FCC

LAPP
Laboratoire d'Annecy de Physique des Particules

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Mechanicals studies and prospect

FCC-EE HTS CCT MAGNET DESIGN PROPOSAL FOR THE FINAL FOCUS QUADRUPOLE AND ITS COOLED BEAM PIPE

FCC week - 2025 May 22th

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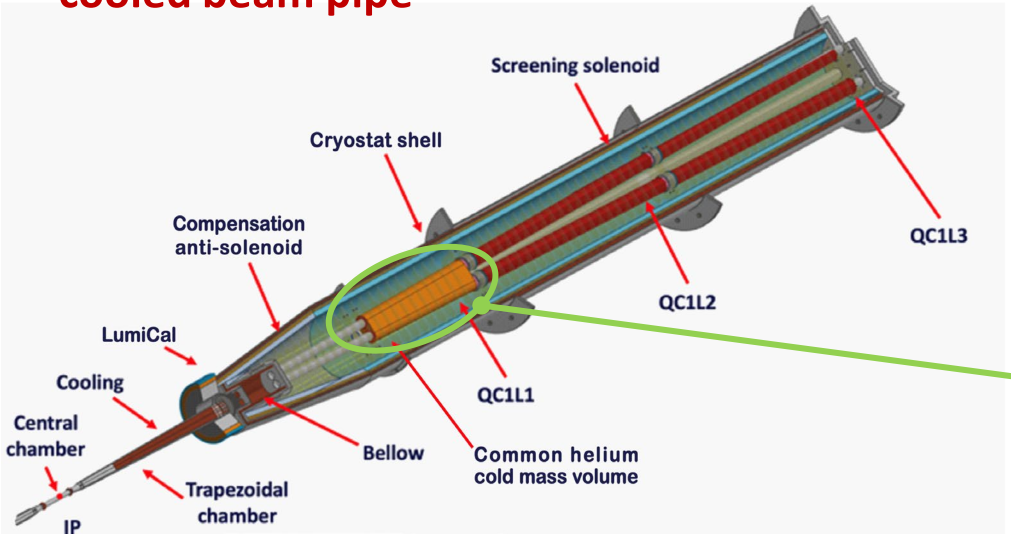
M.Koratzinos, F. Bardi (PSI – CERN)
F. Toussaint (SYMME – Univ Savoie Mont-Blanc)

CONTEXT AND AIM OF THE PROPOSAL:

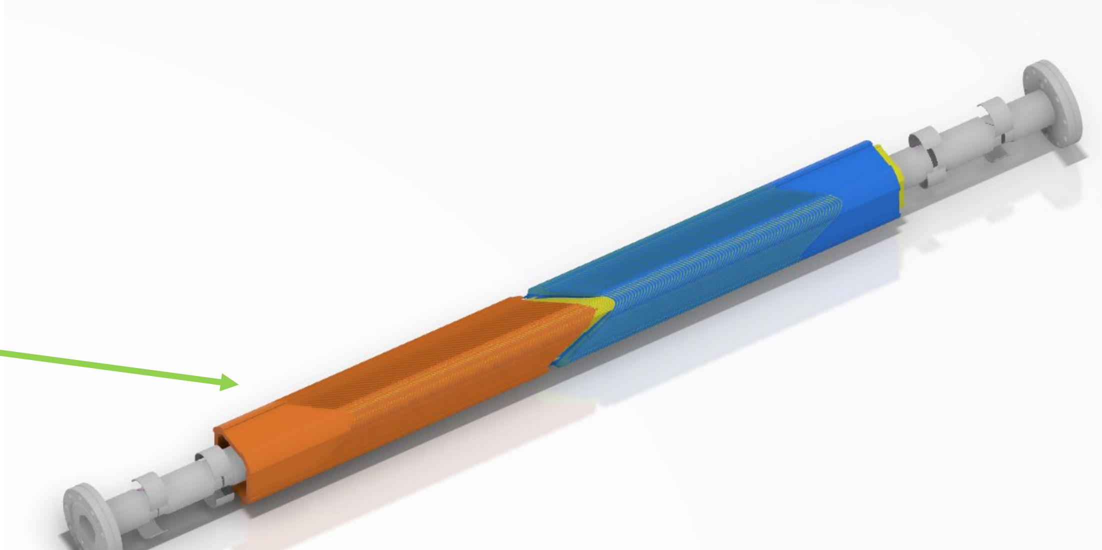
- Current baseline for FF FCC-ee magnets => normal superconductive NbTi magnet
- CCT HTS magnet is a challenging but a promising technology for the future

- Collaboration between PSI (M. Koratzinos, F. Bardi), LAPP (& USMB) & IN2P3 to develop an alternative solution using HTS CCT technology for the final focusing quadrupoles, especially QC1L1

- The target is to demonstrate the feasibility with a reduced prototype **FF CCT HTS quadrupole magnet** and its required **cooled beam pipe**

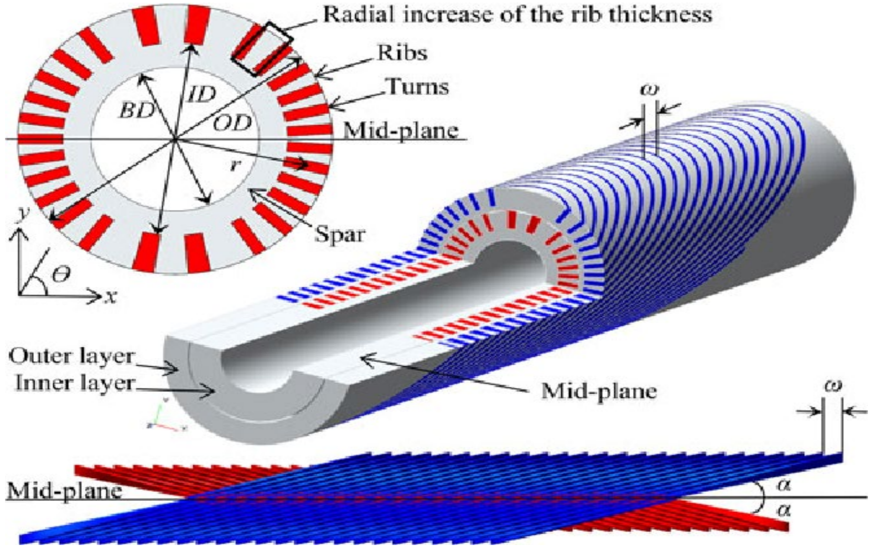


CAD of a cryostat by F. Fransesini

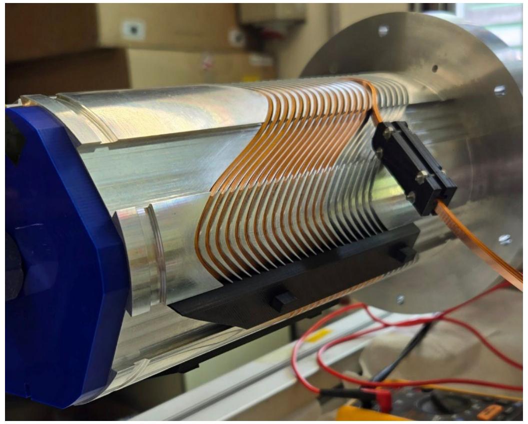


FF HTS CCT magnet and its cooled beam pipe prototype

A MAGNET BASELINE ALTERNATIVE - HTS CCT magnet design for the last final focus quadrupole (QC1L1)



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



HTS CCT sextupole widing – M.Koratzinos

- The High Temperature Superconducting (**HTS**) technology => operate at temperature above 30°K, a sustainable and economical solution

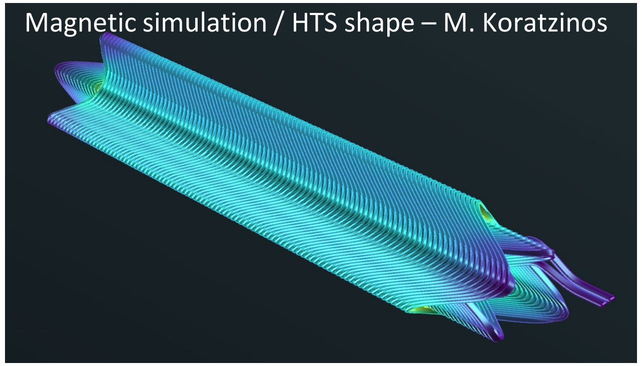
- The Canted Cosine Theta (**CCT**) technology => a magnet design using two opposed solenoid fields with a coil winded inside a single and canted groove => mechanical stress reduced on the conductor + gain of space with a very compact design

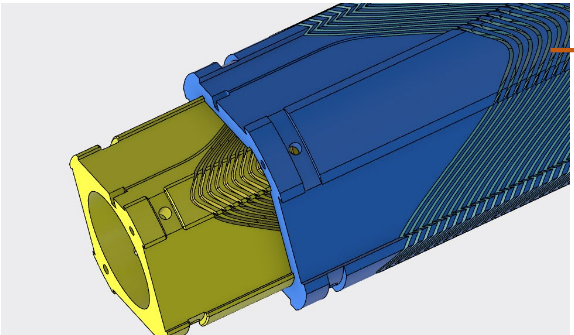
- **HTS and CCT technology could be a good fit for the FCC-ee FF magnets to face the technologic, economic and ecologic challenges**

HTS CCT final focus quadrupole (QC1L1) study in several main steps:

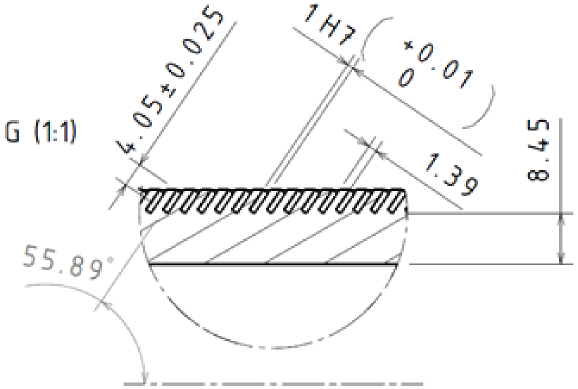
- **FF quadrupole presents critical geometry for such technology, especially the bending angle and the accuracy**

1a - Machining of the needed parts





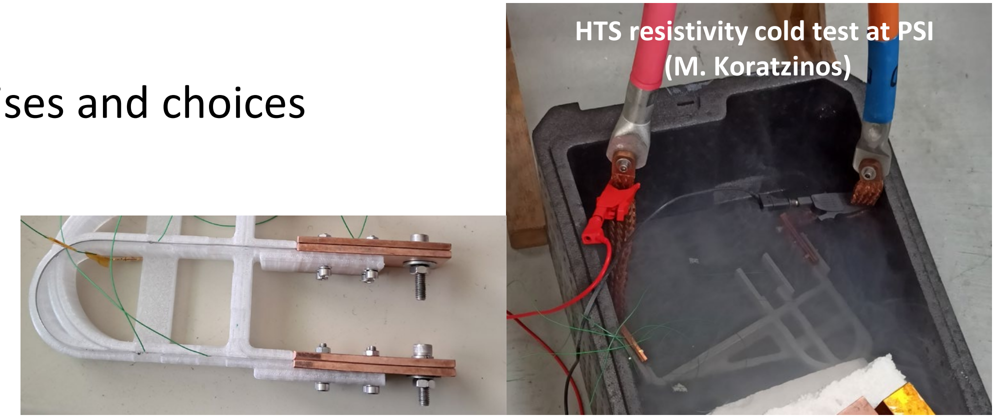
Inner and outer layer of the CCT HTS FF quadrupole – 700 mm long



Stringent specifications of the groove

1b - Behavior of the HTS tape integrated into the structure

- Cold tests, resistivity, power supply which induces compromises and choices for the geometry, HTS tape…



2 – Magnetic performances

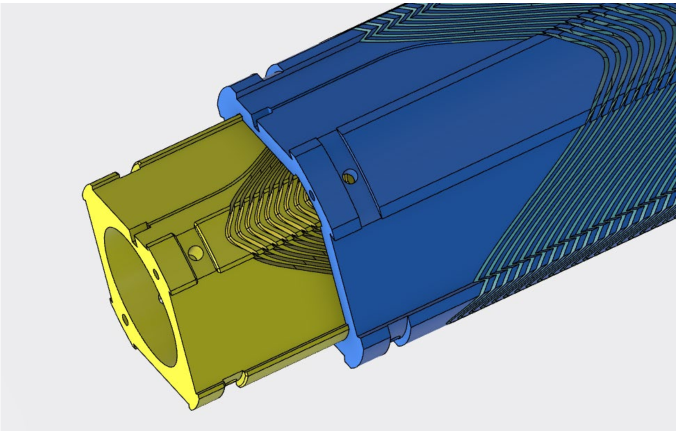
3 - Integration…

HTS CCT FF QUADRUPOLE – Design Evolution

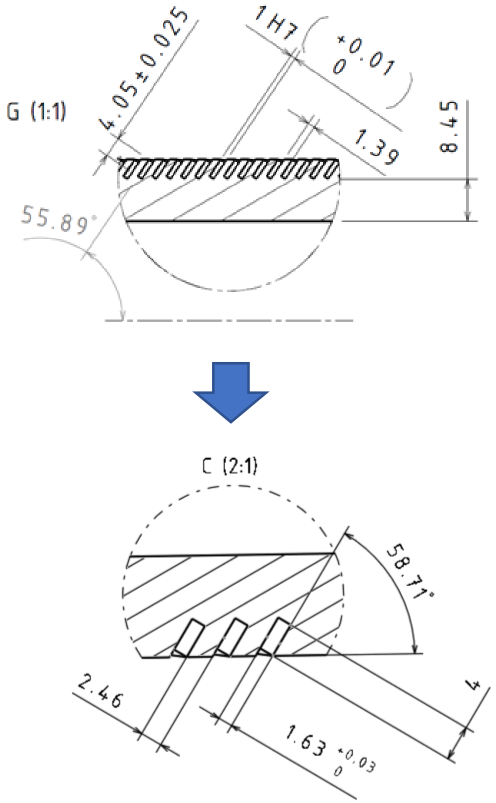
- Resulting of the last mechanical feasibility studies and high current test => design evolution

Update of the quadrupole specifications
Dimensions
Aluminium alloy ~~to be determined~~ Al6082-T6 or Al7075
700mm long for the final piece
~~400mm~~ ~350mm long prototype for magnetic tests
Inner part intern diameter => ~~40mm~~ 41mm
Inner body maximal diameter => ~~65mm~~ 62mm Outer body maximal diameter => 64mm
The groove
4mm to ~~8mm~~ 6mm deep
~~1mm~~ 1,63mm width with a ~~+0,01mm~~ +0,03-0,05mm tolerance
~~0,63mm~~ 1,63mm space between each pass
~0 to +/- 60° inclination relative to the magnet axis

- **New specifications** => dimensions and tolerances easier to keep for manufacturing feasibility + bending angle less damaging for the HTS tape
- **New HTS tape supplier** => a symmetric tape more adapted for bending => 10 insulated tapes for a final thickness of 1580um (50um left for fitting inside the groove)



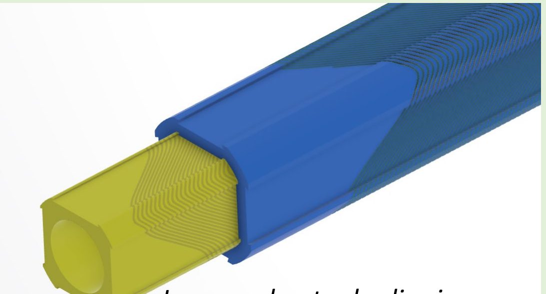
Inner and outer layer of the CCT HTS FF quadrupole



HTS CCT FF QUADRUPOLE – Manufacturing process is very challenging

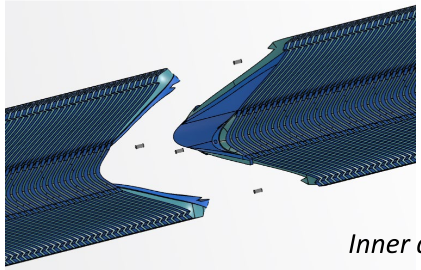
- Quadrupole manufacturing => two options

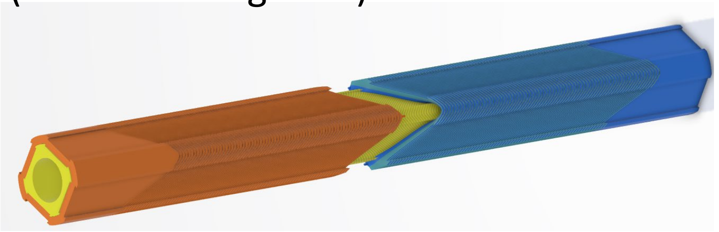
➢ **Option A :** a magnet in two parts : one inner body and one outer body
  - 5 axes machining for the shape / groove
  - Electro erosion wire cutting for the internal surface 700 mm is the current limit, tests are under investigation
  - Benefits => no issues for its assembling and positioning + easy to manipulate
  - Drawbacks => very few industrials with compatible machines + very expensive
  - Status => Only 1 manufacturer is identified with the adapted production means => technical analysis for feasibility and quotation in progress



Inner and outer bodies in one part

➢ **Option B :** a magnet in 4 parts (2 for the inner body and 2 for the outer body) => a cut following the groove trajectory + an alignment system by pins and holes
  - Electro erosion wire cutting for the internal surface + 5 axes machining for the groove and cut
  - Benefits => local industrials with compatible machines easier to find + less expensive
  - Drawbacks => alignment issues to be planed + complexity of the cut to work on + risk of quench if dealignment to be studied
  - Manufacturing => manufacturers closed to Annecy / CERN are identified => technical analysis for feasibility and quotation in progress
  - Design alternative => to have a large gap between two grooves at the centre (under investigation)

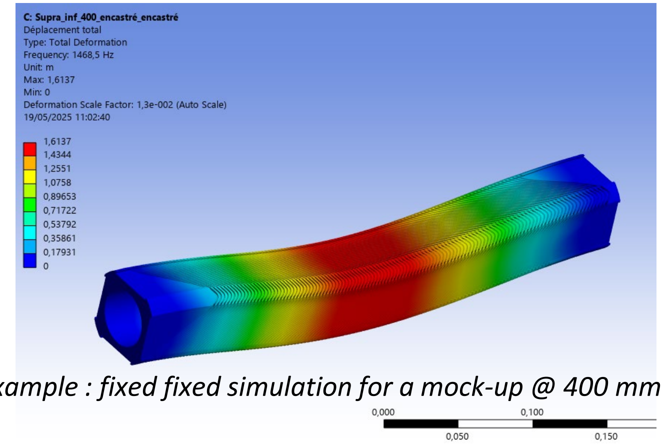




Inner and outer bodies in two parts

HTS CCT FF QUADRUPOLE – Preliminary testing process, some examples to limit the risk of iterations

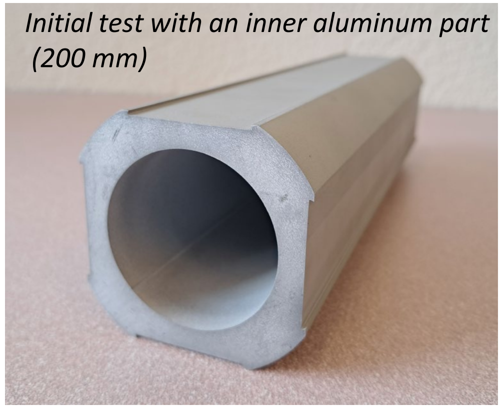
- To characterize the final magnet => several steps of simulation, prototyping and testing
  - Vibration calculation: to avoid any issue during the machining



Example : fixed fixed simulation for a mock-up @ 400 mm long

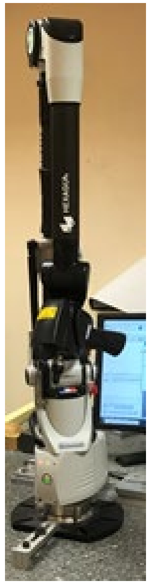
- None critical mode are identified at low frequencies

- Test of wired cutting on a large dimensions (700 mm long) to optimize the process in one part
  - *Preliminary test @ 200mm*



Initial test with an inner aluminum part (200 mm)

- Geometry, flatness and cylindricity are ok but closed to the limits…



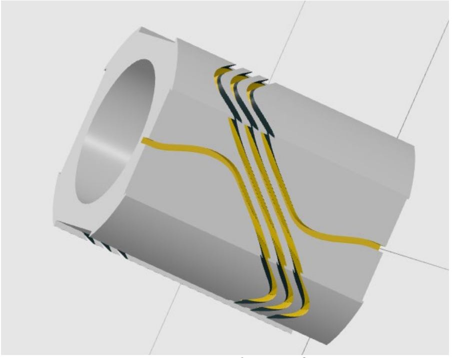
- *Quotation in progress for the 700 mm : a supplier is selected and will be evaluated*

HTS CCT FF QUADRUPOLE – Testing process

- To characterize the final magnet => several steps of prototyping and testing
- Step 1 = The initial tests managed by M. Koratzinos and F. Bardi at PSI => test the resistivity and quenching of the HTS tape at cold temperature and different bending angle => tests ongoing with promising prospects

100mm Quadrupole without before machining the groove

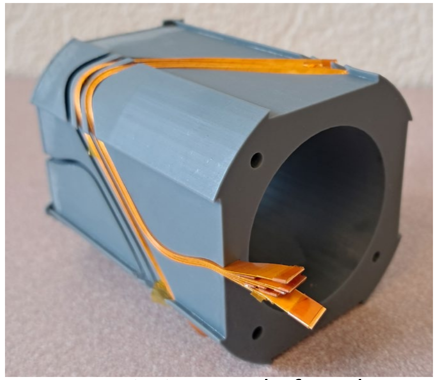
- **Step 2 = an intermediate test of a 3 turns quadrupole in aluminum**
  - Manufacturing a ~80mm inner part quadrupole with a 3 turns groove with local manufacturer => test the manufacturing process and the mechanical feasibility
  - Winding of the HTS tape => test the winding process and its impact on the tape integrity
  - Resistivity test at cold temperature => test the good reactivity of the winded tape
    - *A new winding machine is in progress at LAPP & machining in quotation (NDA are signed)*



3-turns Quadrupole

Quadrupole prototype tests specifications		
	3 turn quad	350mm quad
Field gradient (Tesla/meter square)	-	100
Max field conductor (Tesla)	-	3,6
Current (Ampere)	350	825
Temperature test (Kelvin)	77	40

Specifications comparison between the 2 prototypes



3D printing part before the machining in aluminum

- **Step 3** = magnetic tests => prototyping a whole 350 mm quadrupole and test his magnetic field at cold temperature

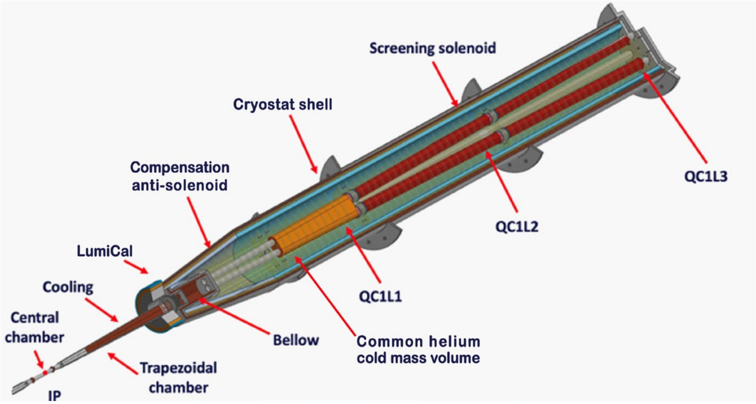
BEAM PIPE – Definition

- A cryostat beam pipe needs compatible with the HTS CCT quadrupole design => development of a dedicated beam pipe :

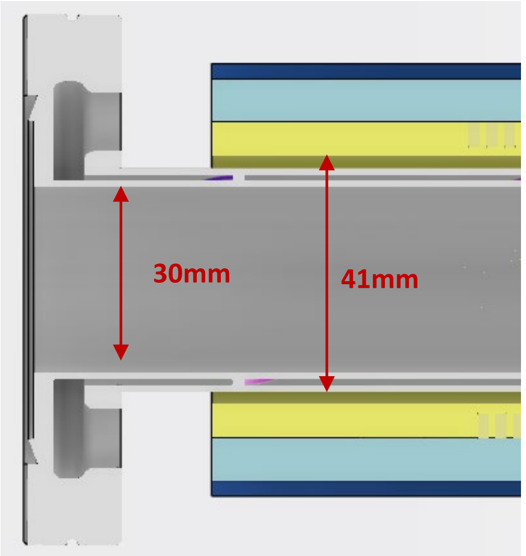
➢ Heat dissipation due to the beam radiation => need of a cooling system for the beam pipe.

➢ A very compact magnet with a 41mm inside diameter and a fixed internal beam pipe diameter of 30mm => a 6mm gap to ensure the beam pipe cooling and the thermic isolation from the cryogeny => integrated cooling system to the beam pipe.

CAD of a cryostat by F. Fransesini

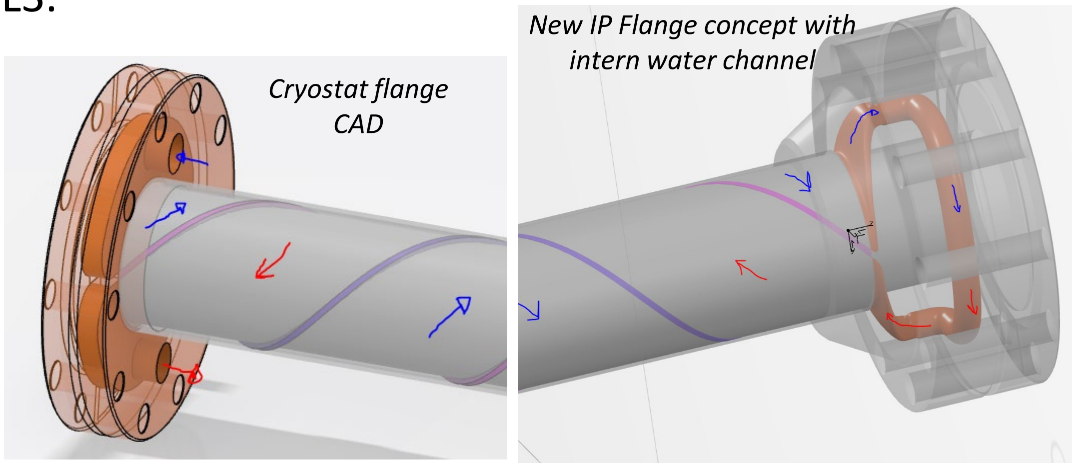


➢ Very little space between the LumiCal and the anti-solenoid, next to the QC1L1 => not enough space to have an access for calorific fluid => fluid access (inlet + outlet) need to be in the same extremity of the pipe, next to QC1L3.



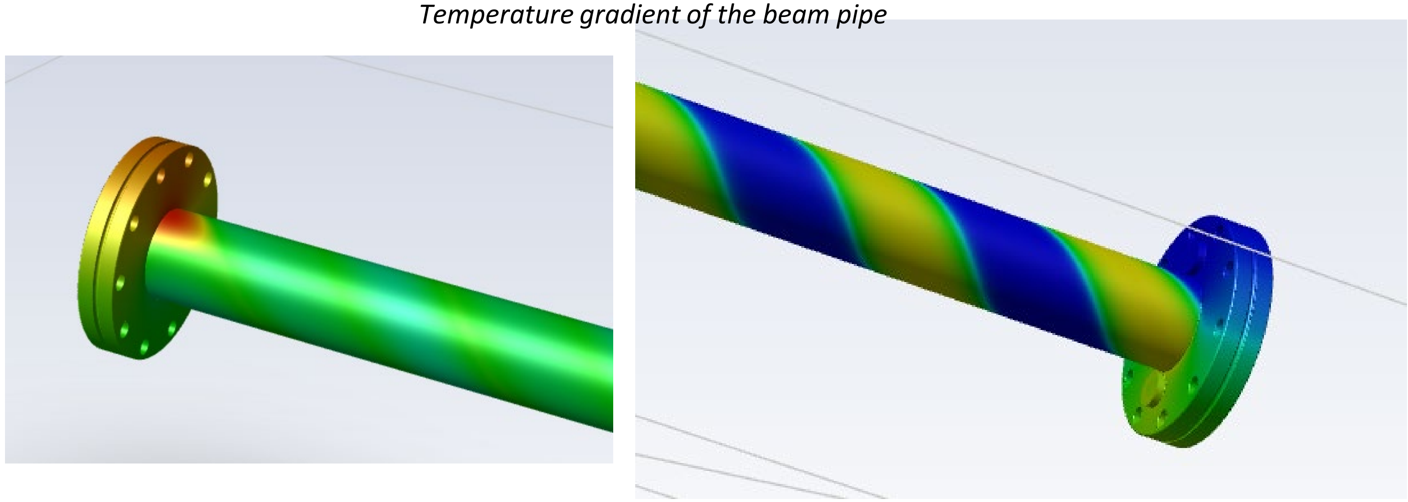
Cutting view of the magnet and pipe assembly

➢ A tube with an internal structure in helix between two walls was selected => a cooling flow all around the tube, back and forth, cooling it down + two custom flanges with inlet, outlet and direction change for the two-way water flow



BEAM PIPE– Numerical analysis

Temperature gradient of the beam pipe



➢ Fluidic and thermic simulations => first results

❑ Initial data :

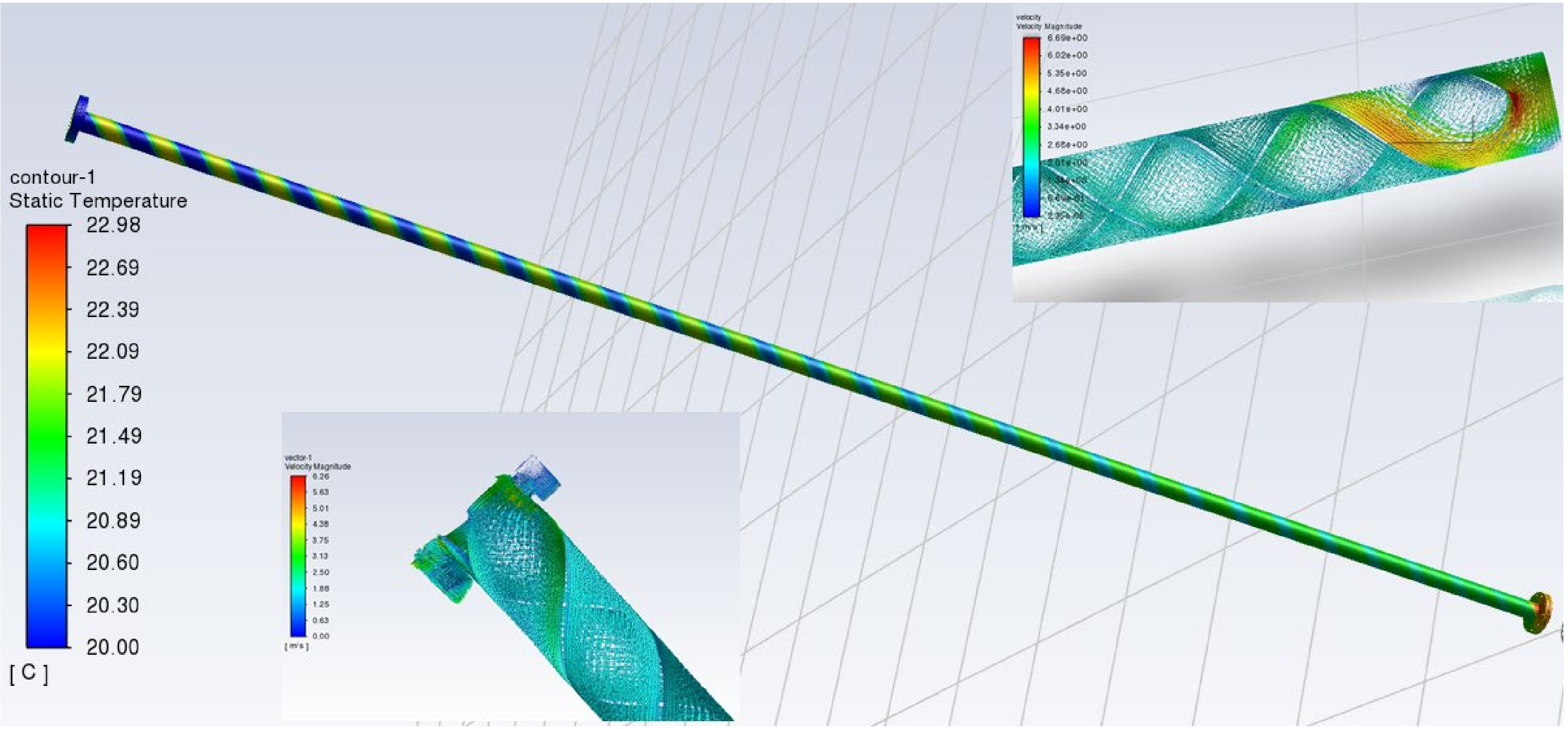
- 20°C water
- 0,2837m2 heated surface (3m tube)
- 300W => 1057,45 W/m2 to evacuate
- Water velocity : 0,5m/s

Numerical results	
Temperature inlet (°C)	20
Temperature outlet (°C)	21,91 (22,08 °C for analytic results)
Température max (°C)	22,98
Inlet pressure (bar)	2,63
Outlet pressure	0
Velocity inlet (m/s)	0,45
Average Velocity outlet (m/s)	0,46
Velocity max (m/s)	0,68
Total heat transfer (W)	-280,37
Mass flow rate (kg/s)	0,035 (0,034 for analytics results)
Wall pressure (Pa)	98,68

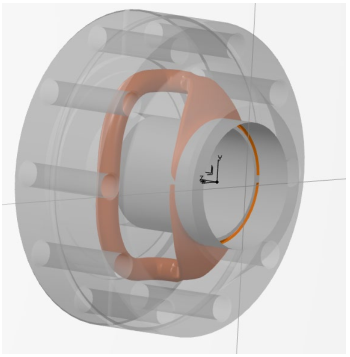
➢ First results : see table + tendencies :

- ❑ Pressure : progressive pressure loss toward the outlet => OK
- ❑ Temperature : progressive increase of temp toward the outlet + high temp around non cooled area + temperature gradient around the spiral towards the outlet => OK
- ❑ Velocity : constant velocity at the spiral center + velocity next to 0 around the walls + high velocity next to turbulence area

BEAM PIPE – Numerical analysis



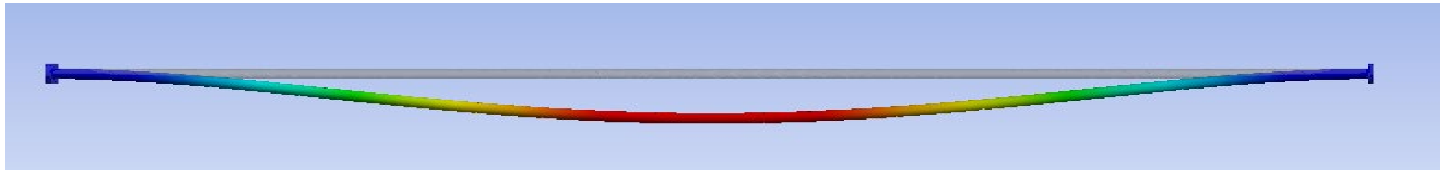
- Coherent and promising results => no need of a high pressure and low temperature flow to cool down efficiently
- In progress => new flange design to reduce turbulences and buckling and also to perform a welding study



New IP Flange concept which will be tested

Static and dynamic simulations :

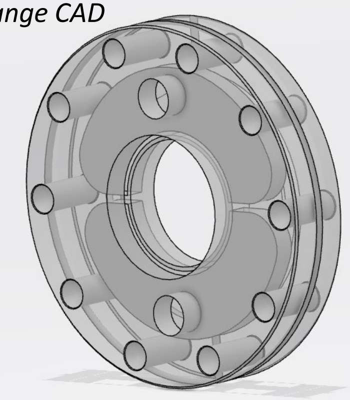
- Low stress and displacement (0,6mm - 5,5MPa) & first vibration mode (23 Hz)



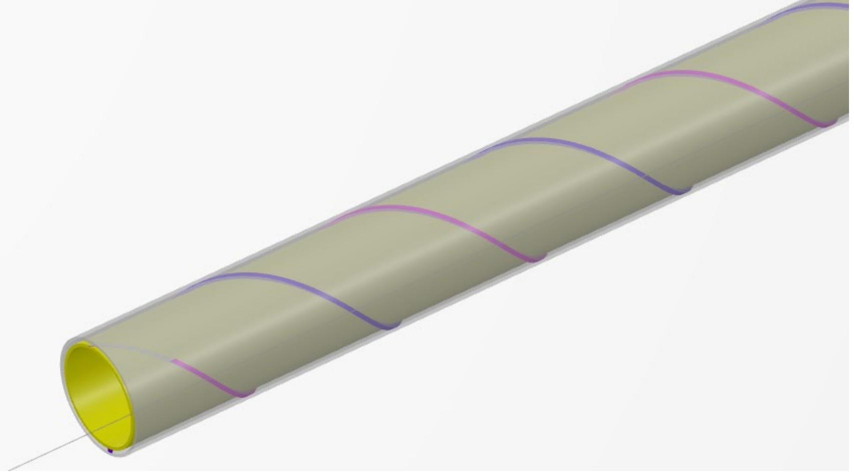
BEAM PIPE – Manufacturing process

- Evolution of the manufacturing process =>
  - Two custom made flanges with internal water channels manufactured by hybrid metal 3D printing (printing and machining simultaneously for a precise surface finish) – An alternative manufacturing process by machining is also being studied.
  - An 30mm tube on which two steel filaments bent and welded to it => the inner tube and the spiral => very precise hand made welding for a good shaping of the filament .
  - A 34mm tube on top of the first tube and its spiral and welded along the spiral trajectory => A continuous welding is not necessary as fluid exchanges between the spirals are accepted (to be confirm by numerical simulations)

Flange CAD



Tube CAD



Beam pipe specifications
Main characteristics
Two flanges with inside water channels + a double wall pipe with a intern double spiral structure
Stainless steel 316L => Strong rigidity + non corrosive + good holding at ultra vacuum
Fluid => water
General dimensions
3 meters long (~cryostat length)
30mm intern diameter 36mm outside diameter 1mm thick wall
1mm thick space for the water flow
Flanges
Metal 3D printed of 2 custom made flanges => recent studies (IJCLAB) shows a very good ultra vacuum resistance with 316L by 3D impression
90mm diameter
Thickness => to be dimensioned to hold to ultra-vacuum
6*7mm diameter holes to connect the flanges to other beam pipe sections

- The quadrupoles mounted before the second flange welding, due to the diameter interference.
- Dis-assembly has to be studied.

BEAM PIPE– Prototyping and Testing process

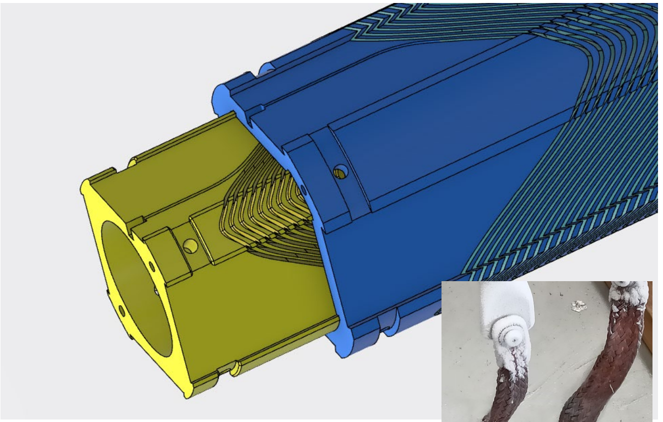
- Flanges prototyping =>
  - Successful intern epoxy tests => identification of a weak point in the design which will be modified with the next design.
  - Intern 3D metal tests were stopped because of material issue => next attempt soon
  - Industrial hybrid impression => feasibility and quotation in progress with the unique company in France with the facilities

- Tube prototyping =>
  - First machining test of a 30mm tube
  - It will be followed by welding test in intern to observe the behaviour of a small steal filament during bending
  - Professional welders already identified => after the first test and with the flanges manufactured, assembling and welding of the small beam pipe prototype

- Test bench =>
  - **Manufacturing a ~1m tube with both flanges, hydraulic connectors and gaskets, all assembled**
  - **Thermic, fluidic and deformations tests => preparation of a test bench at LAPP**

CONCLUSIONS:

- **FF CCT HTS magnet**
  - Preliminary cold tests have allowed to state the specifications and the HTS tape -> Mechanical process is defined and the supplier is selected
  - A 3turns aluminum quadrupole is under progress and will be tested during the next weeks
  - A full prototype of 350 mm will be performed as soon as possible…



- **Cooled beam pipe**
  - The design is well advanced and the dedicated unitary tests are in progress.
  - The process is defined
  - A dedicated tests bench will be carry out at LAPP

- **FCC-ee, especially the MDI, is really a great opportunity to explore new strategic technologies like HTS magnets !**

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Thank you
for your attention!