# R&D ACTIVITIES :
# HTS QUADRUPOLE AND BEAMPIPE

## 2nd FCC Italy & France Workshop

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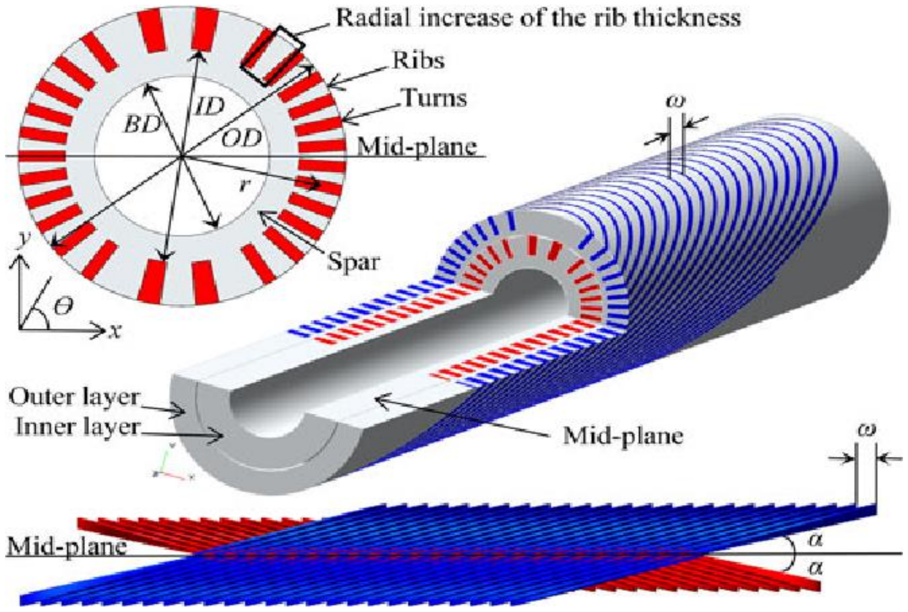
# HTS MAGNET IN FCC – Definition

- FCC project must face technologic, economic and ecologic challenges => HTS magnet can be part of the solution

*REBCO ribbon*

  - A High Temperature Superconducting (HTS) magnet => operate at temperature above 30°K, versus 2°K for classic superconducting magnet (NbTi) => sustainable and economical solution since much less energy is needed to cool down the magnets

*=> M. Koratzinos, "The FCCee-HTS4 project", FCC week 2024, San Francisco*




*Example of a 2-layer CCT magnet layout with rectangular cable - L. Garcia Fajardo*

  - A Canted Cosine Theta (CCT) magnet => a magnet design using two opposed solenoid fields. The HTS material (ribbon) is coiled inside a single and canted groove => reduce the mechanical stress on the conductor + gain of space since it's a very compact design

*=> S. Caspi and all "Canted–Cosine–Theta Magnet (CCT)— A Concept for High Field Accelerator Magnets", IEEE Transactions on Applied Superconductivity · June 2014*

- **HTS technology is a promising and relevant technology for FCC**

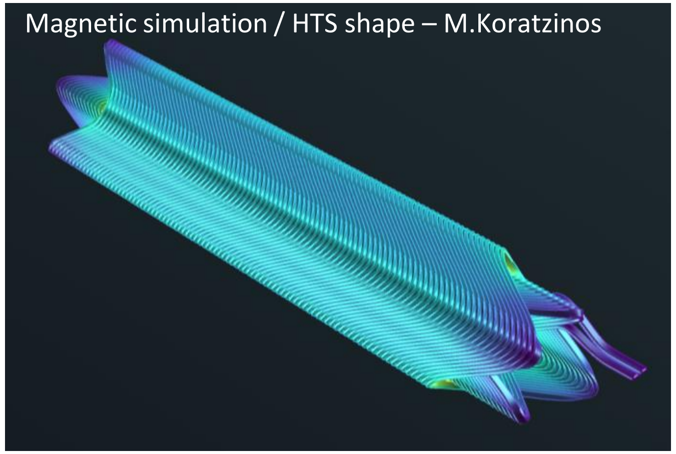
# HTS MAGNET IN FCC – Status and Objectives

- HTS project for FFC (HTS4) started in 2022
  - ➢ In August 2023 => successful cold test of a CCT NbTi quadrupole at PSI

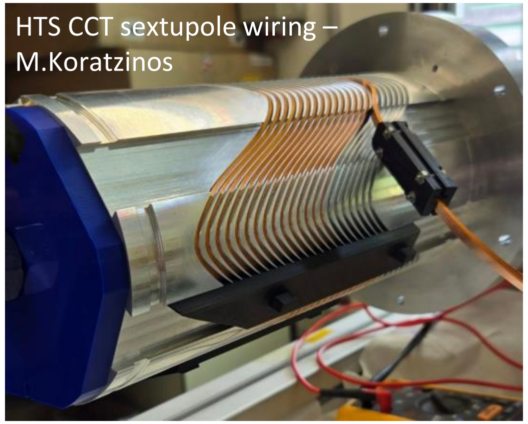
*⇒ M.Koratzinos, "New design of FF quads using HTS" in Frascati 2023*

  - ➢ In June 2024 => a successful manufacturing and winding of HTS CCT sextupole at CERN. It will be followed by the cold test in 2025.

*=> M.Koratzinos, "The FCCee-HTS4 project", FCC week 2024, San Francisco*





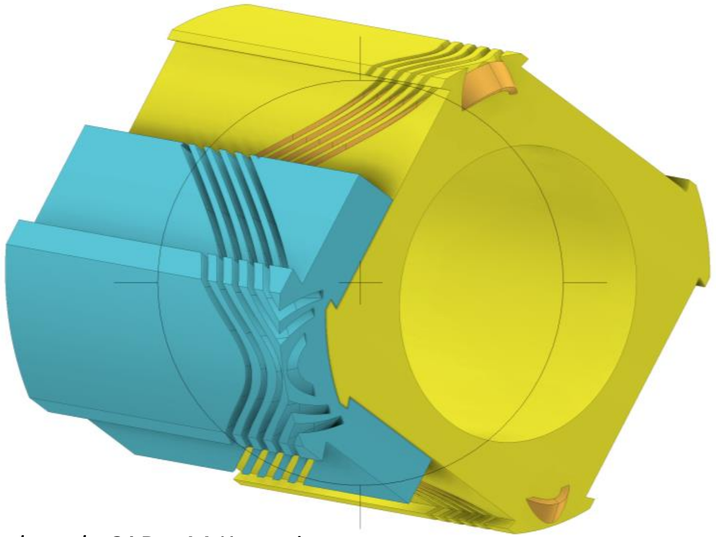




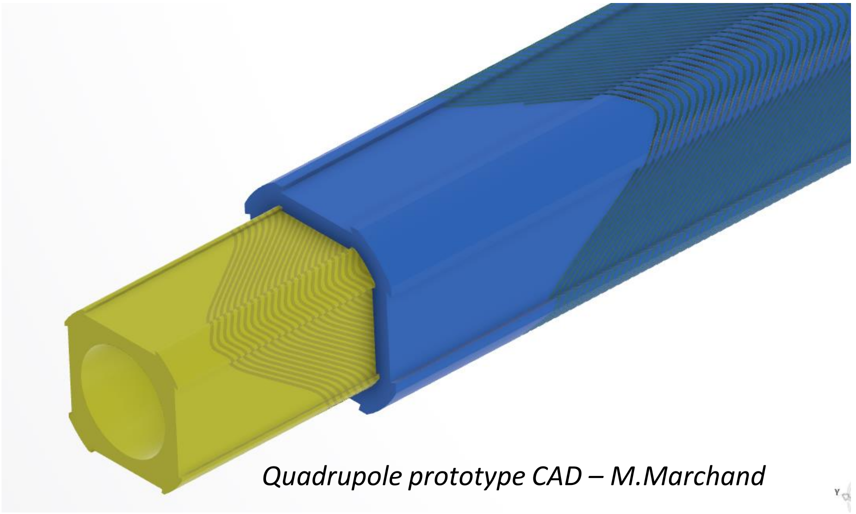

- Approach of the HTS CCT quadrupole manufacturing (LAPP):
  - ➢ Quadrupole part is built according to the coil using magnetic field simulation (M.Koratzinos) => compromise between magnetic and mechanical specifications.
  - ➢ **Main objectives :** Mechanical design, manufacturing process and prototyping of the HTS quadrupole with local manufacturers.
  - ➢ In parallel => development of the beam pipe compatible with the quadrupole design.

# HTS MAGNET IN FCC – Quadrupole Design (1/2)

- A part with a specific geometry
  - To ensure the correct magnetic field is generated => two square aluminium alloy part. The beam pipe passes trough the inner body (yellow), nested in the outer body (blue).
  - **A final part 700mm long and a 400mm long prototype => the design/prototyping process must be adapted to the final dimensions.**
  - A single narrow and canted groove is winded along each magnet, with specifications hard to meet => 4 to 8 mm deep, 1mm width and canted up to +/- 60° with very high tolerances (+0,01mm).



*Quadrupole CAD – M.Koratzinos*



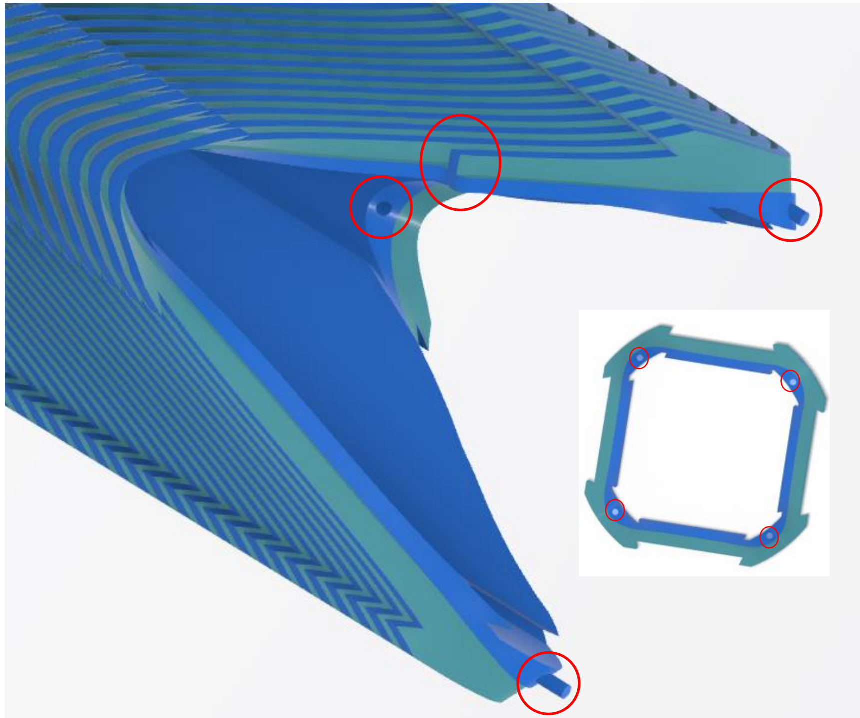
*Quadrupole prototype CAD – M.Marchand*

| Quadrupole specifications |
|---|
| **Main characteristics** |
| Two bodies in => the inner body nested in the outer body |
| Aluminium alloy => to be determine according the best machining process |
| Square shape + rounded edges to facilitate the assembling of both bodies |
| **General dimensions** |
| 700mm long (400mm for the prototype) => two 350mm sections (200mm sections) |
| Inner part => 40mm diameter for the 36mm diameter beam pipe crossing |
| Inner body maximal diameter => 65mm<br>Outer body maximal diameter => 64mm |
| A 0,3mm space between the two bodies => no contact |
| **The groove** |
| 4mm (plane surfaces) to 8 mm deep (rounded surfaces) |
| 1mm width with a +0,01mm tolerance |
| A 1,8mm space between each pass |
| 0 to +/- 60° inclination relative to the magnet axis |
| A surface finish precise enough to not damage the tape => to be determined |

# HTS MAGNET IN FCC – Quadrupole Design (2/2)

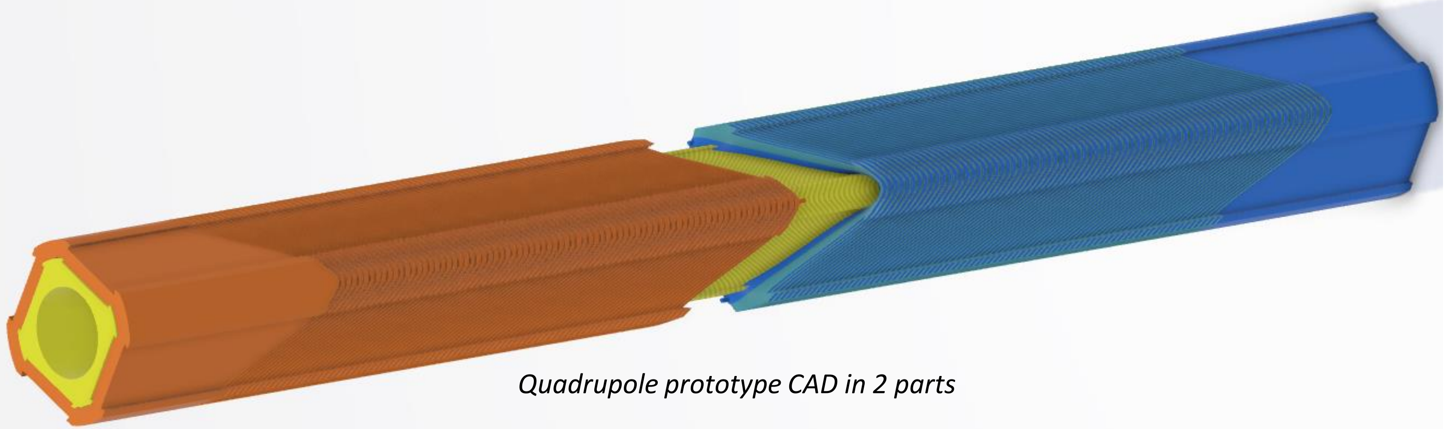
- Feedback from the manufacturers following the feasibility study:
  - Very complex geometry with high precision => magnet is too long to keep the tolerances with current machine technology.
  - Choose between dimensions and precisions => adaptation of the design.

- Bodies constituted of two sections assembled together:
  - Each body is separated in two complementary sections.
  - The bodies are cut along the groove trajectory => clean cut and facilitate the assembling.
  - Two opposed and complementary sections aligned and indexed by a pins and hole system.



*Quadrupole prototype locking and alignment system*

- Assembling and fixation made by an external cage (like for the sextupole) => compression of each elements to stop their movements.



*Quadrupole prototype CAD in 2 parts*

**Conclusion**: a very complex part with high tolerances => find the right manufacturing process and manufacturers.

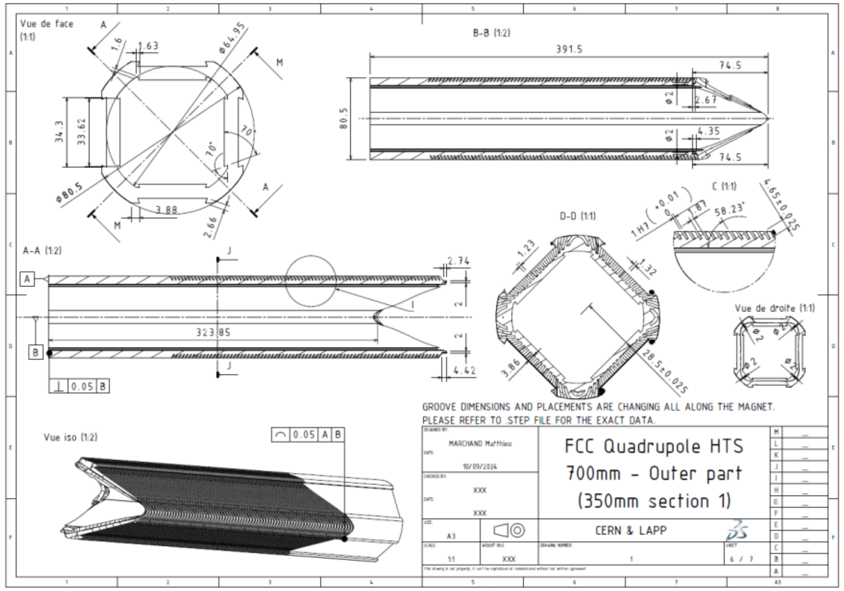
# HTS MAGNET IN FCC - Manufacturing

- The manufacturing process
  - Electro-erosion wiring cutting => for the particular shape of the intern and extern surfaces.
  - Continue multi-axes machining => enables to realise the groove tilt and the section cut geometry.

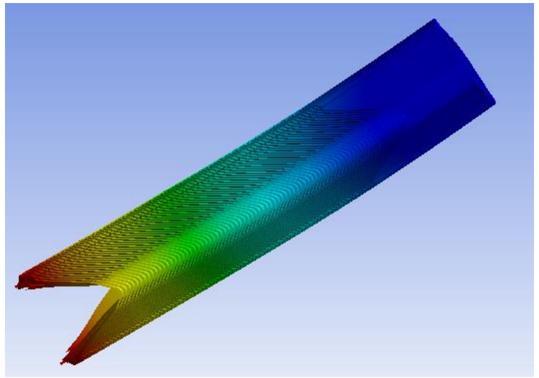
- Vibrations analysis dedicated to the machining process.

- Identification of a local industrial network with a strong expertise to manufacture the 40 FCC final focus quadrupoles (and the hundreds of sextupoles).

- An evolving design => several evolutions to meet the manufacturing limits and physical specifications => find the best compromises
  - A smaller HTS ribbon => 3mm deep groove.
  - A groove stretching around the section cut area => make easier the indexation and fewer the machine errors.
  - Tolerances reduced to match the machine's precision.




*Magnet prototype drawing*



*First flexion mode at several hundred Hz*

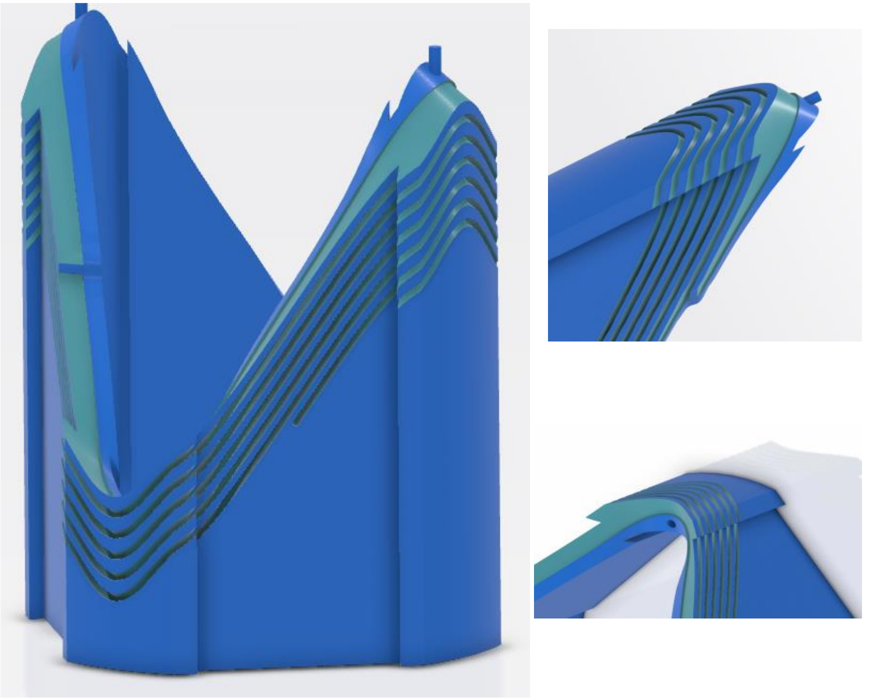
**Observation** : there is a high risk of manufacturing iteration due to the specifications => need to reduce this risk and the prototyping cost

# HTS MAGNET IN FCC – Pre-prototyping at LAPP

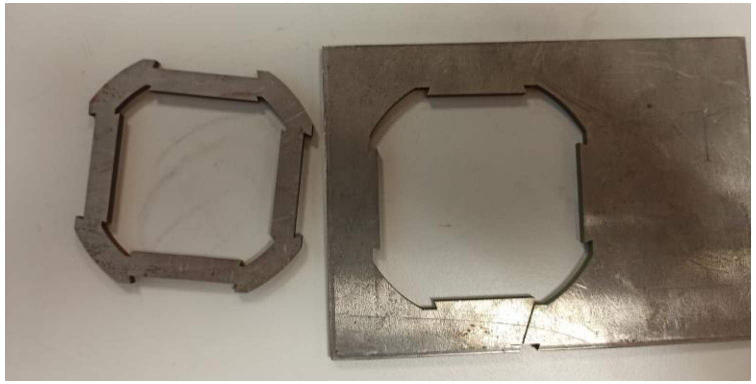
- Pre-prototyping one section of the outer body magnet at a reduced scale => collaboration local university mechanical department (USMB) and LAPP.

- Using the local resources to machine the key elements of the part => manufacturing a 100mm section of the magnet
  - ➢ strong mechanical expertise
  - ➢ 5 axis machine for the 3-5 groove turns and the section's cut
  - ➢ Wire cutting machine for the external surfaces

- Identify the "hard spots" and potential difficulties of the machining process => adapt the design and determine an efficient manufacturing process before launching a production at a real scale.



*Pre-prototyping : Quadrupole section*



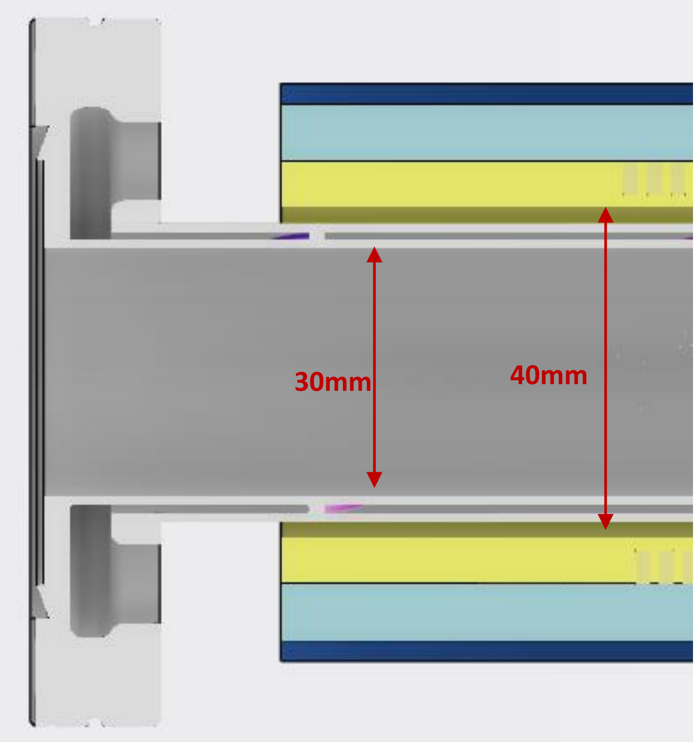
*Quadrupole section made by wire cutting at USMB*

- Manufacturing other sections of the magnet with metrology, vibration analysis, alignment and assembling tests => validation for the real scale prototyping with an industrial partner.

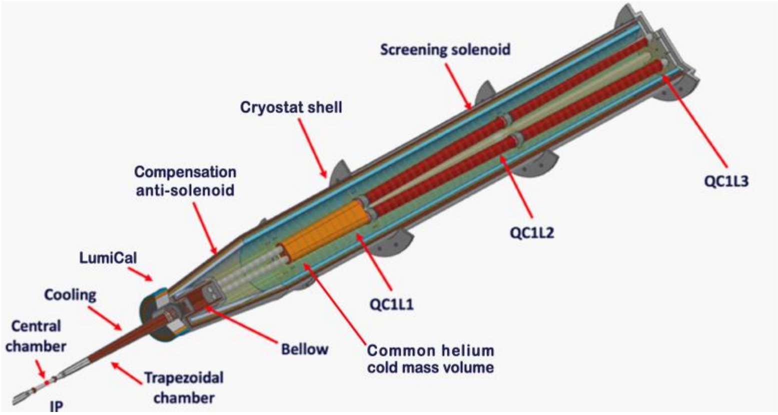
- **Objective :** Increase number of low-cost trials to solve manufacturing problems => reduce the iteration risks for the industrial prototyping => "one shot".

# BEAM PIPE– Definition

- The cryostat beam pipe needs to be compatible with the HTS quadrupole design => development of a beam pipe to respect the local constraints :
  - ➢ Heat dissipation due to the beam radiation => need of a cooling system for the beam pipe.
  - ➢ A very compact magnet with a 40mm inside diameter and a fixed internal beam pipe diameter of 30mm => a 5mm gap to ensure the beam pipe cooling and the thermic isolation from the cryogeny => integrated cooling system to the beam pipe.
  - ➢ Very little space between the LumiCal and the anti-solenoid, next to the QC1L1 => not enough space to have an access for calorific fluid => fluid access (inlet+outlet) need to be in the same extremity of the pipe, next to QC1L3.
  - ➢ They share the same environment => complementary integration issues.
  - ➢ HTS magnet and beam pipe => same industrial local network.




*Cutting view of the magnet and pipe assembly*



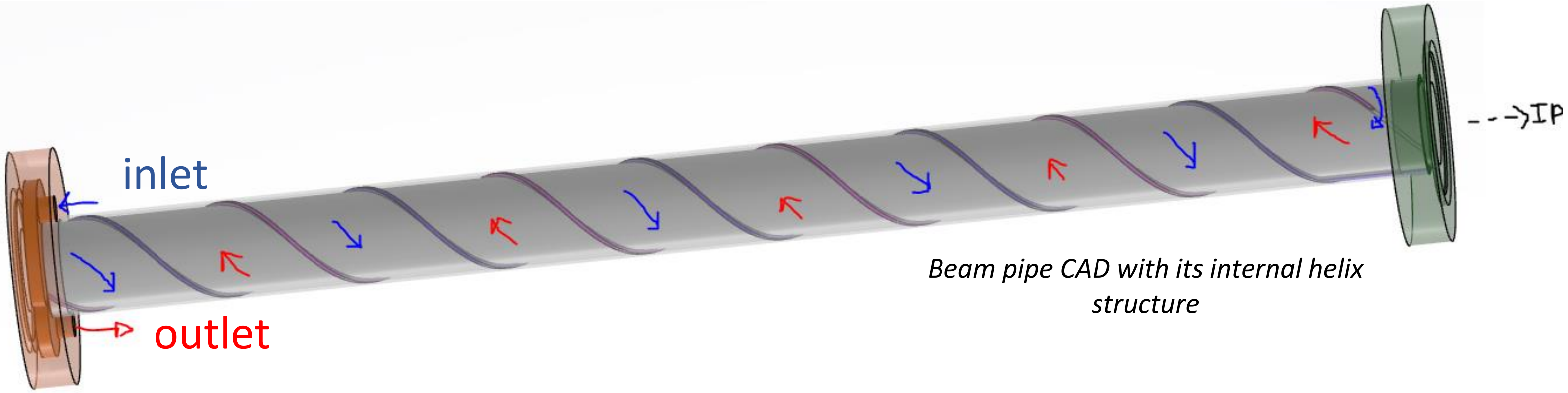

*CAD of a cryostat by F. Fransesini*

**Conclusion :** Due to the geometry of the HTS quadrupole and the physical specifications, a specific beam pipe, compatible with the magnet design, has to be developed.

# BEAM PIPE– Design (1/2)

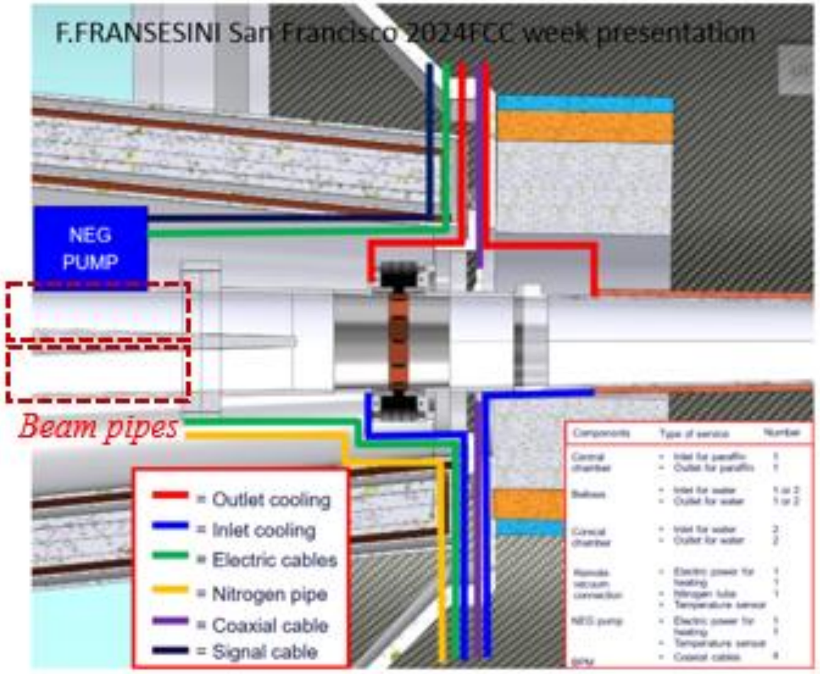
- A beam pipe with a singular integrated cooling system (M.Koratzinos concept):
  - ➢ A custom flange outside the cryostat, near to QC1L3, with inlet and outlet for the two-way water flow.
  - ➢ A tube with an internal structure in helix between two walls => a cooling flow all around the tube, back and forth, cooling it down.

*=> M.Koratzinos, "FCC ee interaction region Concepts" 2022 FCC Week, London*




*Beam pipe CAD with its internal helix structure*

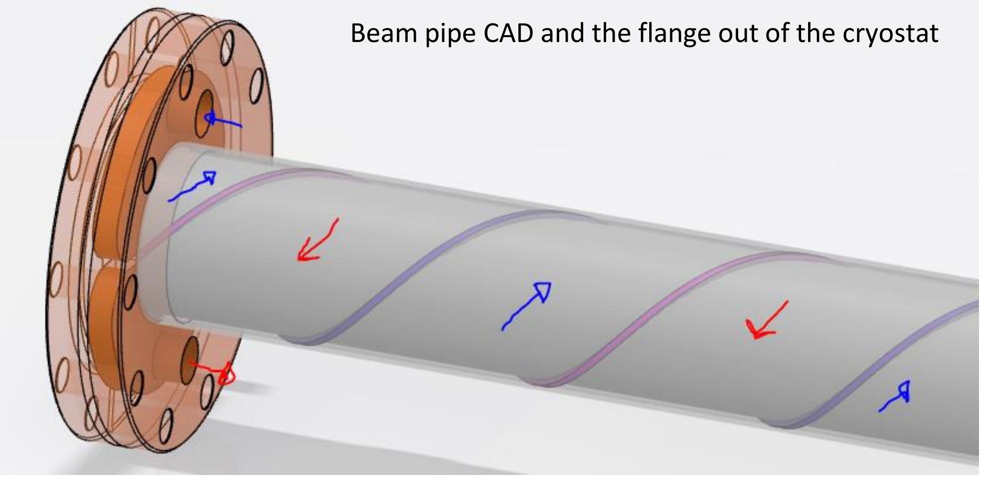
*M.Koratzinos beam pipe concept*

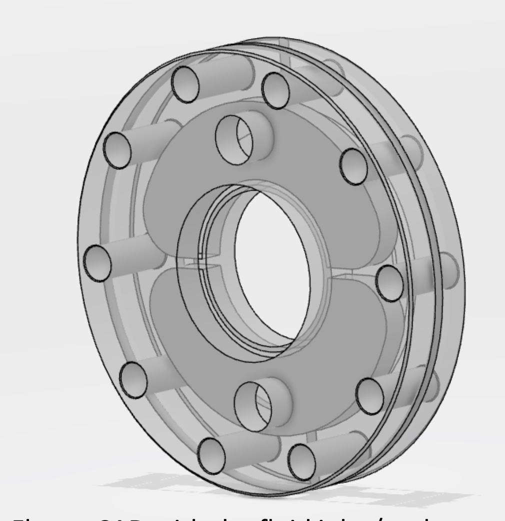


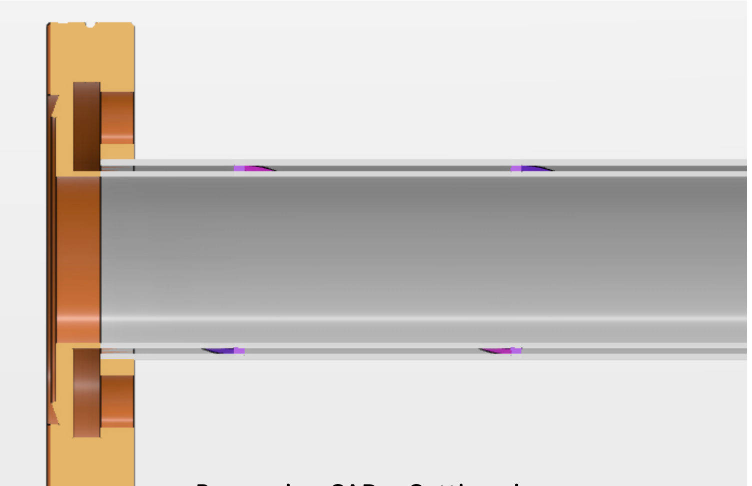

- ➢ A second custom flange inside the cryostat close to the IP (without access to external pipes) => an inside channel enabling the fluid to change directions and come back towards the first flange (outlet).

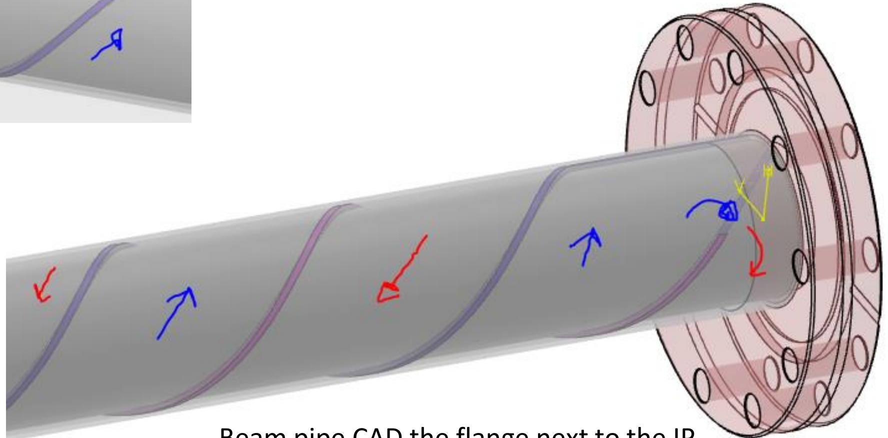
# BEAM PIPE– Design (2/2)

- A singular pipe with strong specifications


Beam pipe CAD and the flange out of the cryostat


Flange CAD with the fluid inlet/outlet


Beam pipe CAD – Cutting view


Beam pipe CAD the flange next to the IP

**Conclusion** : Due to the singular geometry, dimensions and specific water flow, this system needs a strong fluid, thermic and mechanical analysis to study its feasibility.

| Beam pipe specifications |
|---|
| **Main characteristics** |
| Two flanges with inside water channels + a double wall pipe with a intern double spiral structure |
| Stainless steel => Strong rigidity and non corrosive |
| Fluid => water |
| Airtight and leakproof (water flow inside the pipe walls + ultra vacuum inside the pipe + primary vacuum outside the pipe) |
| **General dimensions** |
| 3 meters long (~cryostat length) |
| 30mm intern diameter<br>36mm outside diameter<br>1mm thick wall |
| 1mm thick space for the water flow |
| Surface finish sufficient to not disrupt the internal water flow => to be determine |
| **The Flanges** |
| 90mm diameter |
| 16,7mm thick |
| 2 1/8" holes for water inlet and outlet for the hydraulics connectors |
| 6*7mm diameter holes to connect the flanges to other beam pipe sections |

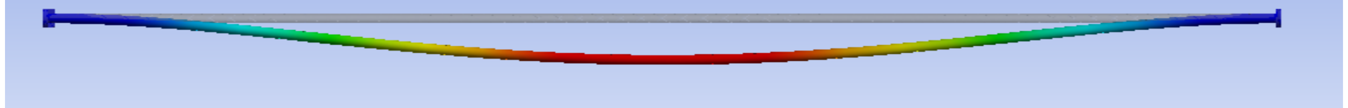
# BEAM PIPE– Fluid, thermic and mechanical analysis

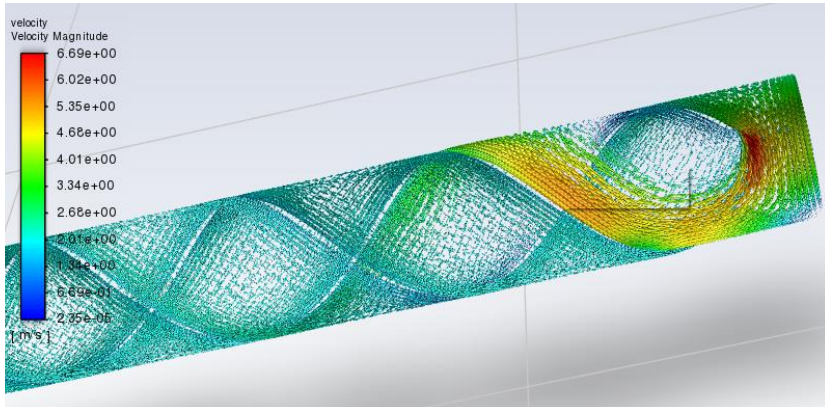
- Several types of numerical simulation => validation of the beam pipe concept + design optimization
  - ➢ Static analysis to study its mechanical performance.
  - ➢ Modal analysis to study vibrations.
  - ➢ Fluid analysis to study the evolution of temperature, pressure, velocity and turbulences along the pipe.

- Simulations in progress (temperature, turbulences) => some leads of improvement are identified (smoother shapes in tube/flange, multi-channels, …).

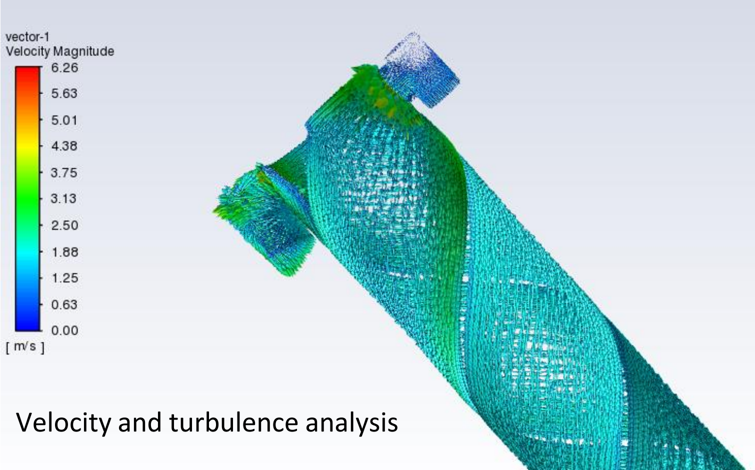
| Boundary conditions | Resolutions |
|---|---|
| **Mechanical analysis** | |
| Fixed at its two flanges | Max displacement : 0,6mm |
| Intern hydrostatic pressure for water flow | Max stress : 5,5 MPa |
| Inside ultra vacuum ($1^{e}$-10Pa) and outside primary vacuum ($1^{e}$-4Pa) | First mode : 23Hz |
| **Fluidic analysis** | |
| Velocity inlet : 1 m/s | Inlet pressure : to be determine |
| Temperature inlet : 20°C | pipe temp : to be determine |
| Surface heat transfer (100W/m) : 1037 W/2 | Water velocity : to be determine |
| | Turbulences : to be determine |

Mechanical displacement analysis






Velocity and turbulence analysis



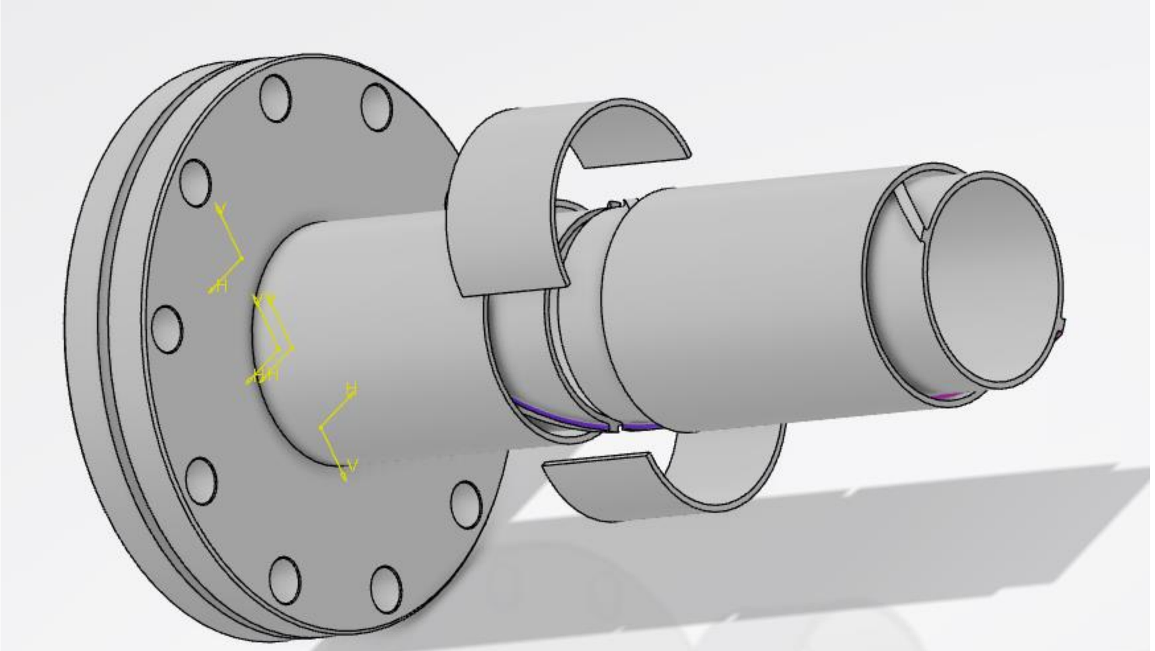

Velocity and turbulence analysis

➢ Need of more precise specifications, especially for turbulences, to adapt the design.

**Conclusion :** need to prototype the pipe to test it and compare the simulation => well-defined manufacturing process.

# BEAM PIPE– Manufacturing and pre-prototyping at LAPP

- The manufacturing process
  - A pipe separated in several sections => a pipe segment, two custom made flanges with a small pipe segment incorporated and a junction part.
  - Each section made by 3D metal printing => some machines can combine 3D printing with machining for a better surface finish (inside the cooling channel).
  - Sections assembled by welding => TIG, electron beam or laser welding : process to be determined according the metal properties and the precisions needed.
  - The quadrupoles mounted before the second flange welding, due to the diameter interference.
  - Dis-assembly has to be studied.



Beam pipe assembled sections

- Just as for the HTS quadrupole:
  - Building a solid local industrial network => combine efforts to find same partners for both parts.
  - Pre-prototyping each of the 4 beam pipe sections => collaboration LAPP – USMB
    - Identify the potential difficulties we could face during an industrial manufacturing and adapt the design if necessary => establish a precise 3D printing strategy.
    - Use this first sections to start assembling (welding), water, thermic, vibration and metrology tests => validation of the process and pipe concept.

# Summary and Outlook

- There are major technological and economical benefits for FCC by using HTS magnets. It’s a technology which has a bright future and the FCC project has the opportunity to be one of the major actors in its development.

- After the manufacturing of a HTS sextupole and waiting for its cold test, an HTS quadrupole is under study.

- The singular magnet design and its environmental constraints make that we need to develop a specific cryostat beam pipe compatible with the quadrupole.

- The first steps of both parts manufacturing has started with their pre-prototyping => validate their concept and anticipate a prototyping at a larger scale.

- The short term actions:
  - ➢ Improve the magnet design and manufacturing process through the pre-prototyping project => groove and section design and manufacturing tolerances and strategy.
  - ➢ Improve the pipe design and manufacturing process through the pre-prototyping project => adapt the design for turbulences + more precise simulations + start to study in detail the welding process for the pipe.
  - ➢ Prepare the manufacturing of the final prototypes (manufacturers are already identified).

- The mid term actions:
  - ➢ Manufacture the magnet and the pipe prototypes with all the instrumental tests (metrology, vibrations analysis, magnet cold tests, beam pipe cooling tests…).

# Thank you for your attention!