Appendix D
A Digression on Manufacturing Techniques for Magnet Components

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CONTENTS

In this Appendix we will illustrate the main processes that can be used to manufacture the most relevant components of a superconducting magnet for particle accelerators. For each component we will outline most suitable fabrication methods and their advantages related to costs, quantities and tolerances.

Presentation organized in two parts:

- Part 1 – Fabrication Methods
- Part 2 – Magnet Components

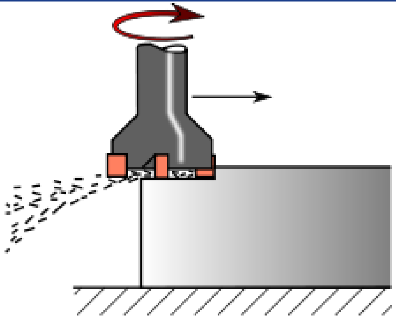
CONTENTS – PART 1

PART 1 – Fabrication Methods:

- Machining
  - Milling, Turning…
  - CNC 5-axis
- EDM Wire erosion
- Fine Blanking
- Extrusion & Drawing
- Additive Manufacturing

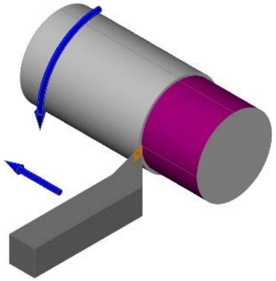
MACHINING: MILLING, TURNING…

Milling is a machining process (cutting process) that uses a milling cutter to remove material from the surface of a work piece…



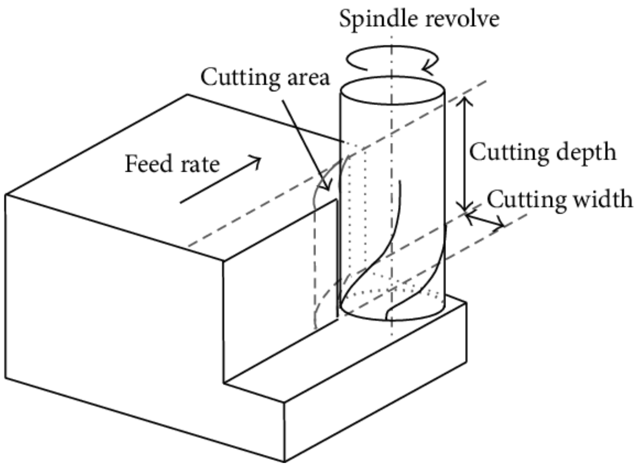
Courtesy: Wikipedia

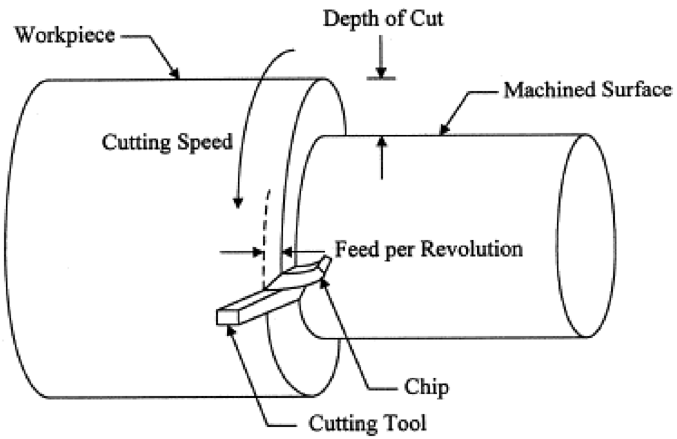
Turning is a machining process in which a cutting tool, typically a non-rotary tool bit, describes a helix toolpath by moving more or less linearly while the work piece rotates…



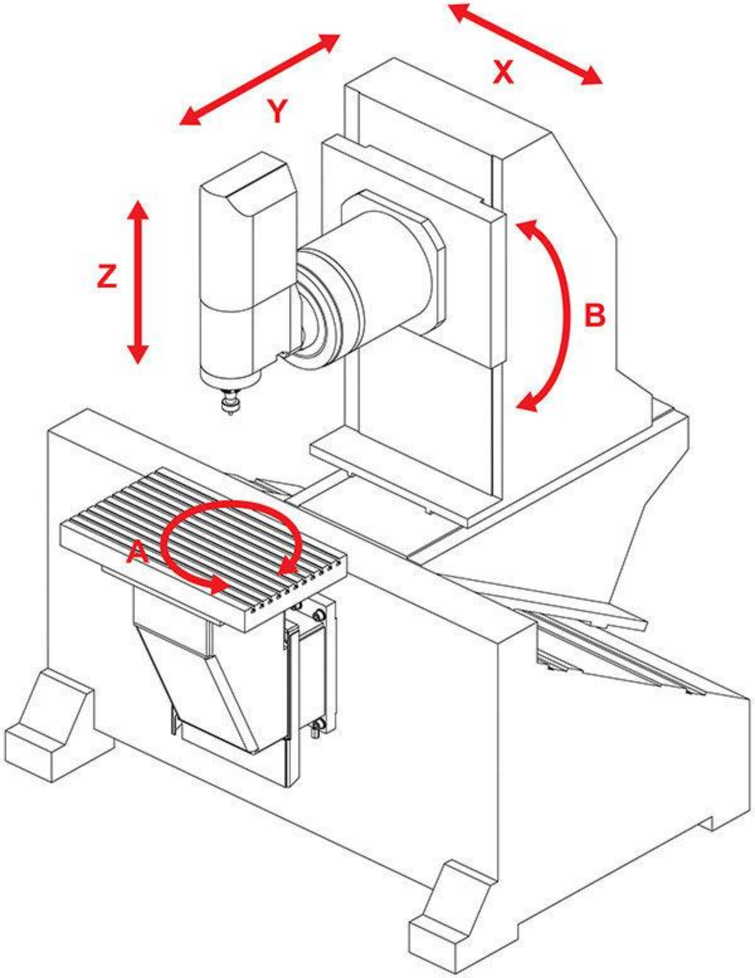
Many parameters depending on materials, geometry of the work piece, tolerances, surface finishing…:

- Cutting angles
- Cutting speed
- Chip shape and dimensions
- Lubrication
- …





MACHINING: CN

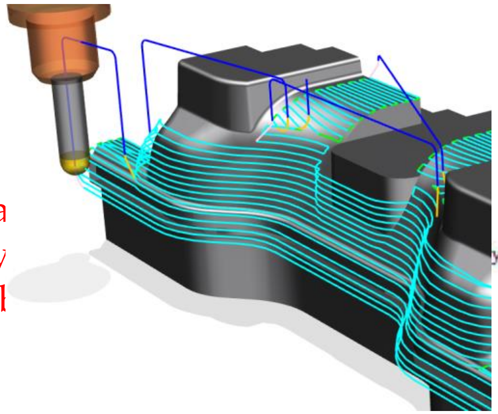


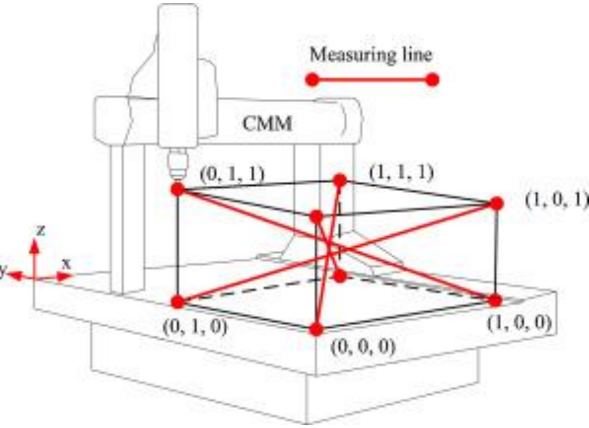
CNC machining:
- Computer Numerical Control (CNC) machining…
- 3, 4, 5 axis machining…
- Diverse machine layout

5-axis machining involves using a CNC to move a part or cutting tool along five different axes simultaneously. This enables the machining of very complex part.

Advantages of 5-axis machining:
- Allow single-setup machining to reduce lead time and increase efficiency as well as tolerances!
- Improved tool life, cycle time as a result of tilting the tool/table to maintain optimum cutting parameters.
- CAM simulations for in-depth study of the cutting tool path…

High Precision Machining (state of the art):
- 10 – 20 µm (related to dimensions)
- Number of machine set-up per work piece!
- CAD-CAM-CMM integration
- A coordinate measuring machine (CMM) is a measures the geometry of physical objects by points on the surface of the object with a prol





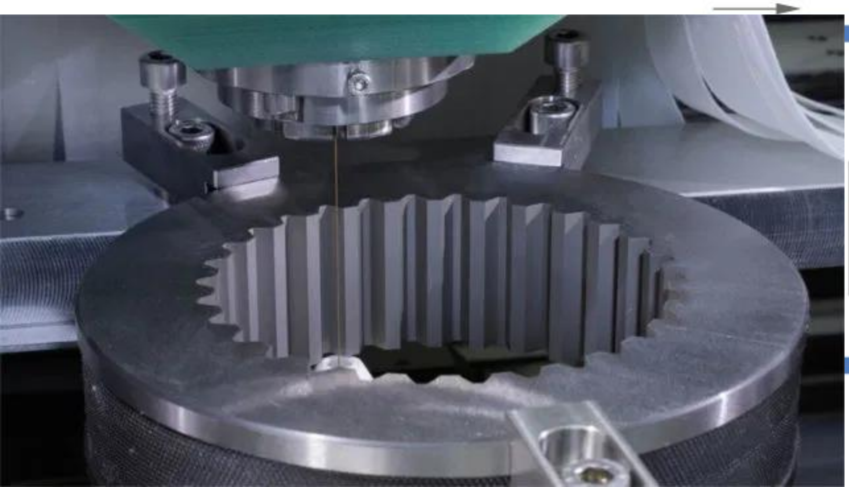
EDM WIRE EROSION

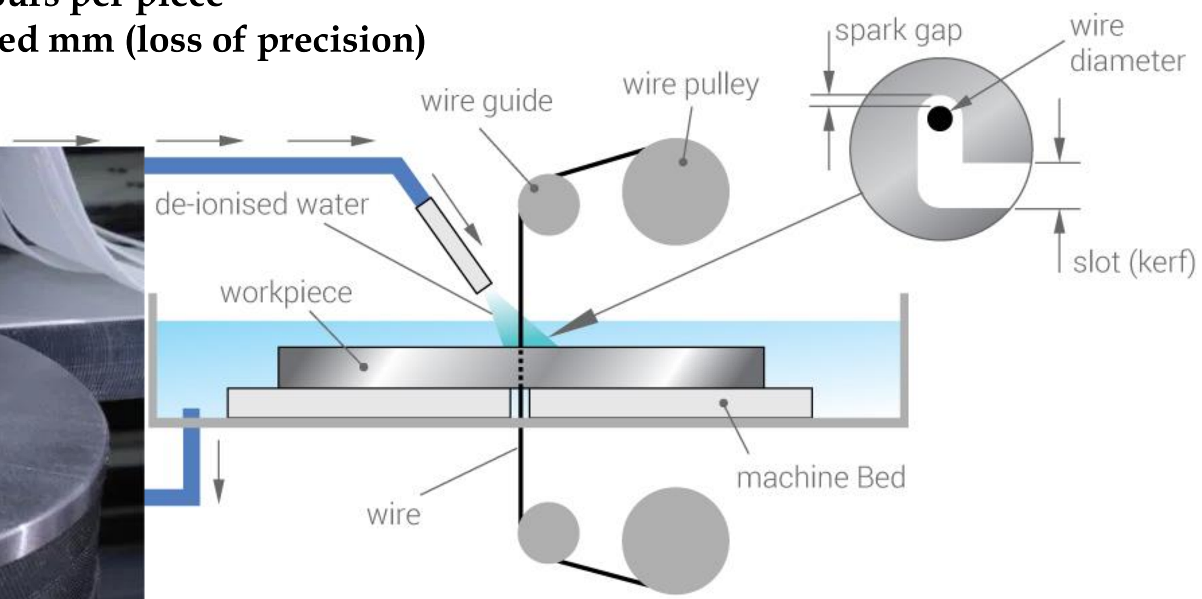
Electrical Discharge Machining is a metal cutting process where material is removed from the work piece through electrical discharges, between the workpiece and a specific tool/electrode

- Tool and electrode are locally/completely submerged in a dielectric fluid (deionized water, oils,..)
- In wire erosion, the tool is a wire constantly fed from a spool

- (+) Efficient for hard metals (otherwise difficult to machine)
- (+) Highly precise (**few hundredths of mm**)
- (+) CNC guided axis…
- (-) Workpiece must be electrically conducting
- (-) Direct contact between piece and dielectric
- (-) Only prismatic shapes. No enclosed features
- (-) Very slow. **Tens of minutes to hours per piece**
- (-) **Thickness limited to 3÷4 hundred mm (loss of precision)**

Typical D_{WIRE}: 0.25mm
[D_{CUT} ~0.35mm]
D_{WIRE} can go down to 0.1mm

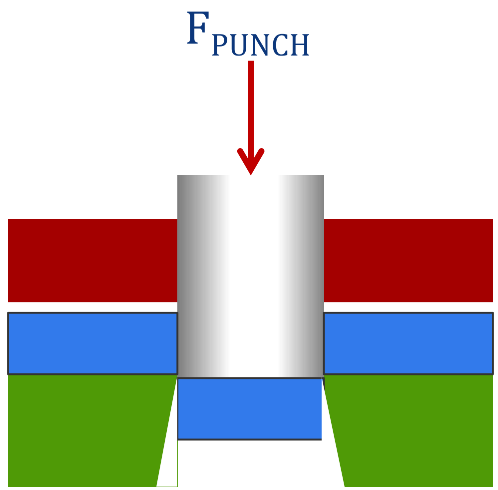


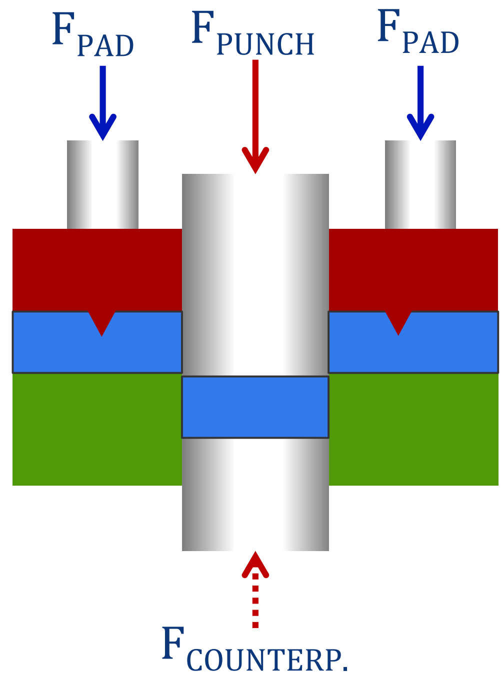


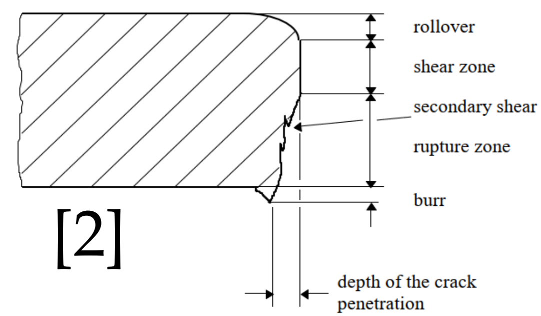
METALWORKING VIA PLASTIC DEFORMATION

- **Shearing or Die Cutting**: process which cuts stock without the formation of chips or the use of burning or melting…a punch (or moving blade) is used to push a work piece against the die (or fixed blade), which is fixed.
  - **FINE BLANKING** is a particular Die Cutting process…
    - Cuts only prismatic shapes
    - Limited thickness
    - Entails large facilities with expensive tools
    - Suitable for large series production
    - Ensures tight tolerances, repeatability and small dispersion…
- **Metal Forming** is the metalworking process of fashioning metal parts and objects through mechanical deformation; the work piece is reshaped without adding or removing material.
  - **EXTRUSION AND DRAWING** are two particular metal forming processes…
    - Produce only prismatic shapes
    - Entail large facilities with expensive tools
    - Suitable for large series production
    - Ensure tight tolerances, repeatability and small dispersion…

BLANKING vs. FINE BLANKING





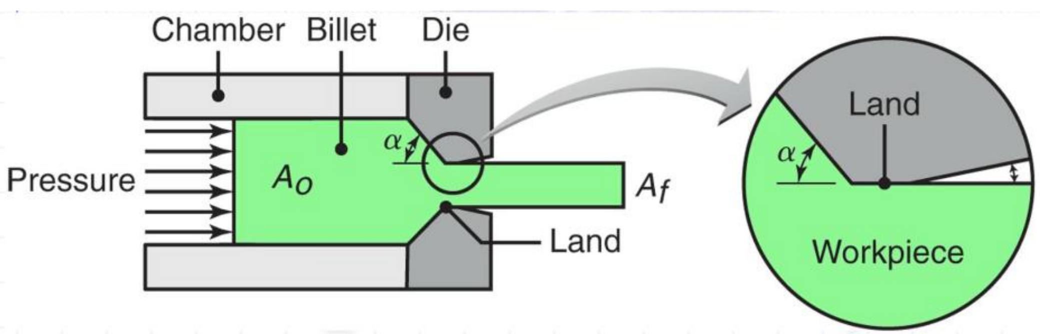


Fine blanking:

- Rupture zone much reduced
- Better surface results at edge
- More precise. More repeatable

	Rupture zone	Depth of crack
Trad. Blank.	Up to most of the thickness	Few/10 mm
Fine Blank.	Negligible	Few/100 mm

[1] *Influence of height and location of V-ring indenter on Void Volume Fraction variations during fine blanking process*, F. Biglari et al. [2020]
[2] *Blanking, Shearing and Trimming*, Hyunok K. et al [link]



Extrusion

A *billet* is **pushed** through a die

- Triaxial compressive stresses above elastic limit

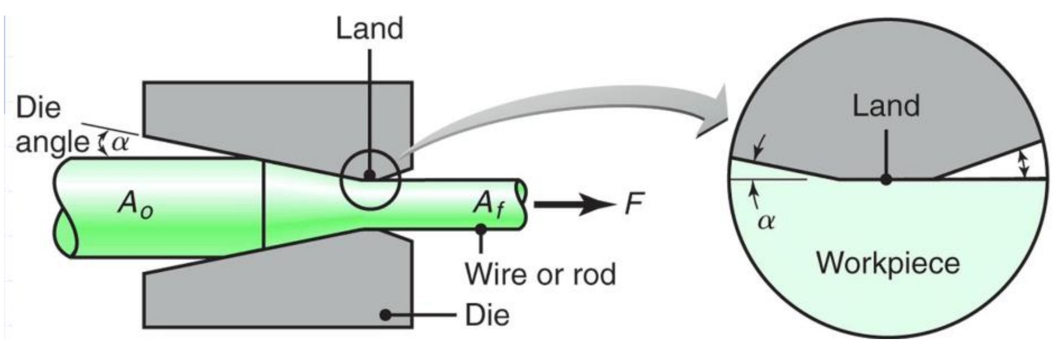
→ Large cross section reduction and geometrical deformations feasible

- Can be:
  - COLD: good dimensional tolerances and surface finish. Work Hardening to be managed…
  - HOT: for materials with low ductility at room temperature

Drawing

A Tube/wire/rod is **pulled** through a die

- intrinsic limits to process, due to tensile leading loads and friction
  - Limited geometrical changes. Typically used for reduction of cross section only
  - Multiple passes needed
- Usually done COLD
- Efficient for thin products
- Low cost and simple tooling
- High precision
- Thermal treatment to compensate work-hardening



ADDITIVE MANUFACTURING

CERN AM WORKSHOP:

Selective Laser Melting (SLM) is an AM technique designed to use a high power-density laser to melt and fuse metallic powders.

What sets SLM apart from other 3D printing processes is the ability to fully melt the powder, rather than heating it up to a specific point where the powder grains can fuse together (sintering)...

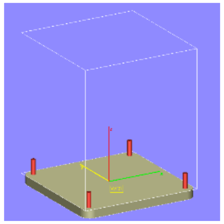
Advantages in terms of reduced porosity, greater control over crystal structure…

Machine:

- SLM 280HL (SLM Solutions)
- 400 W laser (1070 nm)
- Tri-axis scanning system

Build volume:

- 280 x 280 x 360 mm^3
- FULL CAD-CAM integration



Materials:

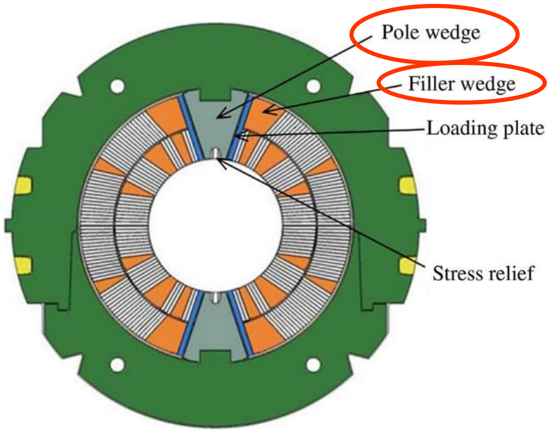
- Currently: niobium (R&D)
- others: Stainless Steel 316L/ titanium alloy

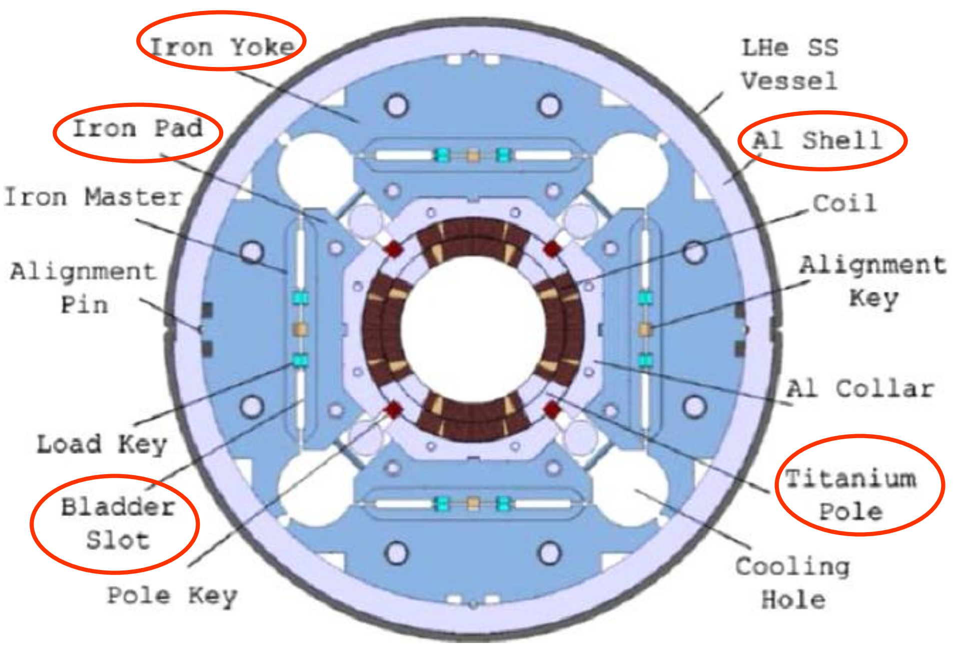
Metal Additive Manufacturing: how does it work ?

Courtesy GE Additive

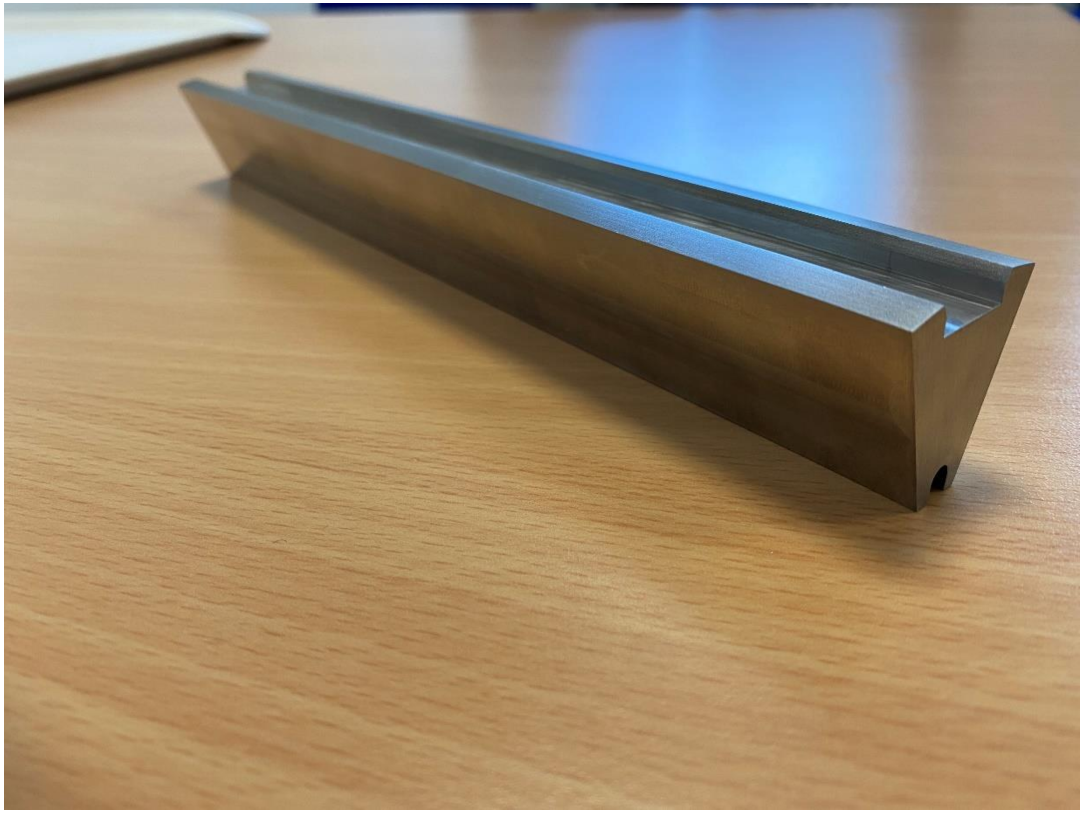
PART 2 – Magnet Components:

- Poles
- End Spacers
- Aluminum Shells
- Collars and Iron Laminations
- Wedges
- Bladders
- CCcosT Former





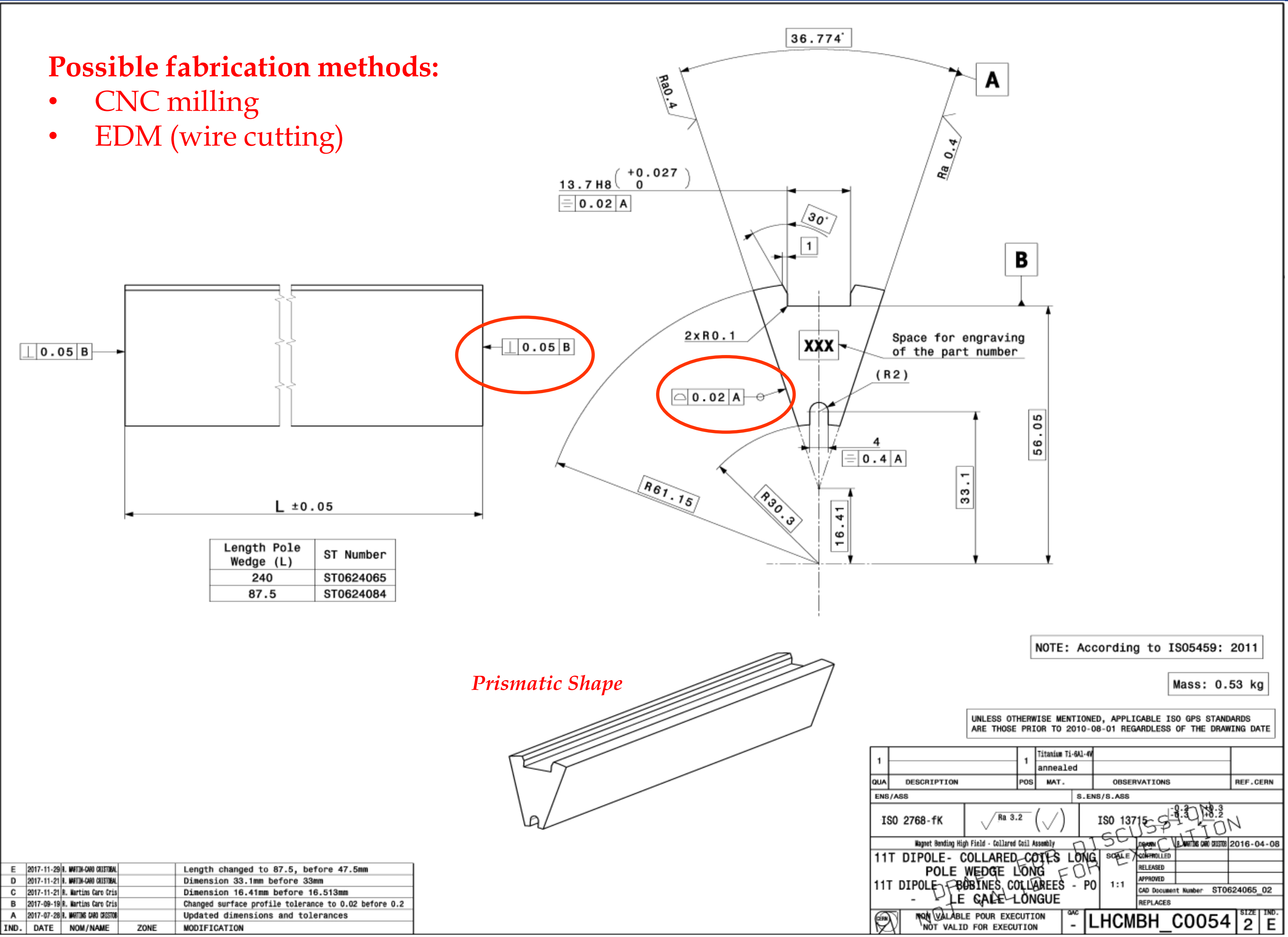
POLES



HL-LCH Dipole Titanium Poles

Possible fabrication methods:

- CNC milling
- EDM (wire cutting)

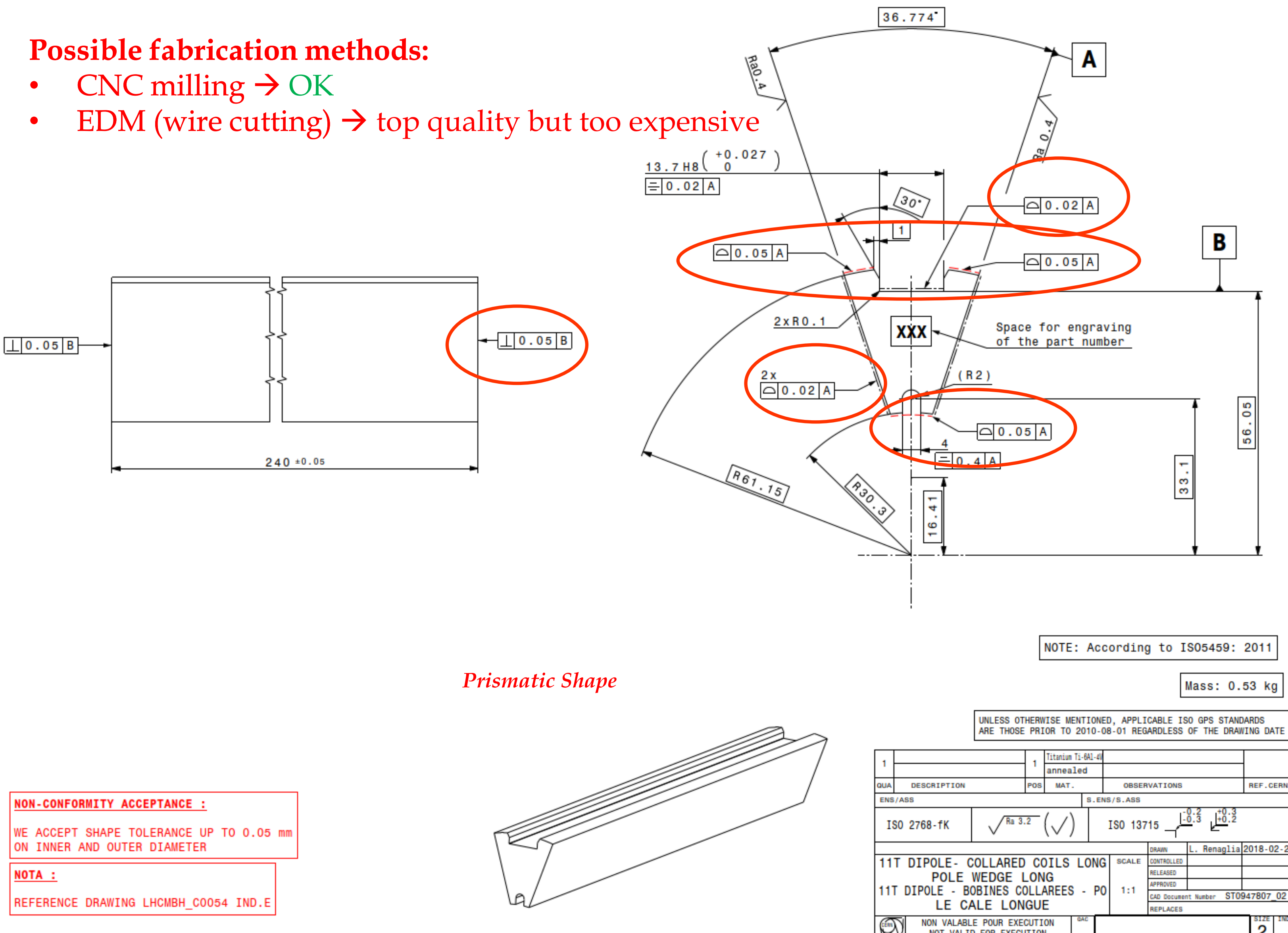


Prismatic Shape

HL-LCH Dipole Titanium Poles

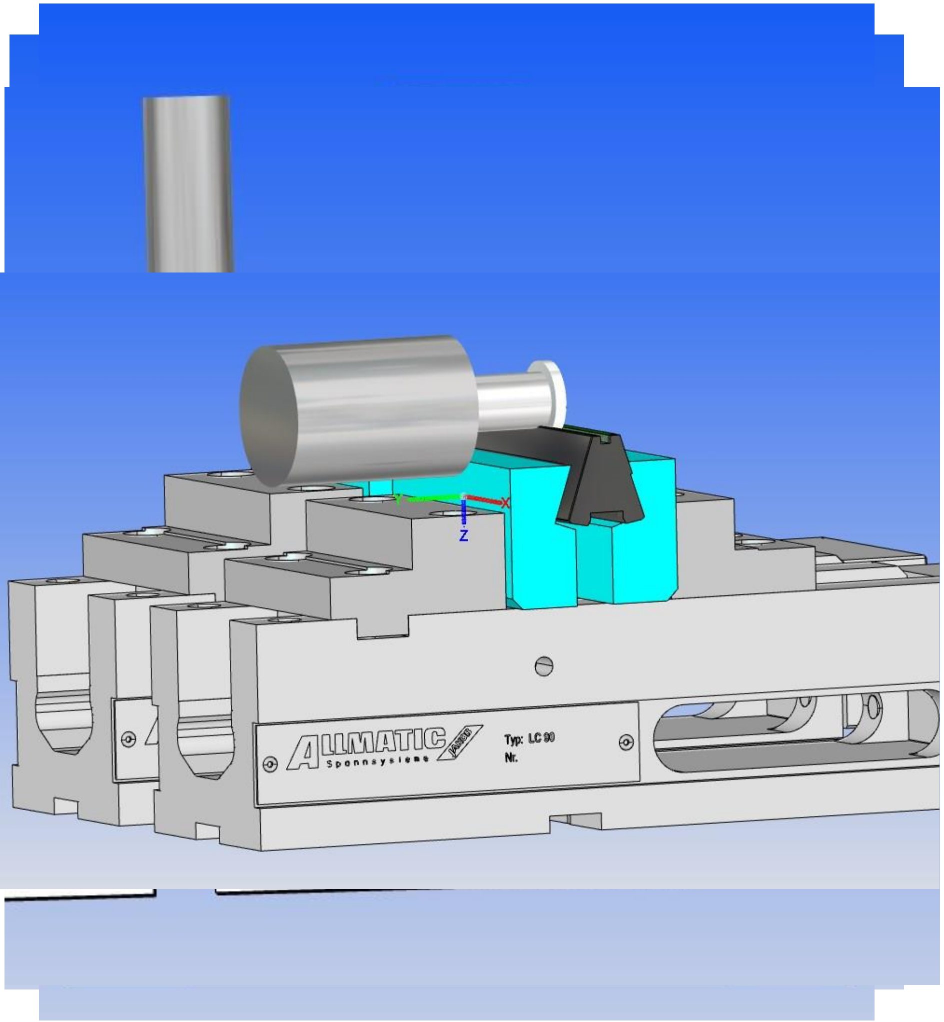
Possible fabrication methods:

- CNC milling → OK
- EDM (wire cutting) → top quality but too expensive



Prismatic Shape

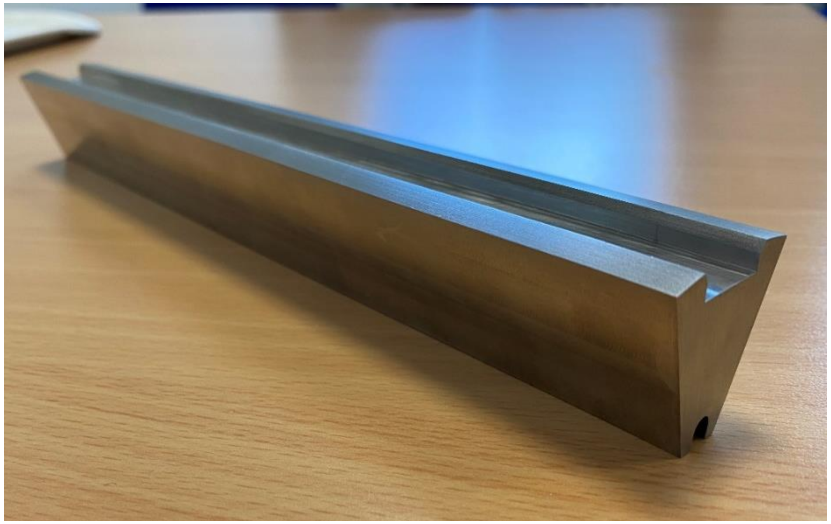
HL-LCH Dipole Titanium Poles



Possible machining steps:

1. Ti rod (raw material)
2. Typical jig interface machined
3. Rough machining (sides)
4. Rough machining (top)
5. Rough machining (top plane)
6. Change tools but not set-up
7. Final machining (sides + top)
8. Change set-up jigs and tools
9. Machine bottom groove
10. Finish the bottom

HL-LCH Dipole Titanium Poles



Material	Titanium (high spring back, high cutting tool wearing)
Raw Material shape	Any…could be *f(qty)* …Rods is a good option
Tolerance	Hundredths of mm (0.02 is already at the limit…)
Quantity	Several tens to few thousands
Manuf. Setup Time	Weeks
Production Time	Up to few hours per piece
Tools Cost	Negligible
Cost x piece	~ few hundred EUR → *f(qty)*

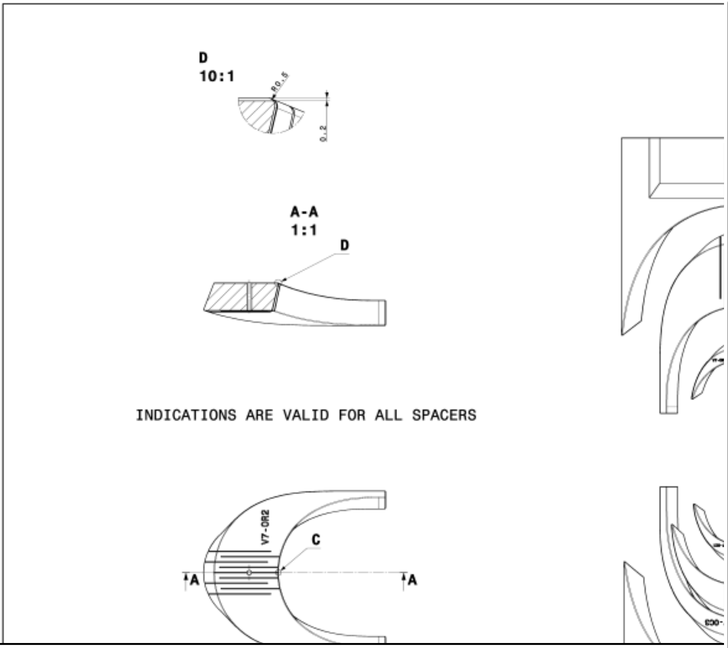
Advantages of machining:

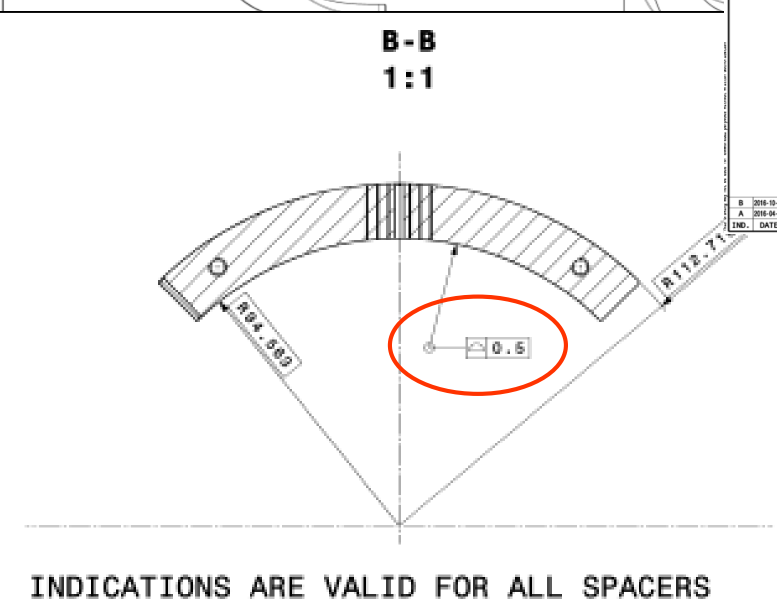
- Good compromise between features (time/cost/tolerance/repeatability/quantity)
- Less expensive wrt EDM (wire cutting)…EDM remains interesting in case of prototyping as well as very small batches (top quality ensured)

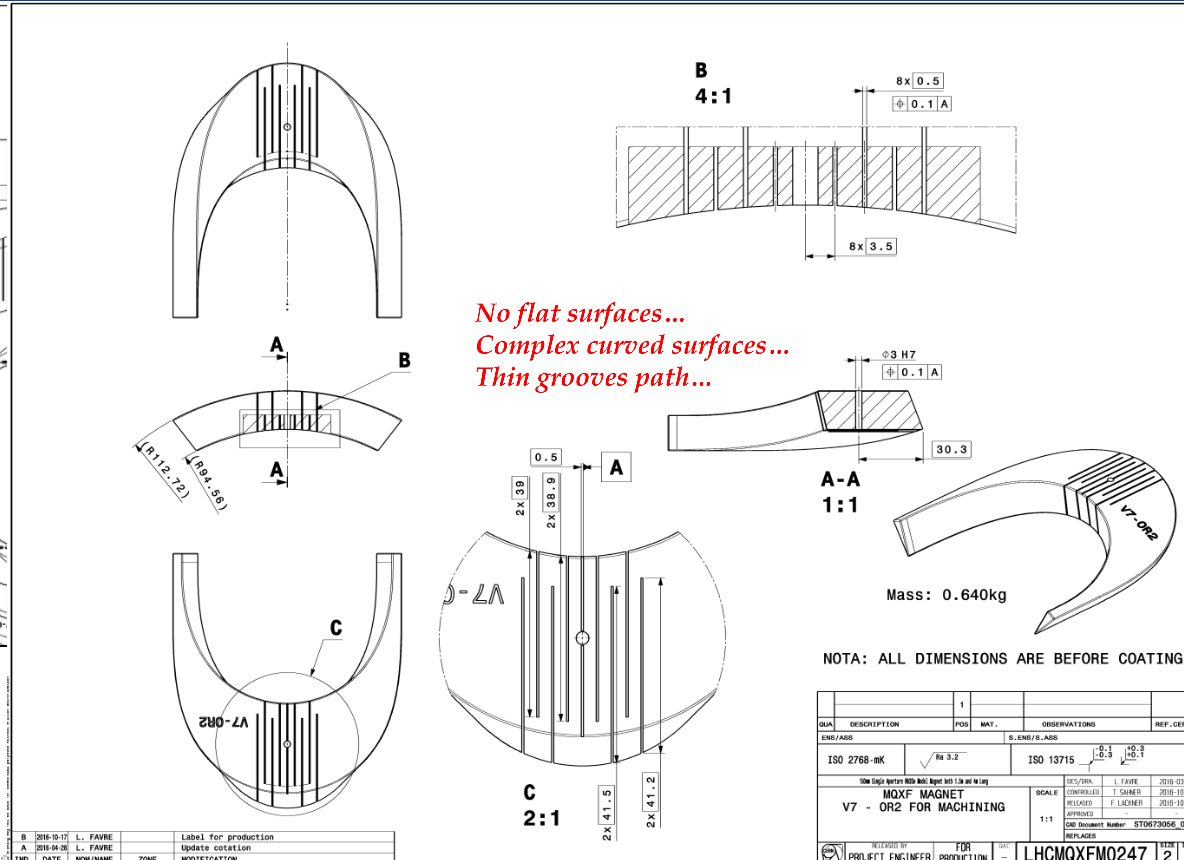
Drawbacks:

- Not cost effective for very large quantities…in that case maybe change the raw material shape…start from cold drawn special profiles…
- Machining step to be studied in-depth to obtain required tolerances
- Tolerances show typical dispersion related to machining…
- Well defined strategy for metrology (CMM) control to be defined wrt quality assurance…

End Spacers







No flat surfaces…
Complex curved surfaces…
Thin grooves path…

Possible fabrication methods:

- 5-axis CNC milling
- EDM (wire cutting)
- Additive Manufacturing…

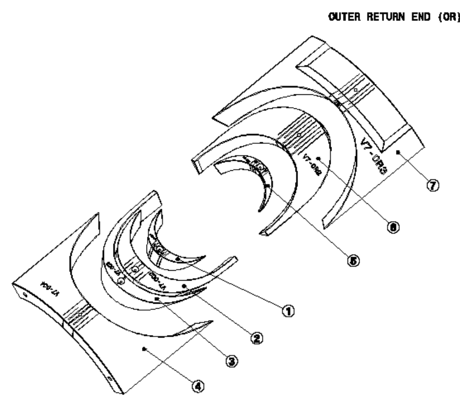
-MATERIAL SEE TECHNICAL SPECIFICATION

-FOR DATUM REFER TO ISO 5459:2011

End Spacers

Possible machining steps:

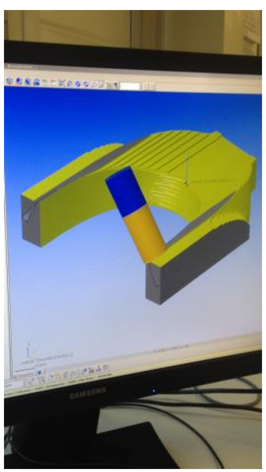
- Purchasing raw material in form of SS bar
- Deep drilling
- Pre-machining by turning
- Stress relief 950°
- Simultaneous five milling axes machining
- Wire erosion (EDM)
- Metrology (CMM)



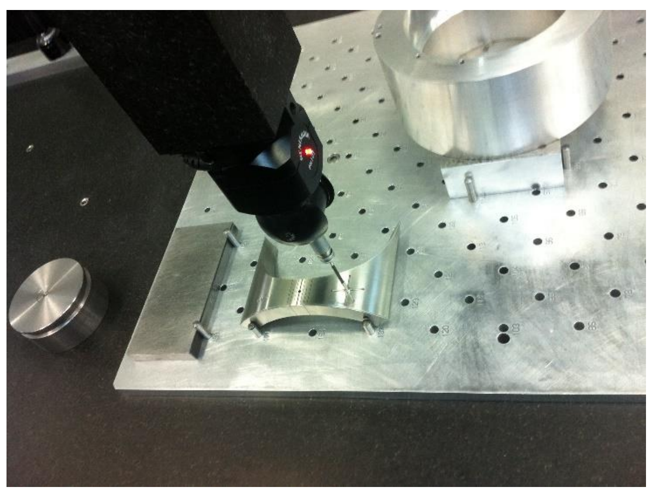
20 complet sets

The challenge is to clamp the pieces during the machining and avoid vibrations…

<5kCHF/Set (coil)

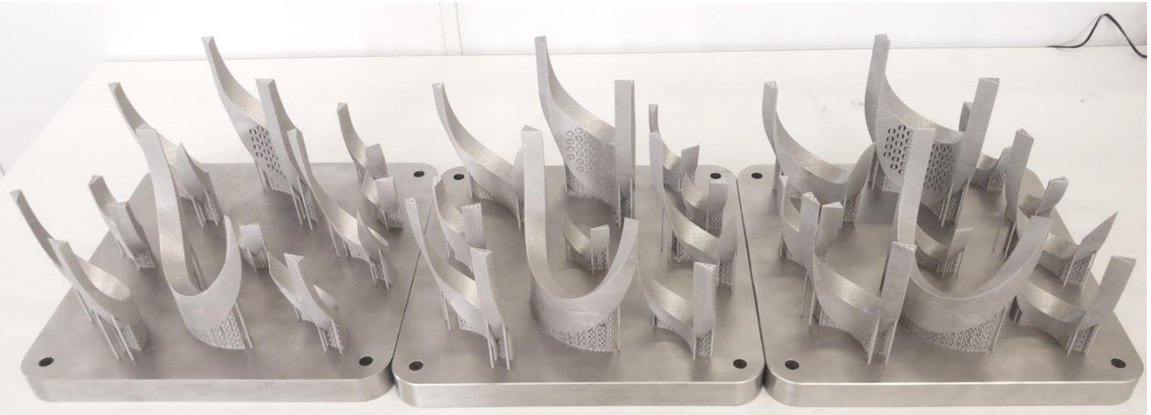


CAM simulation

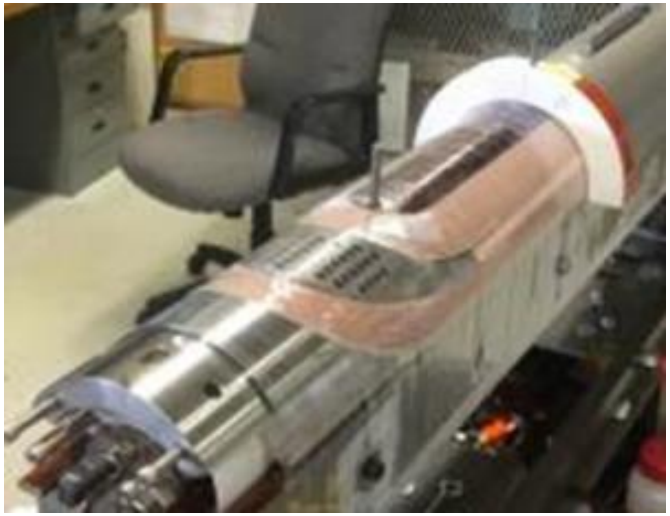


Metrological control with CMM

End Spacers



End spacers after the SLM process

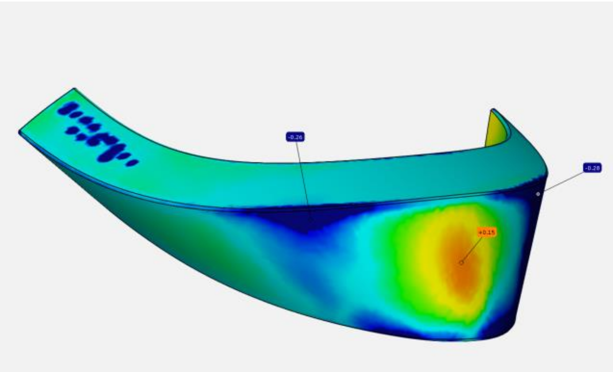


End spacers during coil assembly at FNAL

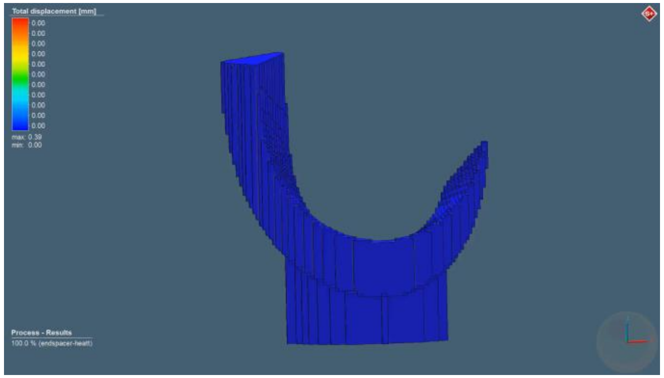
End spacers after the support removal

End Spacers

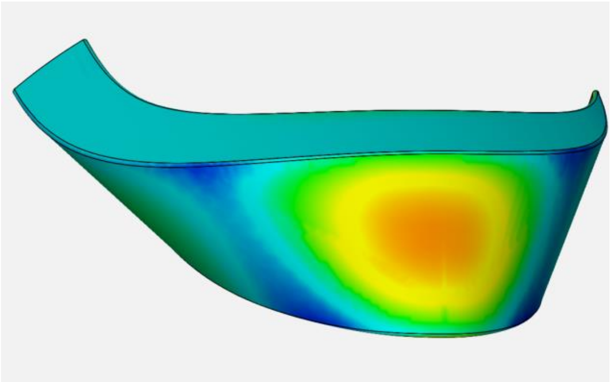
- The SLM process generates uneven heating of the components being manufactured
  - Similar to welding, deformation can occur.
  - These deformation can be predicted by simulation (advanced multiphysics FEM).
  - Compensation of the geometry could be possible to ensure geometry accuracy…



3D scanner

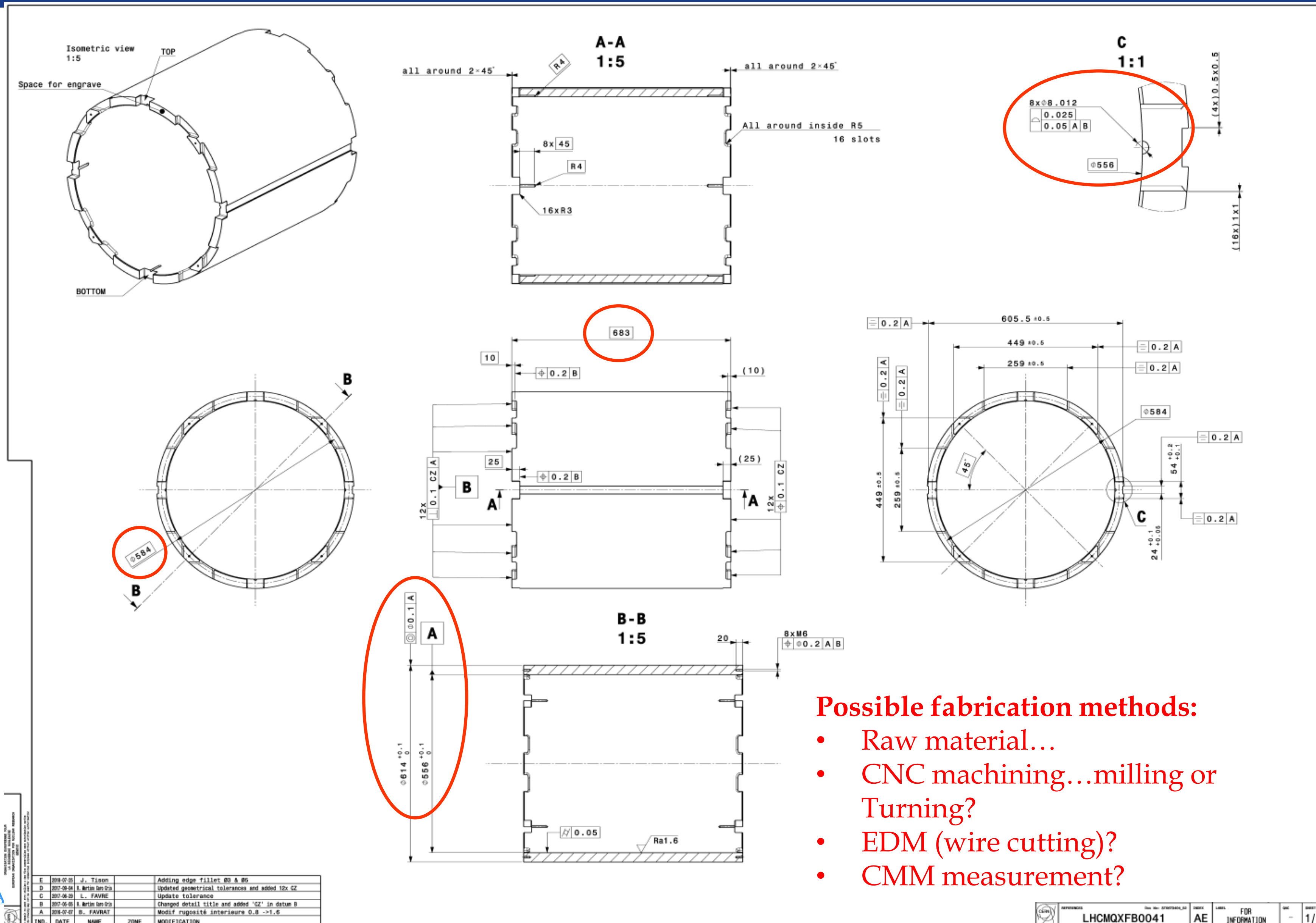


SLM process simulation



Simulation result

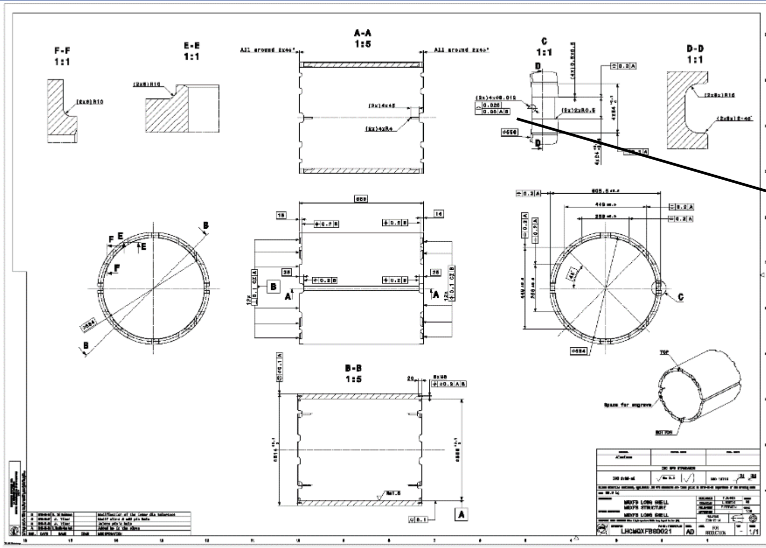
Aluminum Shells: HL-LHC Quadrupole

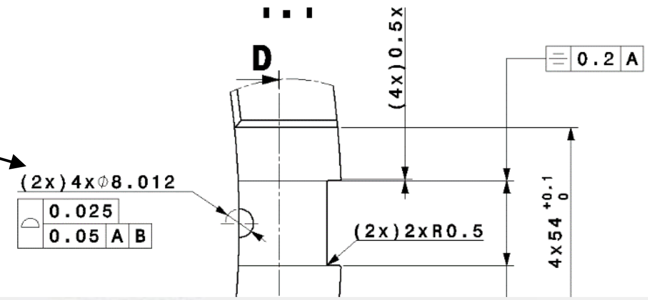


Possible fabrication methods:

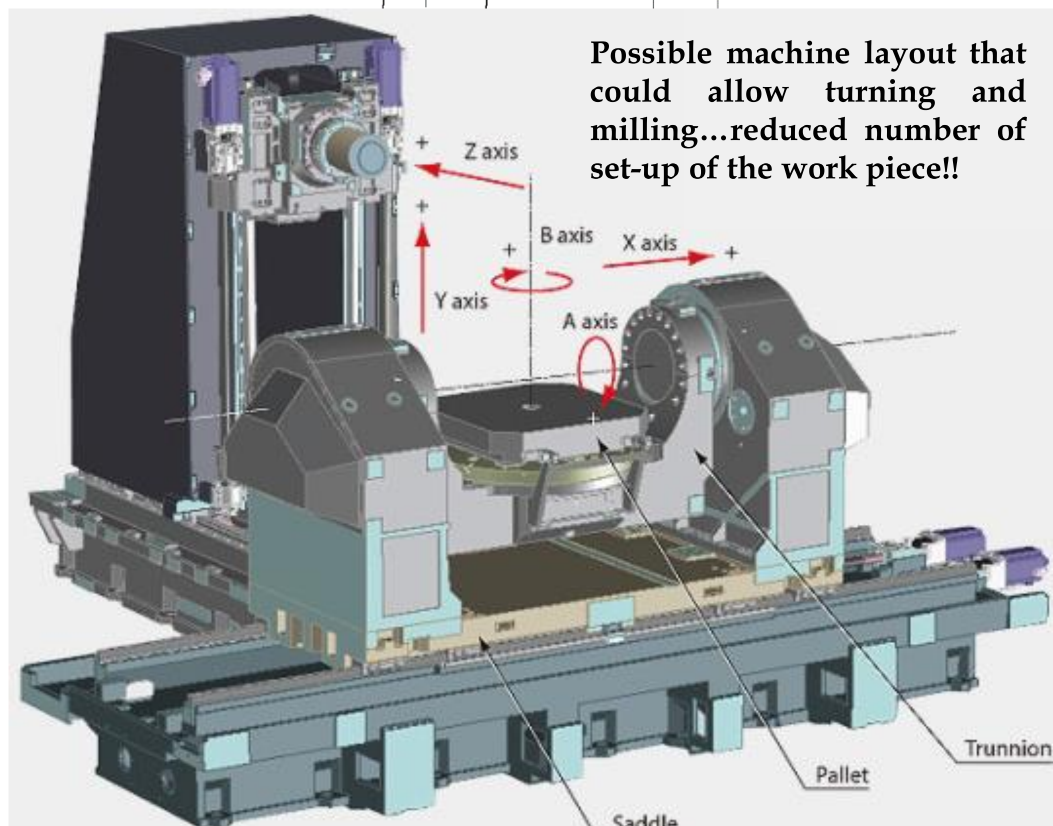
- Raw material…
- CNC machining…milling or Turning?
- EDM (wire cutting)?
- CMM measurement?

Aluminum Shells





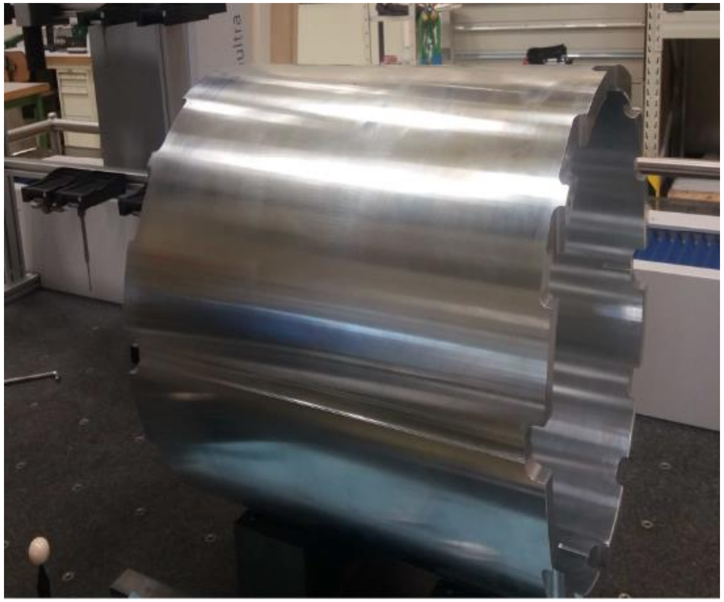
Possible machine layout that could allow turning and milling…reduced number of set-up of the work piece!!



Possible machining steps:

- Raw Material from open die forging or ring rolling forging
- Pre-machining by turning
- Pre-machining by milling
- Final turning
- Final milling
- Metrology
- Test assembling (Go/no go)

Aluminum Shells



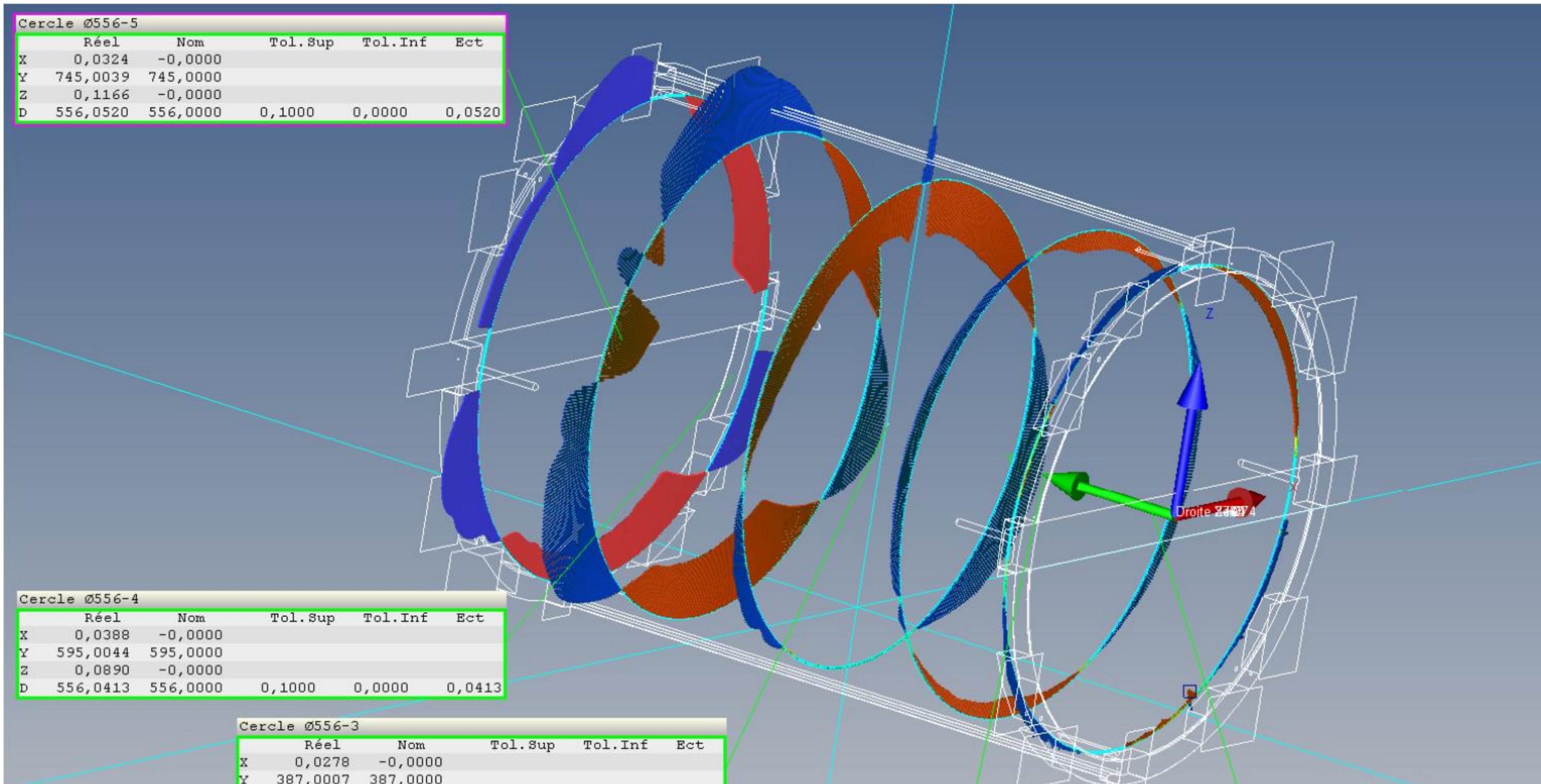
< 10kCHF/Shell

- 60% raw material
- 40% machining
- Qty: ~ 100

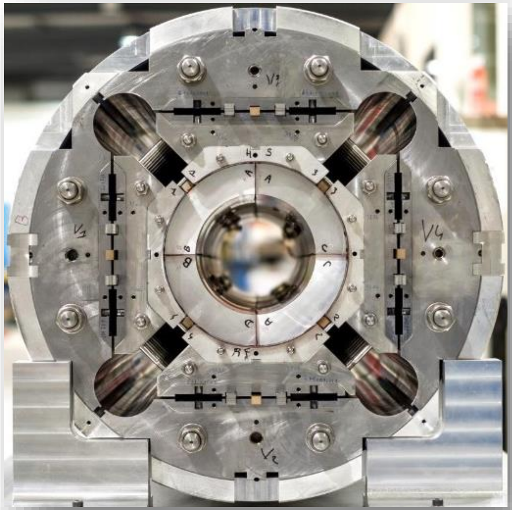
Main Challenges:

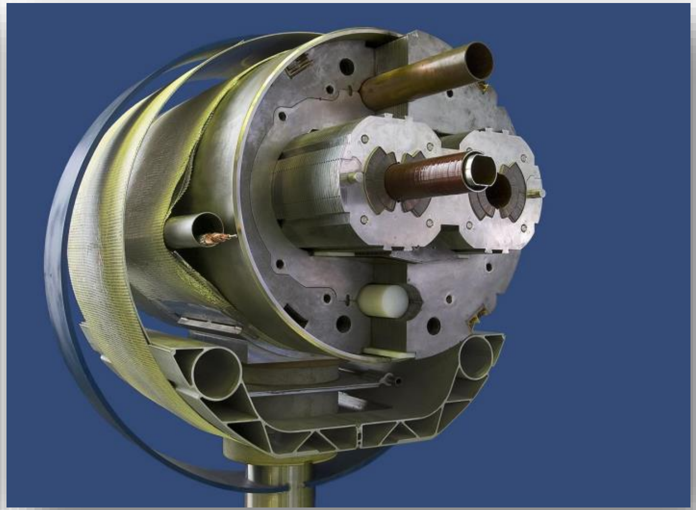
- Raw Material: Quality of forging
- Manage the release of internal stresses during machining operations
- Tight tolerances for the 2x4 grooves
- Uncertainty of measurement (even with CMM!)

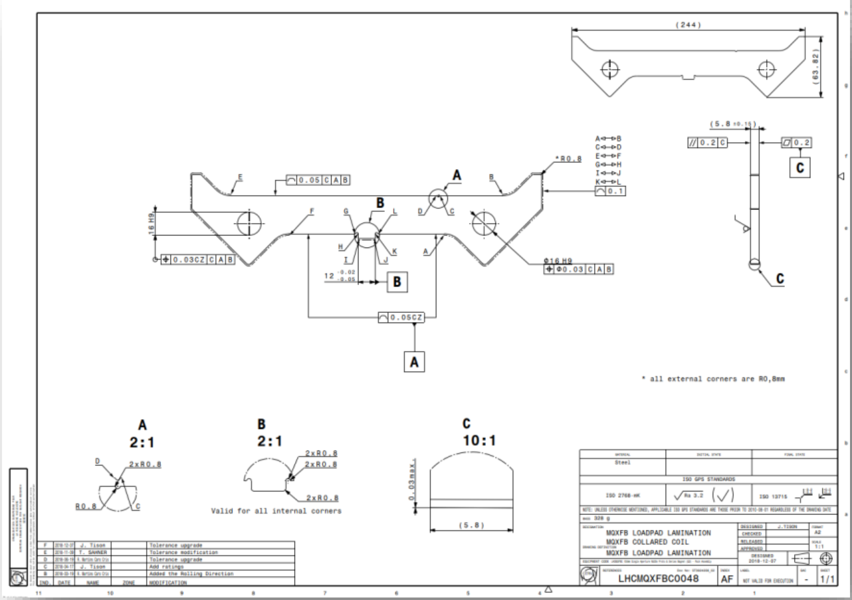
CMM Metrology measurements…



COLLARS AND IRON LAMINATIONS







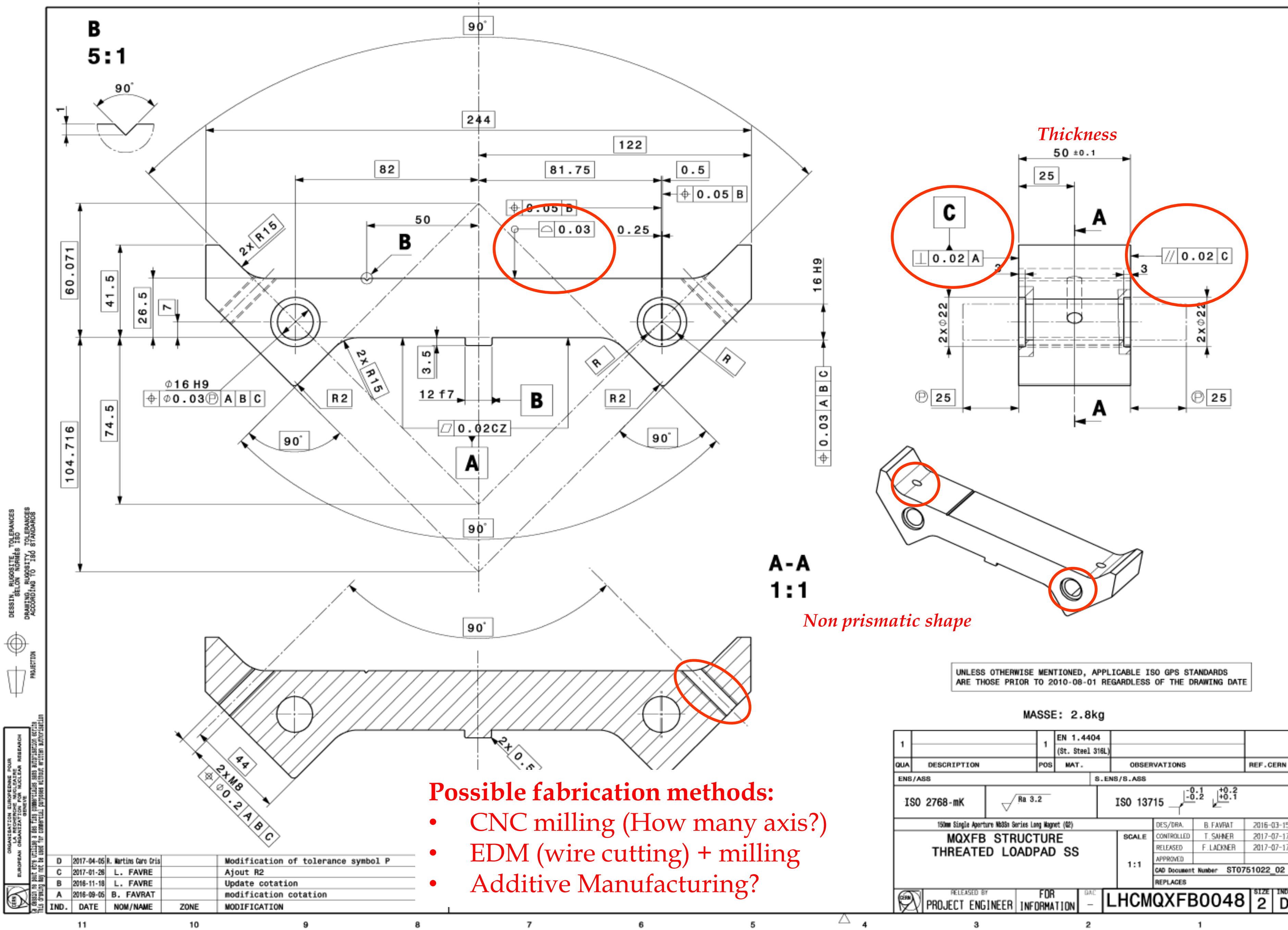
Main Factors Influencing Manufacturing

Material
- Pure Iron (ARMCO®)
- Stainless Steels
- Electrical Steel

Geometrical Features
- Required Tolerances
- Shape (prism…)
- Thickness
  - Thick
  - Medium
  - Fine (shims)

Quantity

Usual manufacturing **techniques**:
- CNC Milling
- Shearing (*traditional* vs. *fine blanking*)
- 'NO Tool' Cutting (laser, wire EDM, water jet)



Thickness

Non prismatic shape

Possible fabrication methods:

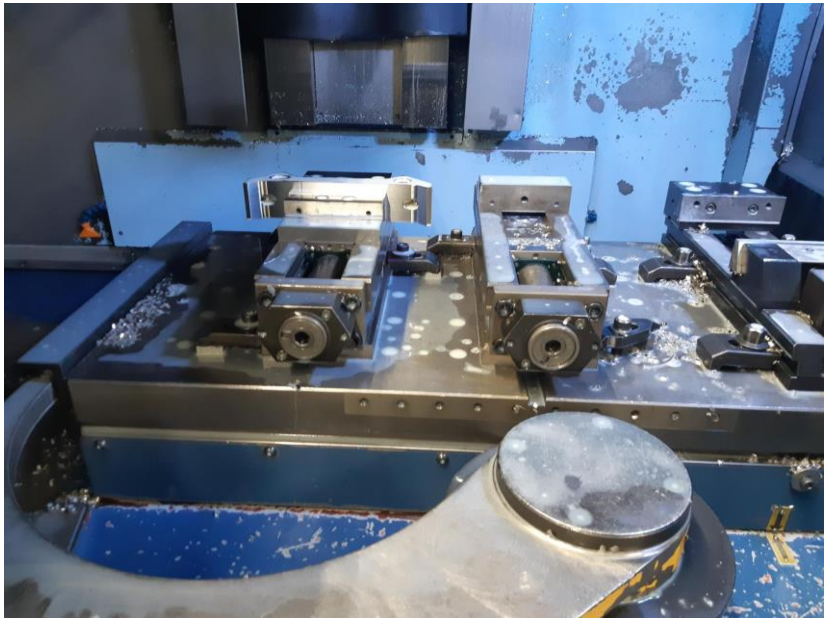
- CNC milling (How many axis?)
- EDM (wire cutting) + milling
- Additive Manufacturing?

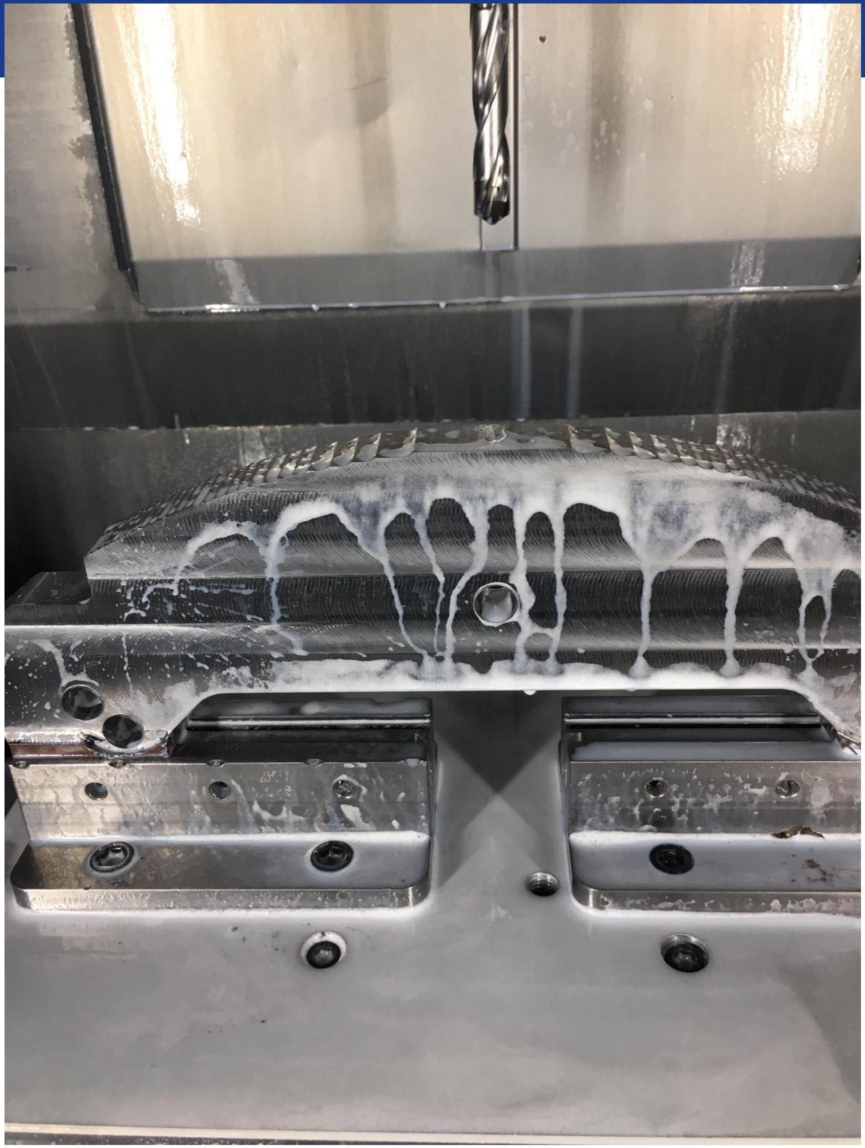
Milling Thick Collars

Material	Any
Raw Material shape	Any (*) (could be *f(qty)*
Tolerance	Hundredths of mm
Thickness	Any
Geometry constraints	No concave sharp edges Minimum ‘hole’ features
Quantity	Prototype to medium size batch (few kpcs)
Manuf. Setup Time	Weeks
Production Time	Up to Tens of minutes per piece
Tools Cost	Negligible
Cost x piece	~ Tens ÷ few hundred EUR → *f(qty)*

Advantages:
- Good compromise between features (time/cost/tolerance/repeatability/quantity)
- Only viable process for thick laminations
- Good flexibility to change also during manufacturing

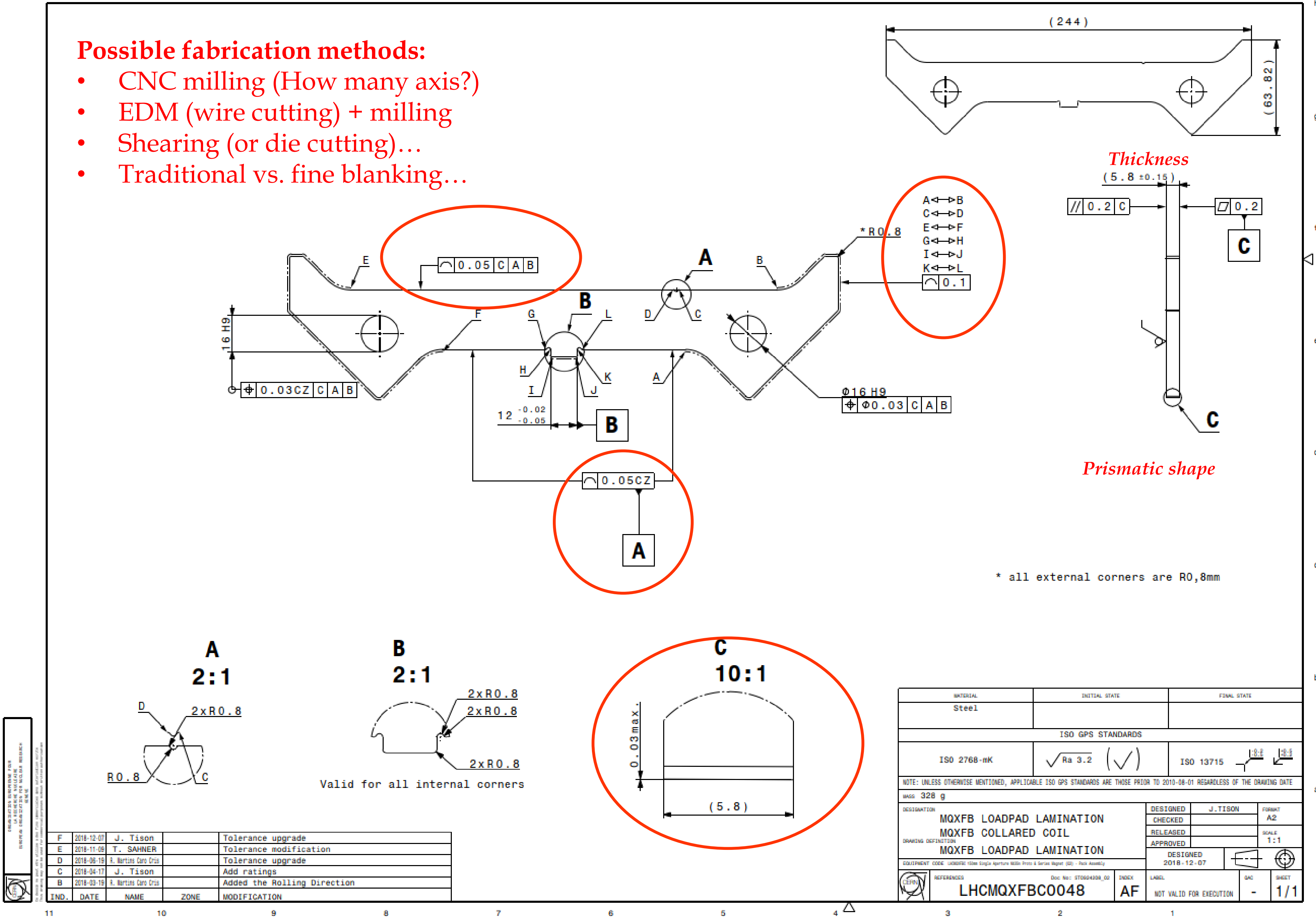
Drawbacks:
- <u>Not cost effective for thin parts</u>
- May call for upstream process for raw material preparation (*)
- Increased geometrical complexity directly amplifies manuf. costs and time



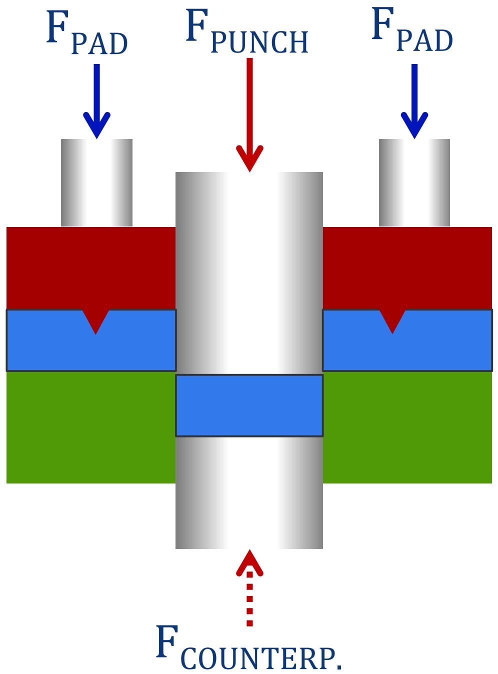


Possible fabrication methods:

- CNC milling (How many axis?)
- EDM (wire cutting) + milling
- Shearing (or die cutting)…
- Traditional vs. fine blanking…



Fine Blanking – Thin Collars and Laminations



Material	**Any**
Raw Material shape	Coils
Tolerance	Few hundredths of mm (for typical laminations sizes)
Thickness	Up 5 ÷ 7mm (depending on materials)
Geometry constraints	sharp edges (bad both as result and for tooling) Minimum 'hole' features (e.g. no pins)
Quantity	Large size batch (many tens of thousands minimum)
Manuf. Setup Time	months
Production Time	Few seconds per piece
Tools Cost	Many tens of kEUR (50÷100k)
Cost x piece	Few EUR

Advantages:
- Highest productivity, repeatability, tolerances
- Immune to shape complexity (up to a certain extent!)
- Reduced raw material preparation

Drawbacks:
- Lowest flexibility to change during manufacturing
- Highest setup times and costs
- Only large quantities

Fine Blanking: RAW Material

Sheets:
- Nowadays, not anymore a standard @ fine-blanking suppliers
- **Should be avoided**. Except (MAYBE) for very (VERY) large productions

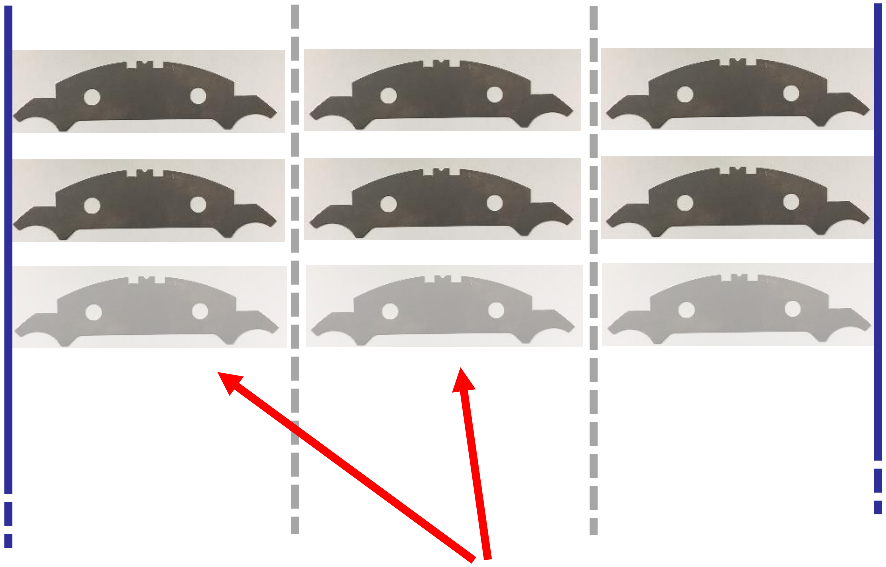
Coils:
- Size required by fine-blanking supplier can differ from provided raw (decoiler diameters, press size, …)
- Either know the wished size before, OR be ready to go through Slitting/Recoiling

https://www.youtube.com/watch?v=S0f7BOQZXOs

Fine Blanking: LAYOUT

Layout of parts on de-coiled sheet:

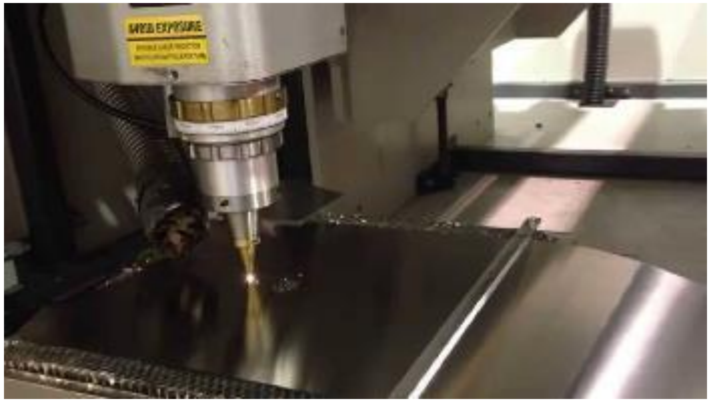
- Also influences required coil dimensions
- Depending on which material and its properties: watch out for different springback due to position w.r.t. the sheet and lamination direction



Potentially different behavior depending on position

Angle w.r.t. lamination might not work (warping)

Laser Cutting Laminations



https://www.youtube.com/watch?v=ADiWMuLcJsQ

Material	**Any**
Raw Material shape	Sheets or Coils
Tolerance	Few hundredths of mm (for typical laminations sizes)
Thickness	Only fine (up to 1 ÷ 1.5 mm)
Geometry constraints	Size of laser beam, especially for thicker pcs
Quantity	Any batch size
Manuf. Setup Time	Days to few weeks
Production Time	many seconds per piece
Tools Cost	Negligible
Cost x piece	Few tens EUR

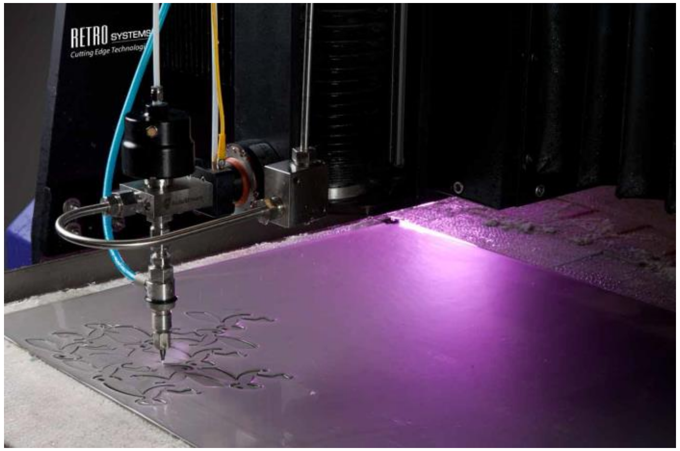
Advantages:

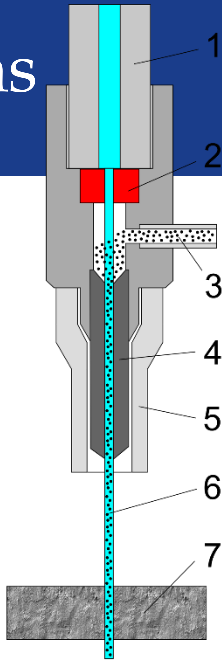
- Good compromise : batches, productivity, repeatability, tolerances
- Immune to shape complexity
- Reduced raw material preparation

Drawbacks:

- Molten edges, especially as thickness grows
- Thermal effects influence precision

Further techniques for Collars and Laminations



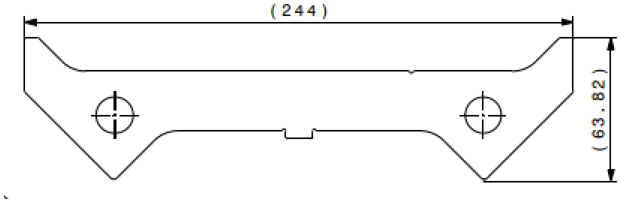


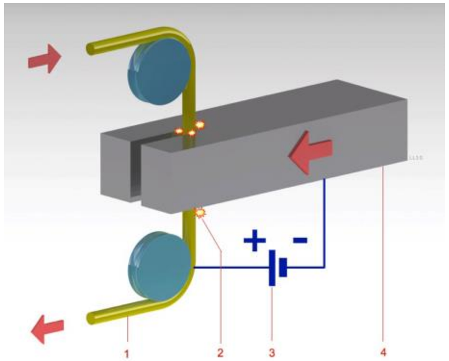
Water Jet:

- Rough cut edge
- Precision: **few tenths of mm**, quickly worsening as function of thickness
- Good preparatory process for milling

Wire Erosion

- Highly precise (**few hundredths of mm**)
- Very slow (tens of minutes to hours per piece)
- Enclosed geometries not possible
- Good for prototypes and small batches



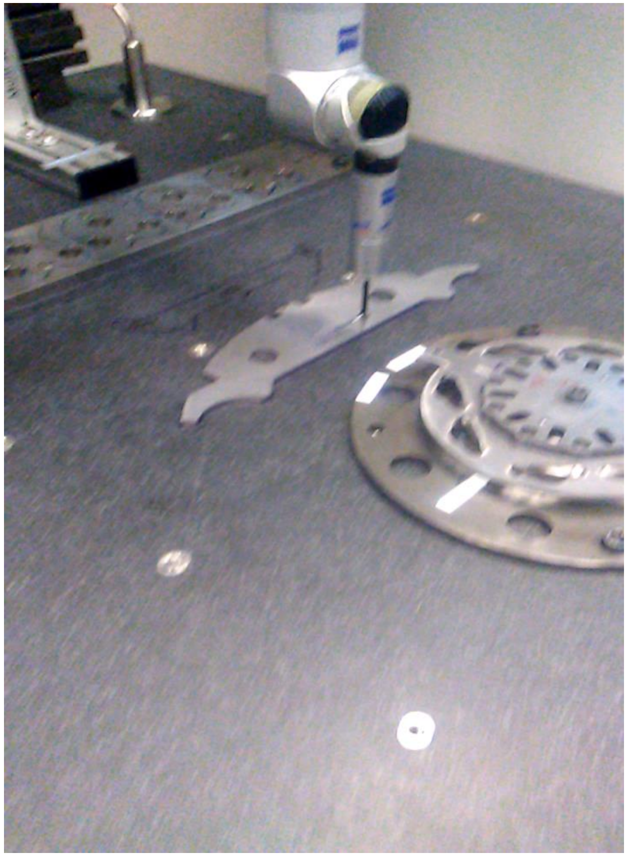


Quality Control for Collars and Laminations

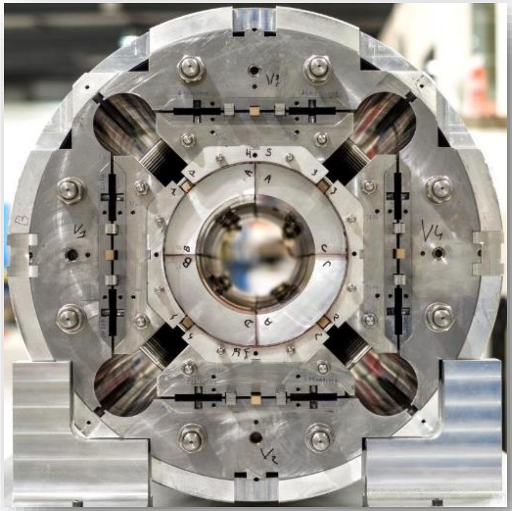
Different processes = different output variability
Different quantities = different influence of such variability

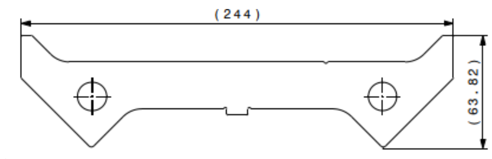
Depending on the specific situation, the correct recipe comes from a good mix of:

- *Full* vs *statistical* quality control
- *Online* vs *offline* control
- Definition of correct requirement: *strict tolerance OR variability*?
- *Full metrology* vs *minimum set* of features (Go/No-Go, Jigs)

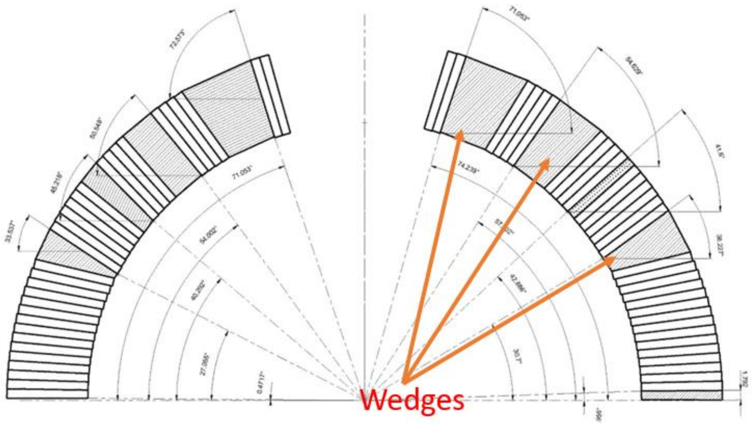


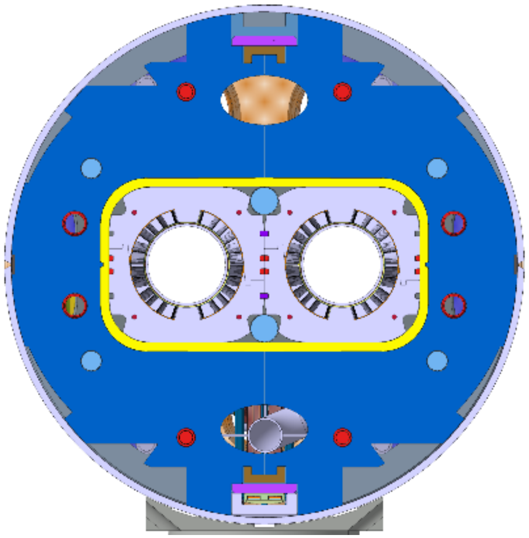
Courtesy Malvestiti SPA





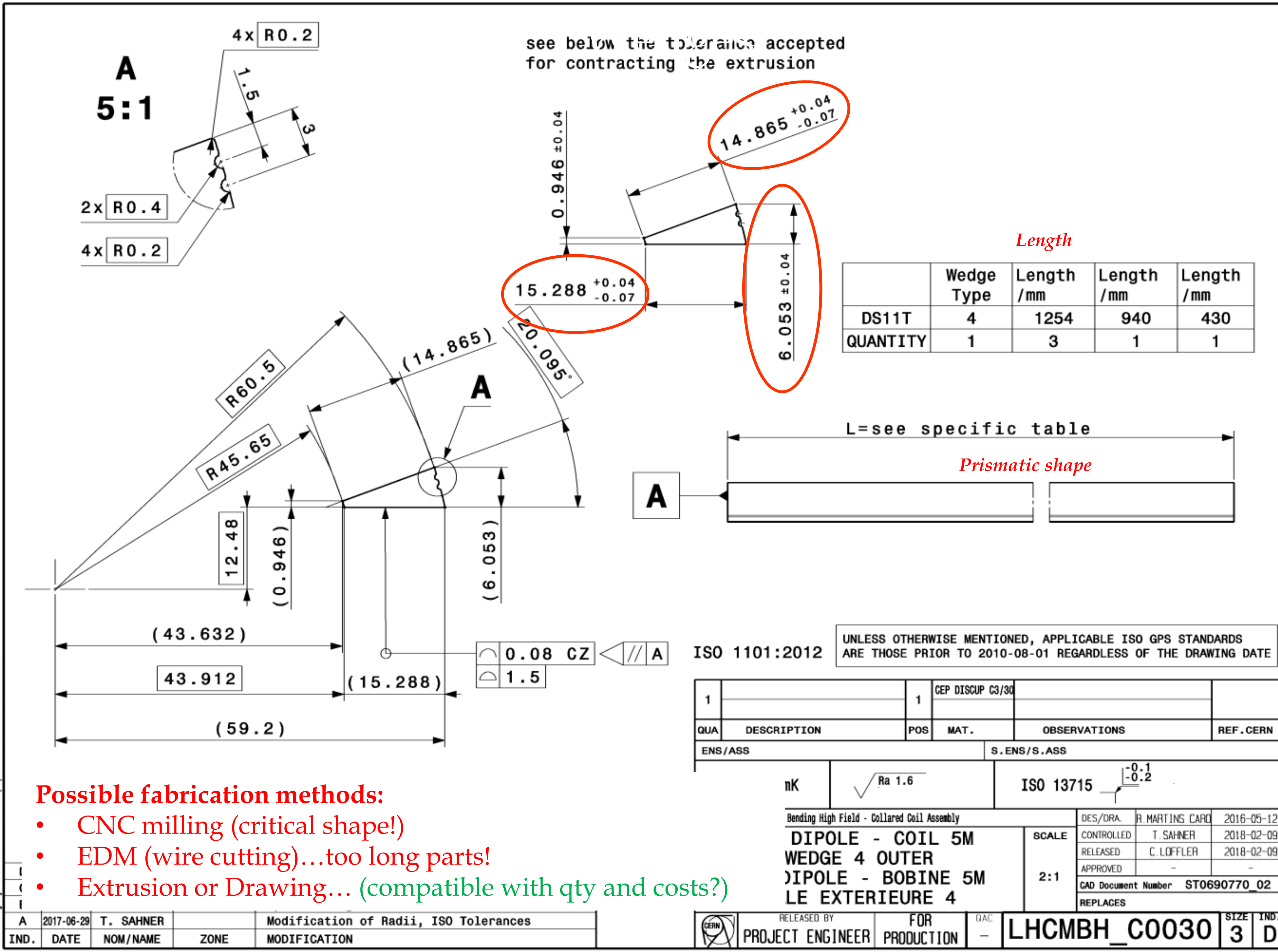
Wedges





Raw Material:

- Generally Cu or Cu Alloys
- Become part of the coil after the winding process…
- Submitted to thermal treatment
    - Curing thermal cycle in case of NbTi
    - Reaction thermal cycle in case of Nb3Sn
- Possible issues resulting from dramatic loss of mechanical properties following thermal treatment…
- If needed, use of Oxide Dispersion Strengthened Copper Alloys to reduce loss of mechanical properties even after thermal cycles…



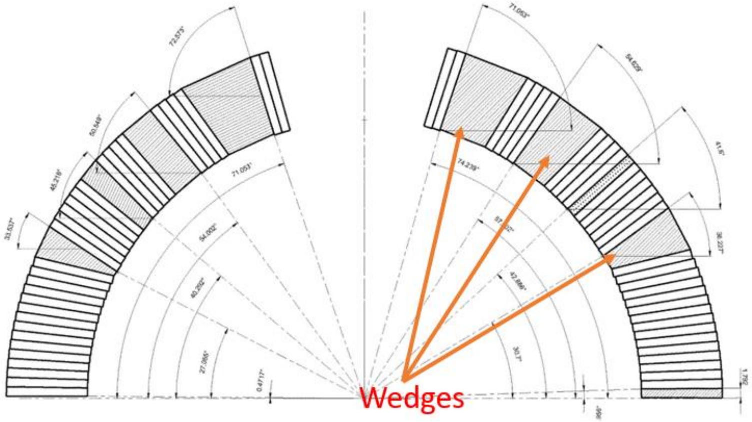
Length

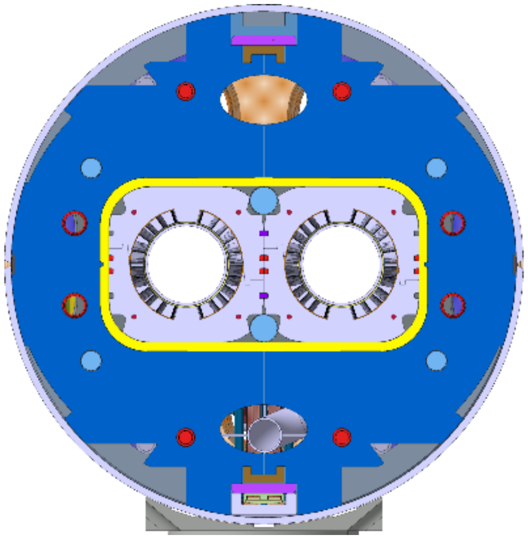
	Wedge Type	Length /mm	Length /mm	Length /mm
DS11T	4	1254	940	430
QUANTITY	1	3	1	1

Possible fabrication methods:

- CNC milling (critical shape!)
- EDM (wire cutting)…too long parts!
- Extrusion or Drawing… (compatible with qty and costs?)

Wedges





Extrusion and Drawings:

- Machining to be considered only for prototyping…very expensive and challenging for long and thin parts!!
- Depending on the shape Extrusion and/or Drawing could be suitable for a production of at least few hundreds meters…
- Relevant is the choice of cold/hot working to obtain suitable tolerances as well as mechanical properties (cold working implies work hardening…intermediate thermal cycles could be necessary…)
- Costs could be estimated at few (1÷5) EUR/cm for a production of few km (at least 1÷2 km) …
- Machining could be 5÷10 times more expensive…depending on quantities and materials.
- AM could be envisaged if a machine with compatible dimensions is available…but Cu Alloys are still not 3D printable…
- EDM is not suitable due to dimensions.

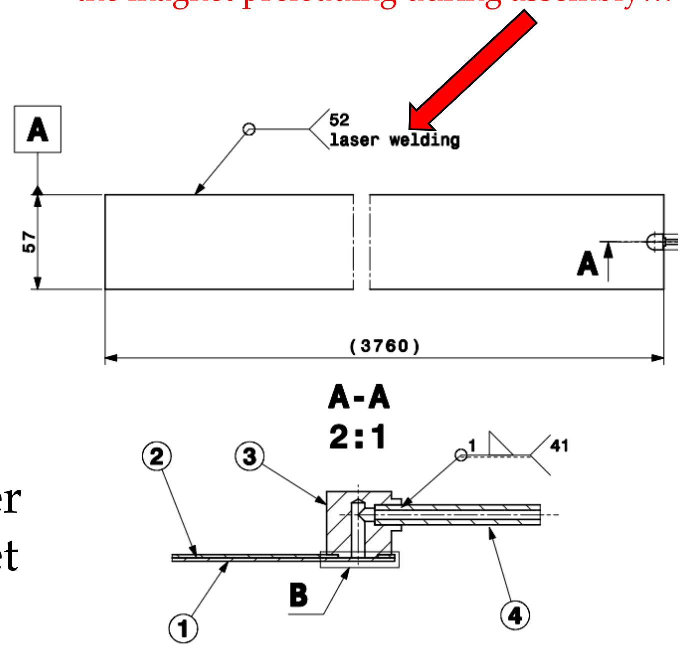
Bladders

Bladders are assembly tools used to preload the magnet during assembly (HL-LHC quadrupole design…).
Actually they are long rectangular pockets with an inlet to provide pressure…

Old fabrication method:

- Precise milling of two stainless steel foils (0.5mm thickness)
- Positioning jigs…
- Laser welding of the foils
- Milling of the inlet components
- Tig welding of the inlet parts

Relevant risk of leak, pressure of 400bars for the magnet preloading during assembly…



~ 500CHF/Bladder
~ 10kCHF/Magnet

Bladders

New fabrication method:

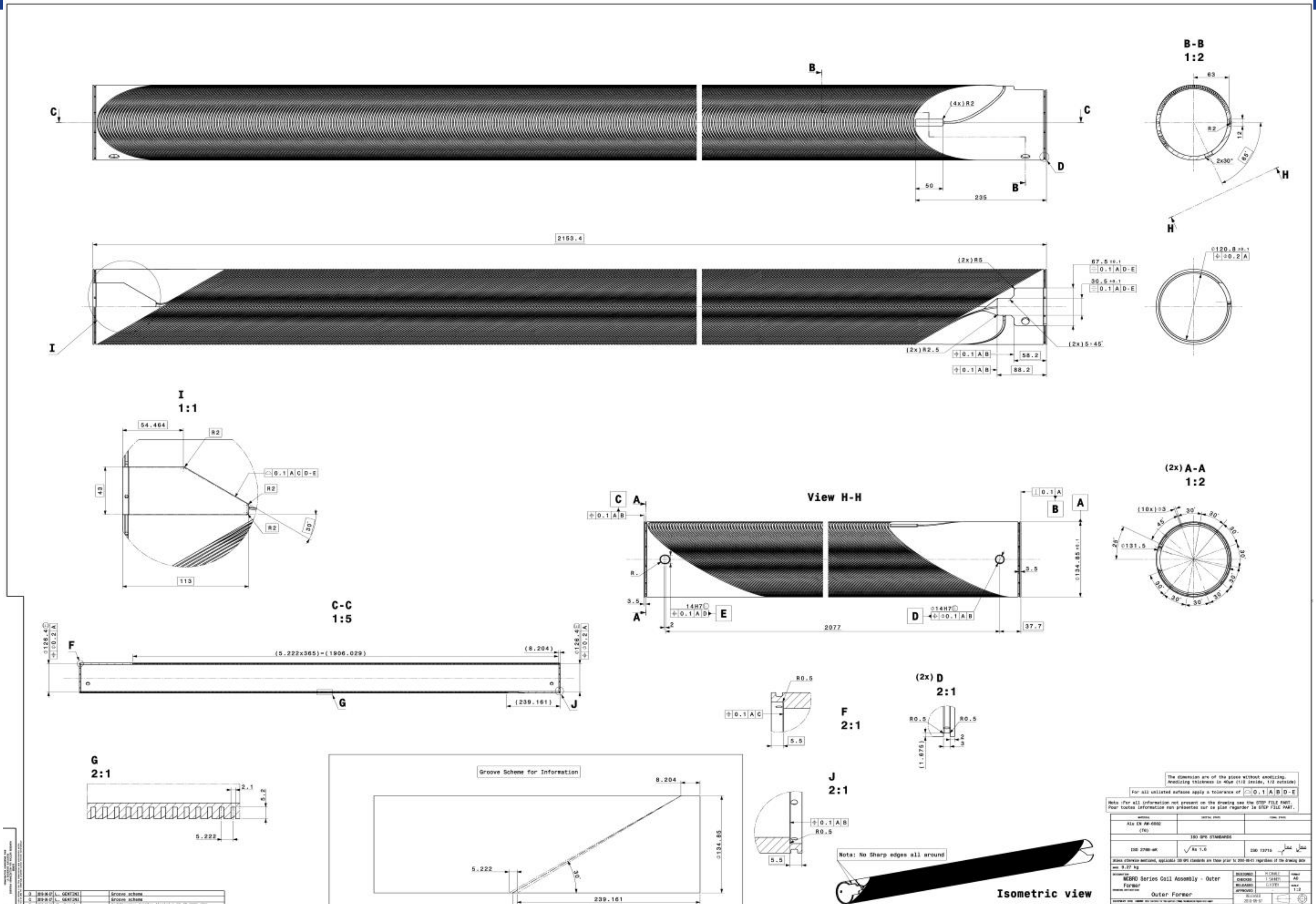
- Cold drawing of the calibrated round tube
- Flatten the tubes with press or rolling machine
- Milling of the end pieces
- Tig welding of the end pieces and capillary tube

~ 350CHF/Bladder
~ 7kCHF/Magnet

Advantages of the new fabrication method:

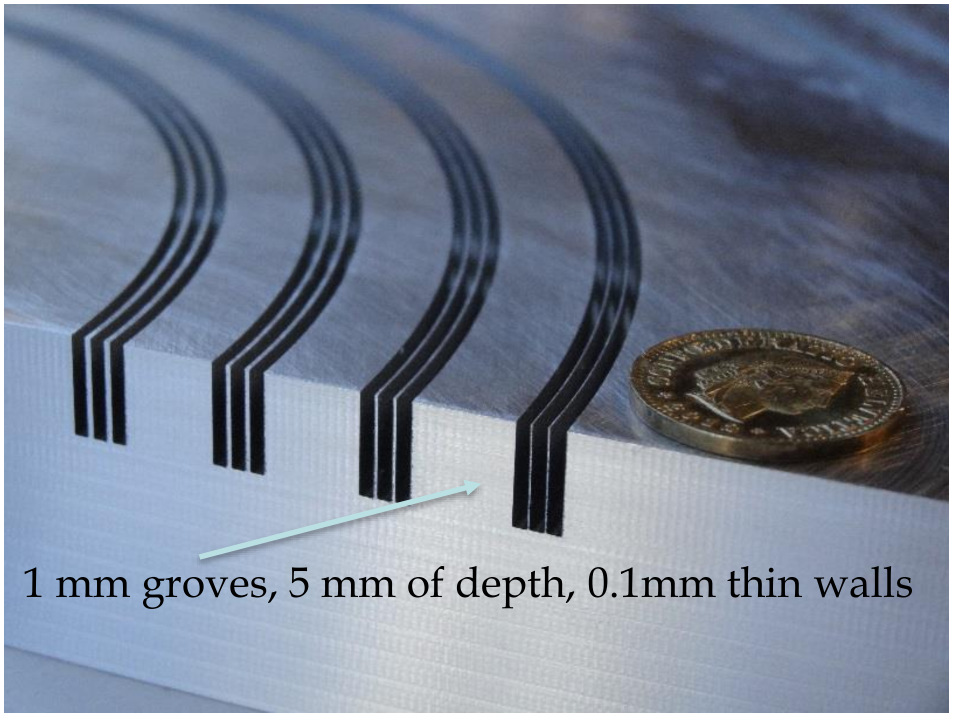
- 30% Cost reduction compare to initial design
- Removed of the longitudinal welds (main causes of the cracks)…improved reliability!
- Possibility to re-use the bladders and to repair them if needed

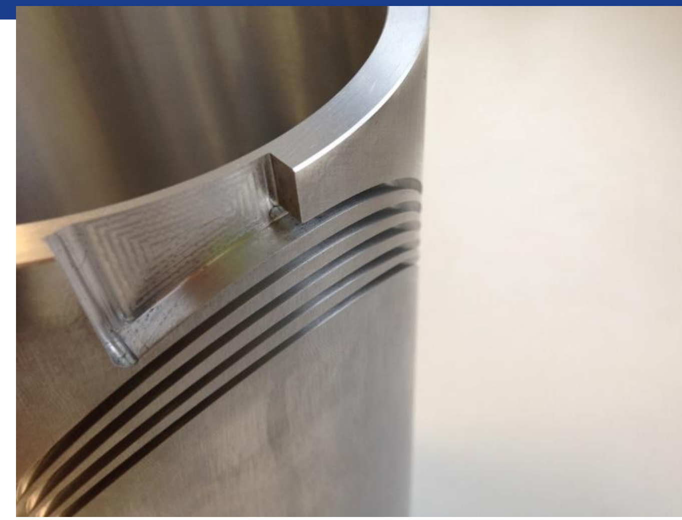
MCBRD Series Coil Assembly - Outer Former

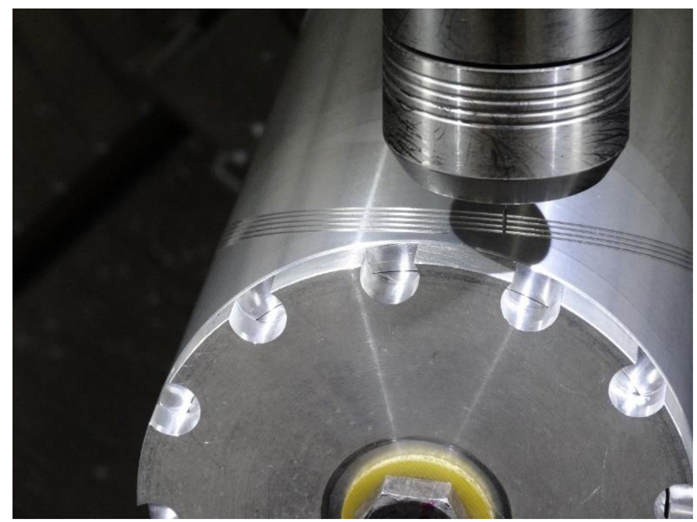


A.

- Prototyping





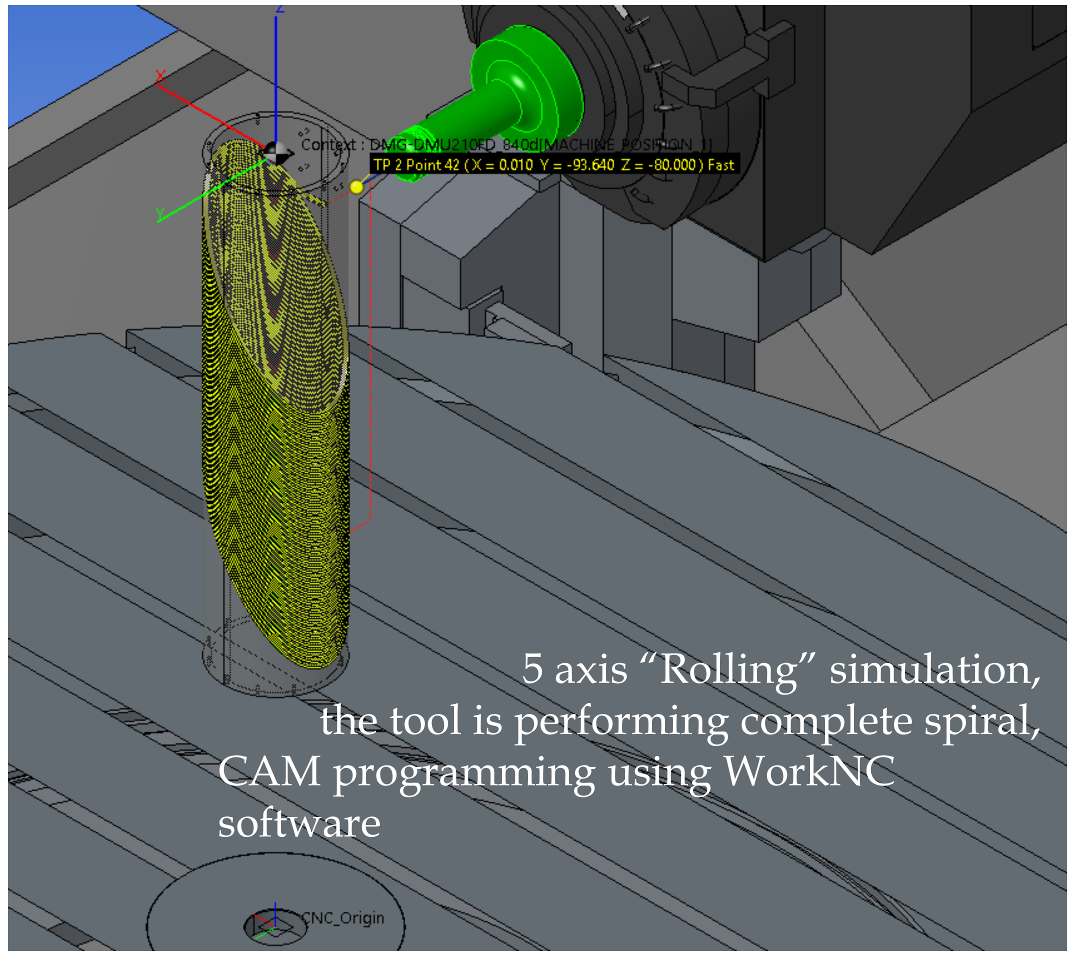


- ✓ Several prototypes done
- ✓ Different materials tested
- ✓ Search for machining feasibility limits

Tooling / Programming strategy choice

High feed mills for roughing
Ø2 mm, 45k rpm, 0.06 plunge

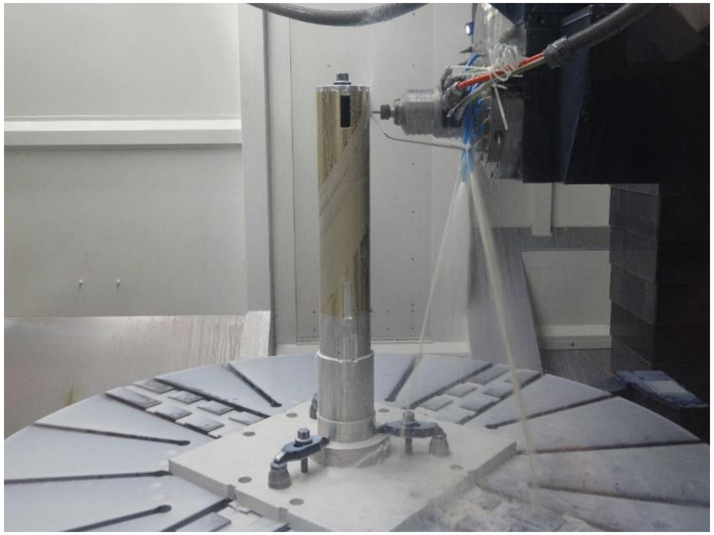
Finishing with
2-floute carbide



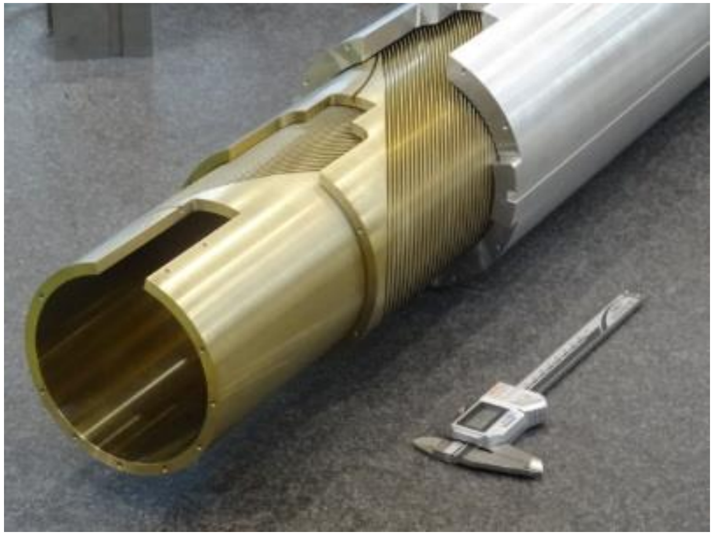
5 axis "Rolling" simulation, the tool is performing complete spiral,
CAM programming using WorkNC software

MCBRD Series Coil CCCT

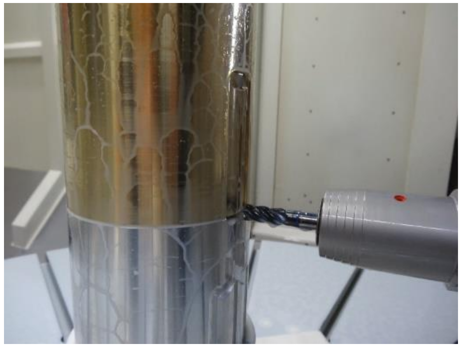
- 500 mm assembly

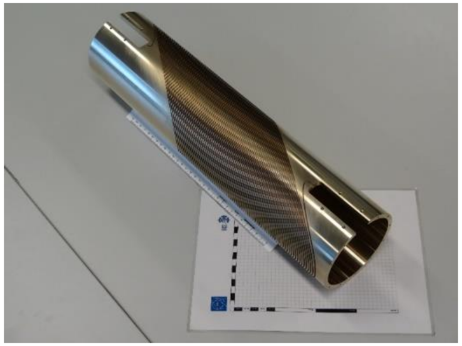


Machining in vertical position on 5 axis DMU210



4 x assemblies manufactured in 2016



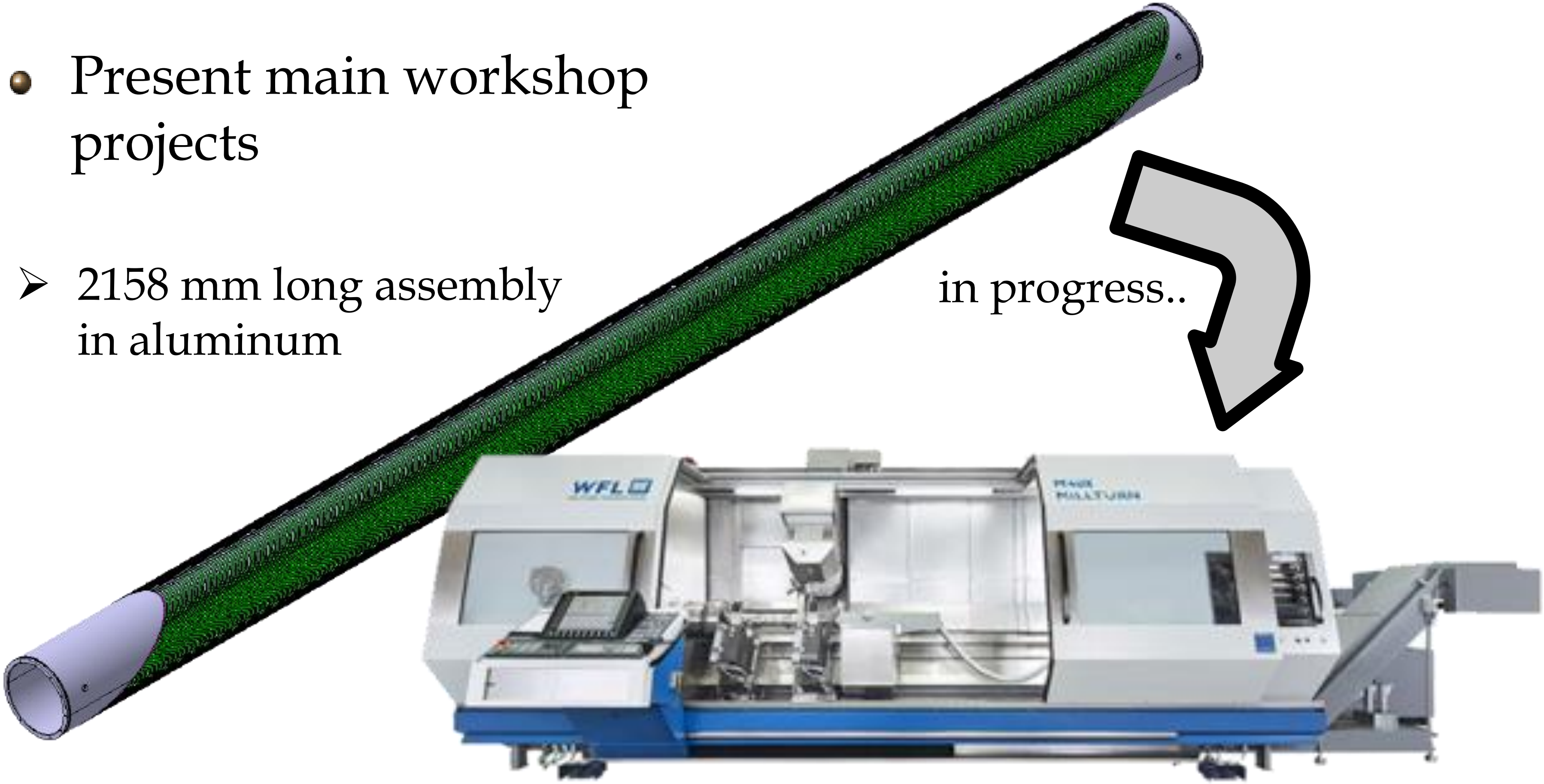


MCBRD Series Coil CCCT

- Present main workshop projects

  - 2158 mm long assembly in aluminum

in progress..



New WFL M40 millturn, 7-axis turning / milling centre (workpieces up to 3000 mm of length)

CONCLUSIONS

- Magnetic Design, Mechanical Design, 3D models, FEM analyses…
  - Functional and Technical Specification…
  - Drawings…Geometrical Dimensioning & Tolerancing (GD&T)
  - Drawings + Technical Specifications → Fabrication, Contracts…
- We need to master GD&T…strong impact on:
  - Quality of the assembling
  - Magnet performances
  - Tight tolerances, repeatability and small dispersion…
  - Fabrication method
  - Costs
  - Choice of raw materials
- Choice of Fabrication methods:
  - Geometrical shapes and Tolerances, quantities, raw materials, costs

Appendix D
A Digression on Manufacturing Techniques for Magnet Components

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European Organization for Nuclear Research (CERN)

EN Engineering Department

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