Introduction to the design of accelerators

M Timmins – CERN

MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS

Engineering Department

Disclaimer

The following lecture has been prepared explicitly for the Mechanical and Materials engineering CAS for educational purposes and the presented study cases are by no means functional components used in accelerators.

Outline

1. Introduction, What is a good design of an accelerator ?
2. Special focus on 2D drawing specifications, functional dimensioning / ISO GPS
3. A practical case, inspired from an existing component at CERN
4. Summary, What you must retain !

1. Introduction

- What are accelerators for ?

Production of a beam for physics purposes.

Physicists fight for beam time.

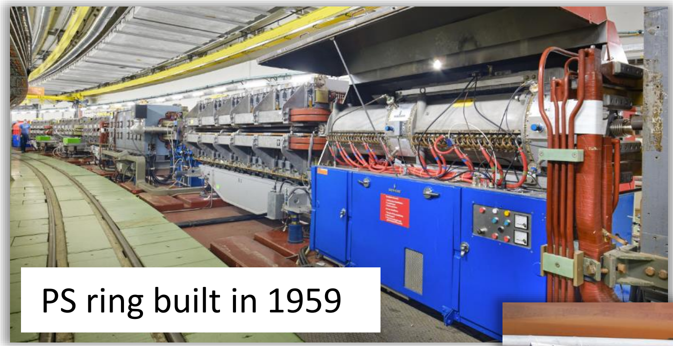
Beam time = Physics time

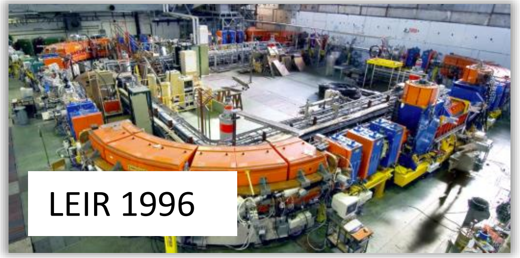
- Accelerators need to be designed for a long lifetime (several decades)

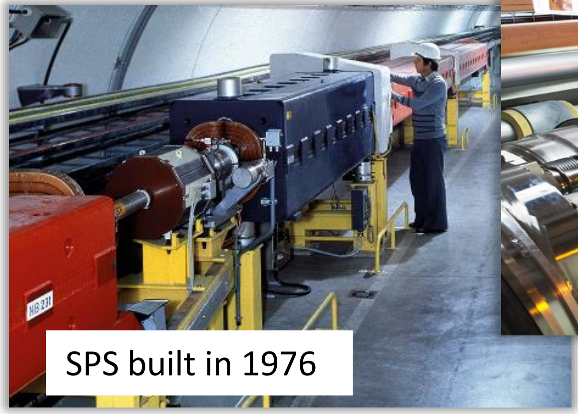
Big investment for society

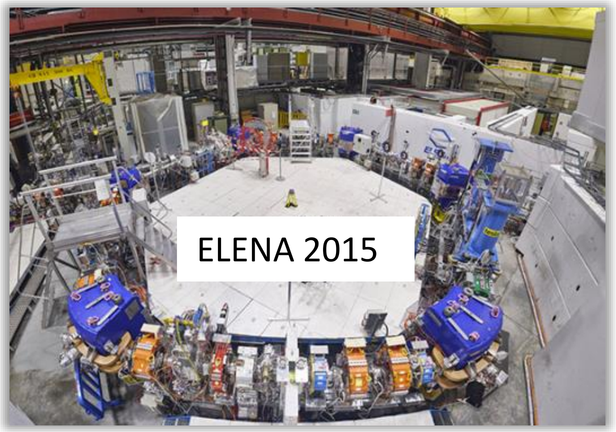
- Accelerators need to be robust and reliable!

1 day without beam in LHC costs **~200 kCHF**







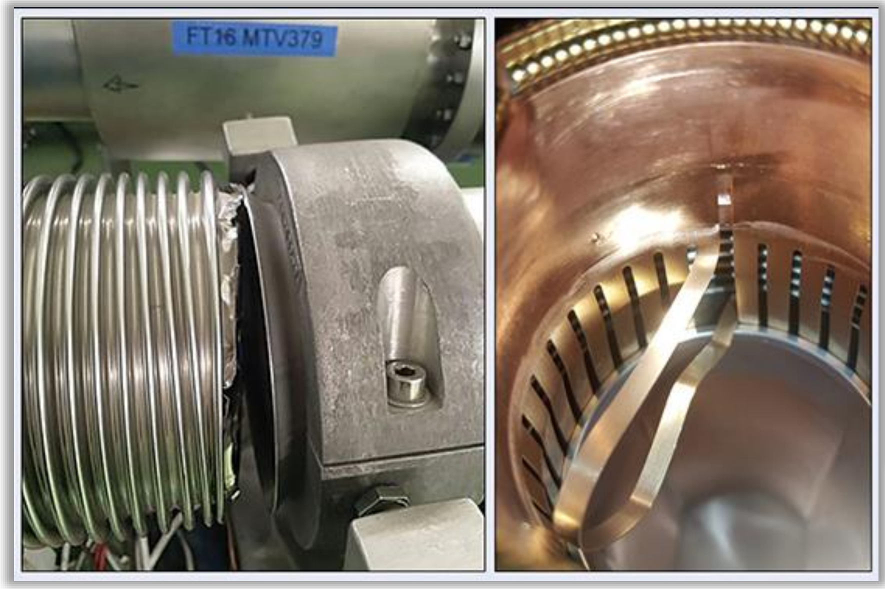


1. Introduction

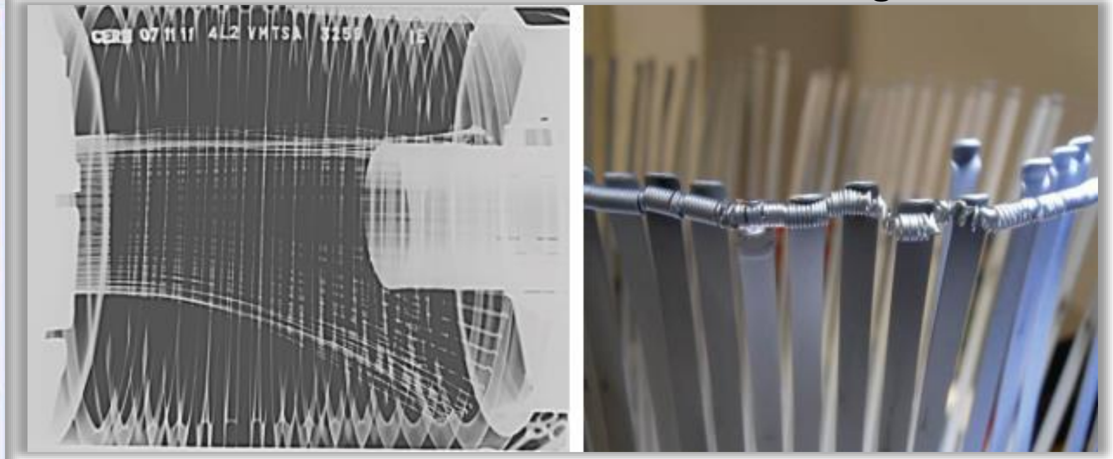
What is a robust and reliable design ?

Damaged LHC dipole interconnexion

LHC jacks ripped from the ground



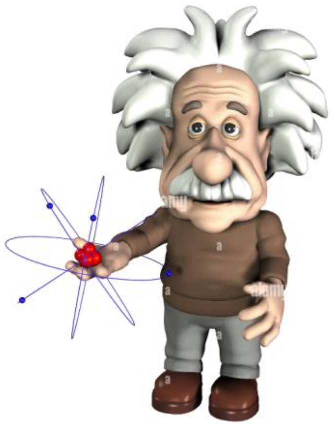
Bellow and RF finger failure



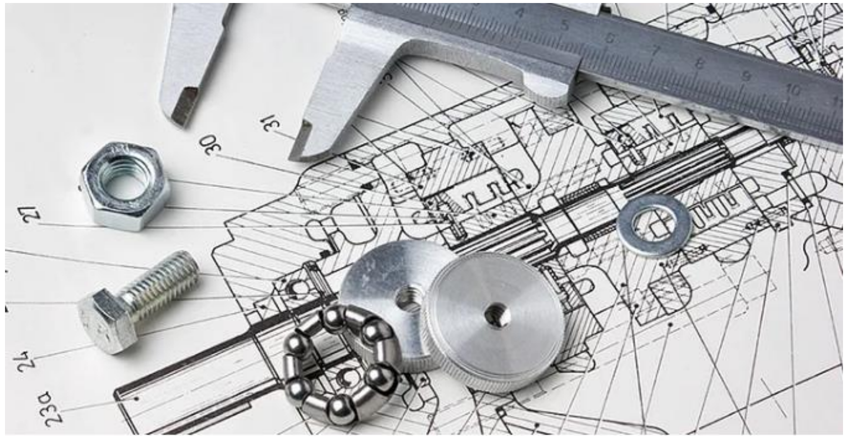
1. Introduction

- Get a good understanding of the functional requirements.

- Translate them it into mechanical engineering specifications which are reachable and measurable. Not so easy ! (dimensional tolerances, material specifications, assembly technics, etc…)



Functional requirement



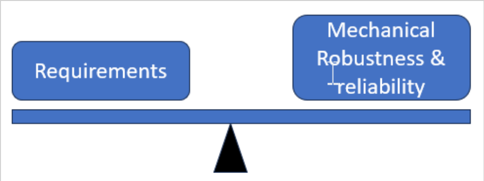
Mechanical specifications

1. Introduction

Identification of the product lifecycle and environmental requirements

Most of these topics will be covered during the CAS

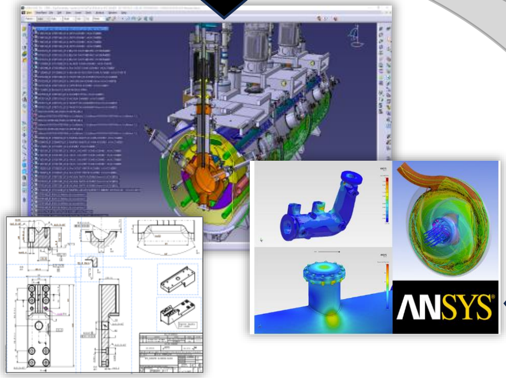
Iterative process:
Challenge the functional requirements



Cost & schedule

Functional requirements

Lifecycle and environment requirements



Material choices, 3D CAD models, calculations, 2D drawings

Transport / handling
inspection
Surface treatment
Metrology
Assembly
Fabrication + stock material
Prototypes / demonstrators

Environment

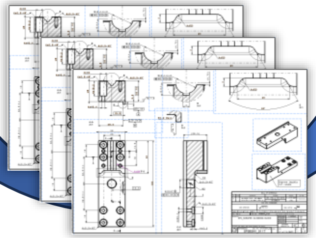
Integration
Alignment
Monitoring
installation
Acceptance tests

Maintenance
Upgrades

Waste
Dismantling

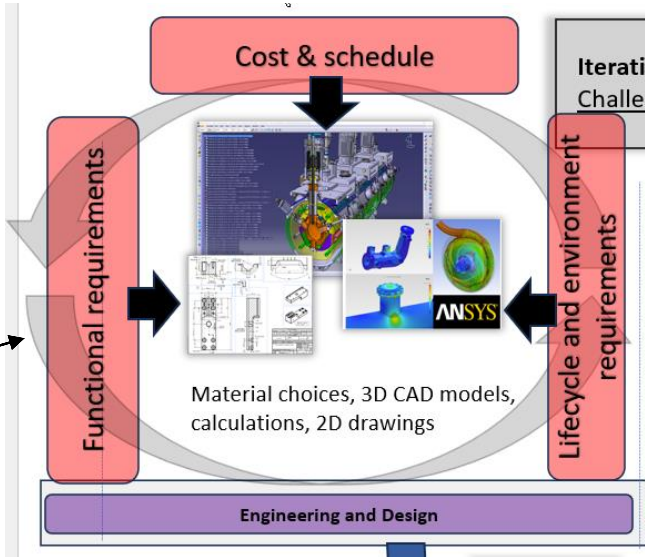
Engineering and Design → **Construction** → **Commissioning** → **Operation** → **Decommissioning**

Engineering product specifications



Quality check

1. Introduction

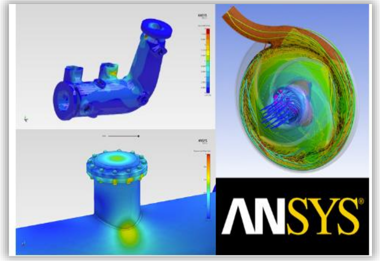


The design phase can be divided into two major steps:

Step 1: Preliminary conceptual design (iterative process)
Goal: To fulfill most of your functional requirements

Preliminary set of material selections, Overall dimensions, type of cooling (gas/water) if needed, level of precision, construction considerations, joining technics (welding, brazing, machining from bulk), coatings, preliminary cost estimates, stock material, material procurement lead times.

Carry out first preliminary engineering structural and thermal calculations.



1. Introduction **Some design hints**

More to come in dedicated lectures during CAS

- Start with proven concepts which meet 90% your requirements. It might be enough ! Before exploring the unknown.

- Design to norms and directives (bolts, pressure vessels). Formulars already embed many years of industrial experience.

- Design to best practices built over time and found in design office handbooks.

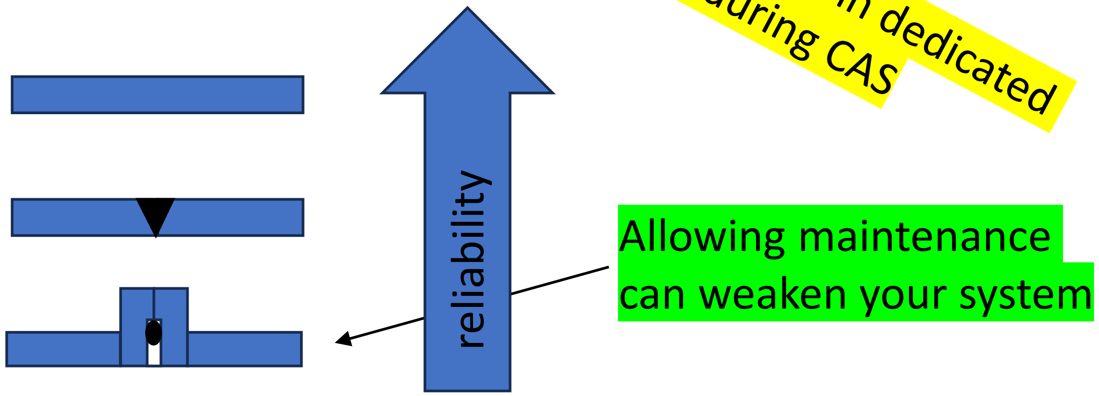
- Cautious in designing welded structures:

    - Large deformations due to local heating, difficulties in guarantying precision, unless remachining after welding (additional costs and complexity)
    - Loss of mechanical structural properties (Aluminium, copper)
    - Higher risk of leaks. (best weld is no weld)

1. Introduction **Some design hints**

More to come in dedicated lectures during CAS

1. Continuous material
2. Butt weld welded joint
3. Sealed joint (ex: for maintenance)



What you should consider when welding (important to respect this order)

1 - Use butt welds if possible. (Follow directives when welds are used in pressure vessels)

2 - If not, make sure you are able to inspect your weld through nondestructive tests such as tomography, ultrasound or die penetrant tests.

3 – If not possible, qualify your joining process (QMOS) by carrying out destructive tests, metallography inspections on representative samples and keep traceability (raw material certificates, inspection report, weld book)

1. Introduction **Some design hints**

More to come in dedicated lectures during CAS

Applications:
- Misalignments
- Axial strokes (for moving equipment
- Thermal contraction

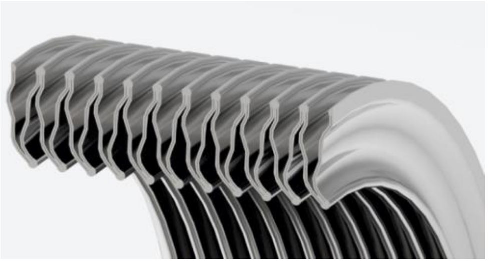
Flexible metal compensators (bellows)

Large flexibility

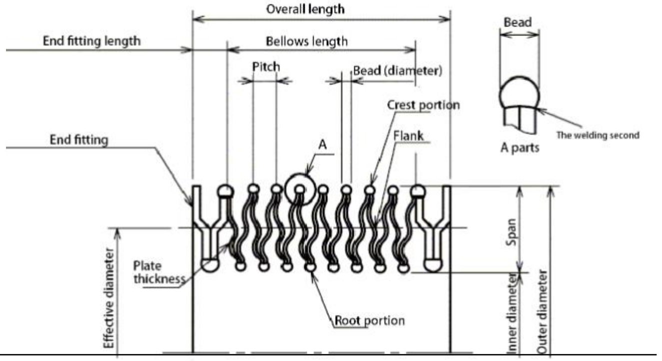
Lower reliability

Edge welded bellows

Independent parts joined together



Numerous welds



Welded bellows

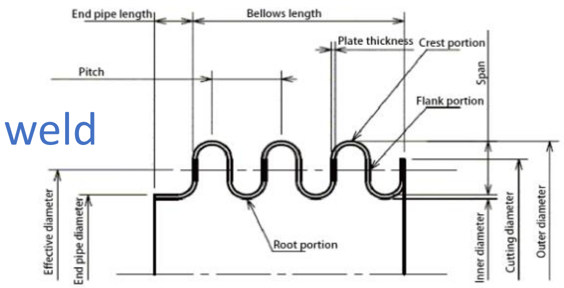
Hydroformed bellows

Lower flexibility

Higher reliability

Continuous material

No weld



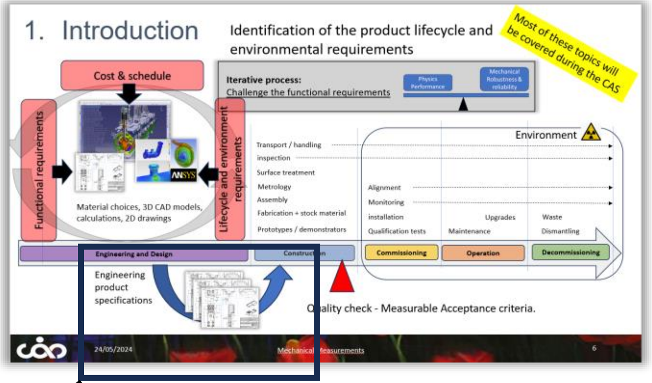
Formed bellows [Flexible tubes]

1. Introduction

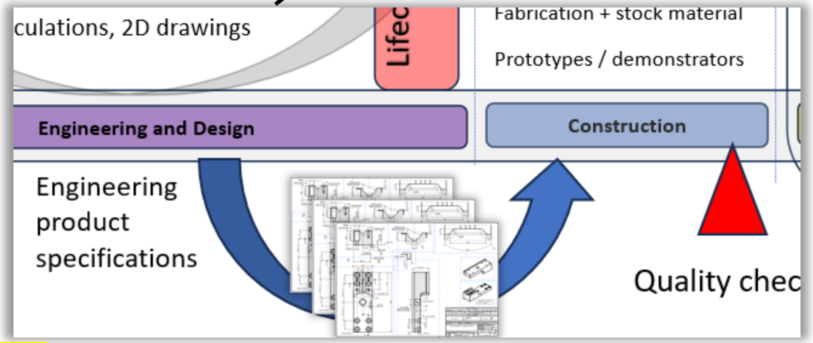
Step 2: Detailed design

Goal: Produce an exhaustive set of 3D models and 2D specification drawings for production.

Keep in mind that the contractual specification for fabrication of a piece of equipment is the **2D drawings** !! This is often overlooked, assuming the 3D model is sufficient.



2D drawings carry the exhaustive set of engineering specifications fulfilling the functional requirements.



material specifications, thermal treatments, coatings, tolerances, welding specifications, and so on…

A well defined 2D drawing contributes to making a robust and reliable design.

1. Introduction **Some hints**

WARNING !

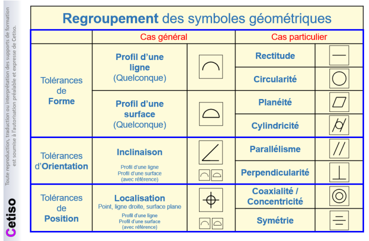
Sub-contracting of 2D drawings from provided 3D models can be dangerous !

Ideally it should be carried out by the same person of through a close collaboration to avoid misunderstanding in the expression of the requirements.

2. Special focus on 2D geometrical specification

What is a well defined 2D drawing in terms of geometrical specifications ?

- Functional dimensioning: Identification of dimensions which relate to your functional requirements
- Use of international standardized language (**ISO GPS** – **G**eometrical **P**roduct **S**pecification)



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Cetiso

Regroupement des symboles géométriques				
	Cas général		Cas particulier	
Tolérances de **Forme**	**Profil d'une ligne** (Quelconque)	⌒	**Rectitude**	—
			Circularité	○
	Profil d'une surface (Quelconque)	⌓	**Planéité**	⏥
			Cylindricité	⌭
Tolérances d'**Orientation**	**Inclinaison** Profil d'une ligne Profil d'une surface (avec référence)	∠ ⌒ ⌓	**Parallélisme**	//
			Perpendicularité	⊥
Tolérances de **Position**	**Localisation** Point, ligne droite, surface plane Profil d'une ligne Profil d'une surface (avec référence)	⌖ ⌒ ⌓	**Coaxialité / Concentricité**	◎
			Symétrie	⌯

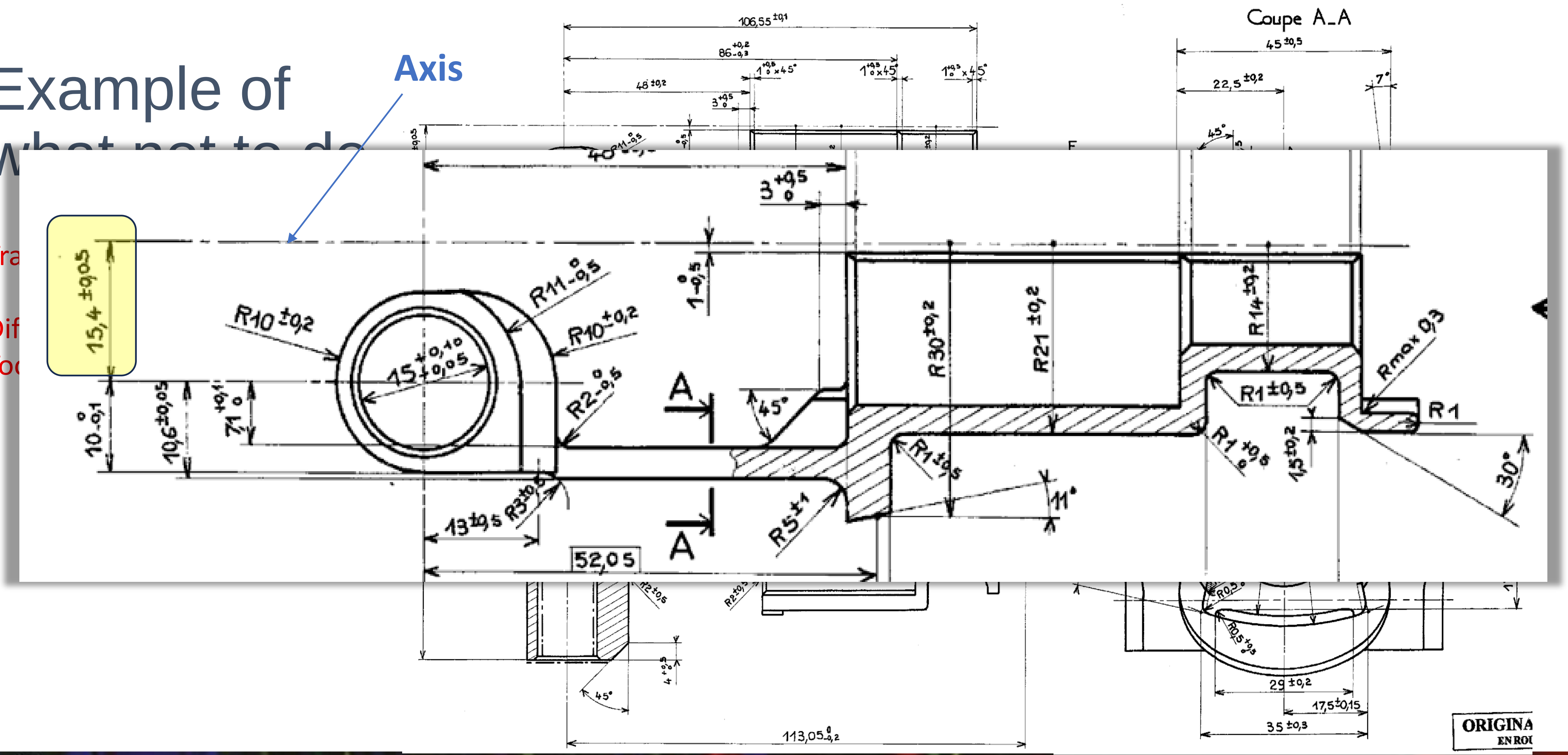
Commonly known as **GD & T** (**G**eometrical **D**imensioning and **T**olerancing)

2. Special focus on 2D geometrical specification

Example of what not to do

Tra

Dif
Toc

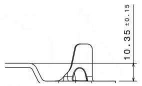


2. Special focus on 2D geometrical specification

Courtesy to J-Y Jacotin

Traditional way of tolerancing parts

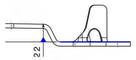
Clearance on drawing



Actual part

(slight angular defect)

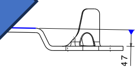
First measurement



Second measurement

?

Within spec



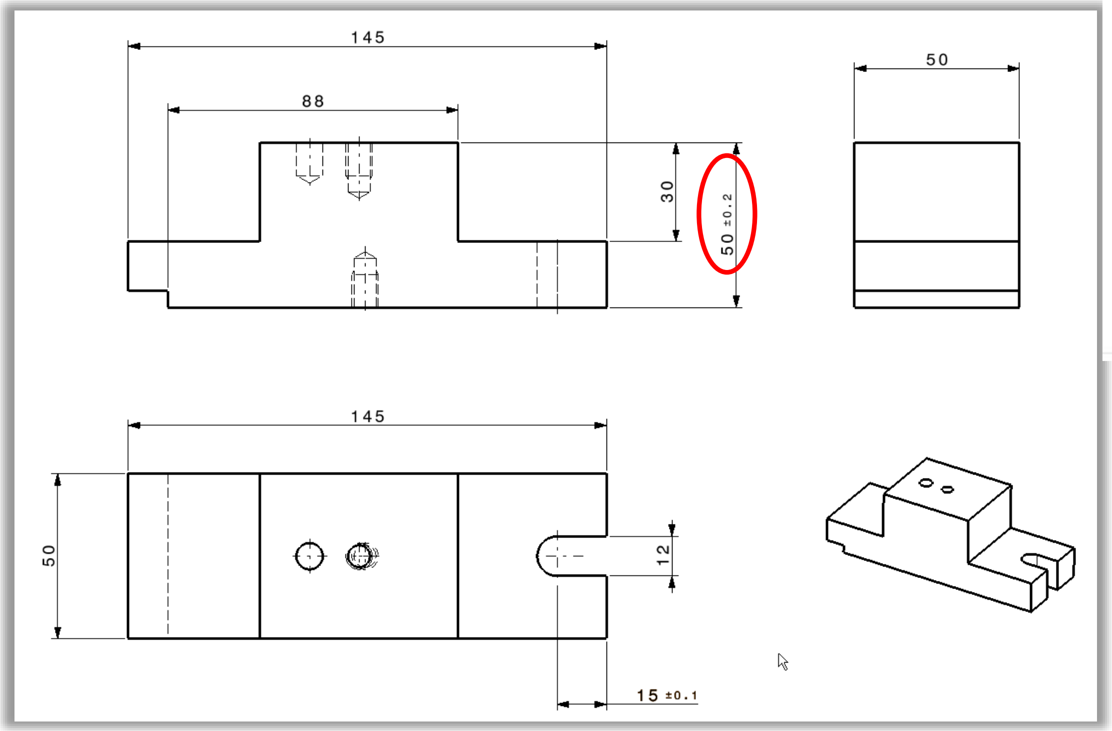
Out of spec

2 Options:

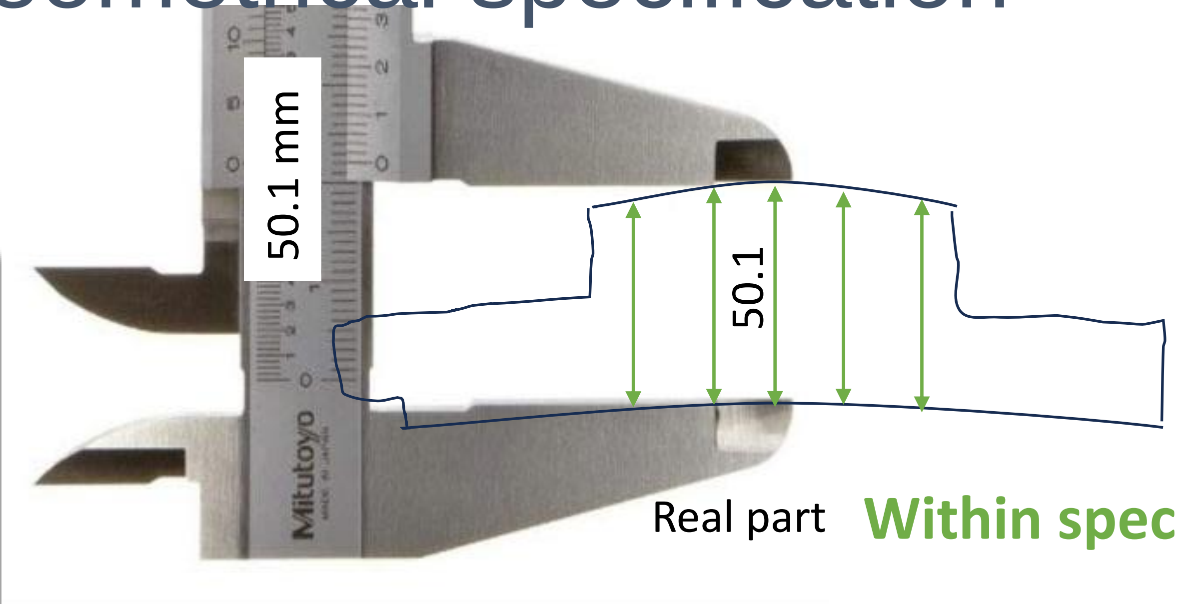
- You make new ones = higher cost
- You accept the part and risk to have failures

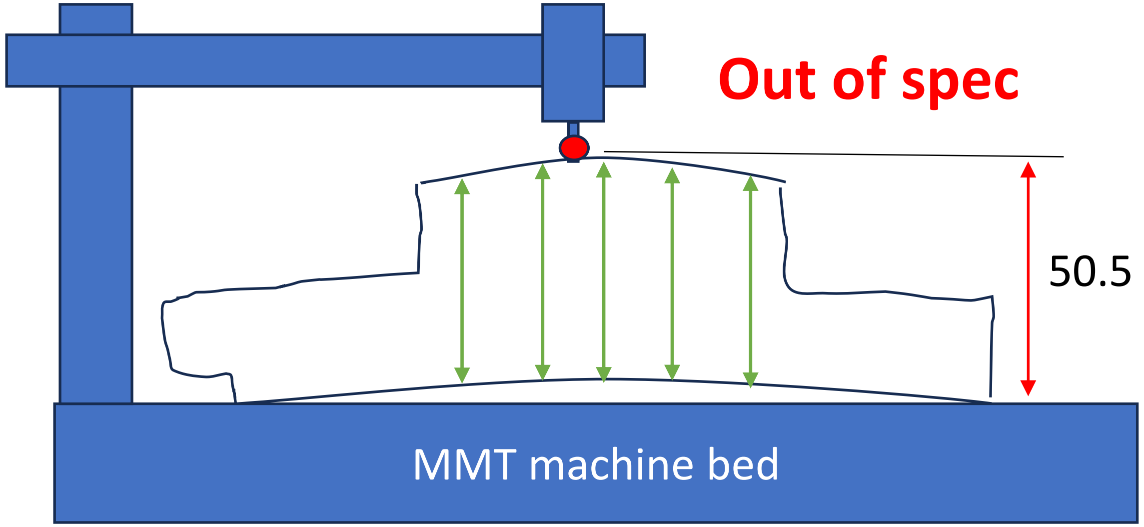
2. Special focus on 2D geometrical specification

Traditional dimensioning using linear dimensions are not precise enough to express a need in a clear way



Drawing spec



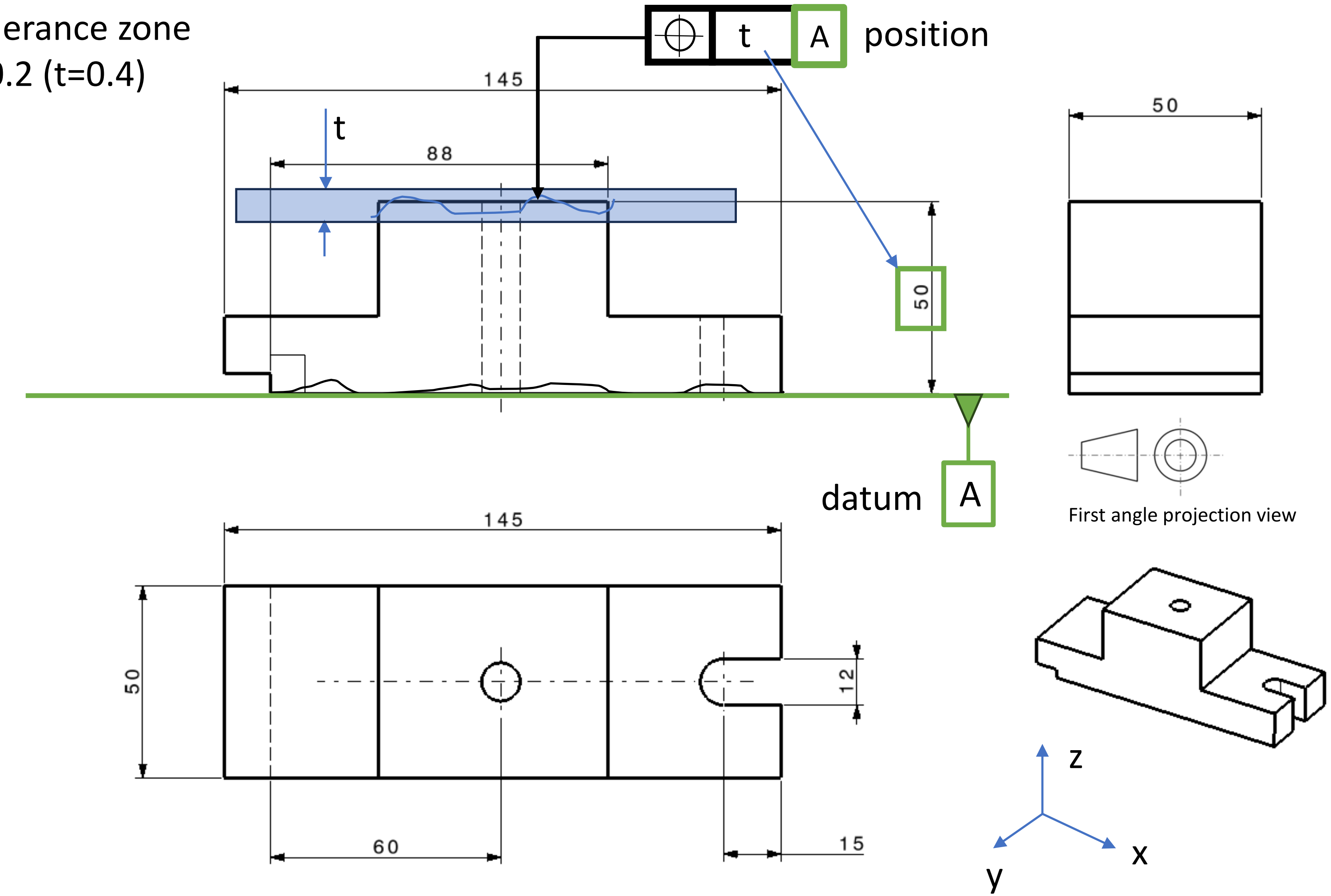


Does it respect your need ?

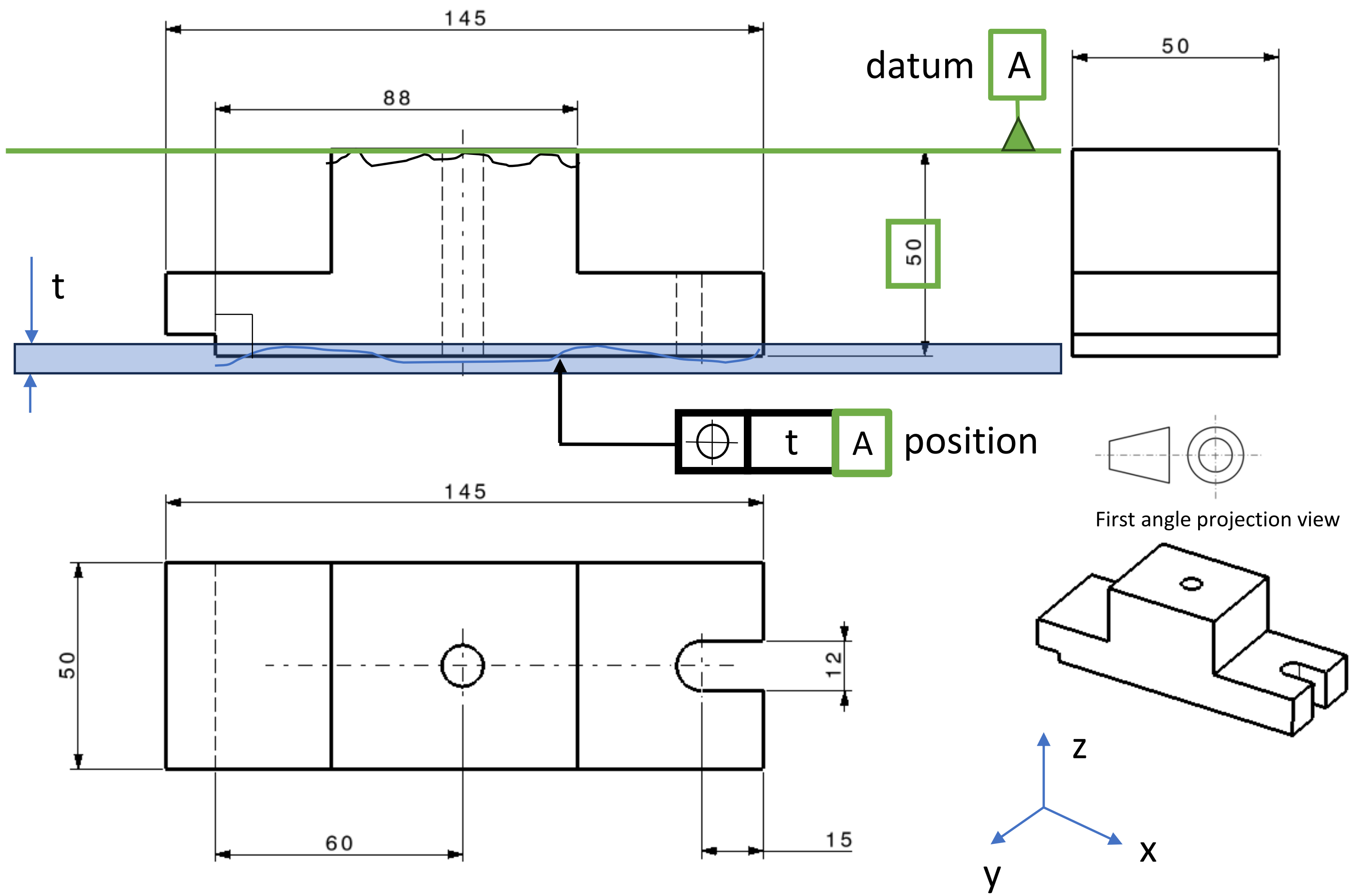
Real part Out of spec

2. Special focus on 2D geometrical specification

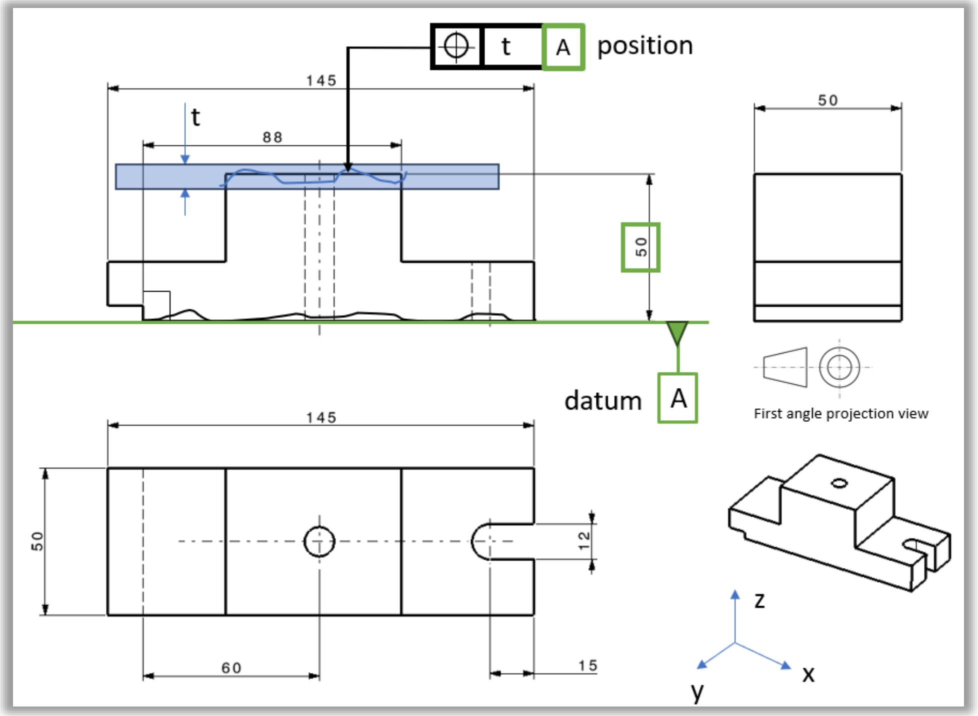
t = tolerance zone
Ex: ±0.2 (t=0.4)

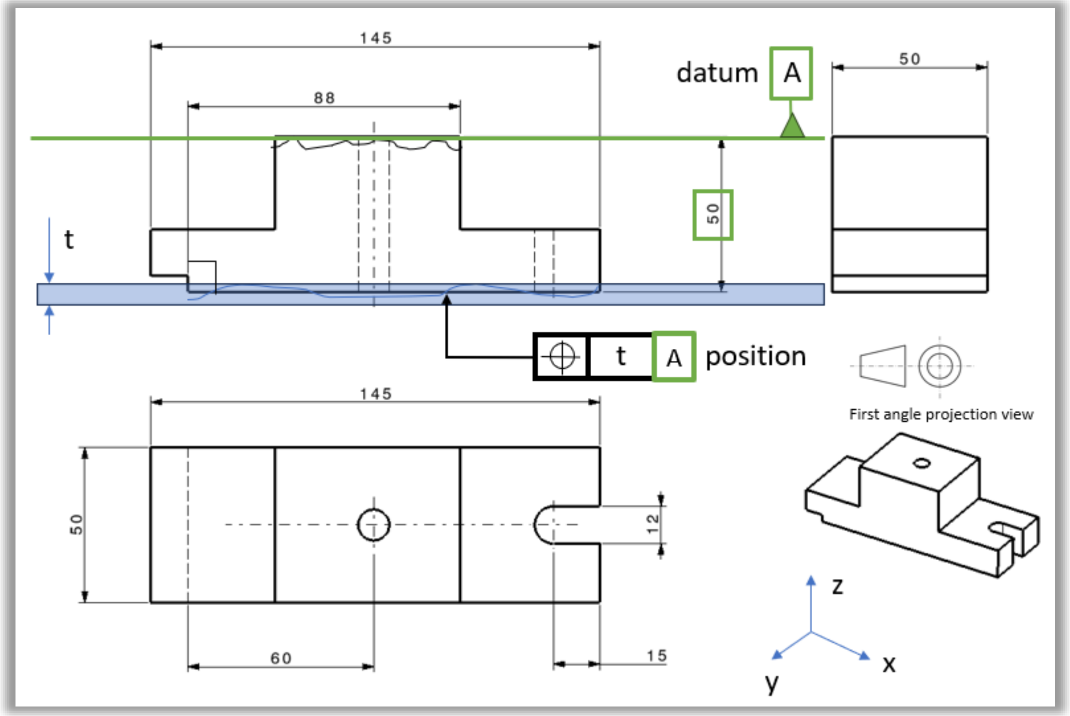


2. Special focus on 2D geometrical specification



2. Special focus on 2D geometrical specification

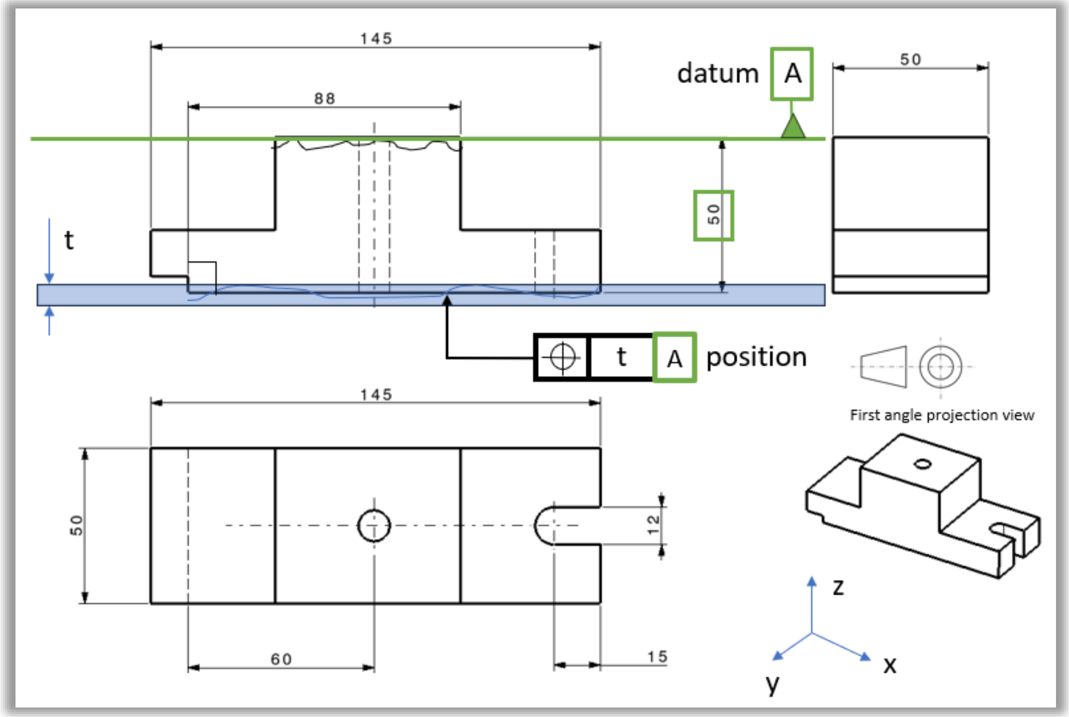


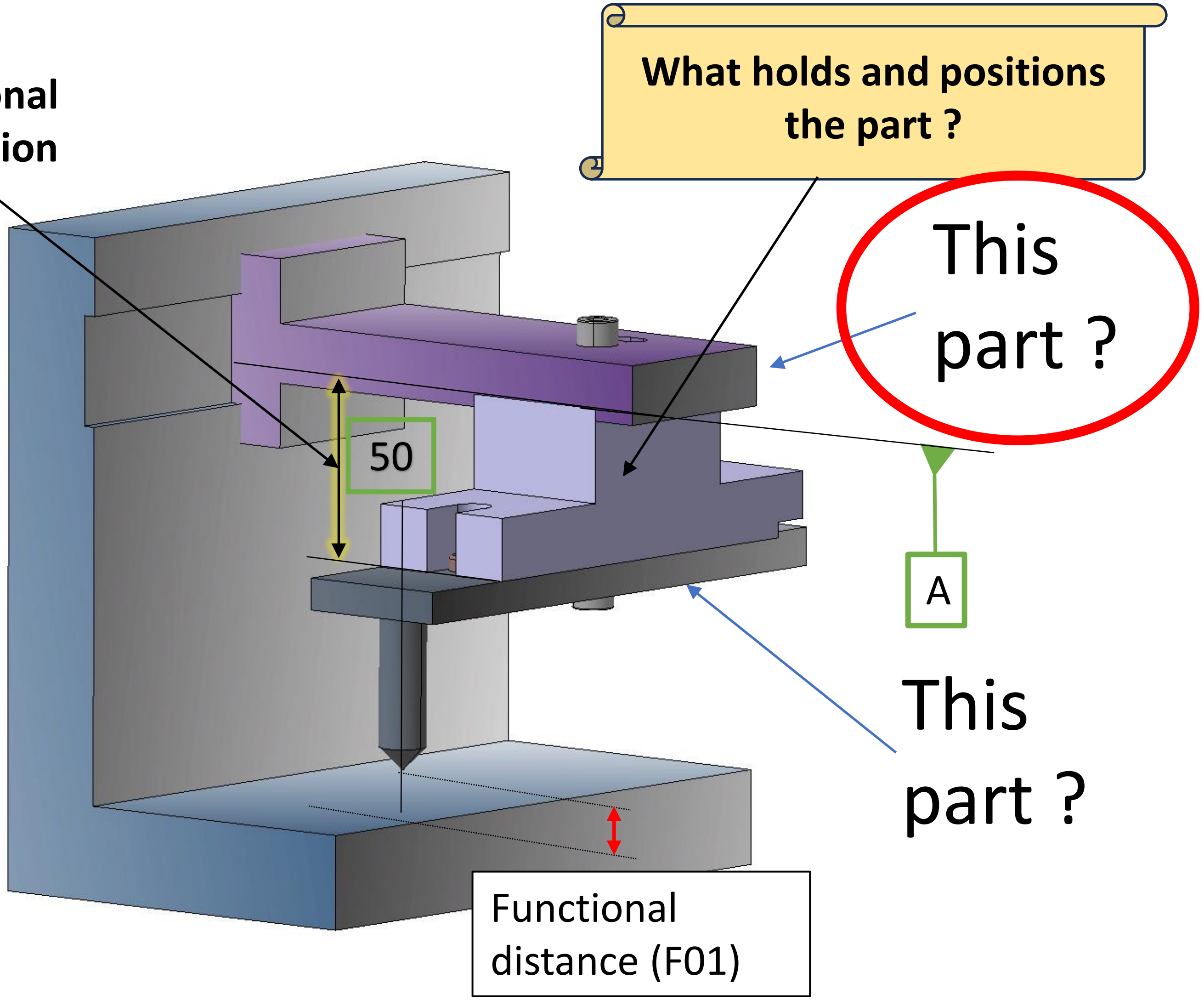


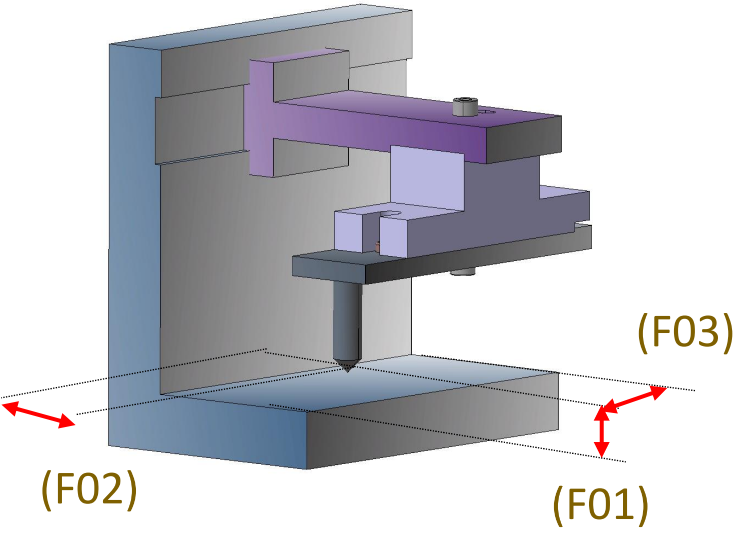
How do we choose the correct surface for setting our datums ?

2. Special focus on 2D geometrical specification

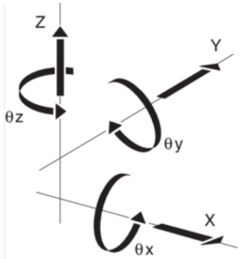
The context of the assembly





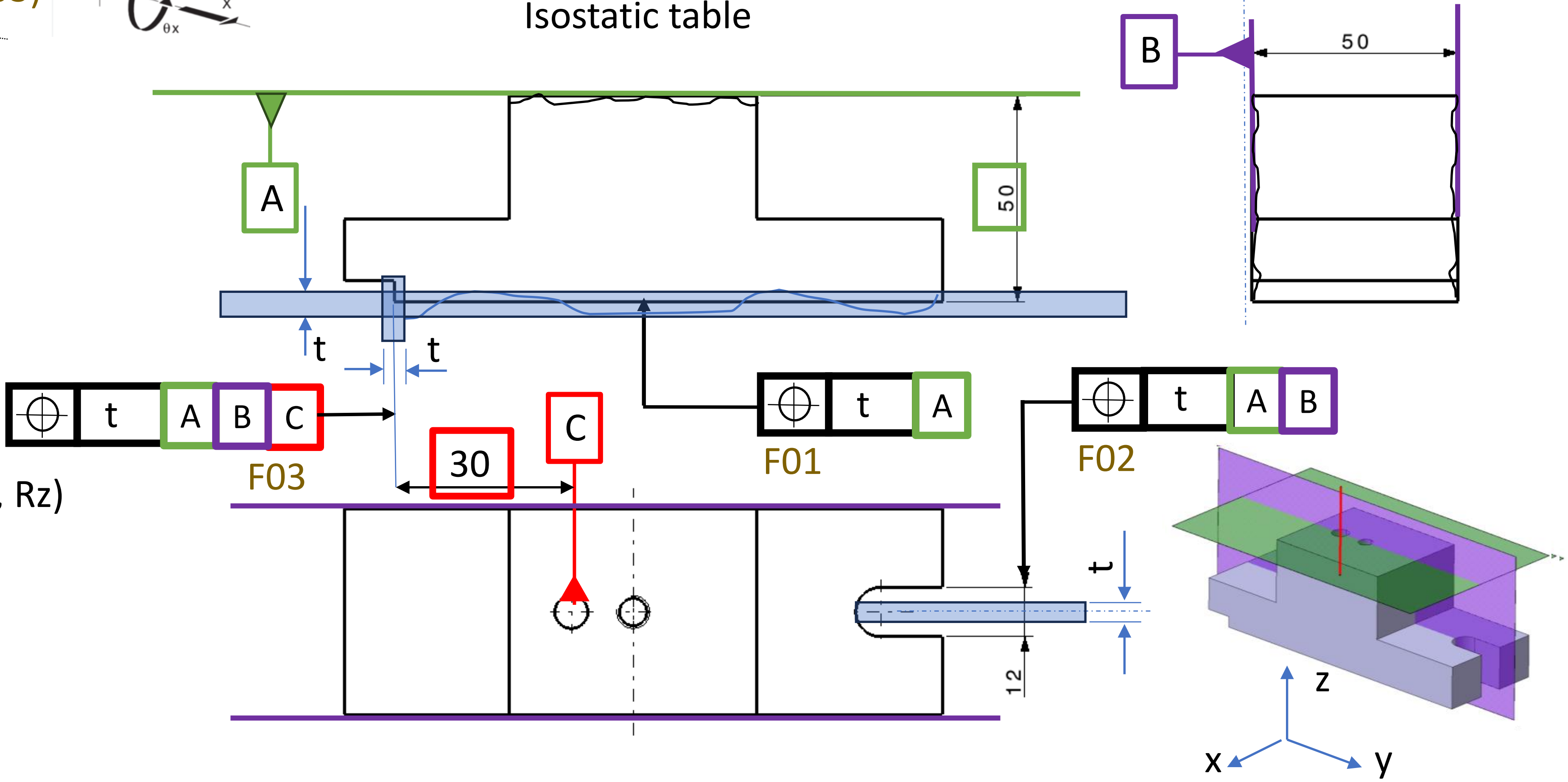


6 degrees of freedom



	X	Y	Z	Rx	Ry	Rz
A			x	x	x	
B		x				x
C	x					

Isostatic table



A: Primary datum:

Orientates the parts and block 3 degrees Of freedom (Tz, Ry, Rx)

B: Secondary datum

Blocks 2 degrees of freedom (Tx, Rz)

C: Tertiary datum

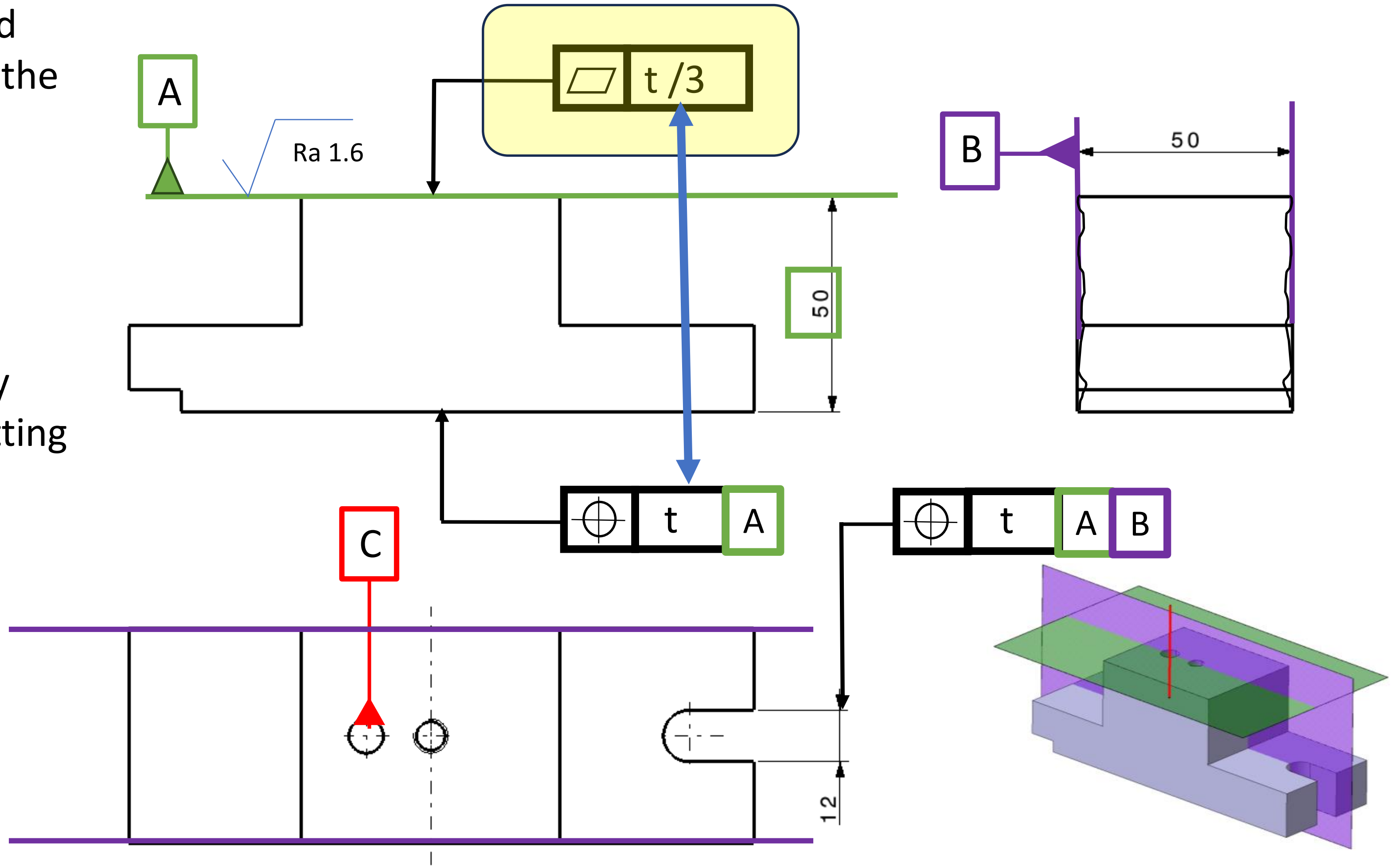
Blocks 1 deg of freedom. (Ty)

2. Special focus on 2D geometrical specification

Containing shape on Primary reference

1. Primary datum feature should always be more precise than the positioned element. (factor between 2 and 3 - based on industrial feedback).

2. Roughness specification are commonly applied to primary references but also to all matting surfaces in general



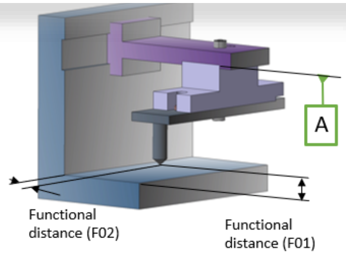
Advantages of the ISO GPS language

- Avoids interpretation ambiguities
- Creates bonds between design, fabrication and control
- Optimizes costs

Functional specification

Advantages of functional dimensioning

- To better target and express your need
- Enhances the comprehension of how the part is intended to be used.
- Clarifies what dimensions are critical and need to be checked in metrology.



	X	Y	Z	Rx	Ry	Rz
A			x	x	x	
B		x				x
C	x					

Isostatic table

A: Primary datum:
Orientates the parts and block 3 degrees Of freedom (Tz, Ry, Rx)

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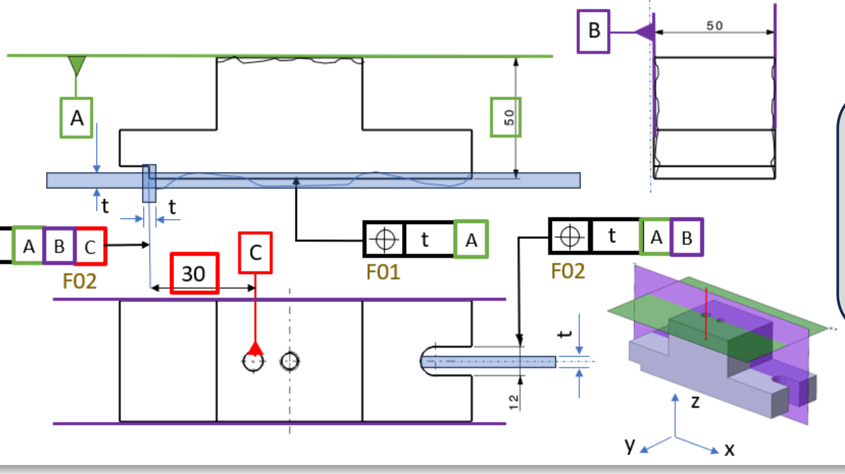
Blocks 2 degrees of freedom (Tx, Rz)

C: Tertiary datum
Blocks 1 deg of freedom. (Ty)

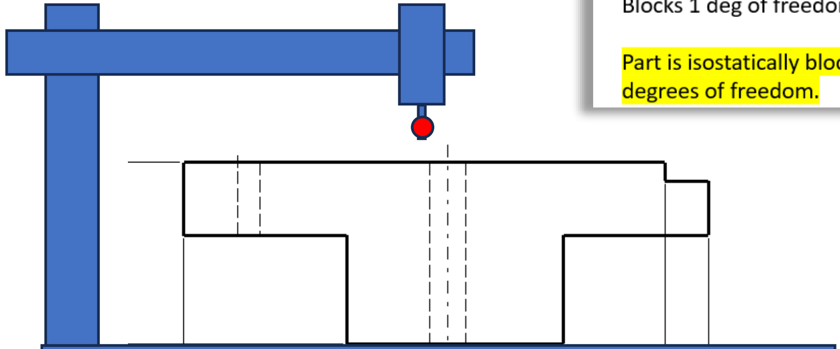
Part is isostatically blocked in all degrees of freedom.



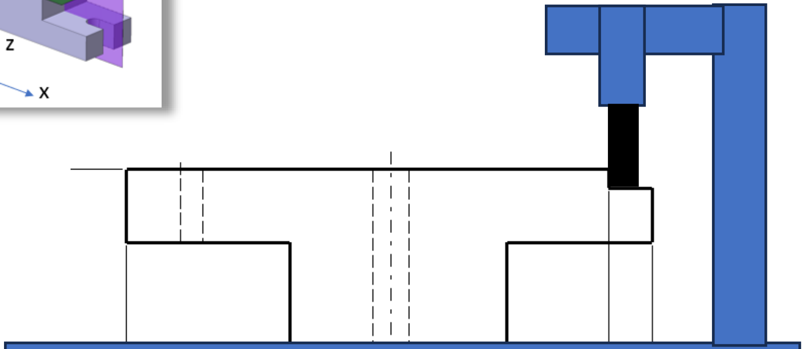
Drawing specification

Clear specification of measurement for metrology.

Gives a clear explanation of the functionality to help the manufacturer in applying the best fabrication process



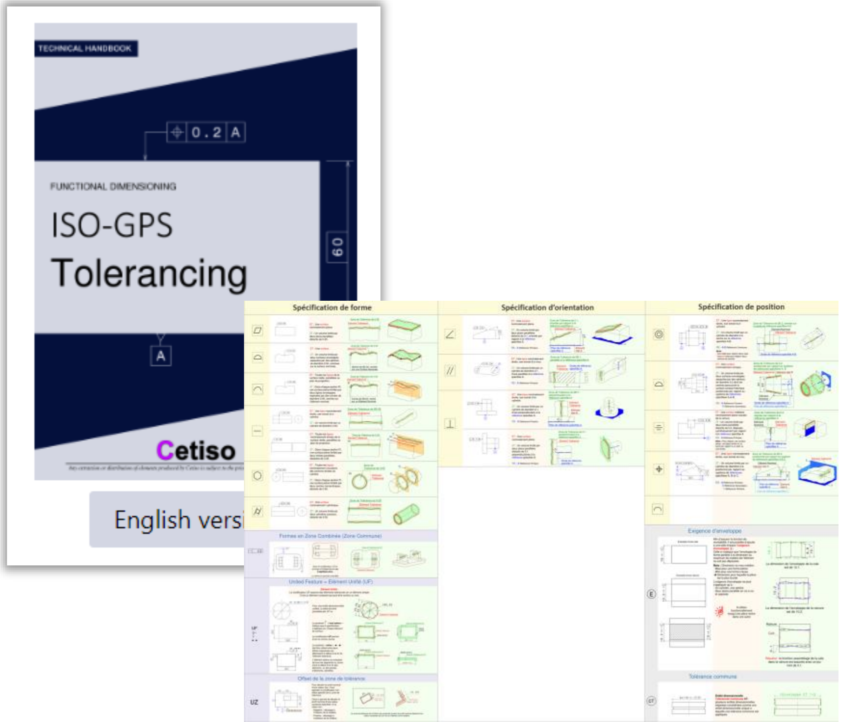
MMT machine bed



CNC Milling machine bed

Understanding basics rules of GD&T and ISO GPS framework

Click here to access to ISO GPS booklet



ISO GPS Symbol definitions

Cetiso

Regroupement des symboles géométriques

	Cas général		Cas particulier	
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	Profil d'une surface (Quelconque)	⌓	**Planéité**	⏥
			Cylindricité	⌭
Tolérances d'**Orientation**	**Inclinaison** Profil d'une ligne Profil d'une surface (avec référence)	∠ ⌒ ⌓	**Parallélisme**	//
			Perpendicularité	⊥
Tolérances de **Position**	**Localisation** Point, ligne droite, surface plane Profil d'une ligne Profil d'une surface (avec référence)	⌖ ⌒ ⌓	**Coaxialité / Concentricité**	◎
			Symétrie	⌯

Many thanks to Cetiso (Mr Jacotin)

Understanding basics rules of GD&T and ISO GPS framework

Application of ISO GPS on drawings:
ISO 14405 - Specification by dimension
ISO 1101 - Tolerances of form, orientation, location and run-out
ISO 5459 - Datum and datum system
ISO 5458 - Pattern and combined geometrical specification
ISO 1660 - Profile tolerancing
ISO 10579 - Dimensioning and tolerancing — Non-rigid parts
ISO 17863 - Tolerancing of moveable assemblies
ISO 2692 - Maximum/Minimum material requirement and Reciprocity
ISO 16792 - Digital product definition data practices
..... Etc (ISO3040...)

Courtesy to T. Cappelli

- Complementary standard to define non-functionnal dimensional tolerancing:

- Standard for general tolerancing linked to specific Manufacturing method:
- ISO 2768 - Part produced by material removal (machining)
- ISO 13920 - Welded constructions
- NF-E02-352 - Cut and formed parts
- ISO 9013 - Thermal cutting (laser)
- ISO 8062 - Molded parts

- Standard for general geometrical tolerancing not linked to any specific manufacturing method:
- ISO 22081 - General geometrical specifications and general size specifications

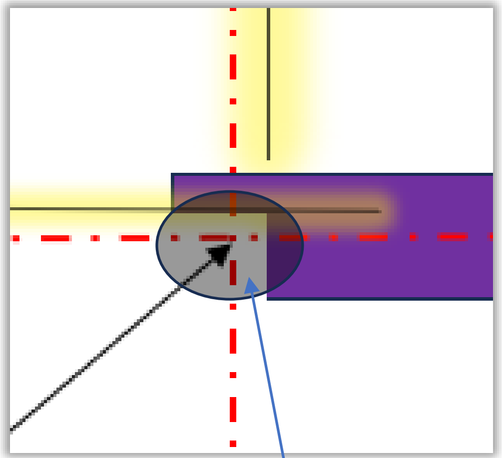
3. A practical case

Application of functional dimensioning and ISO GPS language to a practical case

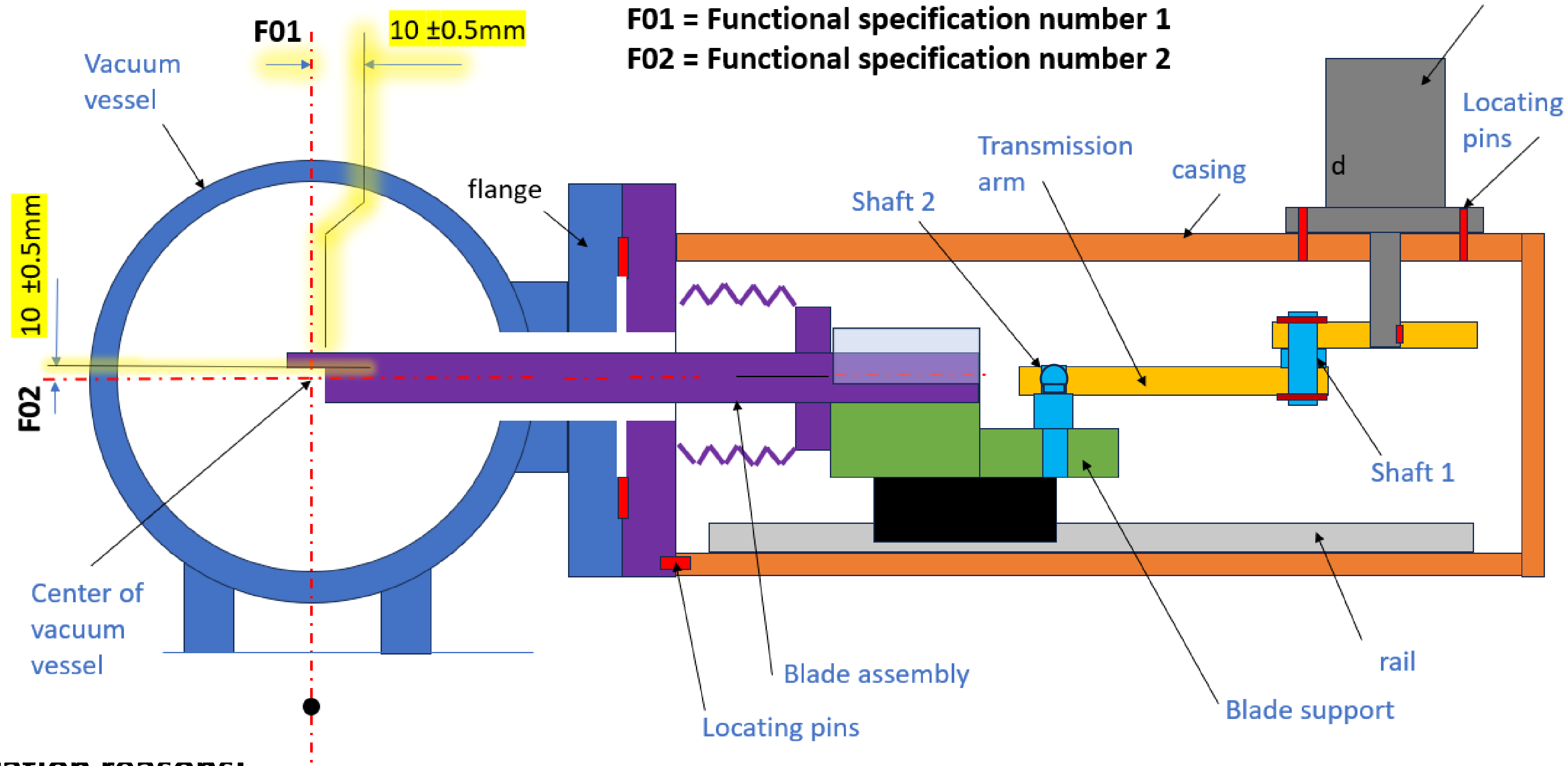
Inspired from a scraper design for the SPS machine at CERN

Courtesy to the STI group.

Scraper example



Beam cross-section

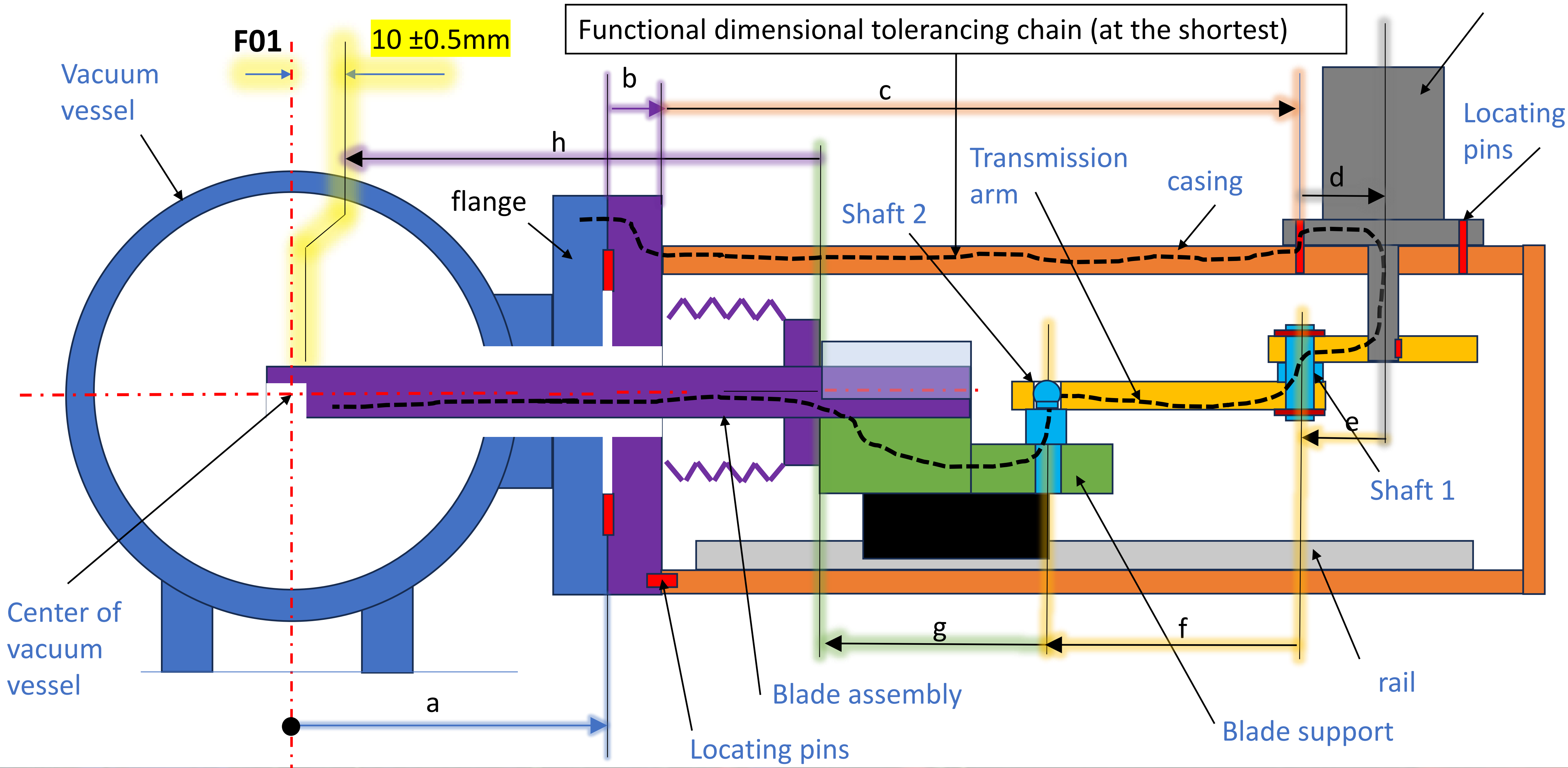


Assumptions for simplification reasons:

- No orientation defects
- Pin fits are considered without play
- Vacuum flange considered perfectly in position with respect to the center of the tank.
- Flanges are perfectly in contact after compression of the vacuum gasket.

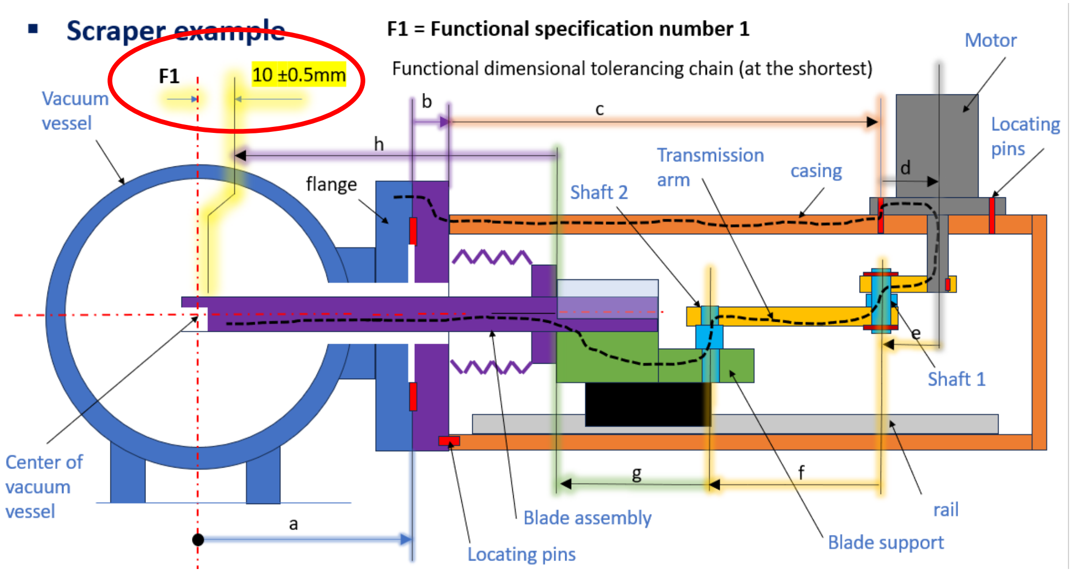
Scraper example

F01 = Functional specification number 1



- Are we in spec ?

F01 = Functional specification number 1



Results:

Functional condition F01: 10 ±0.5 mm,

result: **10 ±0.61 mm** (out of spec)

Σ of tolerances method (alternatively you can use min/max method)

	Designation	Nominal dimensions	Tolerance ±	Interval
a	flange mating surface	100.00	0.2	0.40
b	flange thickness	20.00	0.02	0.04
c	pins in the casing	250.00	0.05	0.10
d	motor shaft	40.00	0.2	0.40
e	transmission shaft interface:	30.00	0.05	0.10
f	ball sphere interface	- 80.00	0.05	0.10
g	blade carrier	- 80.00	0.02	0.04
h	tip of shaft	- 270.00	0.02	0.04
	Nominal clearance	**10.00**		
	Σ of tolerances			**1.22**

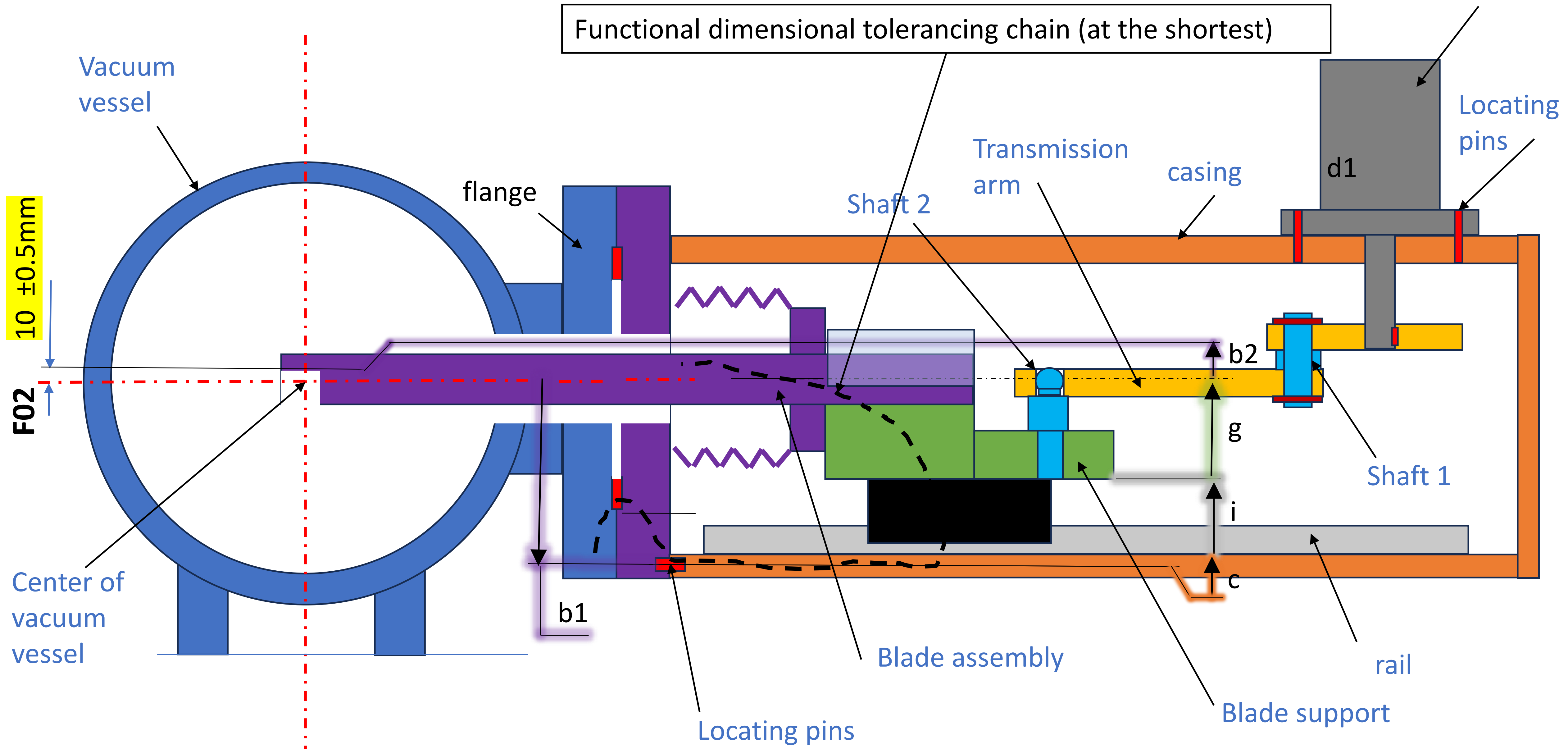
Dimensions tolerance based on conventional manufacturing means.

Any solution ?

- **Reduce the number of parts in the chain**
- **Tighten tolerances (impact on cost)**
- **Add an adjustment system (impact on cost and robustness)**

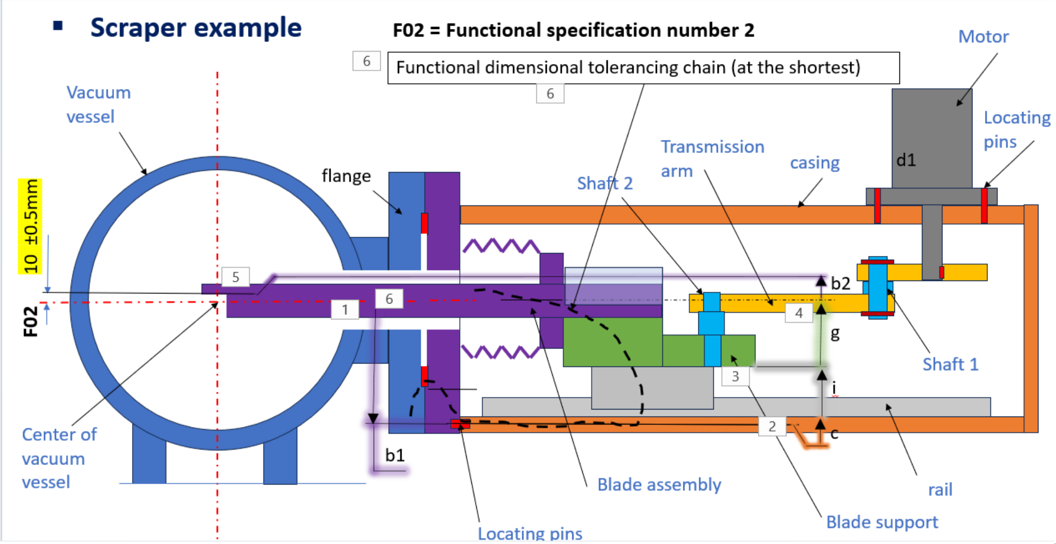
▪ Scraper example

F02 = Functional specification number 2



▪ Are we in spec ?

F02 = Functional specification number 2



Results:

Functional condition: F02: 10 ±0.5 mm,

result: **10 ± 0.32 mm (in spec)**

Σ of tolerances method (alternatively you can use min/max method)

	Designation	Nominal dimensions	Tolerance ±	Interval
a	Flange axis position	-	0.02	0.04
b1	locating pin position	- 50.00	0.05	0.1
c	case lower surface	5.00	0.05	0.1
i	rail and slider height	20.00	0.1	0.2
g	blade shaft position	25.00	0.05	0.1
b2	blade tip	10.00	0.05	0.1
	Nominal clearance	**10.00**		
	Σ of tolerances			**0.64**

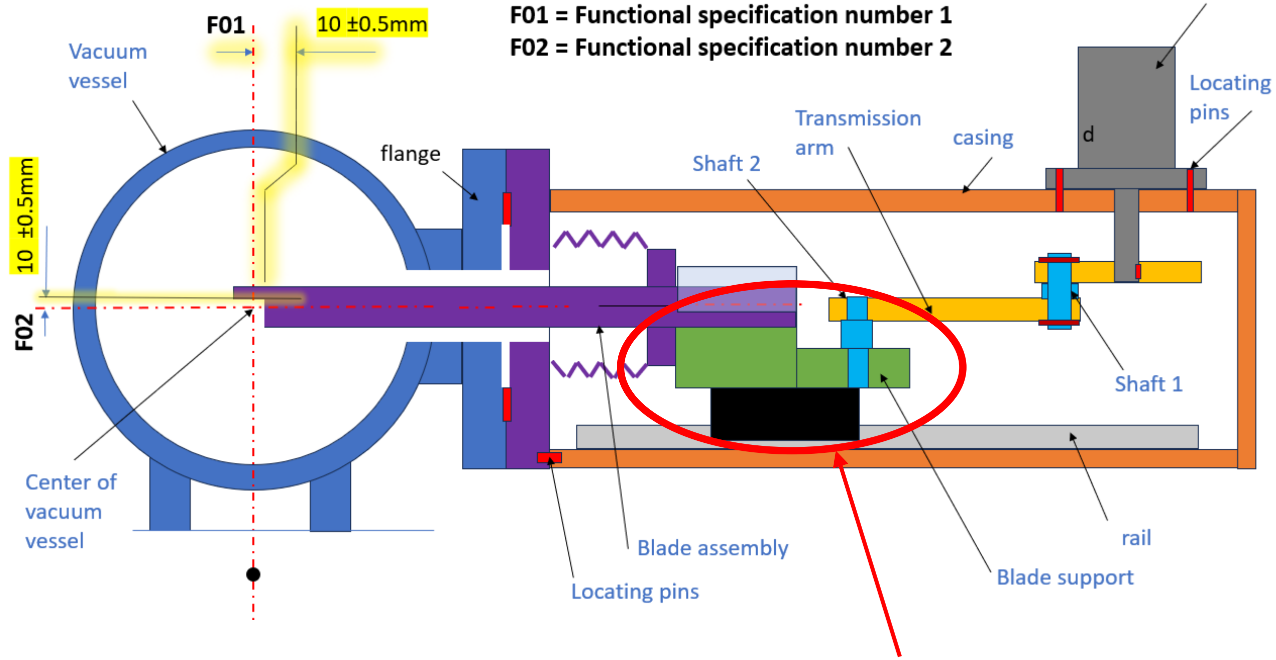
Number of elements in the chain is lower, so we can meet the spec.

Dimensions tolerance based on conventional manufacturing means:

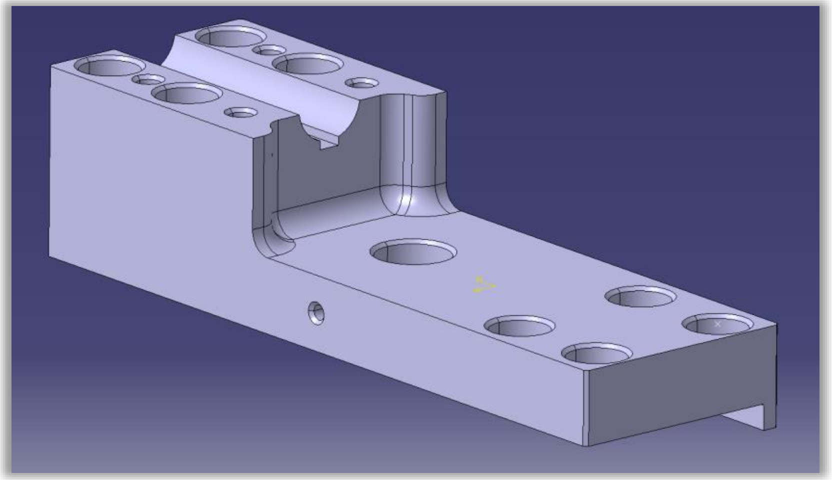
Let's produce the 2D drawing of the "blade support" according to its 2 functional specifications (F01 and F02)

- **Scraper example**

F01 = Functional specification number 1
F02 = Functional specification number 2



Blade support



Remember, we need the context ?

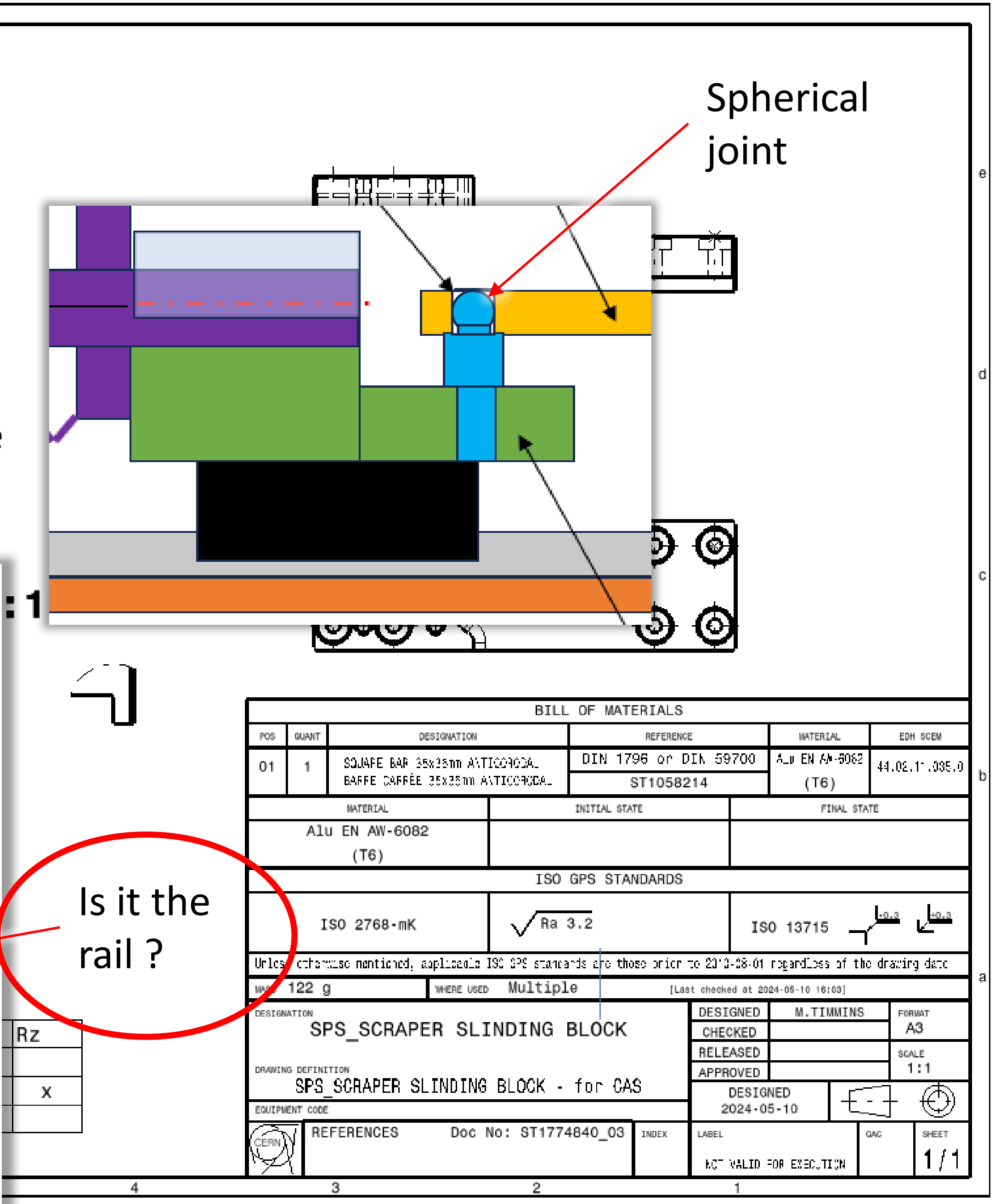
What holds and positions the part ?

Is it the Blade ?

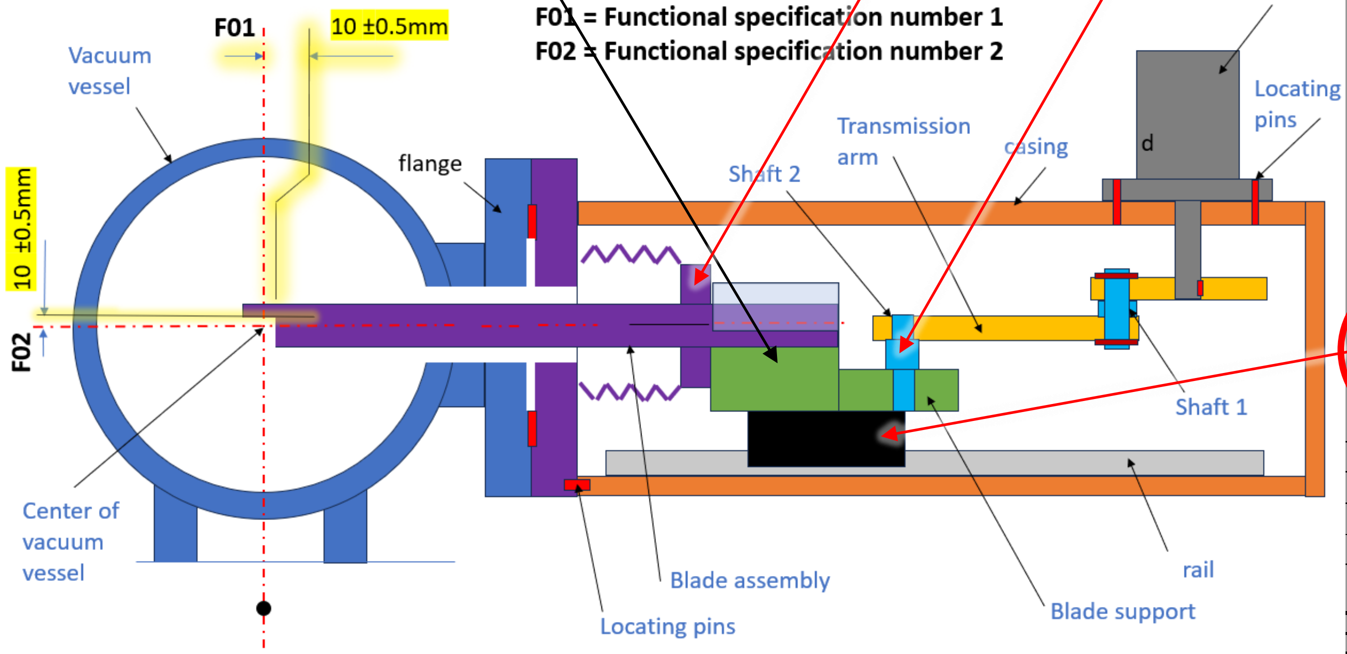
Is it the shaft ?

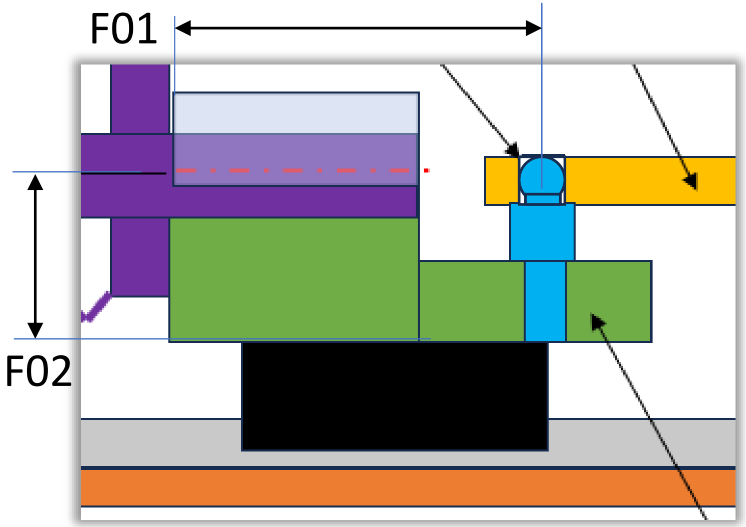
Is it the rail ?

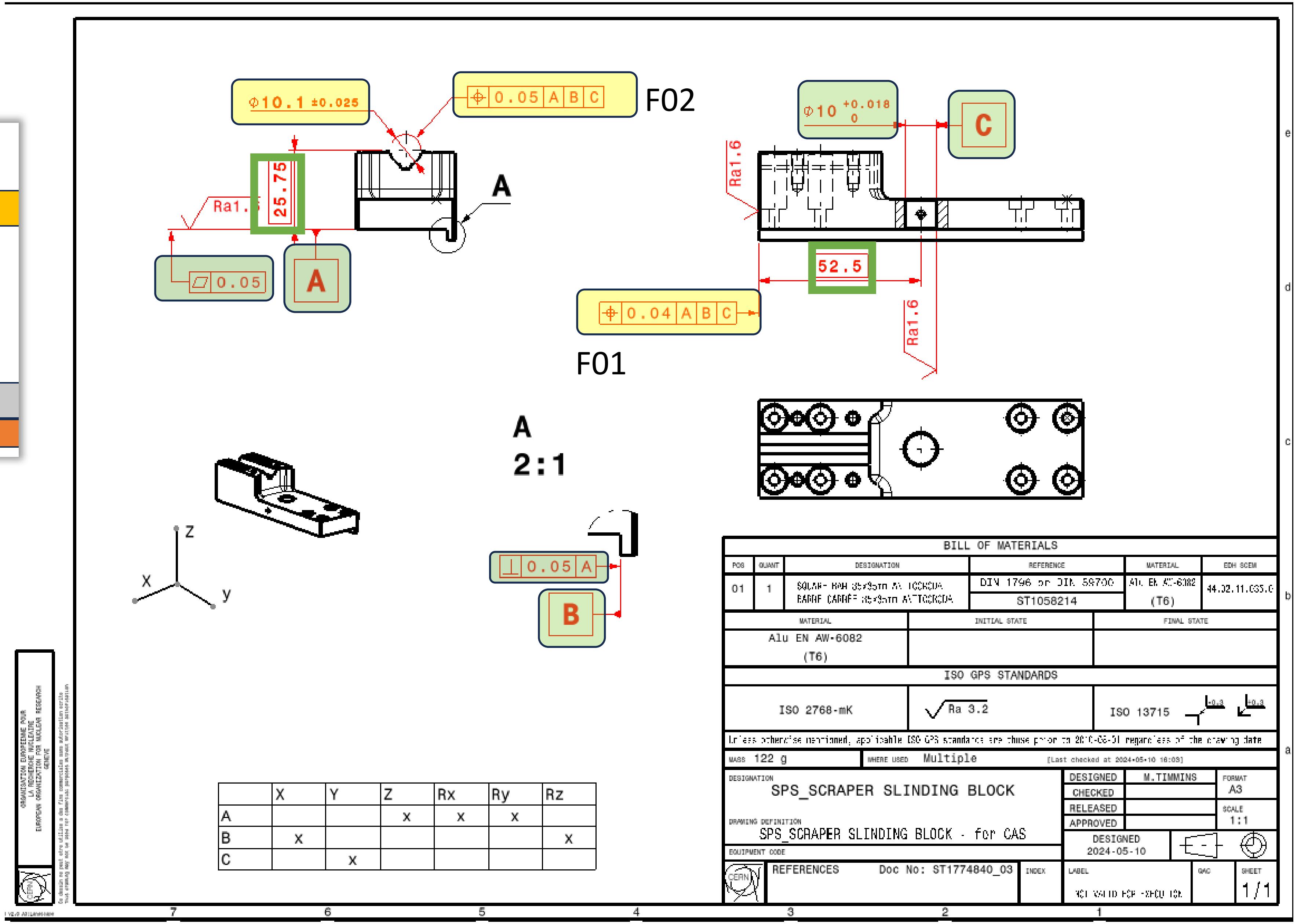
Spherical joint



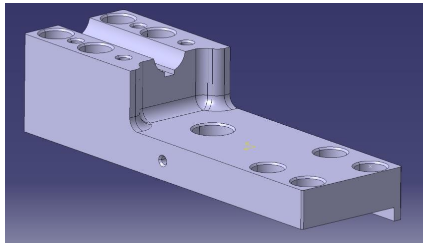
- **Scraper example**





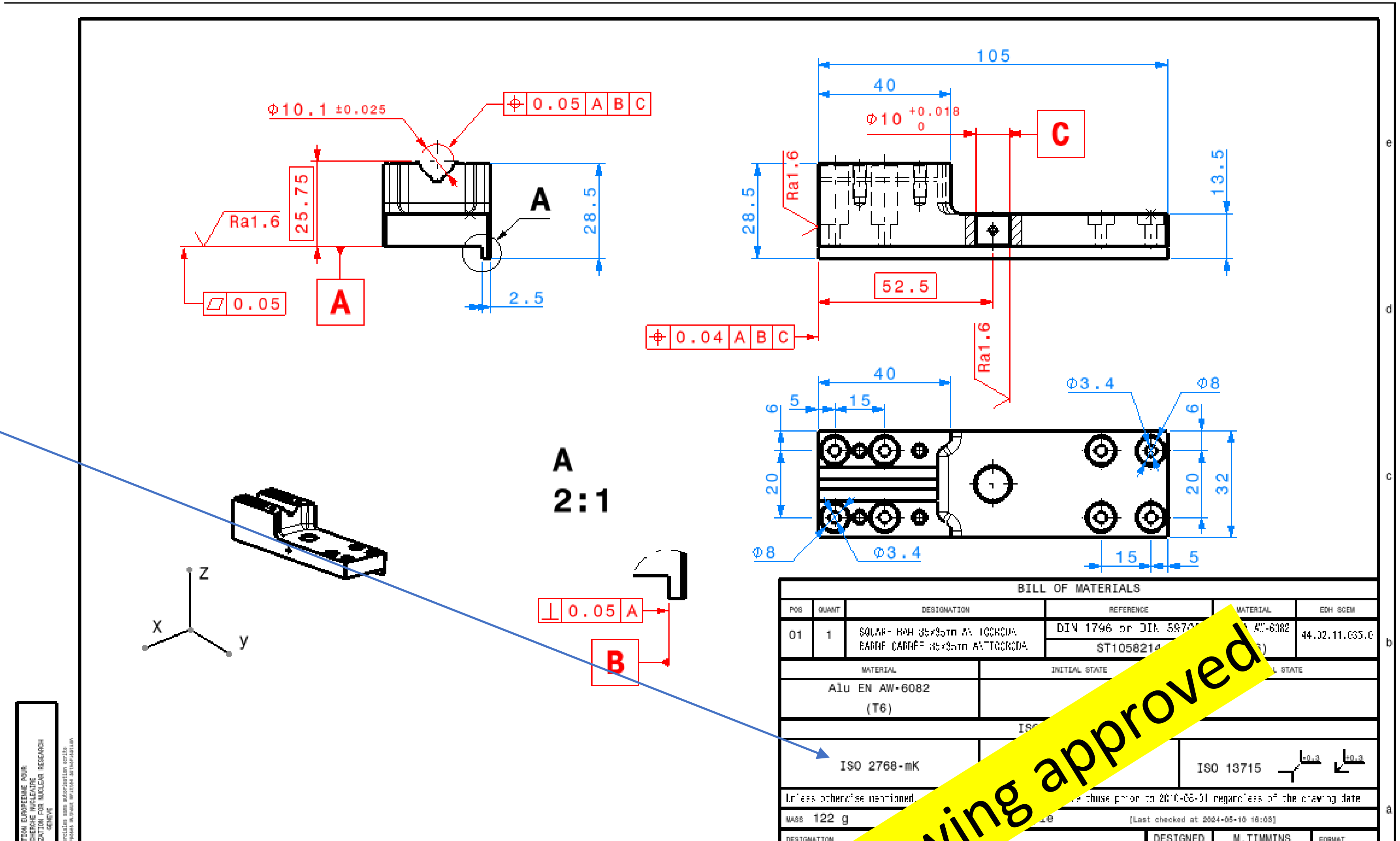


	X	Y	Z	Rx	Ry	Rz
A			x	x	x	
B	x					x
C		x				



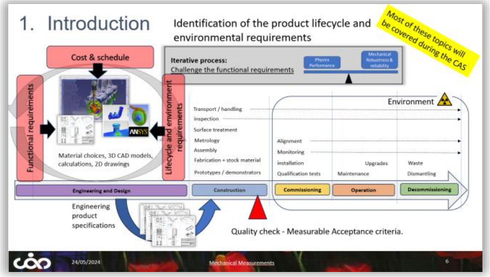
Functional dimensions

Nonfunctional dimensions. Needed for fabrication. Tolerance relate to standards (ISO 2768)



	X	Y	Z	Rx	Ry	Rz
A			x	x	x	
B	x					x
C		x				

4 - Summary



- Robust and reliable design remember down time cost (200 kCHF/day).
- Well defined requirements including lifecycle and environment ones
- 2D drawings are your contractual specification for building your equipment.
- What positions the part = good definition of your datum system.
- Make sure all your fabrication specifications are measurable.

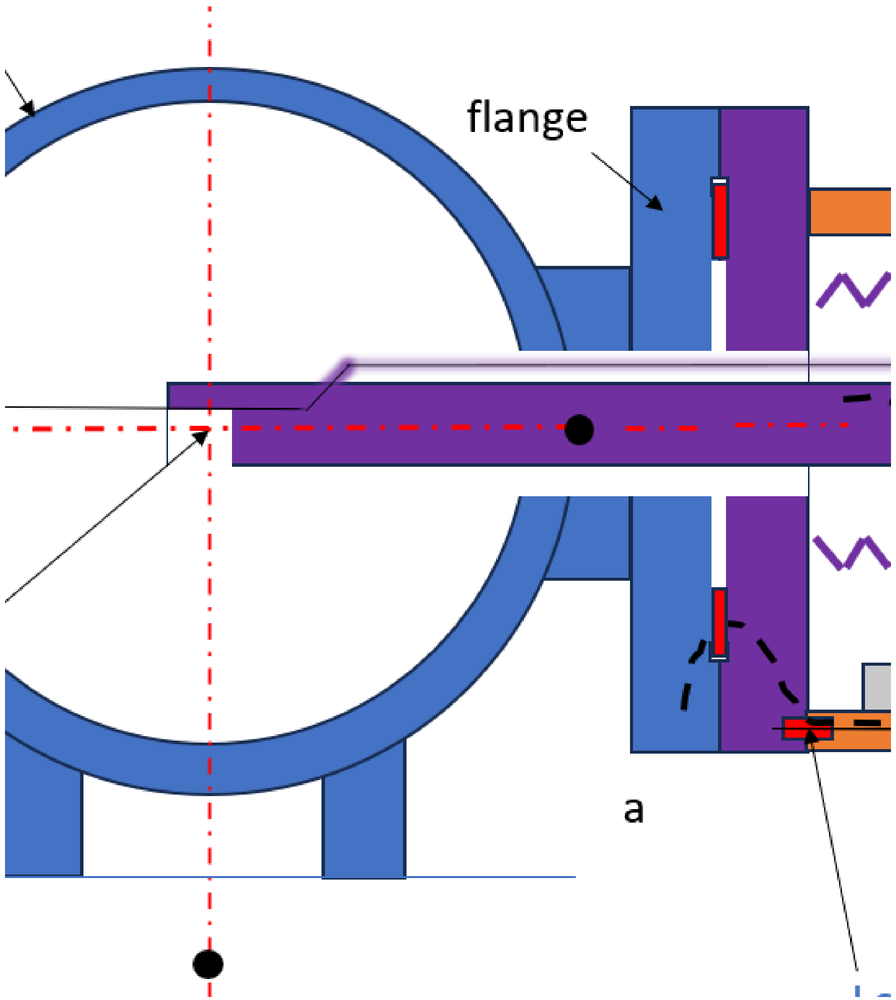
Thank you very much

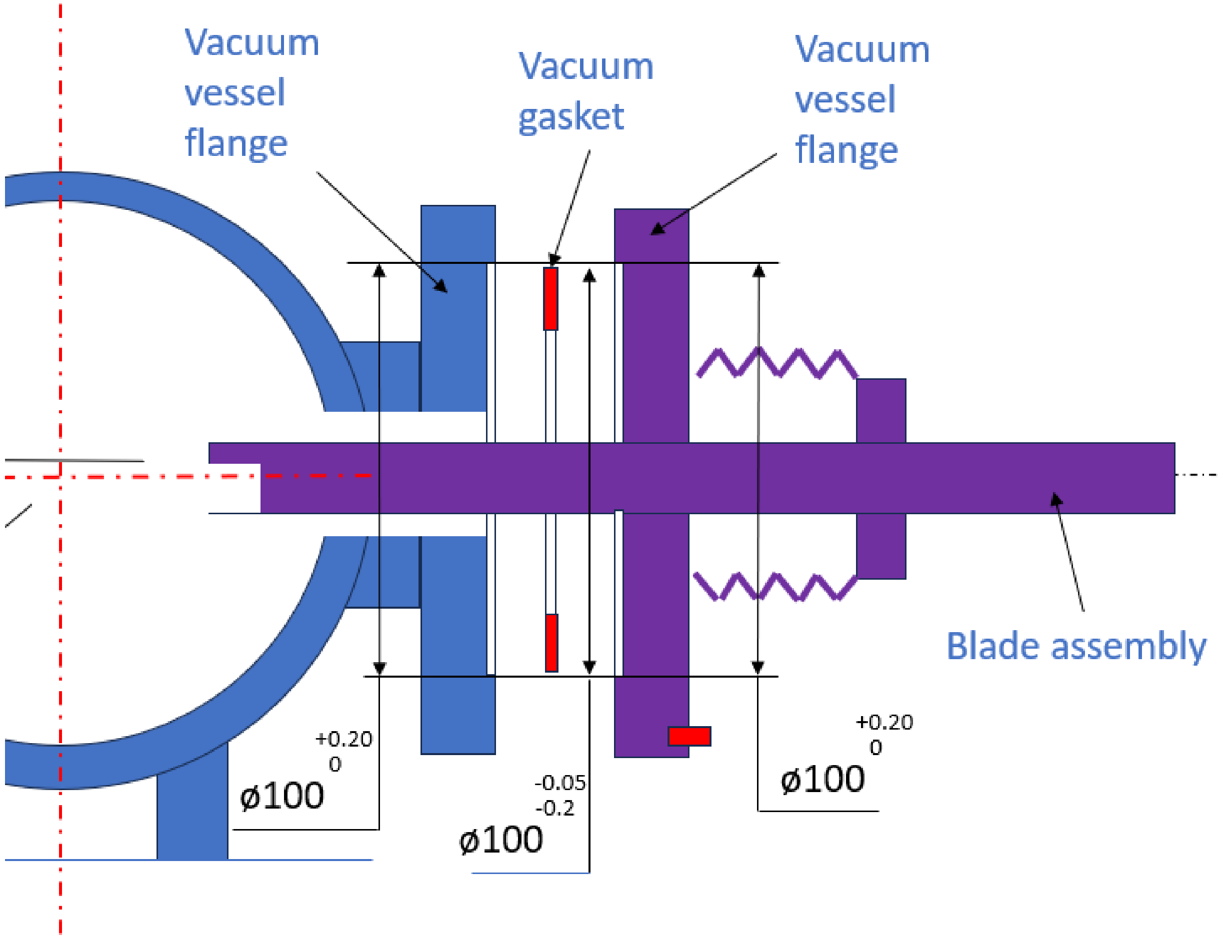
Questions ?

Engineering Department

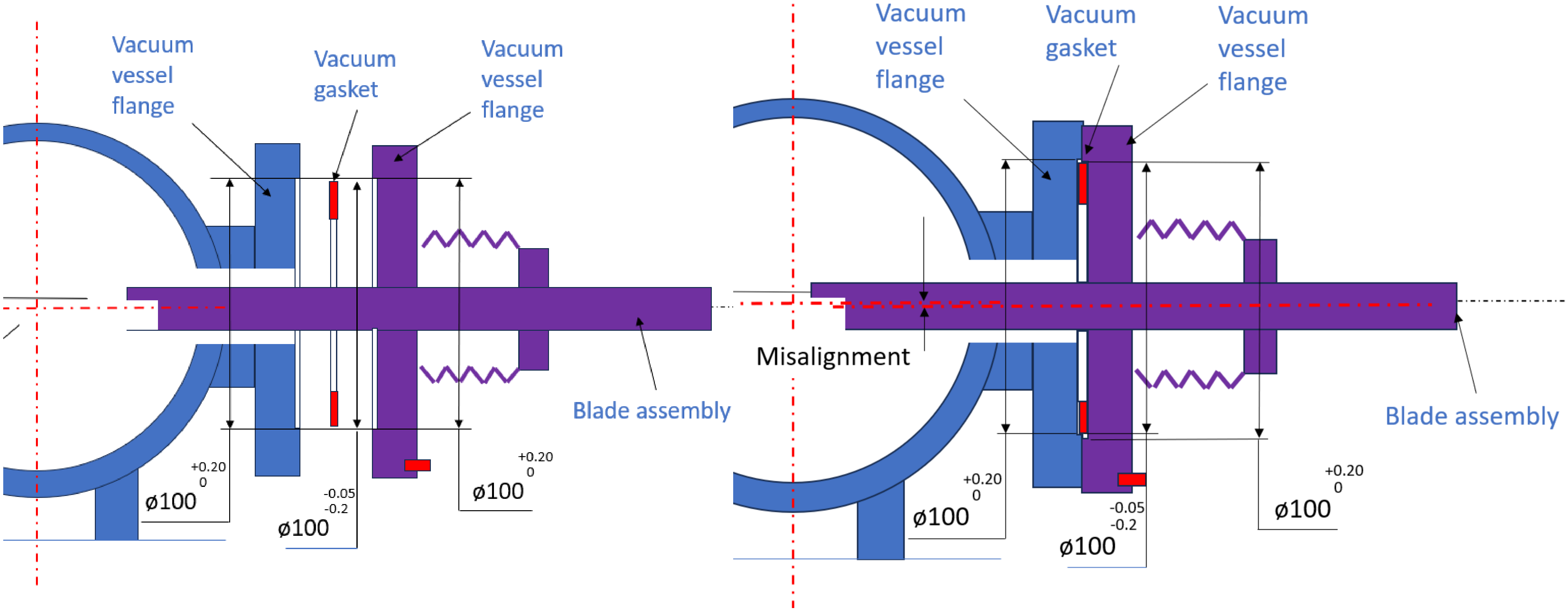
Back-up slides

What is the resulting misalignment value between the blade assembly flange and the vacuum vessel flange ?





What is the resulting misalignment value between the blade assembly flange and the vacuum vessel flange ?



1 - Min/Max method

Max. misalignment=
a max - x min + b max
50.1 - 99.8 + 50.1
= 0.4

Min. misalignment=
a min - x max + b min
50 - 99.95 - 50
= 0.05

2 - Σ of tolerances method

Center your tolerances around nominal values

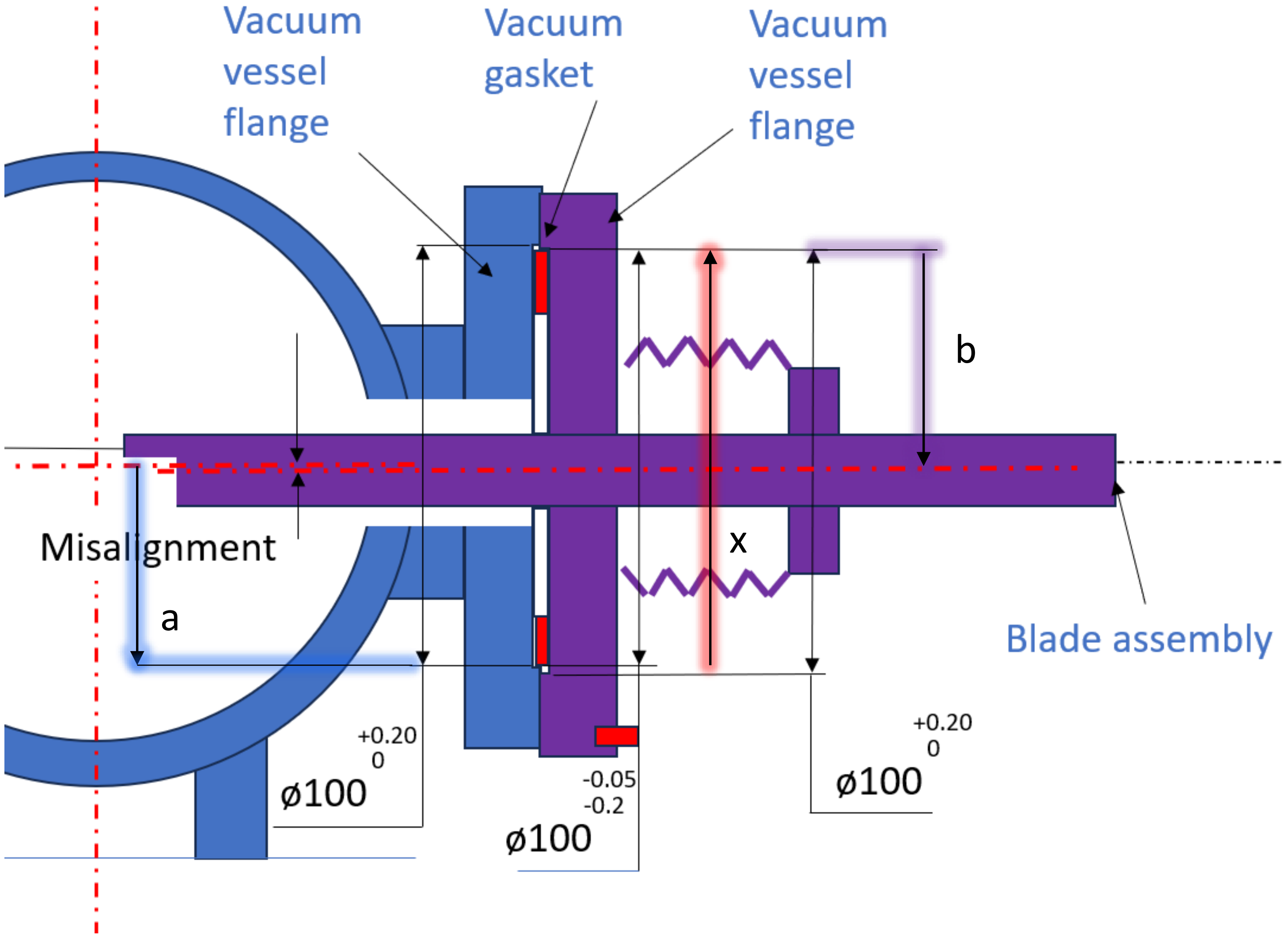
$ø100^{+0.20}_{0}$ = $Ø100.1^{±0.10}$

$ø100^{-0.05}_{-0.2}$ = $Ø99.875^{±0.075}$

Nominal misalignment:
a – x + b
50.05 – 99.875 + 50.05 = 0.225

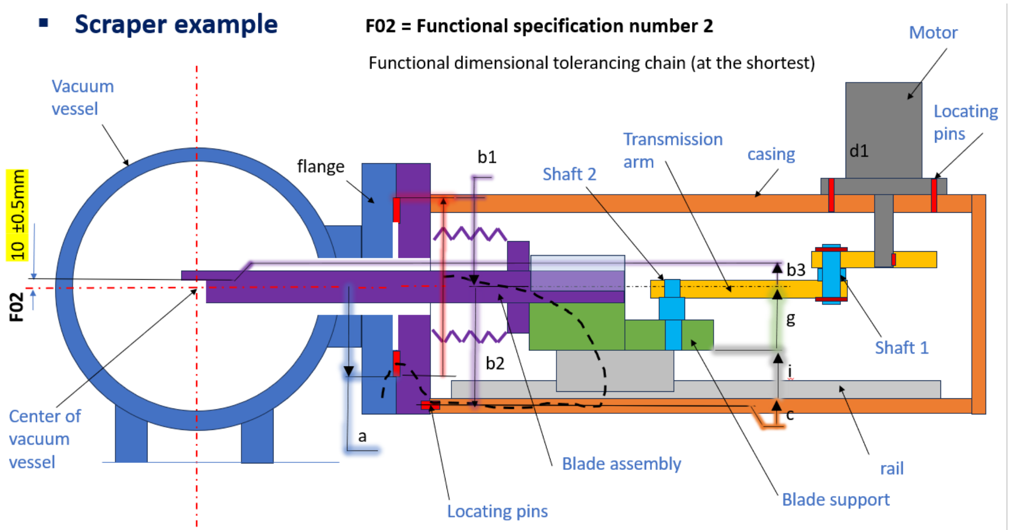
Σ of tolerances = 0.1 (on radius) + 0.15 (on diameter) + 0.1 (on radius) = 0.35

Misalignment = $0.225^{±0.175}$ Max = 0.4, Min = 0.05



▪ Are we in spec ?

F02 = Functional specification number 2



Results:

Functional condition: F02: 10 ±0.5 mm,

result: **10 ± 0.52 (out of spec)**

	Designation	Nominal dimensions	Tolerance ±	Interval
a	Flange axis position	-	0.02	0.04
b1	locating pin position	- 50.00	0.05	0.1
c	case lower surface	5.00	0.05	0.1
i	rail and slider height	20.00	0.1	0.2
g	blade shaft position	25.00	0.05	0.1
b2	blade tip	10.00	0.05	0.1
	Nominal clearance	**10.00**		
	Σ of tolerances			**0.64**

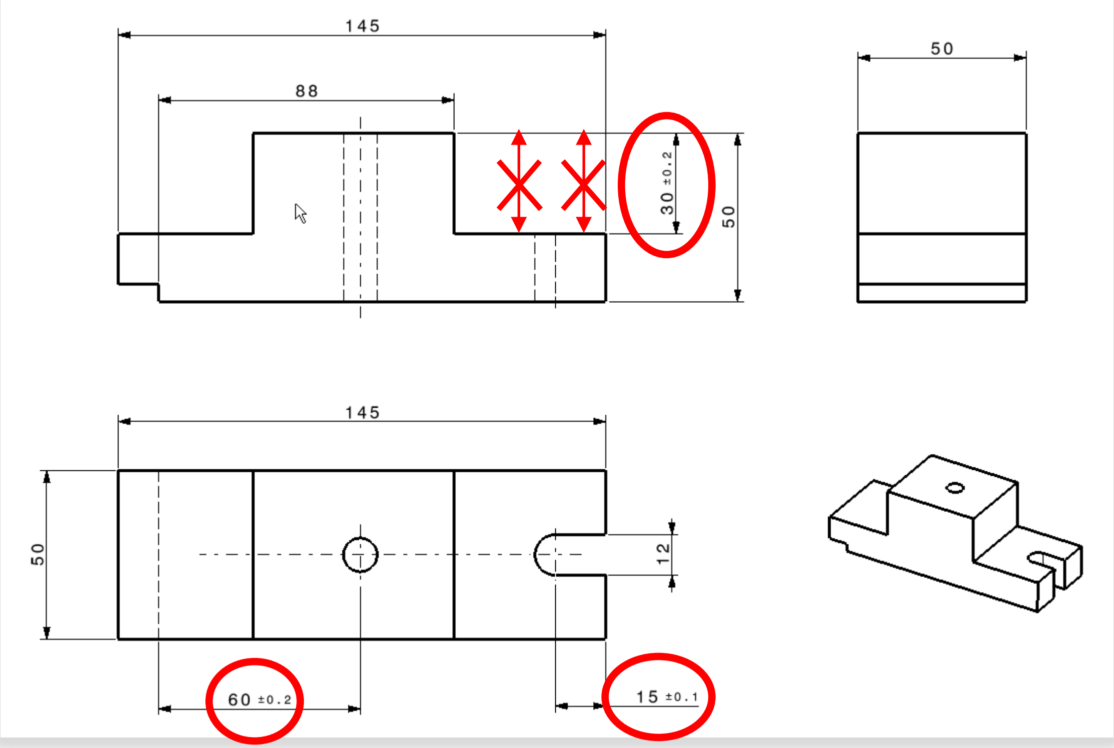
+ misalignment: 0.4 = 1.04

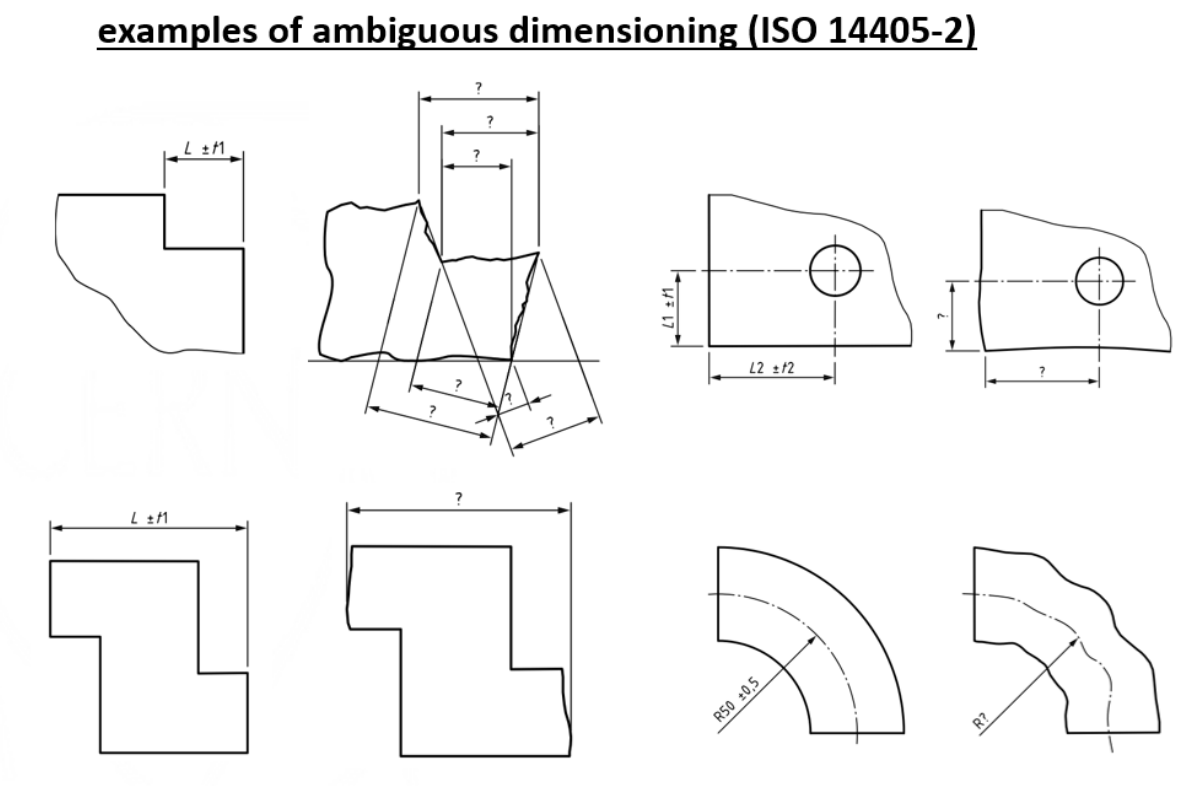
Any solution ?

Dimensions tolerance based on conventional manufacturing means:

2. Special focus on 2D geometrical specification

Many compagnies still use "traditional" dimensional tolerancing, which is too ambiguous

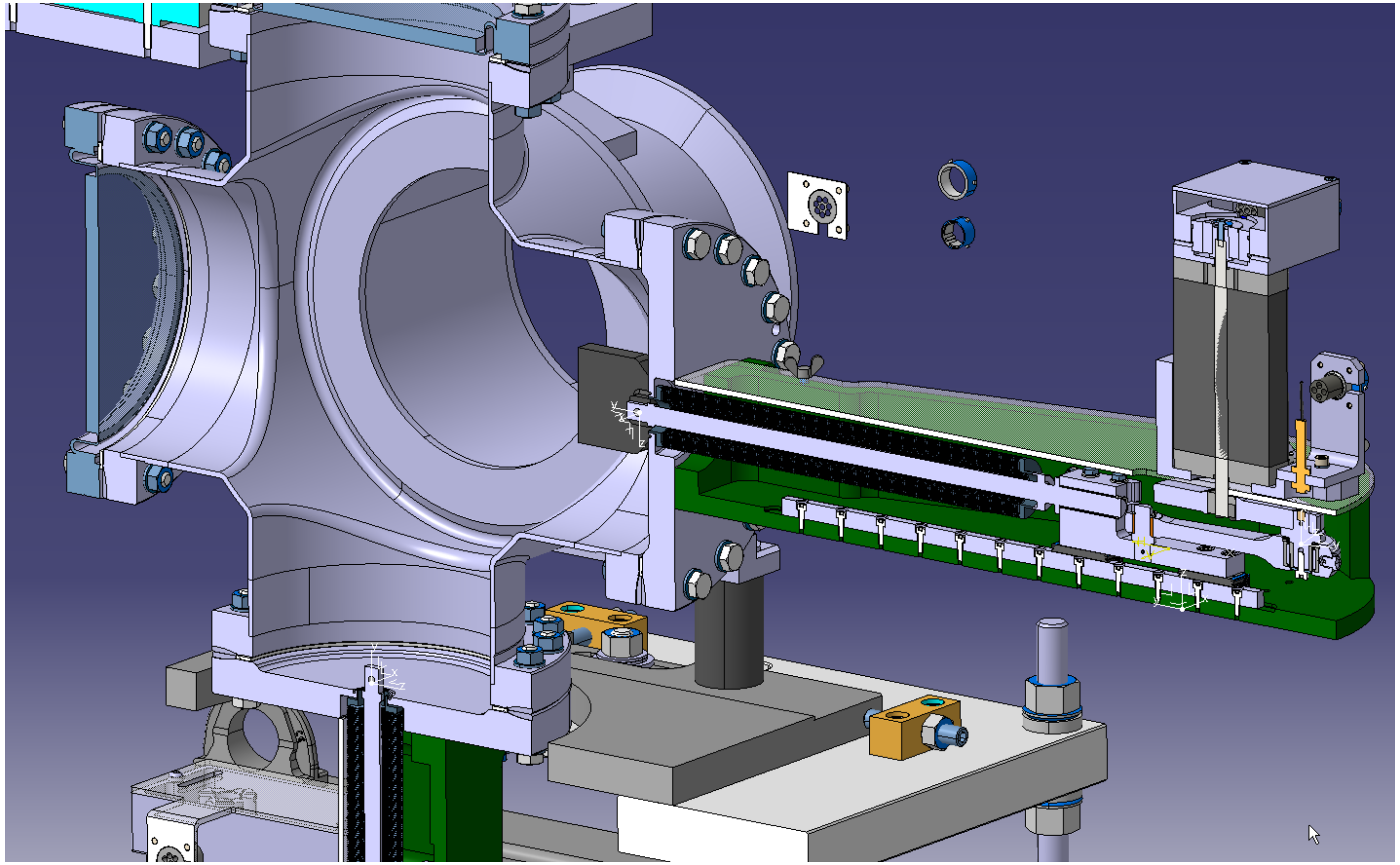




Example of ambiguous dimensions

3. A practical case

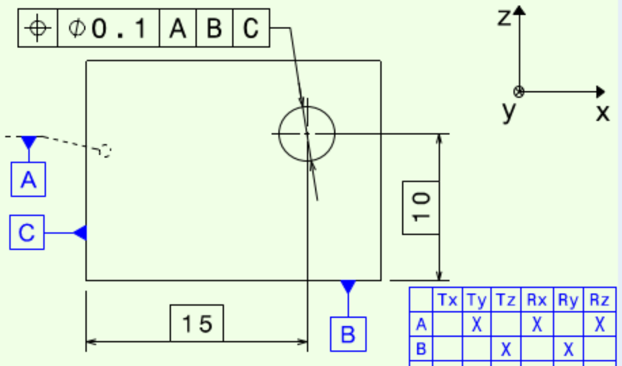
	Name	Criteria	Level/Spec	Flex
MF01	Allow the operator of the CCC to remove the transverse tails losses	Stroke of the blade	100mm total (-78mm /+22mm)	±2mm
		Operational scraping	20% (up to 10% in each plane)	
		Precision	Resolution Repeatability	±0.005mm ±0.05mm
		Scraping cycle speed	500ms (Fast and slow motion)	
		Number of cycles	100,000 cycles/year for 20 years	
		End switches	1 In / 1 Out for each movement	±10,000 cycles
		Motor + Coder	To be chosen during development	
				Ref BE/CEM
		Operational scraping	100% (entire beam) at top energy and intensity without damage	In accord with BE/CEM
	Accidental scenario			
		Slow scraper mode	100% scraping in 1 second	
	Additional scenario	Multiple scrapings	Up to 10 scraping per cycle (individually settable scraping percentages)	
MF02	Allow the operator of the CCC to obtain the profile of the tail losses of the beam	Monitoring of the finger position with BLM signal	Combine position with result on software that draw the profile.	To be confirmed on defined if possible.
		Position of the BLM from scraper	BLM shall be fixed to the floor to not loose the reference year to year.	
CF01	Shall hold scraper blade	Fixation with arm	Evacuation of heating	TBD
		Easy change of the active blade	1 or 2 unlosable screws	N/A
		Measure the blade temperature	Thermocouple in contact with blade but hold by arm	If possible
CF02	The blade shall be adapted for the beam parameters.	See Beam intensity in the SPS Material	See EDMS 2407464 TBD (actual Graphite R4550)	To be confirmed by thermos calculation depending of the design



- Datum system →

B, secondary specified reference, is in **exact theoretical orientation** with respect to A.

C, tertiary specified reference, is in **exact theoretical orientation** with respect to A and B.



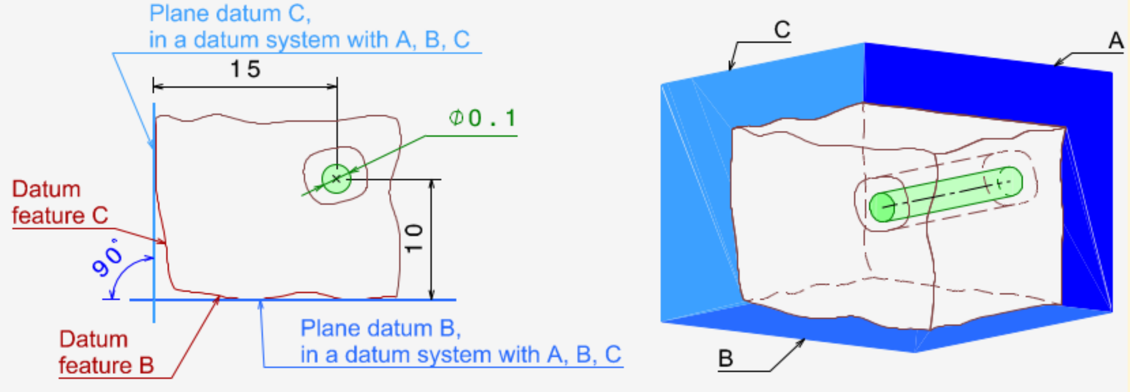
	Tx	Ty	Tz	Rx	Ry	Rz
A		X		X		X
B			X		X	
C	X					

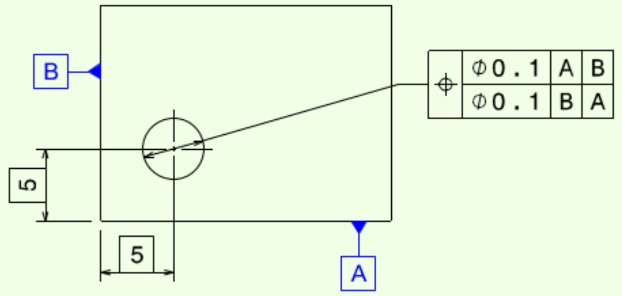
The datum system is:

A: primary datum

B: secondary datum

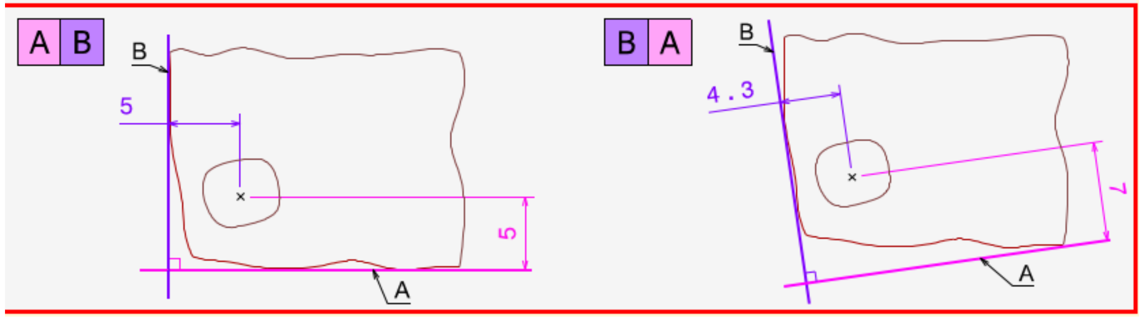
C: tertiary datum





Common error

Changing the order of the datum system will modify measurements



Understanding bas

Inclusion of geometrical tolerances

The location includes the orientation, which includes the form.