SCAN_ALL_COMP	175	-0.1327	-257.0665	-372.9887	-3621.9146	428	0.0034	3.3671	10.4909	-3649.9799

Description	: CFRP Spherical Mirror	Order	:
Customer	: ADINOLFI Marco	Department	:
Drawing number	: RICH1-SM-01	Inspector	: BURKOWSKI Maciej
Serial number	: 1	Inspection date	: 28-JUN-2019-10:38:32
Remarks	: 2175891	QDS-Version	: Q7 - V 7.12.16361-R-4
Article number	:	Measuring device	: PMC 12 10 7 # 336





CLIC Disks

LINAC 4
Chopper/dump

PRECITEC LR
Optical sensor

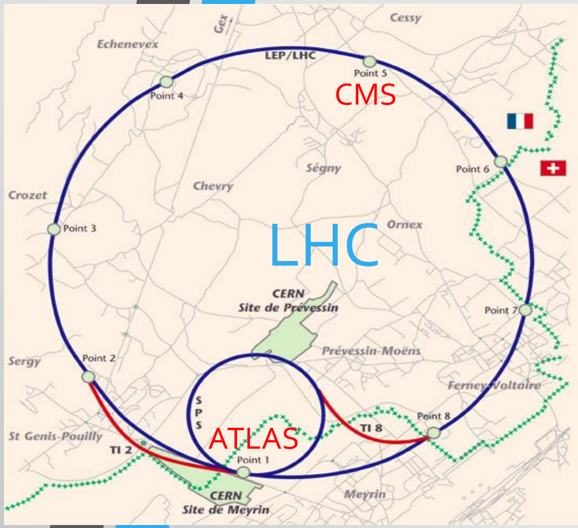
Equipment

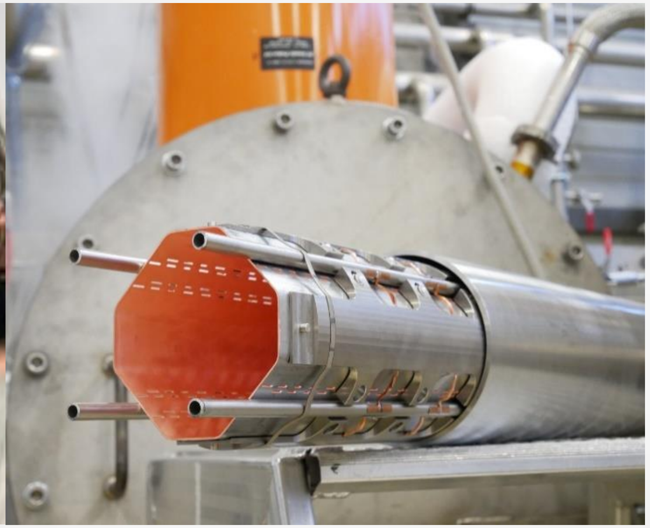
C-Track

HandyPROBE

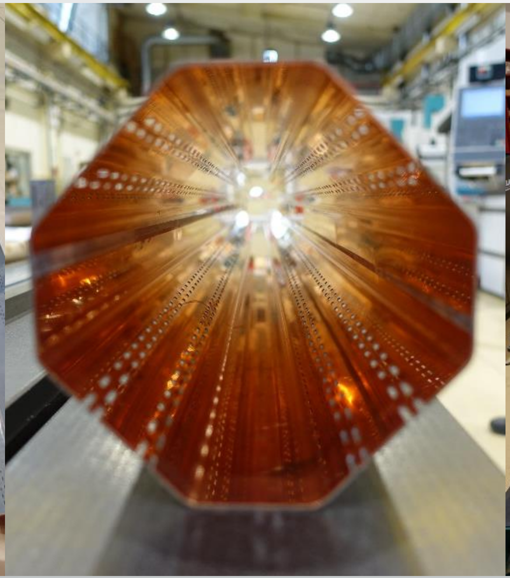
MetraSCAN

METRASCAN CREAFORM 3D SCANNER
Beam Screen





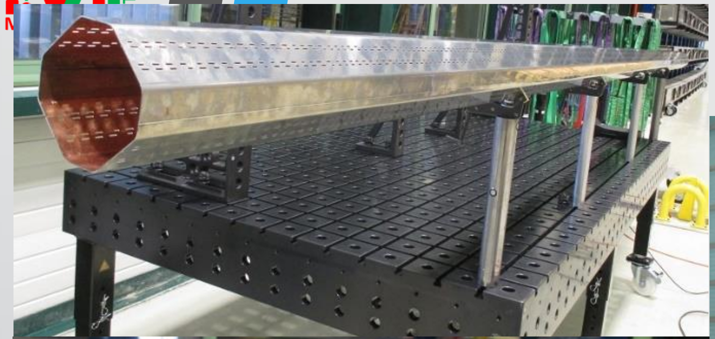
- Final focalization Magnets
- Called Inner triplet
- New Inner Triplet for the focalization of the beam around ATLAS and CMS experiments
- New Beam Screens

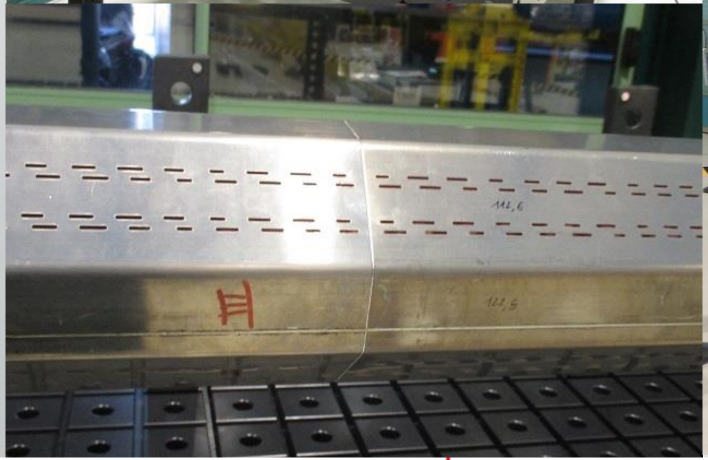


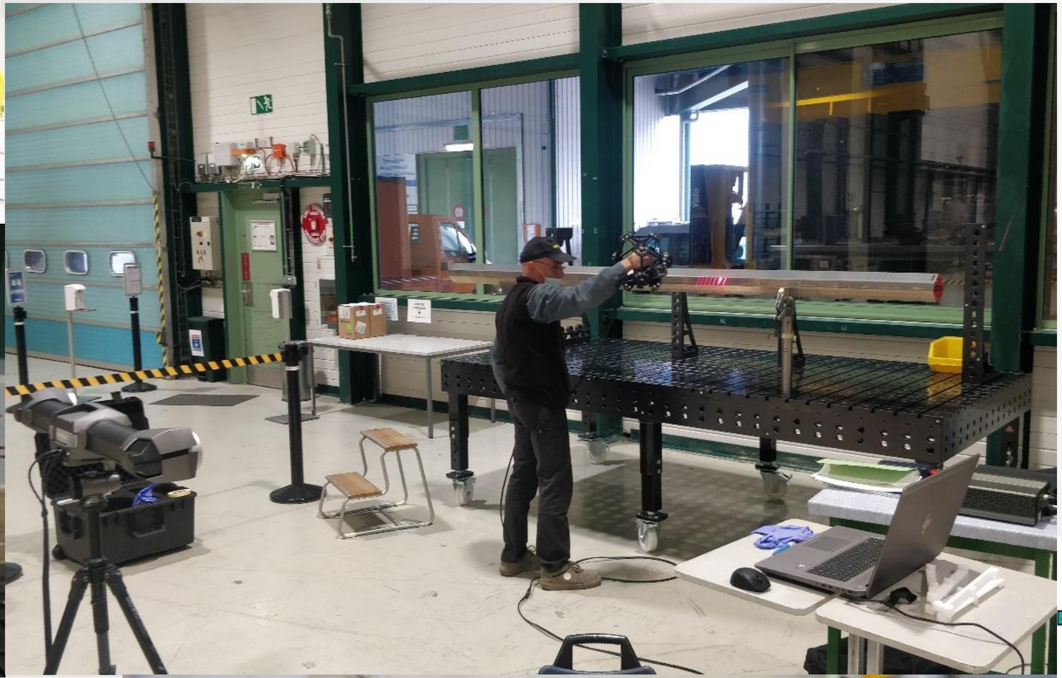
- EN/MME in collaboration with BE department
- Production of 51 beam screens in total
- About 650 m including spares
- Segments number : 227
- Segment length : 2800 mm
- Length welded BS : up to 14 m

METRASCAN CREAFORM 3D SCANNER

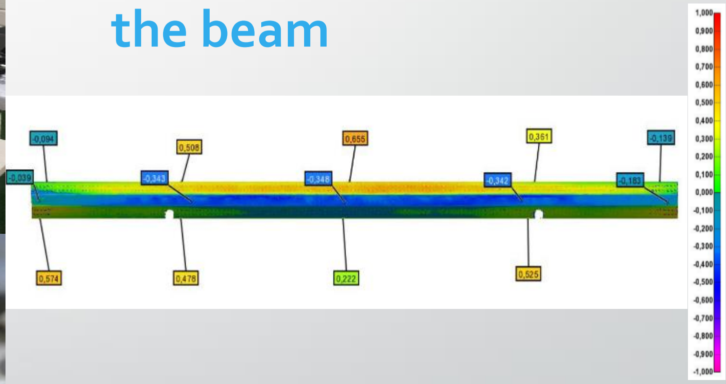
Beam Screen

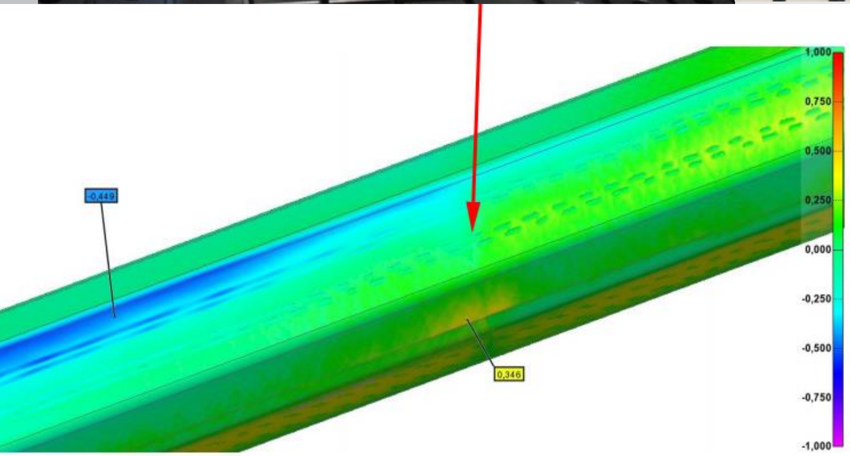


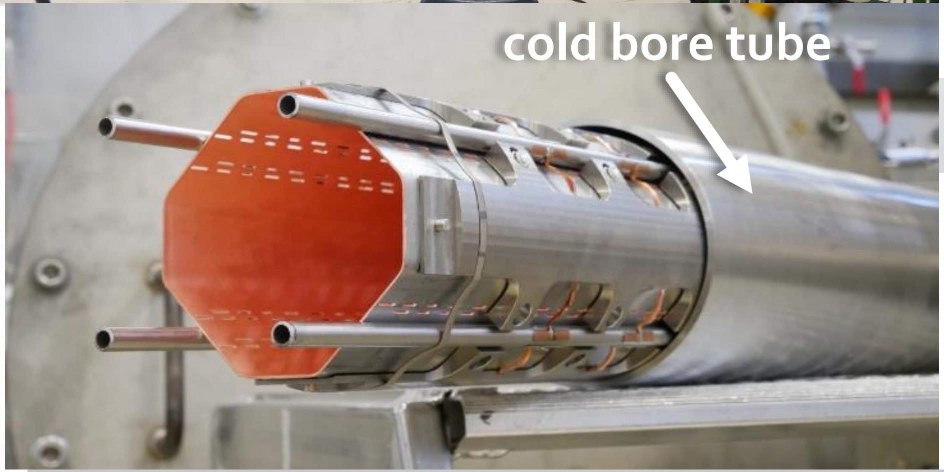


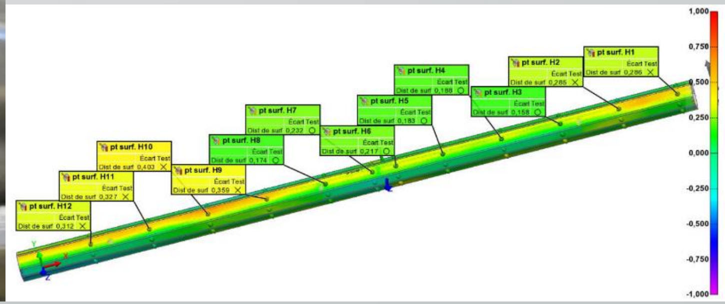


1. Measure the geometry of the beam screen (BS)
2. Straightness after welding of the segments
3. Guarantee the entrance of the assembled BS in the cold bore tube
4. Control the aperture for the beam



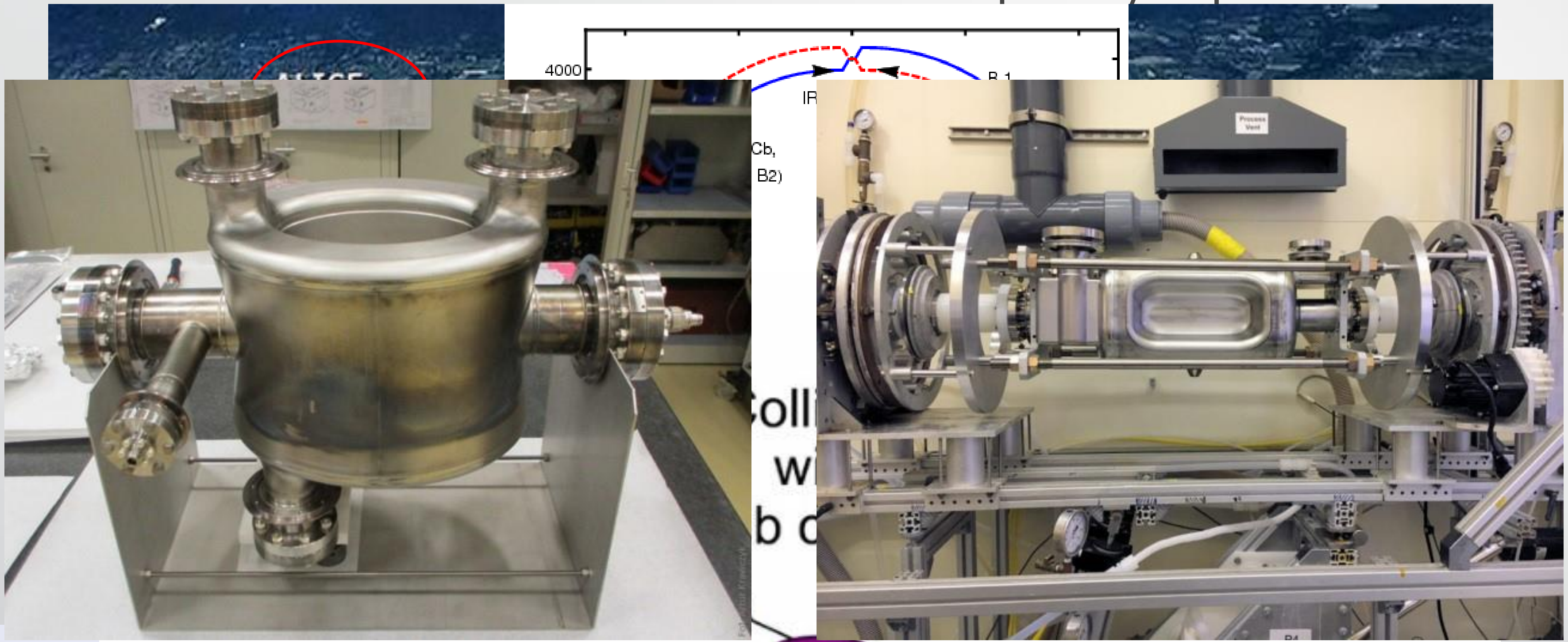


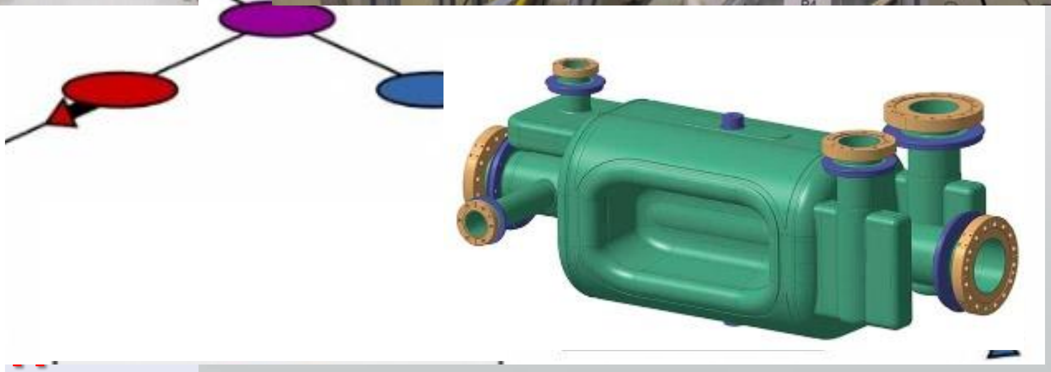




CRAB CAVITIES DQW & RFD

Double Quarter Wave & Radio Frequency Dipole

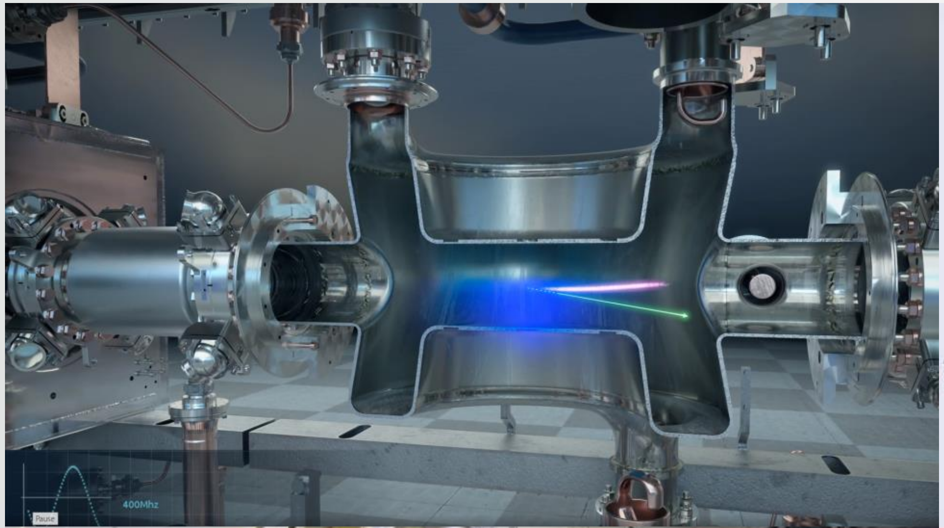


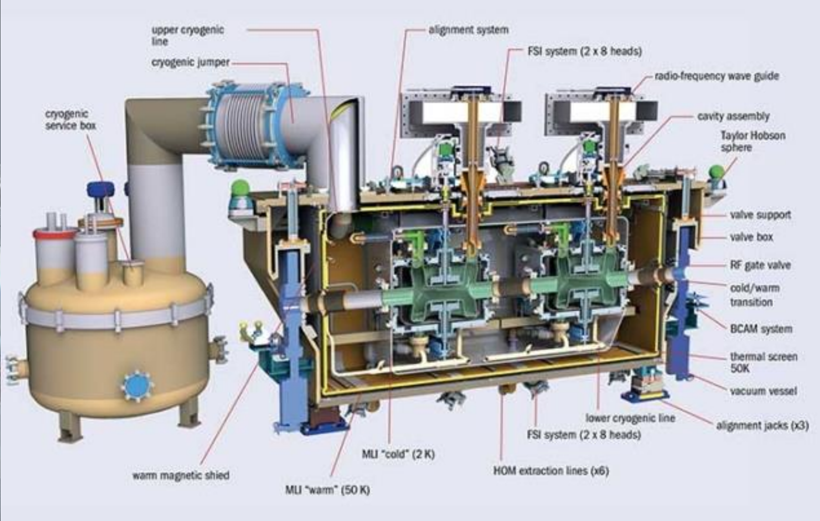


CRAB CAVITIES

CRAB CAVITIES DQW & RFD

Complex process…



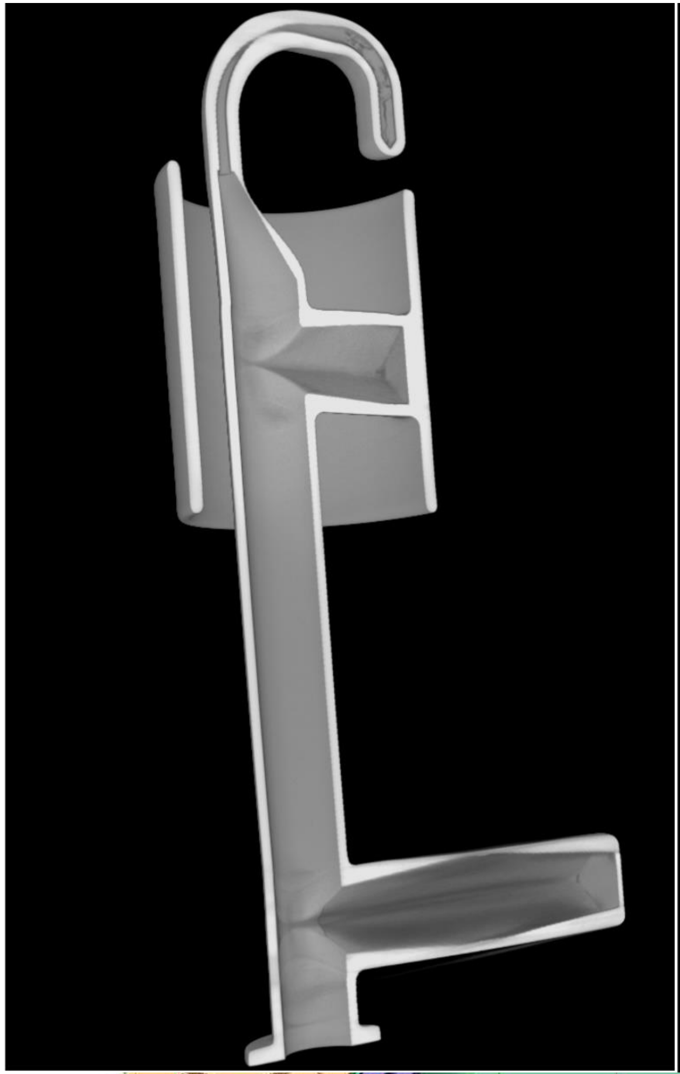


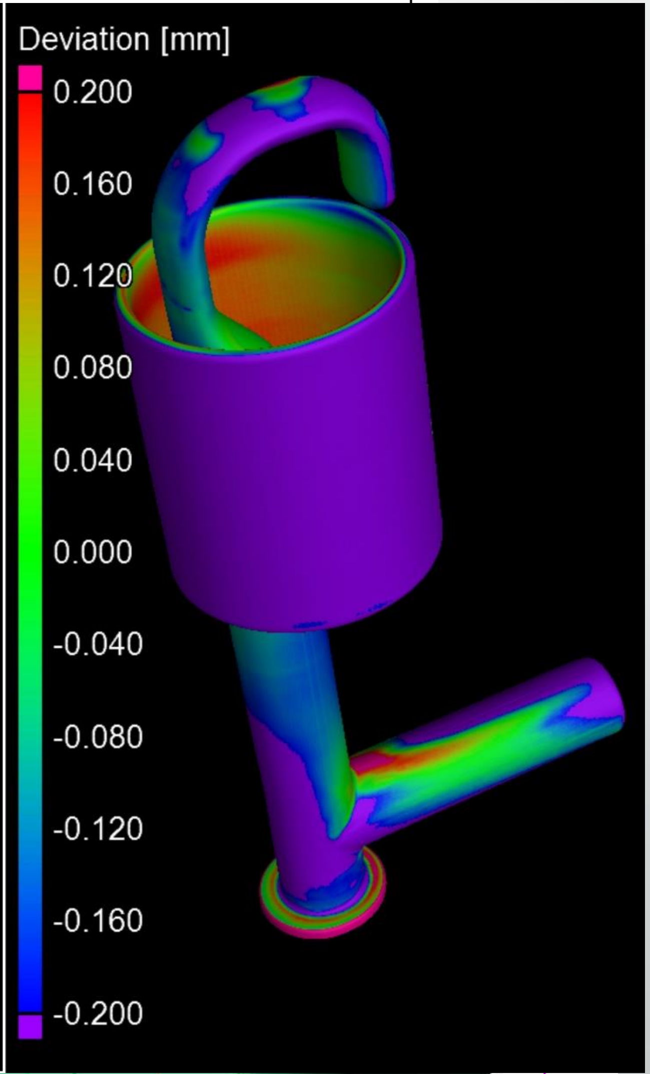
- Design
- FEM calculations
- Magnetic simulations
- Vacuum
- Cryogenics
- Radio Frequency
- Metrology
- Alignment
- Mechanical test
- …

CRAB CAVITIES DQW & RFD

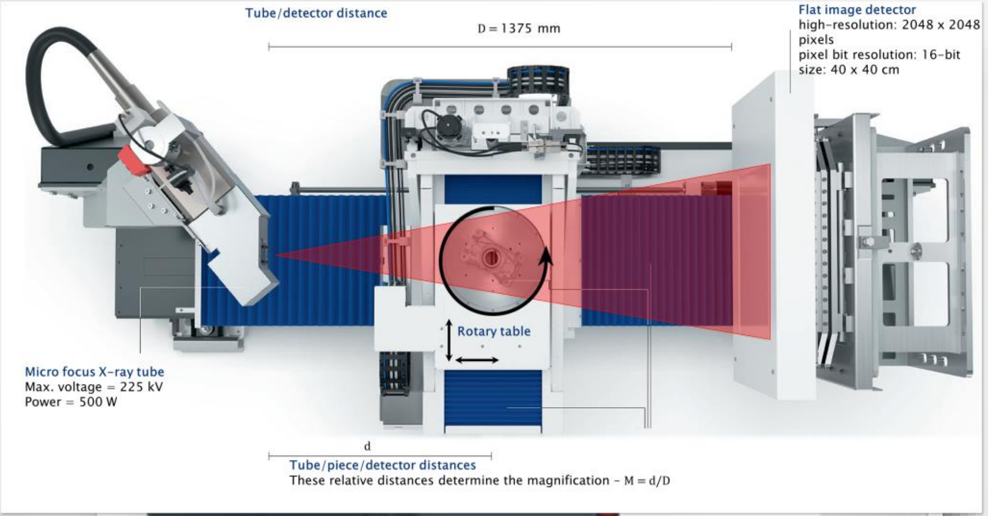
Few key parts

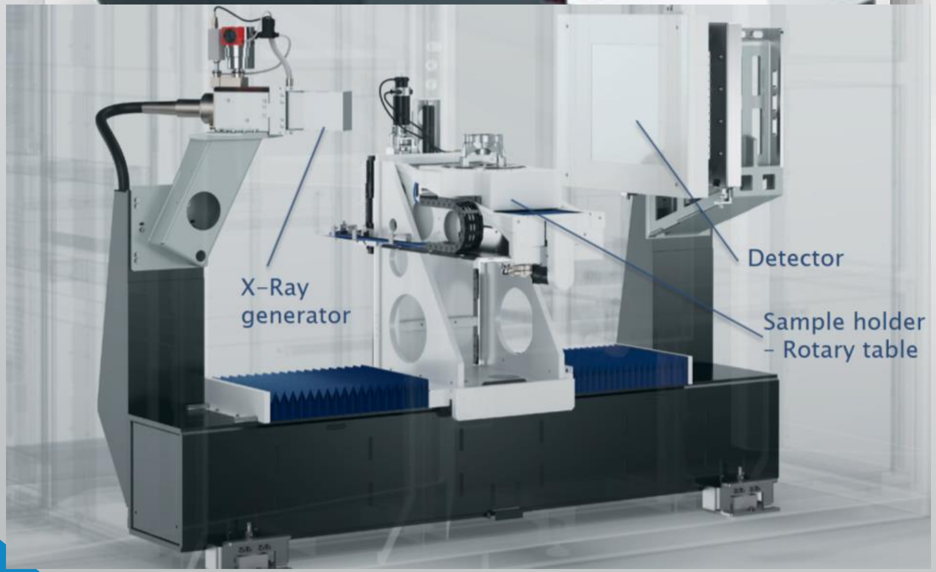
CRAB CAVITIES DQW & RFD





TOMOGRAPH
Microfocus X-Ray system





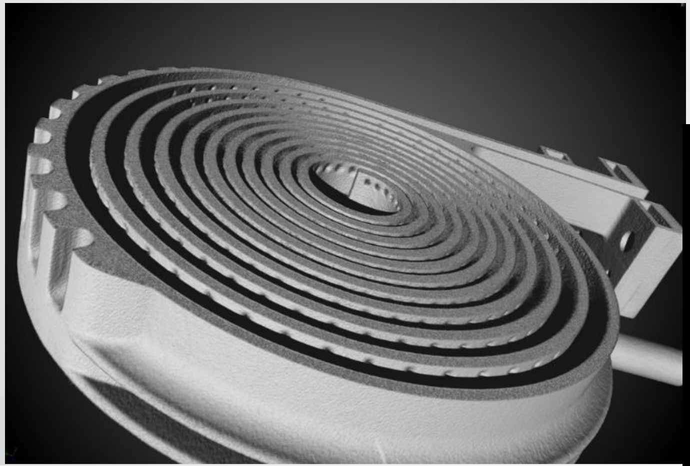
ZEISS METROTOM 1500 Delivered December 2017

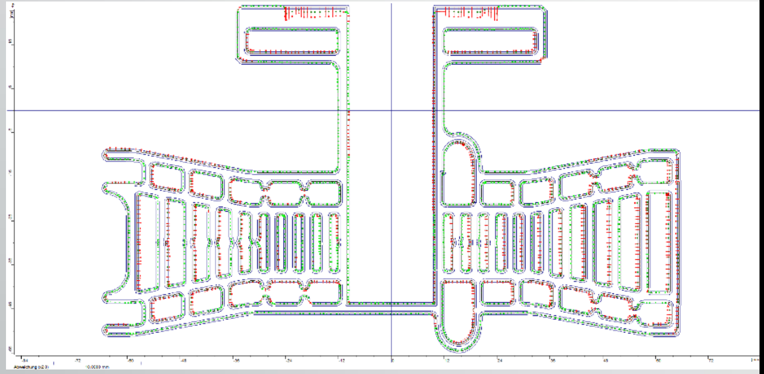
- FDD: 1500 mm
- Max. voltage ≥225 kV, max.
- Focal spot size ≤7 µm;
- Imager : 2048 x 2048 pixels,
- Max. pixel size: 200 µm,
- Image processing : 16-bit;

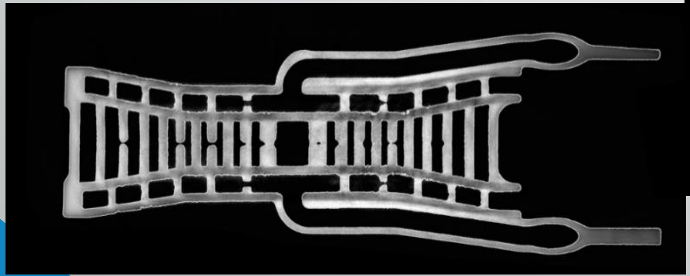
65 535 grey levels

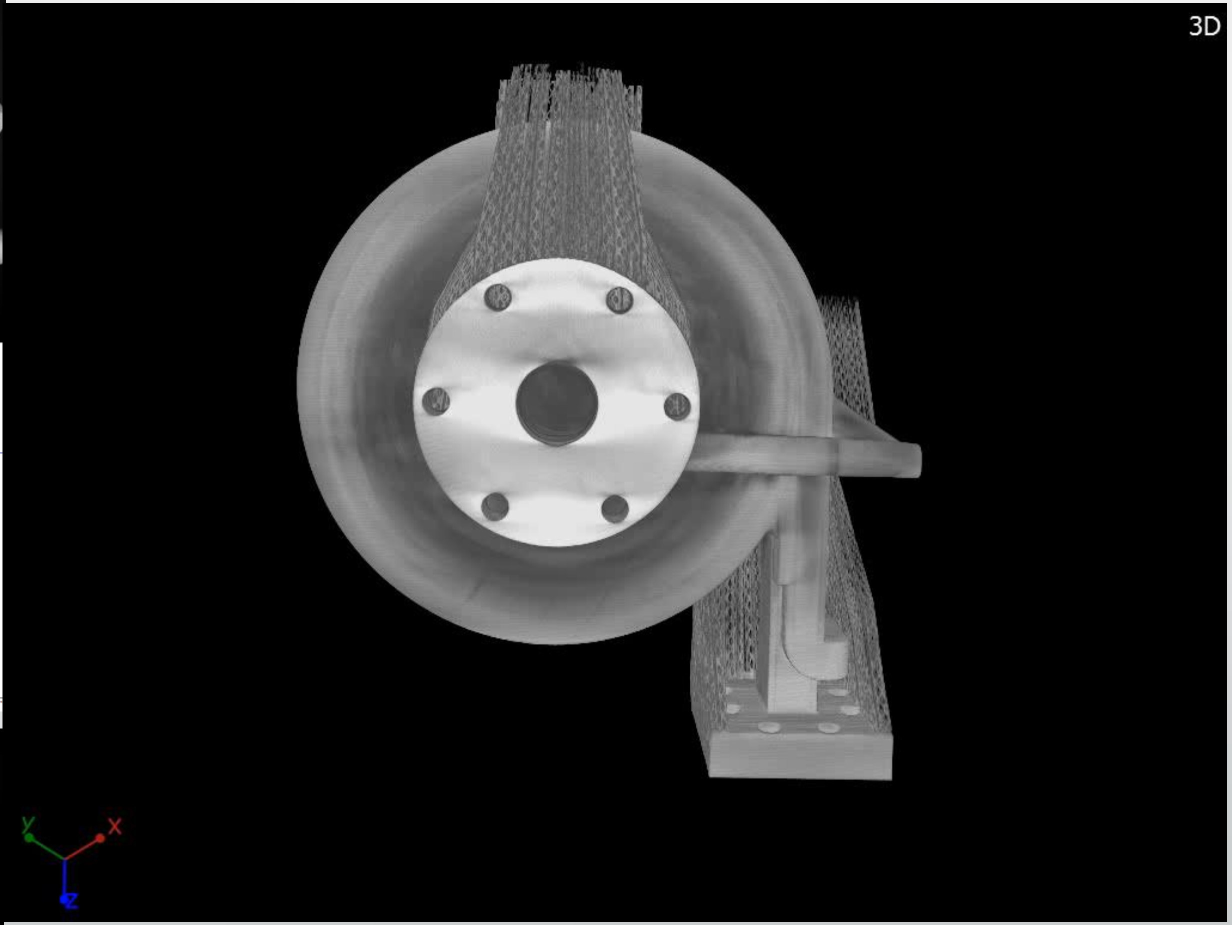
Micro Tomography

METROLOGY APPLICATIONS



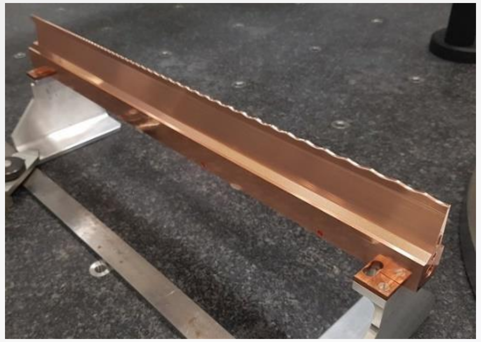
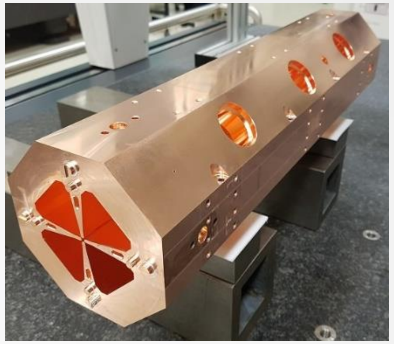
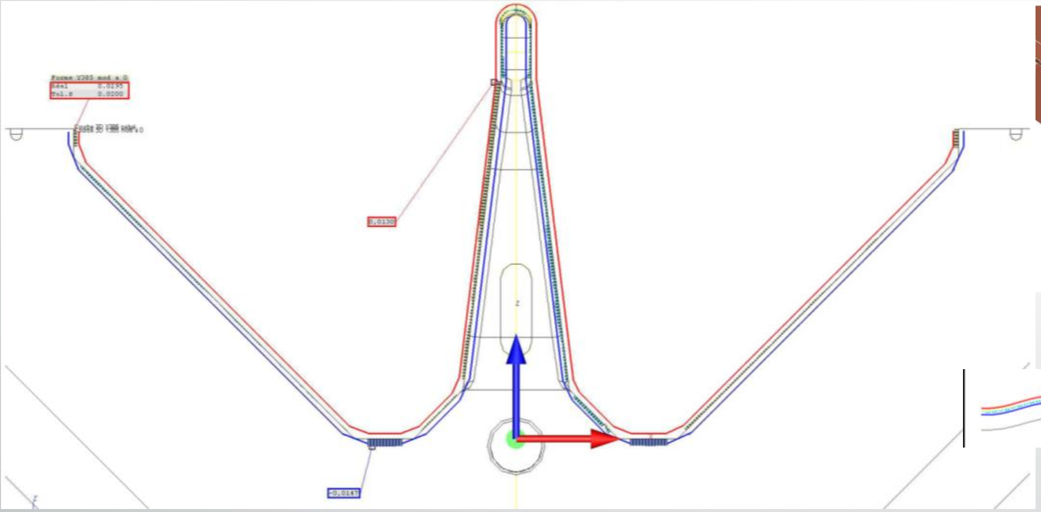
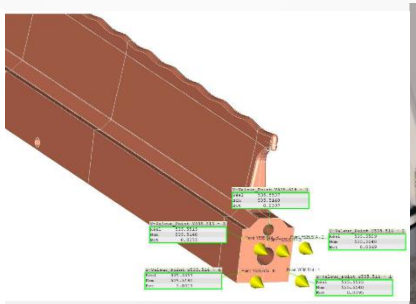
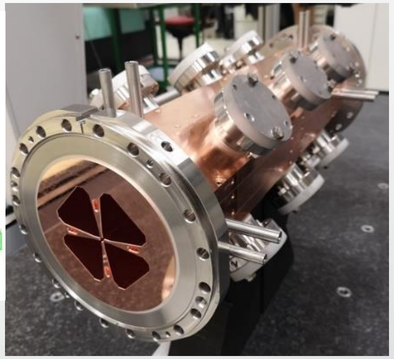
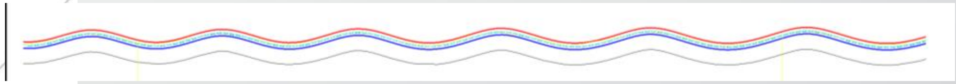
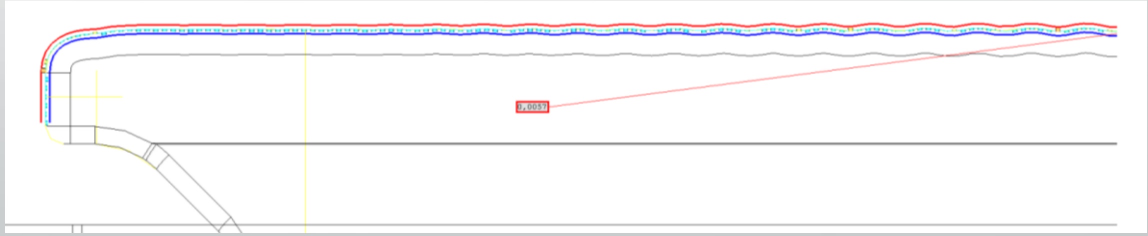






HF-RFQ – PROTON THERAPY



- Follow up of all the fabrications steps
- Tolerances ±0,005 mm was obtained
- Verification of each part after machining process
- Check if before and after brazing
- Final check to confirm the results obtained by the radio frequency tests

CMM : Prismo Ultra

With Rotary Table (RT)

ZEISS PRISMO ULTRA

Measuring Range

18.12.10	1800 x 1200 x 1000 mm^3 (RT)
24.12.10	2400 x 1200 x 1000 mm^3

Accuracy (according to ISO 10360)

MPE E0	**1.2 + L/500 µm**
MPE R0	**0.8 µm**
MPE THP	1.2 µm / 45s

Thank you for your attention

Ahmed CHERIF
EN/MME-MM, CERN - 27th November 2020

Ahmed.Cherif@cern.ch