LMQXF cold mass and MQXF magnets alignment

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Outline

Plan for straightening MQXF magnets and to align them in the LMQXF cold masses based on the assembly experience (Summary of the presentation given in the "Coil, Structure & Alignment WG" Video-meeting in September the 24th)

Magnet straightening

- *Overview of the MQM and MQY experience*
- *Proposal for the MQXF(A/B) magnets*

Magnets alignment in the cold mass

- *IR cold masses experience (series 600)*
- *Proposal for the LMQXF cold masses*

Cold mass finishing

Summary

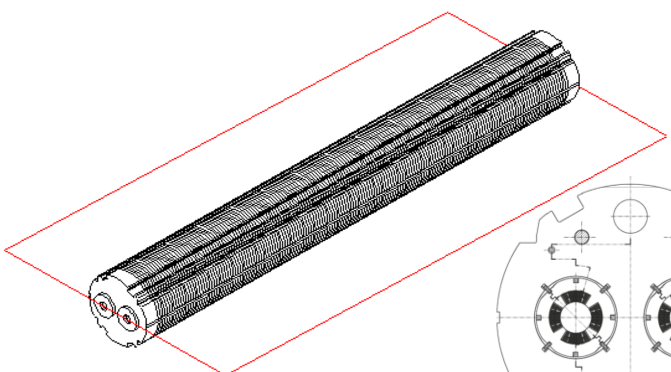
Proposed method

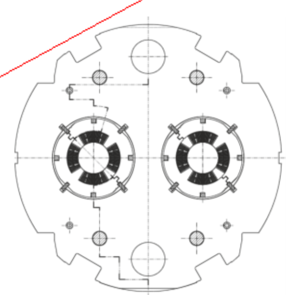
Alignment process based on:

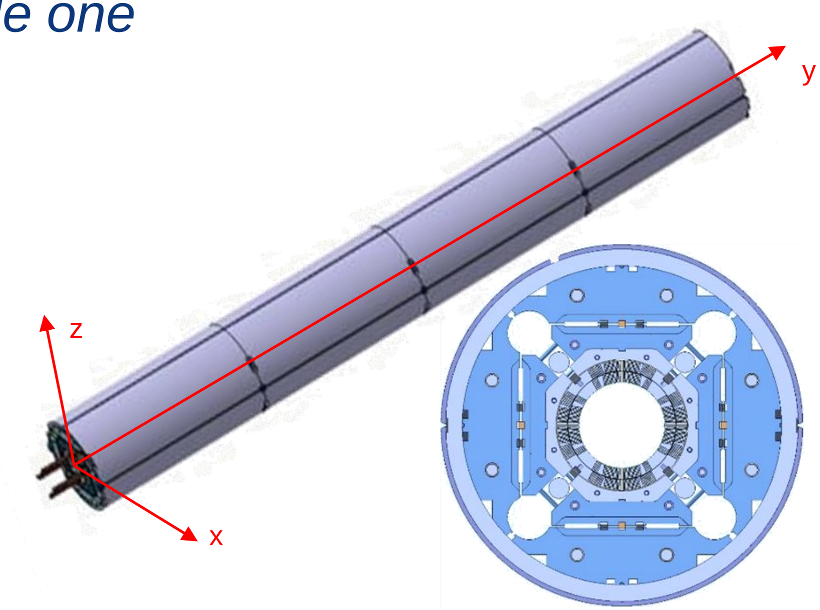
- ***past experience** on the insertion quadrupole (MQM & MQY) cold masses using a **mechanical approach***
- ***fine-tuning** method using **geo-magnetic measurements***

*Taking into account **3 main differences**:*

- *Laminated structure vs aluminium cylinder sectors*
- *Two apertures magnet vs single one*
- *NbTi coils vs Nb_3Sn ones*







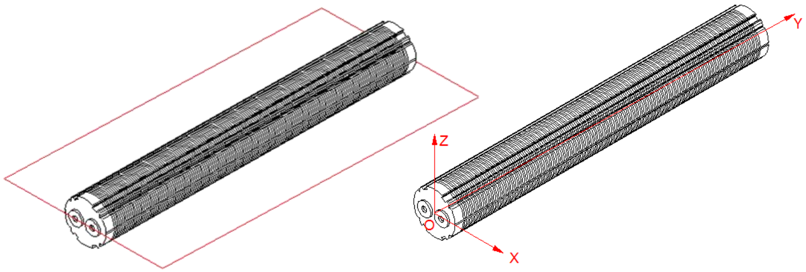
Magnet straightening

Magnet reception – Pre-alignment

The aim of the magnets pre-alignment is to assess the real magnet geometry with its theoretical model.

MQM,C,L-MQY

Ideally the mechanical magnet shape is a cylinder drilled with two parallel holes.
The theoretical plane defined by the two apertures axis will be named mechanical plane or mean plane of the magnet. In reality, this plane is the one fitting the better the apertures axis.

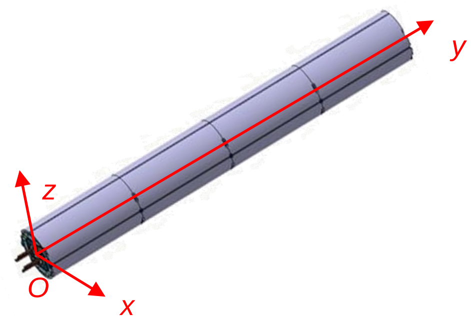


The definition of the global coordinate system is the following:

- XY is the mechanical plane described previously,
- $\overline{Y}\overline{Z}$ is the mechanical mid-plane of the magnet, defined as the symmetry plane of the super-conducting coils,
- $\overline{Y}$ is the mechanical axis, defined as the intersection of the horizontal $\overline{X}\overline{Y}$ and vertical $\overline{Y}\overline{Z}$ symmetry planes of the magnet,
- O is the origin fixed on the $\overline{Y}$ axis on the connection side end plate.

MQXF

Ideally the mechanical magnet shape is a cylinder drilled with one concentric hole.
The theoretical axis is based on mechanical measurement along the aperture or by magnetic measurements.



The definition of the global coordinate system is the following:

- *O is the origin on the Y axis on the connection side end plate*
- *Y is the mechanical or the magnetic axis of the magnet*
- *X and Z are the quadrupole symmetry planes obtained by magnetic measurements with X horizontal and Z vertical*

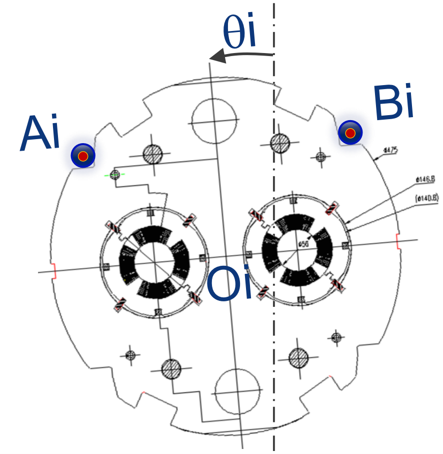
Magnet straightening and measurement

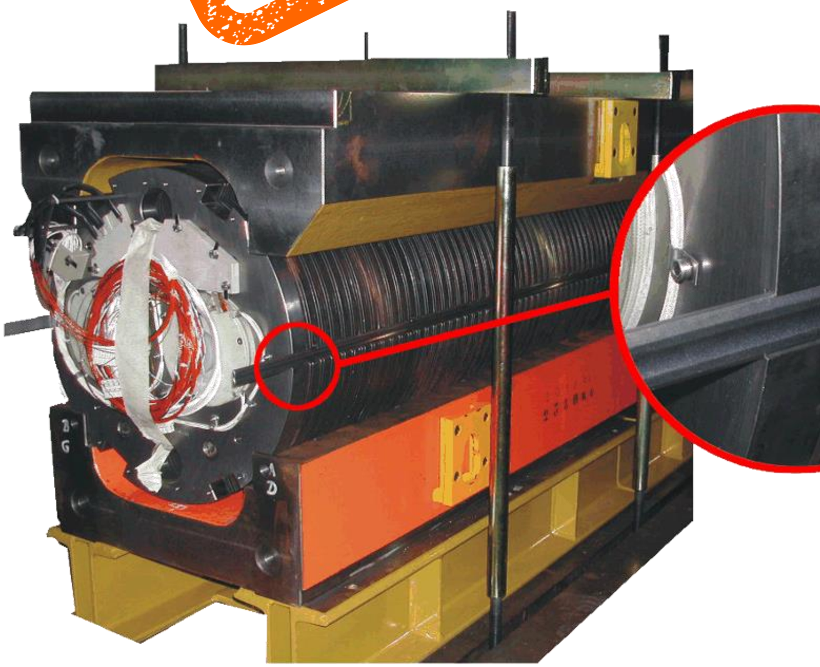
IR magnets yoke alignment and measurement

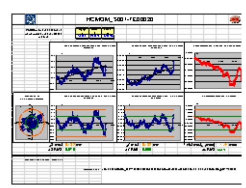
The determination of magnet *mean axis* consists in the calculation of the best line approximation of the yoke centres, i.e. the straight line that best fits the data by using the "least squares" method (see annex).

The Oi local positions are determined by the measurement of two points on the laminations straightening faces. Taking the assumption that the distance between the lamination centre and the straitening faces is constant and equal to the theoretical one, i.e. 140 mm on the X axis and 133 mm on Y, the abscise and elevation coordinates and the twist angle calculations are the following:

Fully Mechanical alignment







Traveller

Magnet straightening and measurement

Analysis after alignment over the global production:

Quadrupoles MQM, MQMC, MQML, MQY
From 2.6 up to 5m

	Average	min	max	RMS
Δxmaxi (mm)	0.203	0.077	0.389	0.084
Δzmaxi (mm)	0.185	0.085	0.423	0.073
αmaxi (mrad)	0.619	0.186	1.407	0.267

Correctors MCBC, MCBY
1.1m

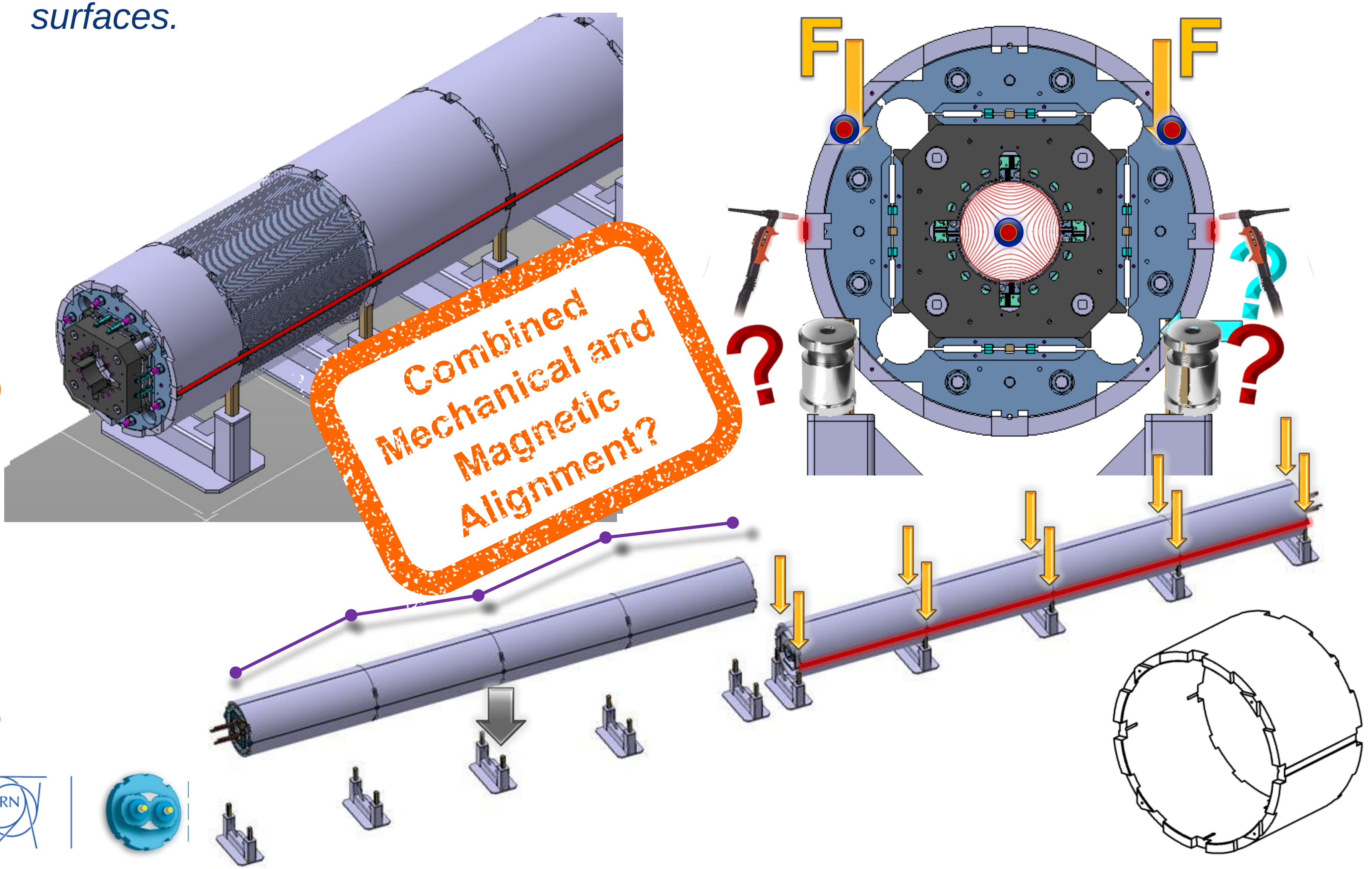
	Average	min	max	RMS
Δxmaxi (mm)	0.129	0.071	0.368	0.050
Δzmaxi (mm)	0.107	0.049	0.182	0.028
αmaxi (mrad)	0.449	0.164	1.208	0.227

Targeted values

ΔXmax= ±0.2 mm
ΔZmax = ±0.2 mm
αmax = ±2 mrad

Magnet straightening and measurement

MQXF alignment initial plan consists in applying adequate forces on the magnet yoke through the Al cylinder to stand on the well precise alignment bench surfaces.



Coil straightening simulation

Courtesy of G. Vallone

Problem statement:

- If the coil is not straight, the magnet will be bended / twisted
- The application of the shell may irreparably damage the coil
- It is necessary also to consider how these forces add-up to cool-down stresses

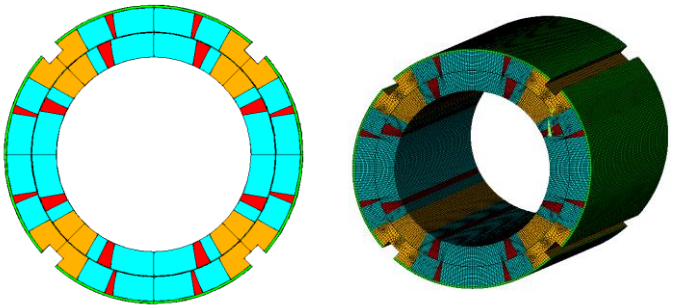
Challenges:

- Apply the loads in a *realistic* way
- Foresee the possible shapes of the coil
- Torque action can be measured (twist), not the bending (depends on the curvature)

$$M_f \sim y'' , M_t \sim \phi \rightarrow y'', \phi = f_{1,2}(x)=\ldots?$$

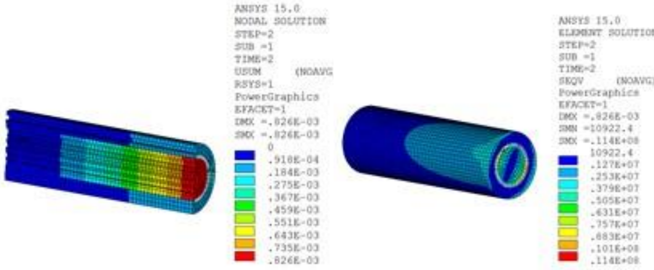
Possible approaches 1:

- Reciprocal solution: the coil is loaded to generate the deformed shape. Consequent stresses are equivalent to the ones necessary to straighten it:
  - Beam model of the coil (can be solved also analytically for bending)
  - Solid model of the coil



Possible approaches 2:

- Assembly simulation: the coil is deformed and then inserted into the assembly. Load is applied by means of local contacts (collars).
  - Requires a full model of the assembly (asymmetric)
  - The approach works for simple problems
  - Works also for the coil (but is incompatible with symmetric boundary conditions)



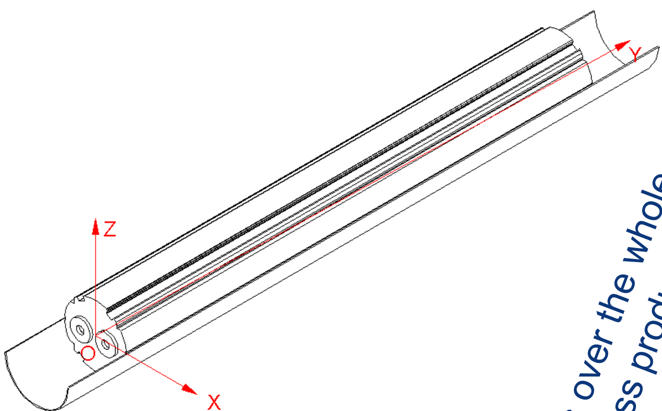
Magnets alignment in the cold mass shell

STEP 3: MAGNET YOKE ALIGNMENT IN THE BOTTOM SHELL

IR magnet yoke alignment in the cold masses

Once they are pre-aligned, the magnets are settled in the lower half shell which constitute the half of the Helium container.

Assemble the magnet to the shell, i.e. aligning the magnet mechanical plane parallel to the plane set by the beveller's root faces is not a goal. Nevertheless the operation must be executed with the required accuracy to allow the alignment keys point welding to the shell. This welding intends to convey the shell inertia to the magnet yoke during the alignment phase in order to control the magnet deformation, i.e. to avoid the magnet elasticity to bring it back to it's original shape.



Targeted values

$\Delta Xmax = \pm 0.1$ mm

$\Delta Zmax = \pm 0.1$ mm

$\alpha max = \pm 1$ mrad

Analysis over the whole cold mass production

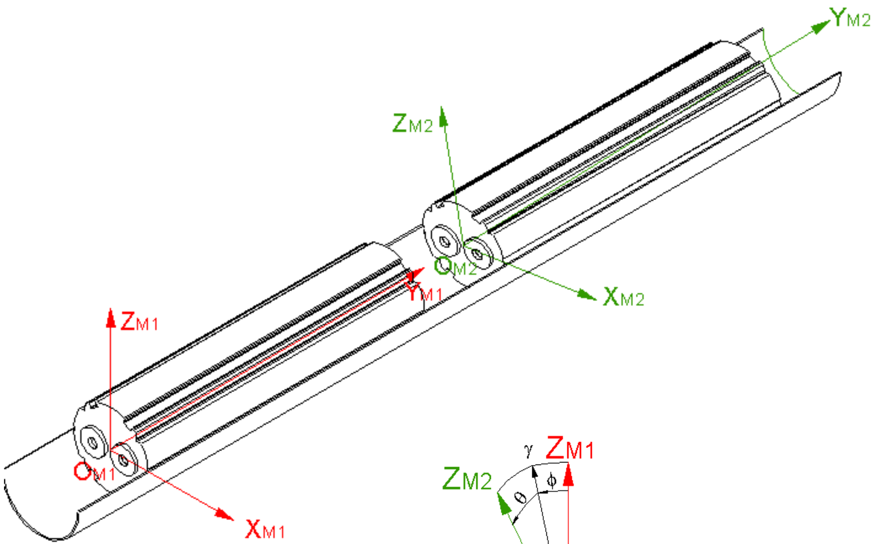
	moy	min	max	σ
Δxmaxi (mm)	0.170	0.071	0.435	0.083
Δzmaxi (mm)	0.153	0.049	0.690	0.086
αmaxi (mrad)	0.539	0.164	1.407	0.261

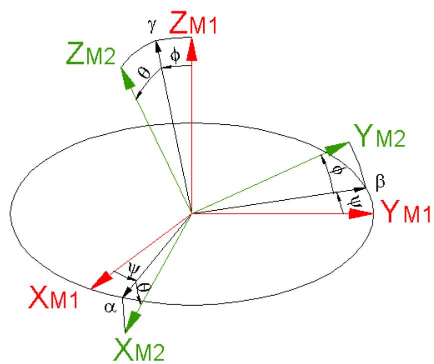
~ 15% gain in straightness

RELATIVE MAGNETS ALIGNMENT IN THE COLD MASS

IR magnet alignment in the cold masses

The positioning of magnet respect to an other requires to fix 6 degrees of freedom in the space: 3 translations and 3 rotations.
In IR cold masses case, up to 7 magnets had to be aligned inside the shells.
The situation between two magnets is illustrated using Euler angles.





$\vec{\alpha}$ is the $\overrightarrow{X_{M2}}$ projection on the $\overrightarrow{X_{M1}}\overrightarrow{Y_{M1}}$

$\vec{\beta}$ is the $\overrightarrow{Y_{M2}}$ projection on the $\overrightarrow{X_{M1}}\overrightarrow{Y_{M1}}$

$\vec{\gamma}$ is the $\overrightarrow{Z_{M2}}$ projection on the $\overrightarrow{Y_{M1}}\overrightarrow{Z_{M1}}$

RELATIVE OFFSETS

The *relative longitudinal offset* ΔY_M is the distance between the magnets origins OM1 and OM2 projected on the $\vec{Y}$ axis

$$\Delta Y_M = Y_{OM2} - Y_{OM1}$$

The *relative horizontal offset* ΔX_M is the distance between the magnets origins OM1 and OM2 projected on the $\vec{X}$ axis

$$\Delta X_M = X_{OM2} - X_{OM1}$$

The *relative vertical offset* ΔZ_M is the distance between the magnets origins OM1 and OM2 projected on the $\vec{Z}$ axis

$$\Delta Z_M = Z_{OM2} - Z_{OM1}$$

RELATIVE ANGLES

The *relative roll angle* ϕ is the angle between the orthogonal vectors of the magnets mechanical planes measured around $\overrightarrow{X_{M2}}$

$$\phi = \widehat{\overrightarrow{Z_{M1}}\vec{\gamma}}$$

The *relative pitch angle* θ: is the angle between the magnets mechanical planes measured around $\vec{\beta}$

$$\theta = \widehat{\vec{\gamma}\overrightarrow{Z_{M2}}}$$

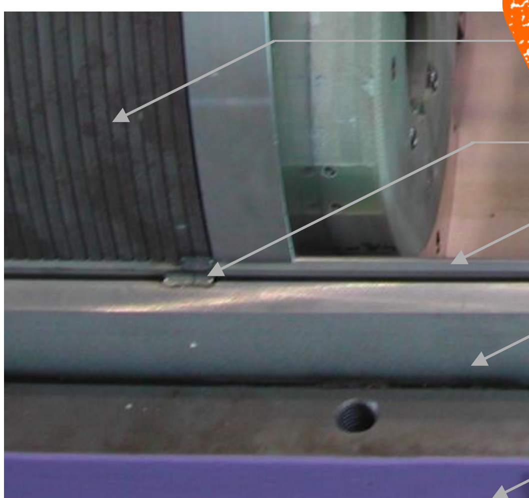
The *relative yaw angle* ψ: is the angle between the magnets mechanical planes normal around $\overrightarrow{Z_{M1}}$

$$\psi = \widehat{\overrightarrow{X_{M1}}\vec{\alpha}}$$

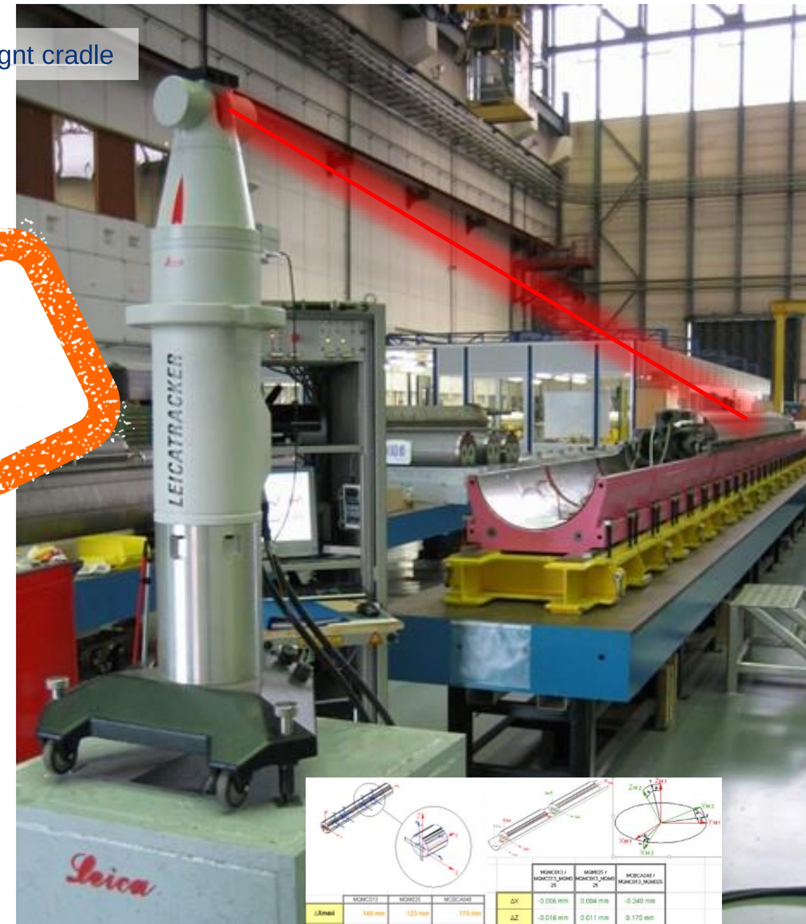
RELATIVE MAGNETS ALIGNMENT IN THE COLD MASS MEASURMENT

The determination of magnet *mean axis* consists in the calculation of the best line approximation of the yoke centres over the set of magnets, i.e. the straight line that best fits the data by using the "least squares" method (see annex).

IR magnet alignment in the cold masses



Fully Mechanical alignment

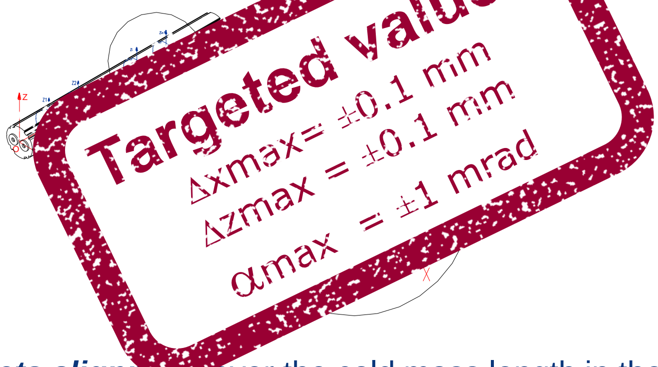


Travellers

Magnets positioning in the half shell statistics

IR magnet alignment in the cold masses

Magnets yoke alignment over the cold mass length in the cold mass referential



	mean	min	max	σ
Δxmaxi (mm)	0.170	0.071	0.435	0.083
Δzmaxi (mm)	0.153	0.049	0.690	0.086
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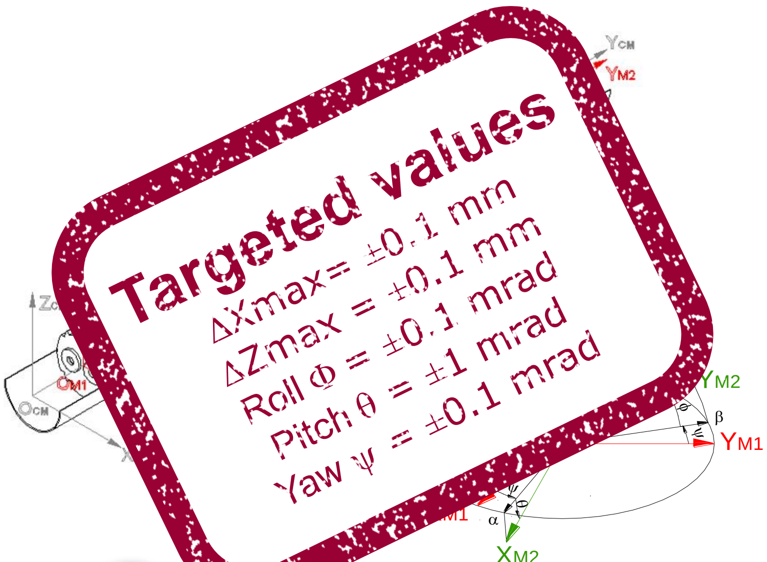
Magnets alignment over the cold mass length in the cold mass referential



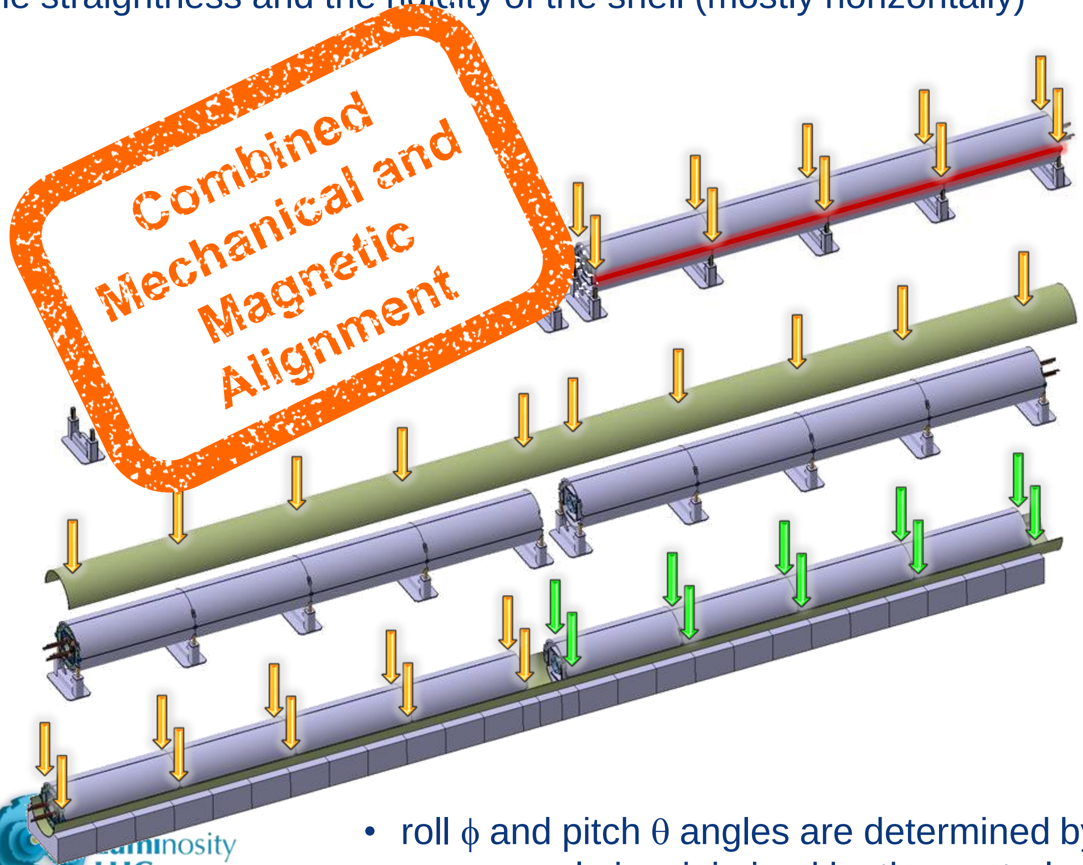
	Quads		Correctors	
	Mean	σ	Mean	σ
ΔX (mm)	0.001	0.022	0.003	0.250
ΔZ (mm)	0.002	0.027	0.303	0.231
Roll ϕ (mrad)	-0.009	0.078	-0.143	0.182
Pitch θ (mrad)	-0.006	0.193	-0.059	0.389
Yaw ψ (mrad)	-0.012	0.061	-0.036	0.209

- roll ϕ and pitch θ angles are determined by the alignment cradles
- yaw ψ angle is minimized by the control of the shell straightness

LMQXF MAGNETS ALIGNMENT

The alignment from one magnet to the other is provided by the tooling on the assembly bench.
The straightness and alignment accuracy are provided by:

- The distance between the supports (fixed by the magnet design)
- The supports alignment (horizontally and vertically)
- The inertia of the alignment key
- The gap between the yoke structure and the supports (horizontally)
- The rigidity of the magnet and the force applied for the alignment (vertically)
- The straightness and the rigidity of the shell (mostly horizontally)



Tack welds of the key in between the Al cylinder on the magnet yoke

Tack welds of the key to the stainless steel shell in the welding cradles **after geo-magnetic measurements**

- roll ϕ and pitch θ angles are determined by the alignment cradles
- yaw ψ angle is minimized by the control of the shell straightness

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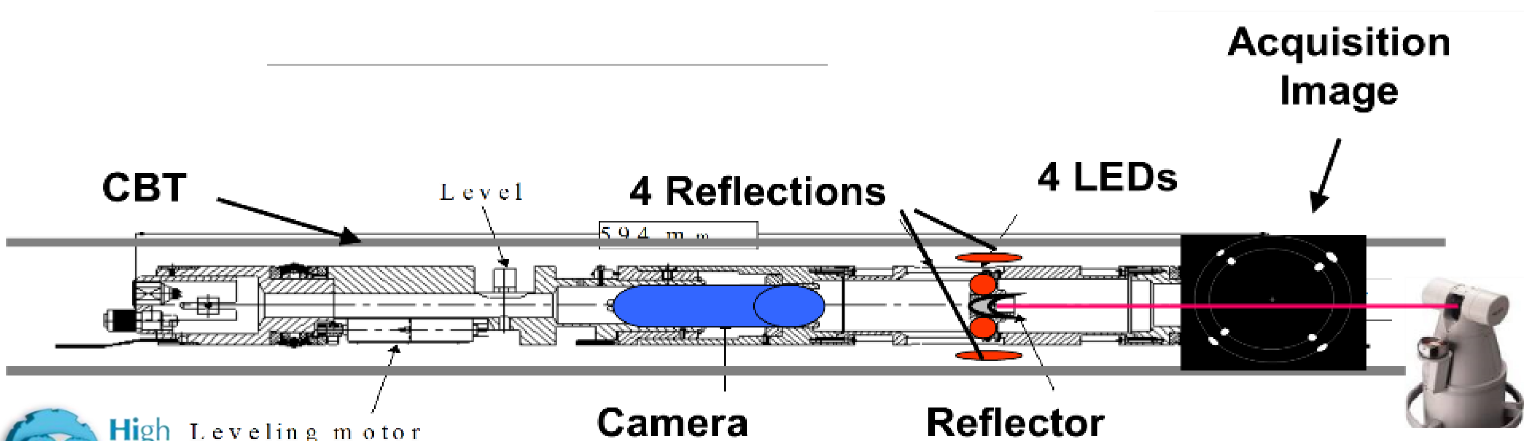
AC mole example and principles

Courtesy of J. Garcia Perez

- Born in 2000. Old system with most of its components (hardware & software) obsolete but still working well with the old infrastructure-equipment.
- Characteristics: **100 mm length coil**. **Centred reflector**.
- Optical system (with CCD camera embarked) for cold bore geometry measurements and inspection.
- **Magnetic axis scan**, so pitch and yaw angles available for alignment if needed. **No big current needed** (AC power, from few mA to 1A, 25 Hz). **Magnetic angle measurement** for any type of magnet.
- It was **able** to measure the axis of LHC dipoles at cold in SM18. It measured all Short Straight Section LHC magnet assemblies automatically.
- Difficult to adapt to different bore diameters. Not optimised for field quality.



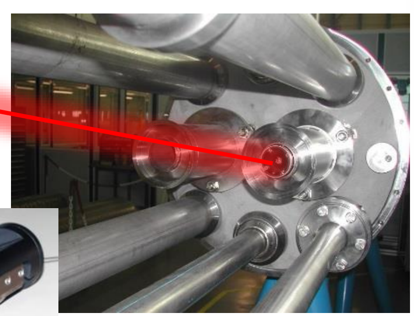
Cold mass finishing

Cold masses equipment

IR quad and main dipole cold masses components alignment and measurements

The shape of the IR quadrupole cold masses (as well as the main dipole ones) is represented by the shape of the **CBT axes**. To determine the datum plane for the next steps of the assembly, the CBT axes should be measured and compared with the theoretical axes of the cold mass.
The tubes have a 50mm diameter and are 5 to about 15m long.
To measure the axes, the sole valid measuring techniques that assure the required accuracy at the given conditions rely on **optical methods**. The measuring instrument used is a **LTD500 laser tracker** based on interferometric techniques. A mechanical mole centred with respect to the CBT holds a reflector as target while traveling through the tube. The position of this reflector, describing the axes of the CBT, is measured with the LTD500 in a common Cartesian coordinate system.
An **external network system** is measured together with the CBT axes and expressed in the datum plane coordinate system. Measuring this network system and making the same 3D data transformation on the values expressed in the datum plane system allows the positioning and the checking of the different components of the assembly. The only requirement is the **stability** of the network with respect to the CM and vice versa. With this condition fulfilled, the components can be positioned with an **accuracy** that is only **limited by the precision of the positioning tools**.
A **semi-automated measuring system** is created to guide the operators during the measurements and positioning operations, as well as to reduce time and the possibility of errors using a sophisticated measuring system during the construction of the cold masses.

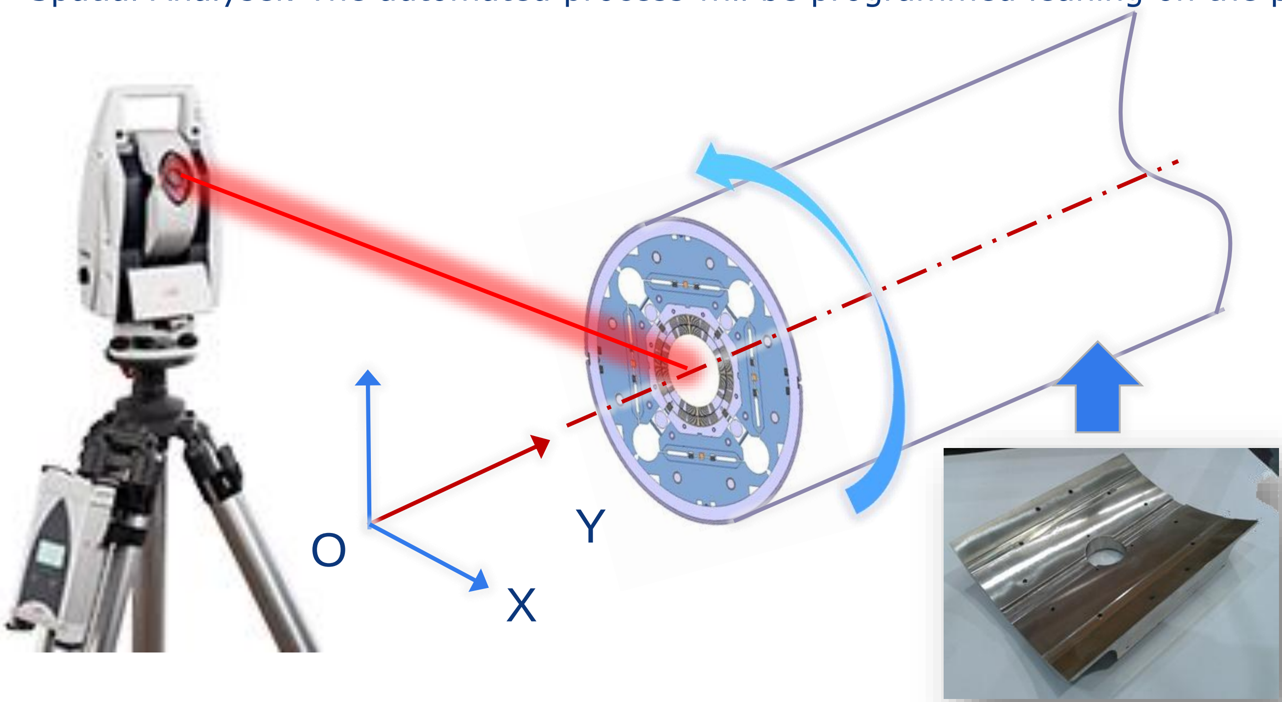
[extracted and adapted from **LHC Project Report 709**]

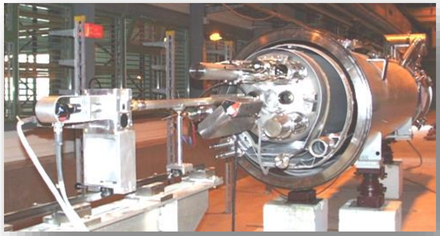



LMQXF cold masses equipment

The finishing procedure for the triplet quadrupole cold masses is very **similar** to the one used for other LHC cold masses.
The main difference comes from the fact the assemblies close to the experiences are equipped with **only one beam pipe**. Where the coordinate system is defined by the “reference plane” in most of the cases, the cold bore tube measurements provide only one axis of the CS. We propose to define the second axis needed to represent the cold mass by using **magnetic measurements** and to **combine** it with **geometric data** to define the CS as well as the origin.

The laser tracker LTD500 will be replaced by AT-402 or AT-930, Axyz software will be substituted by Spatial Analyser. The automated process will be programmed leaning on the present developments.





Existing QIMM and DIMM magnetic measurement rotating coil systems

Results are transferred in a common coordinate system materialized by fiducials in the extremities

Analysis over the production

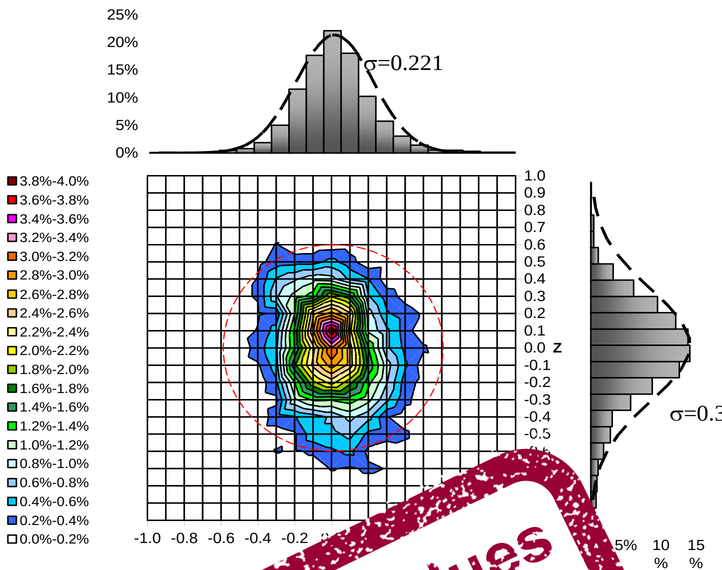
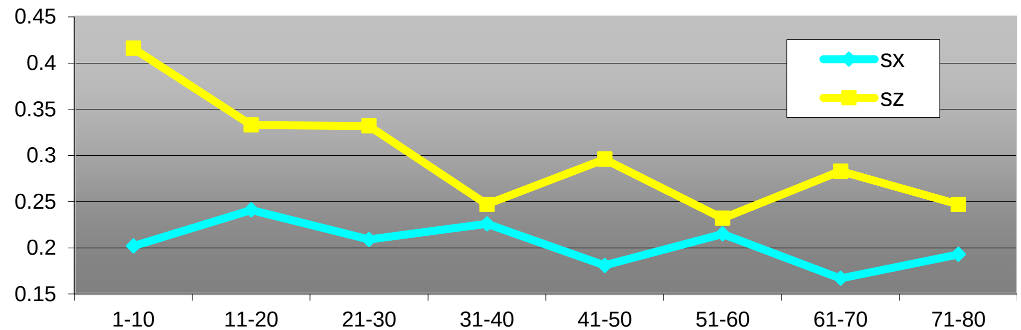


Fig. 8. Distribution of ... ontal and vertical planes

Spread of the beam tube measurements per fabrication decade

Series Number	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80
σ^x	0.202	0.241	0.209	0.226	0.181	0.215	0.167	0.193
σ^z	0.416	0.333	0.332	0.247	0.296	0.232	0.283	0.247



Targeted values

ΔXmax= ±0.6 mm

ΔZmax = ±0.6mm

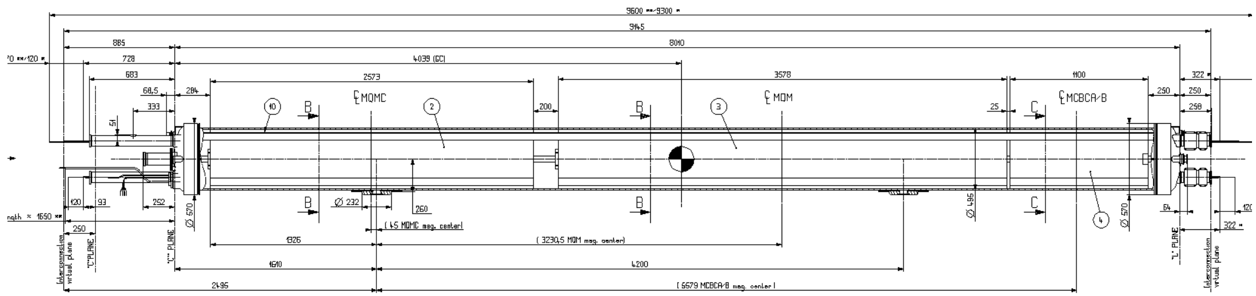
...es mostly from the general tendency of the beam tube to sag inside the correctors: ...imise the sag along the quadrupole and the radial clearance between the beam ...orrectors than in the quadrupoles

- ... troduced during the production to eliminate local deformation
- The ... vertical plane has steadily reduced to 0.25 mm, and is fully compatible in the latest production to that in the horiz... lane.

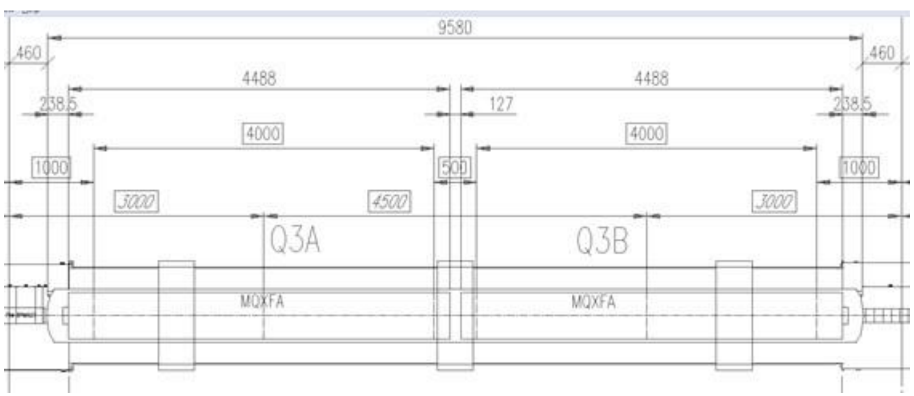
⇨The alignment is stable and well within the tolerance

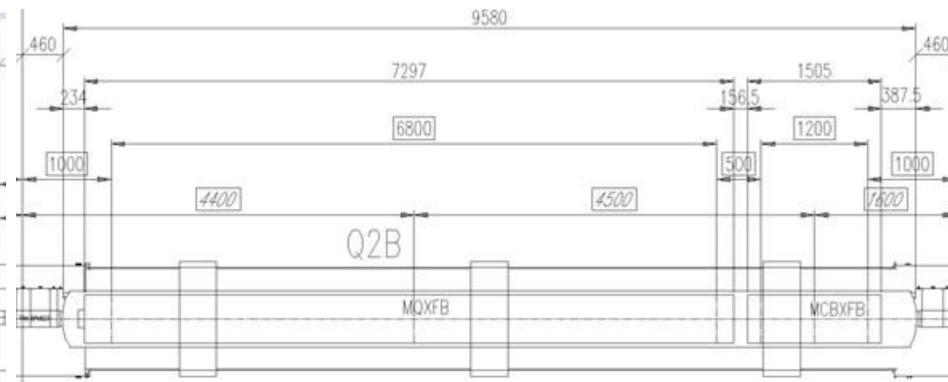
[Extracted and adapted from Production of the Superconducting Matching Quadrupoles for the LHC Insertions, MT19]

Possible improvements on the LMQXF cold masses compared to the LMQM/Y ones



- Integrate the corrector magnet in the deflection optimisation
- Design symmetrical cold masses with 3 supports
- Develop a centring system for the cold bore tube





Machined cold bore with higher inertia (see C. Garion talk)

Stiffness of the aluminium cylinder sections pro or con ?

Try to standardize Q1 and Q3 cold bore thickness (spare policy)

To be kept in mind

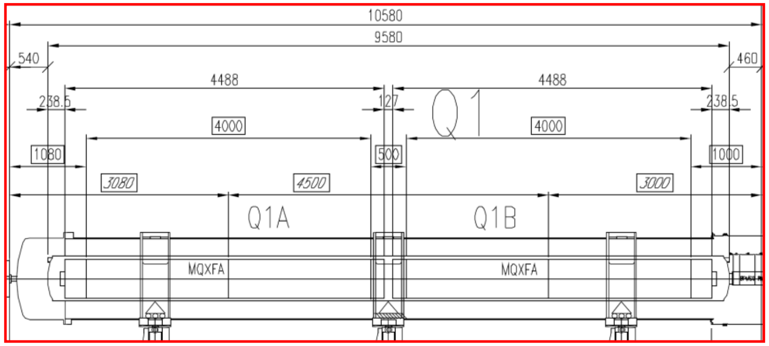
- *An alignment system between the collar noses and the cold bore tube has to be design to insure the* ***concentricity of the beam pipe to the coils*** *(same for orbit corrector magnets MCBXFB)*
- *MQXF* ***handling tooling*** *has to be studied carefully in order to maintain the different segments and sections alignment to minimise shear and bending in the coils especially on the long version MQXFB*
- ***No straightening action*** *has been foreseen inside the shrinking cylinder* ***segments*** *during the cold mass assembly phase*
- *The* ***alignment budget*** *shall be defined and specified. The required tolerances on the shapes will drive the magnet components, the tooling and the cold mass design and may refine the assembly procedures*

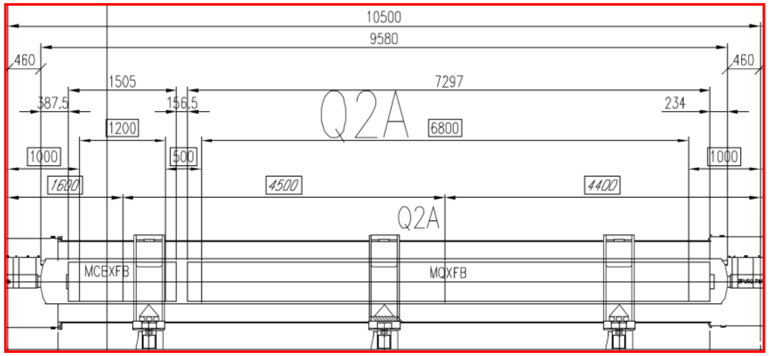
Summary

- *LMQXF cold masses assembly and alignment proposal is **based on past experience***
- *Alignment **points density is quite low** but the Aluminium cylinder rigidity in between should insure a good straightness along the MQXF magnet segments*
- ***MQXFS model** assembly will be followed closely by the cold mass designers and producers in order to assess the magnet behaviour, to refine the present proposal and to anticipate components and tooling changes*
- *The cold masses assembly require an **accurate alignment bench** to straighten the magnets and to align them.*
- ***Geomagnetic measurements** are required to minimise the rolling angle between the magnets and the cold mass supports*

Back-up slides

Magnet layout in the cold masses

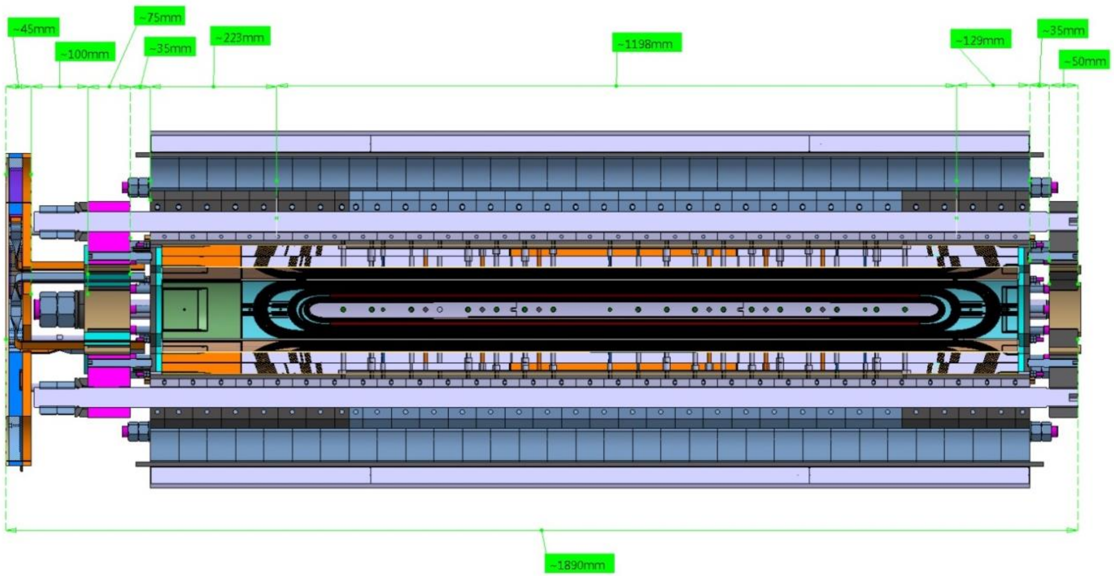




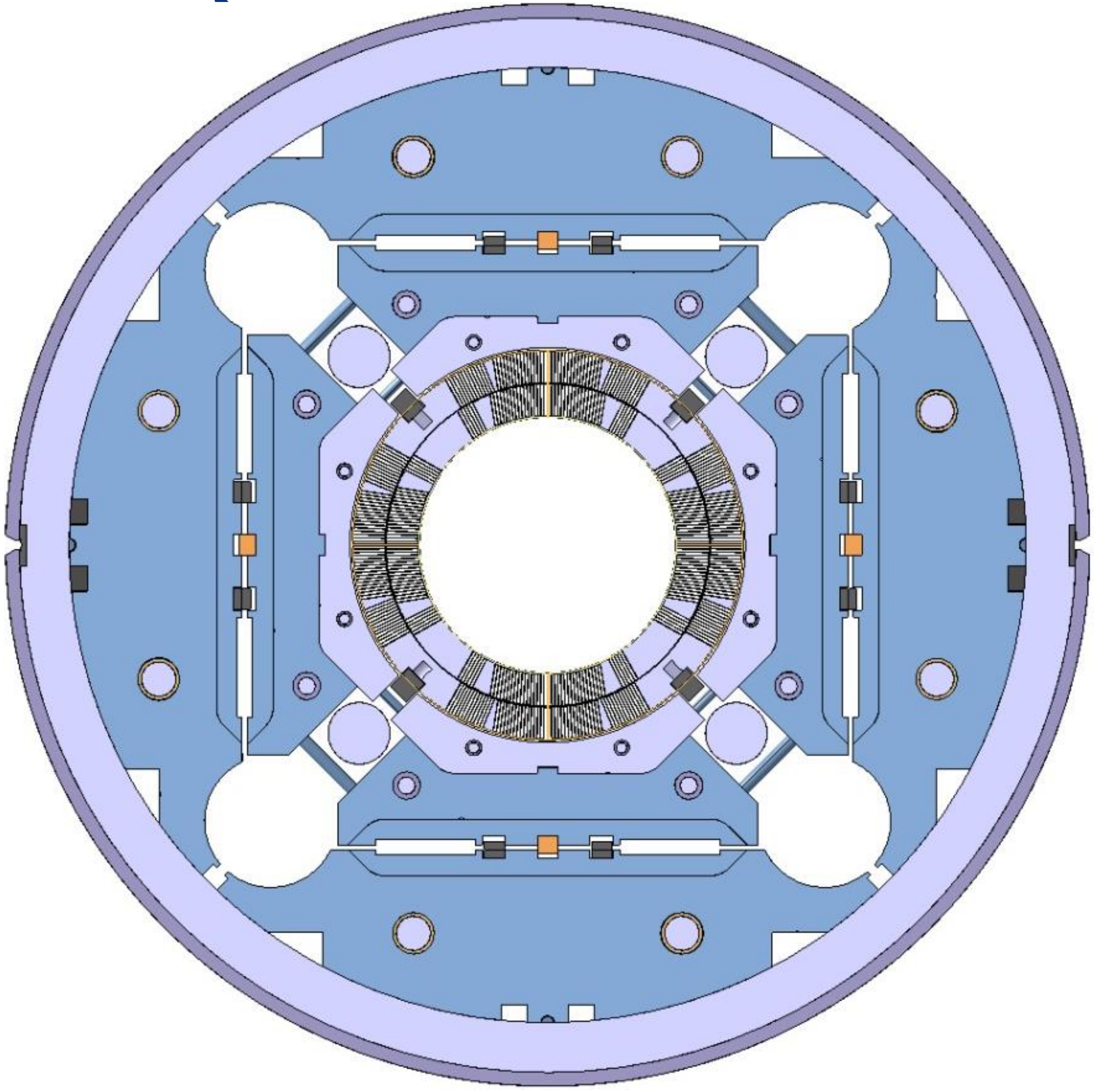
From magnetic length to end of magnet (end-plate + connection box)

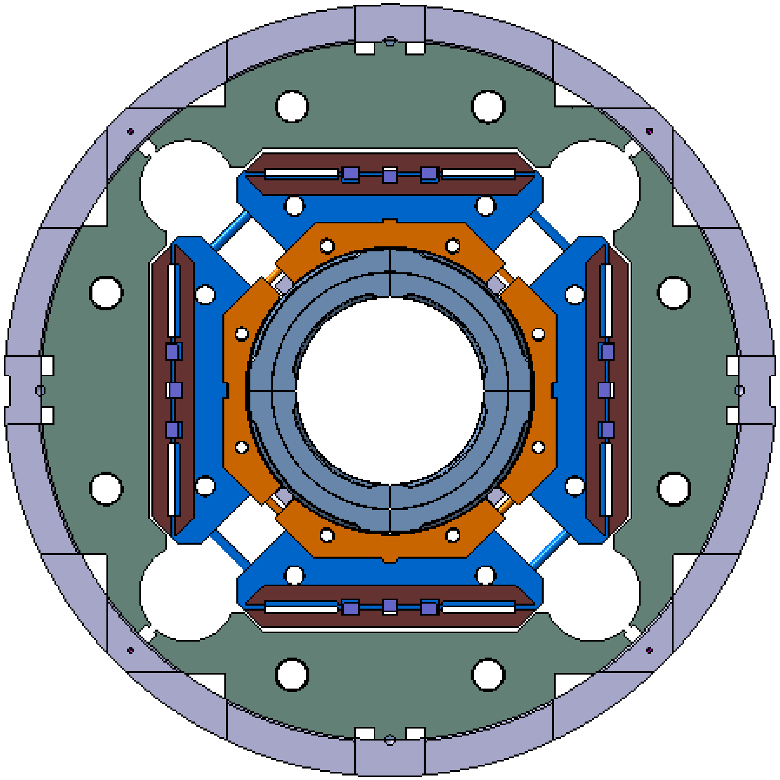
Connection side: **478 mm**

Non-connection side: **214 mm**



MQXF cross sections





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MQXF Coil