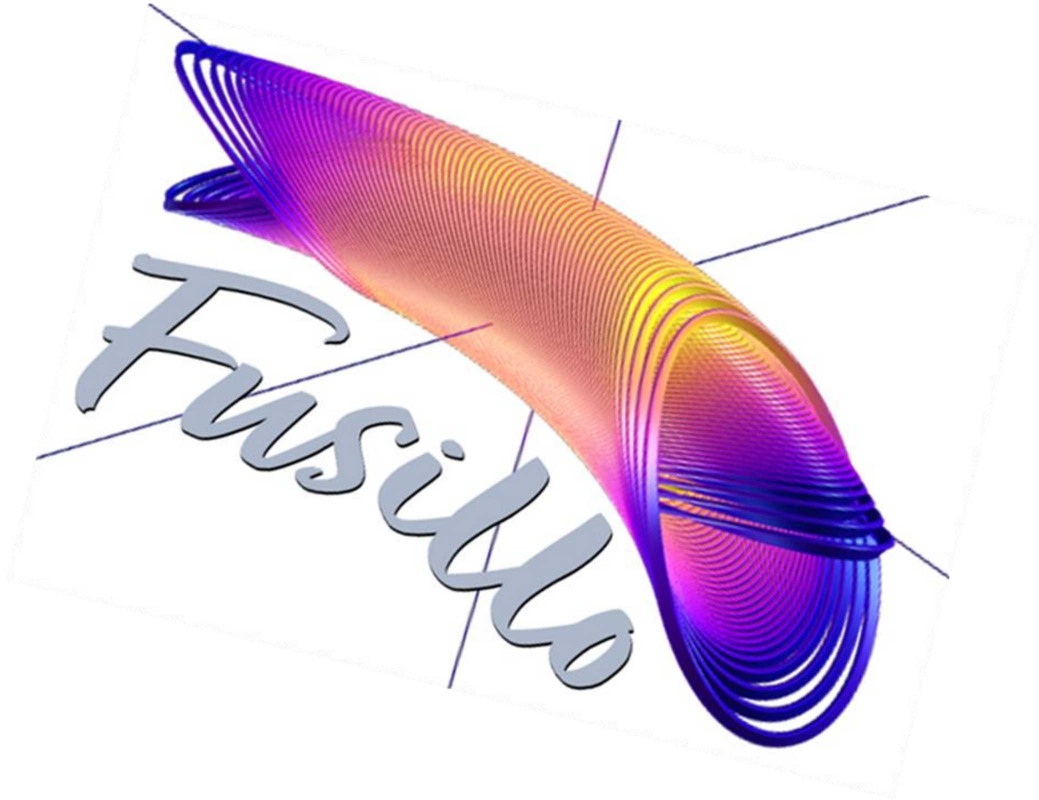
Thanks to the full teams:

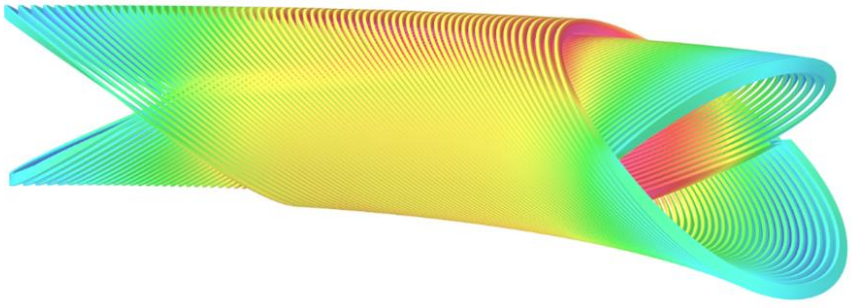
A. Haziot, A. Foussat, L. Gentini , E. Urrutia, R. Ferriere, K. Scibor, D. Molnar,, S. Russenchsch, C.Petrone , F. Mangiarotti, D. Tommasini, F-O Pincot S. Clement, J-S. Rigaud, C. Urscheler, C. Fernandes, F. Garnier, J. van Nugteren, PSI team: B. Auchmann, M. Day, O. Kirby, team in Hungary : D.Barna , E. De Matteis ………………. *Plus, many more to be added!*

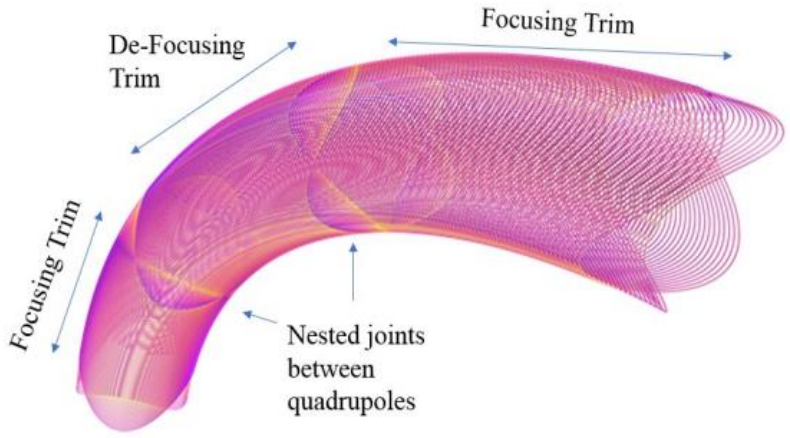



*By*
*Glyn Kirby*
*and the Teams*

# What is Fusillo ?

*Fusillo* is a proof-of-concept magnet development to show we can build this novel, low-cost type of magnet, multi function, with small curvature.
Late it is planned to introduce a set of quads for it to be used in a detector.






Future quadrupole tripled insert

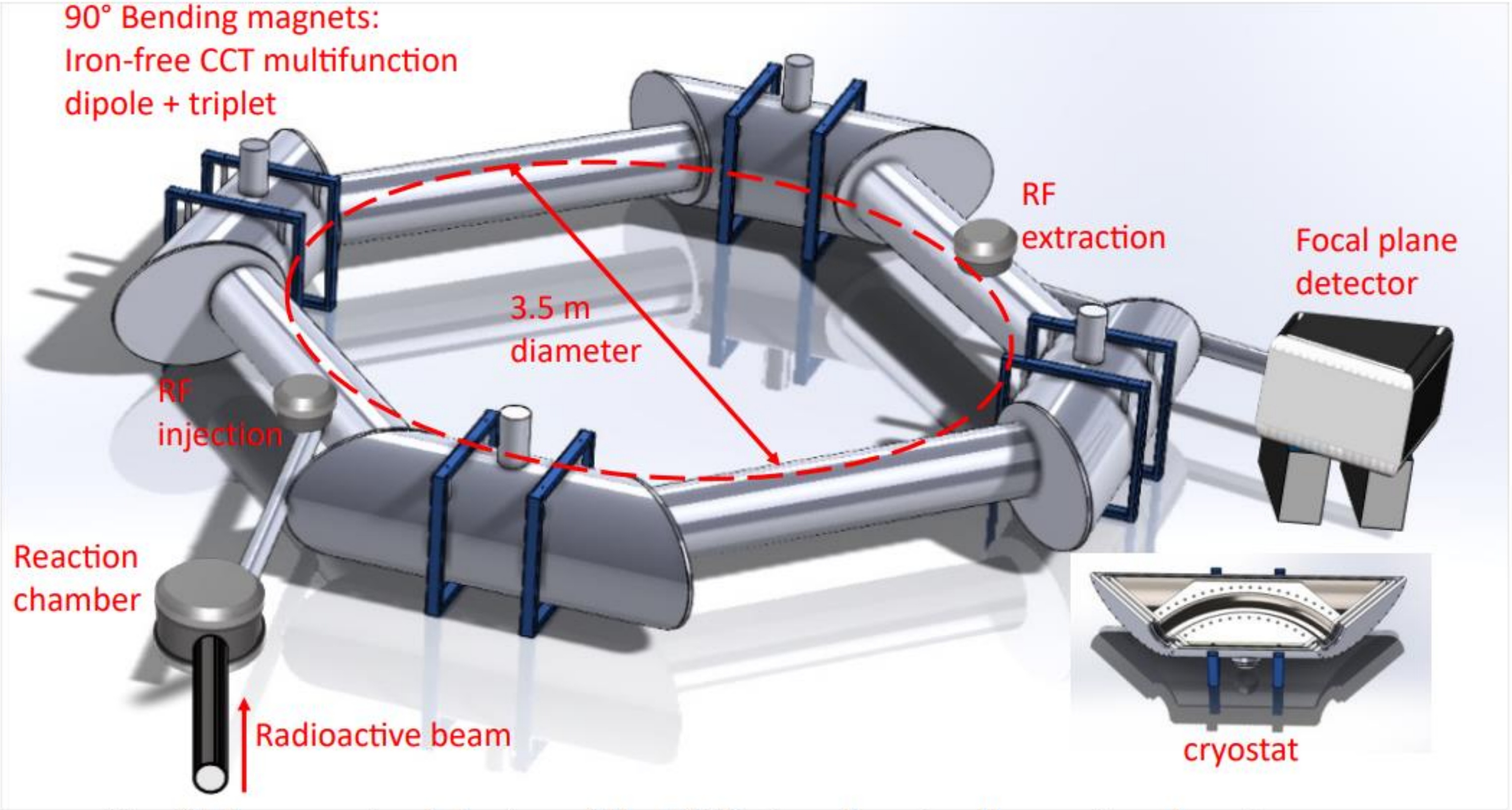
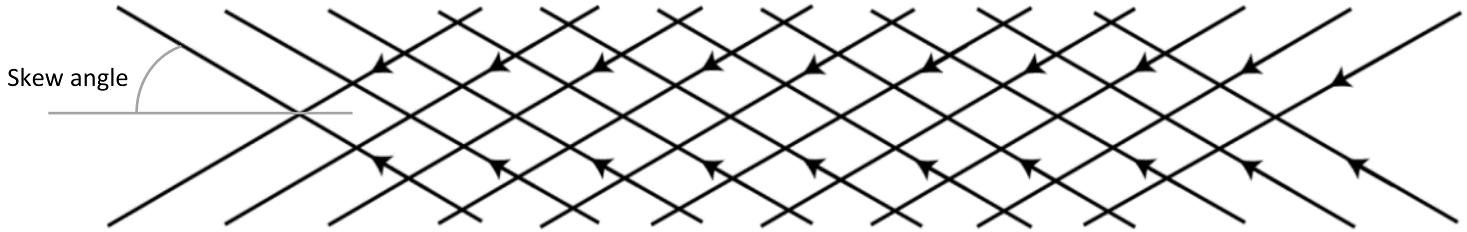
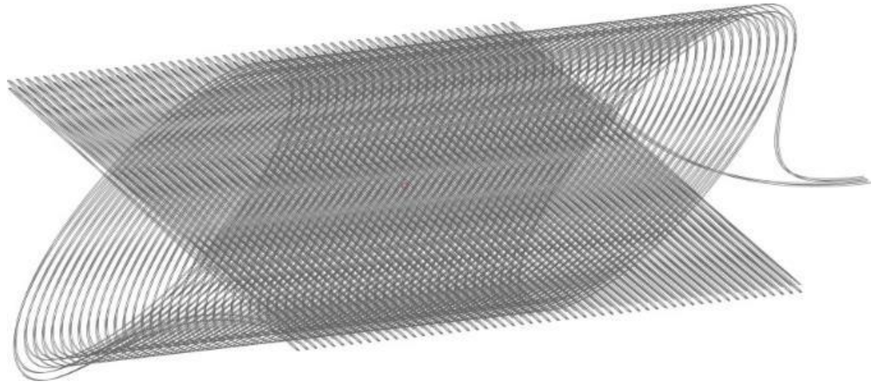



*Fig. 2. A conceptual design of the ISRS ring showing the main subsystems.*

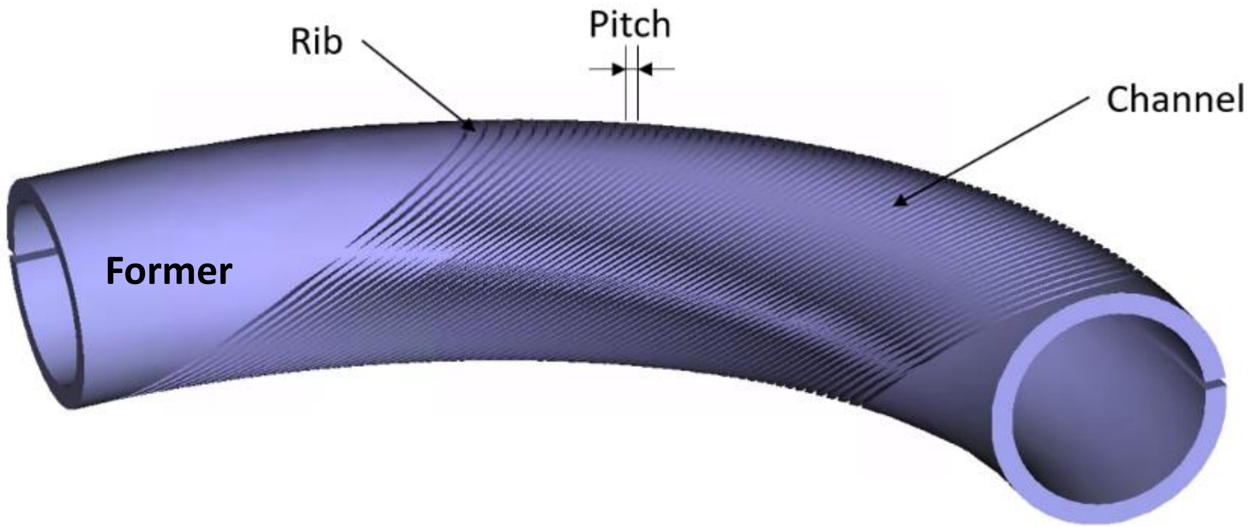
*Cryostat Model curtesy of O. Kirby PSI*

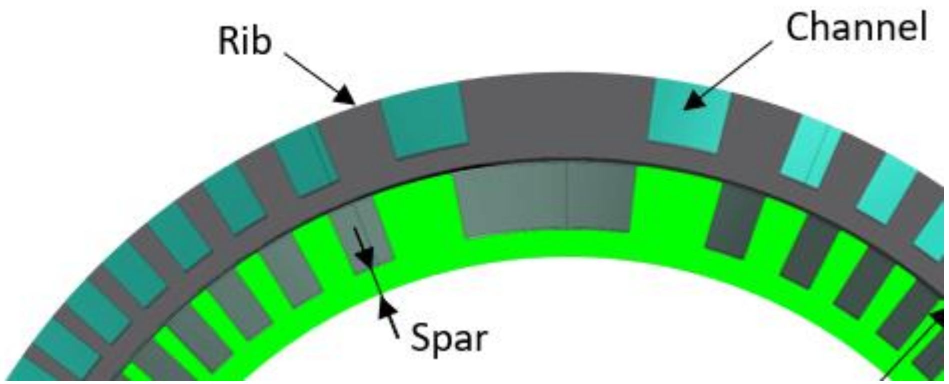
# Canted Cosine Theta: CCT



- Idea from the 1969.
- 2 nested canted solenoids.
- Dipolar field components add up.
- Axial field components cancels.

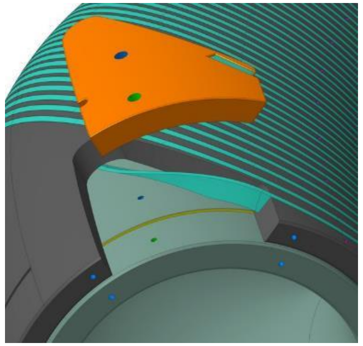


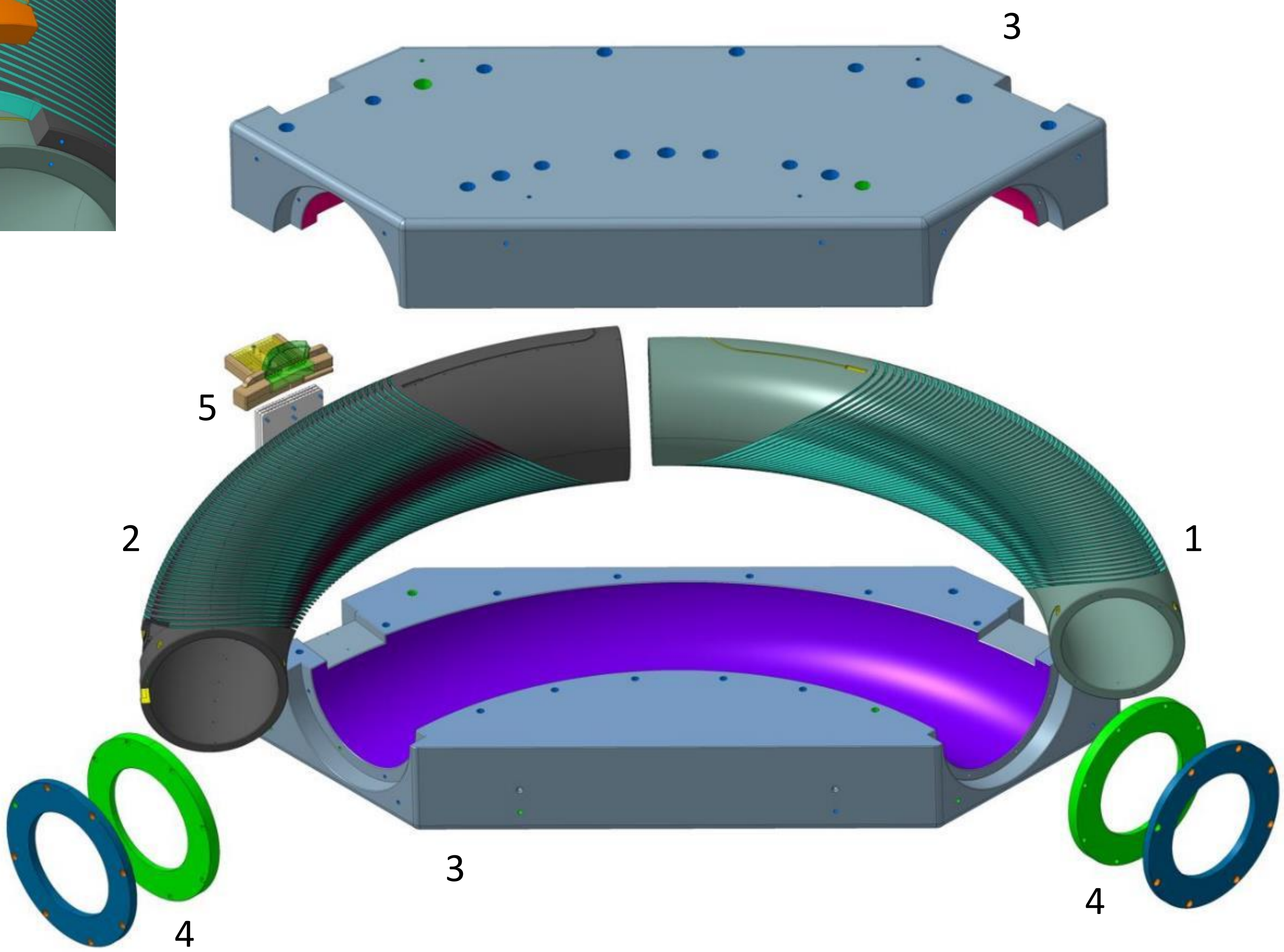

D. Meyer and R. Flasck, Nuclear Instruments and Methods **80**, 339-341 (1970)

# Description

**Main parts**
1. Former, inner layer
2. Former, outer layer
3. Clamp shell
4. Flanges
5. Electrical Connection box

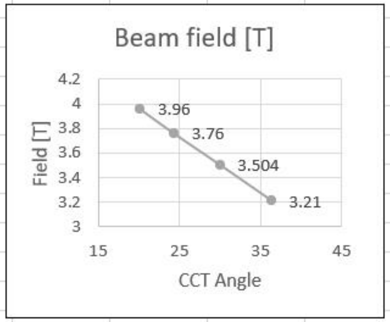


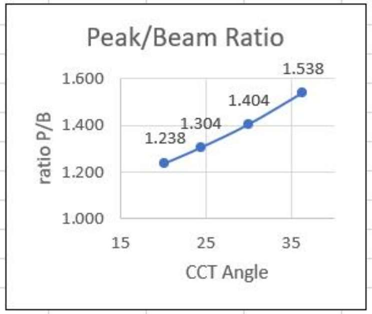
| Former Parameters | Values | |
|---|---|---|
| | Inner layer | Outer layer |
| Curvature radius | 1.0 m | |
| Angle between coil ends | 90° | |
| Minimum free aperture | 231 mm | |
| Number of channel turns | 66 | |
| Minimum rib thickness | 0.5 mm | |
| Spar | 7 mm | 5 mm |
| Coil inner radius (centre) | 127.50 mm | 150.70 mm |
| Former inner radius (centre) | 120.50 mm | 145.70 mm |
| Former outer radius (centre) | 144.60 mm | 167.80 mm |
| Taper | 5 mm from end to end | |
| Number of ropes per channel | 10 | |
| Number of turns per layer | 70 | |
| Former material | Aluminium 6082-T6 | |

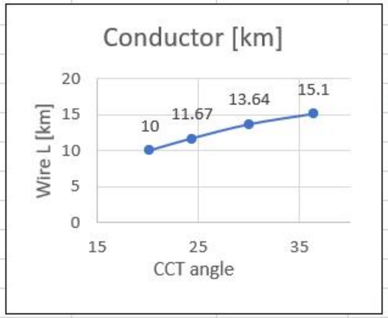


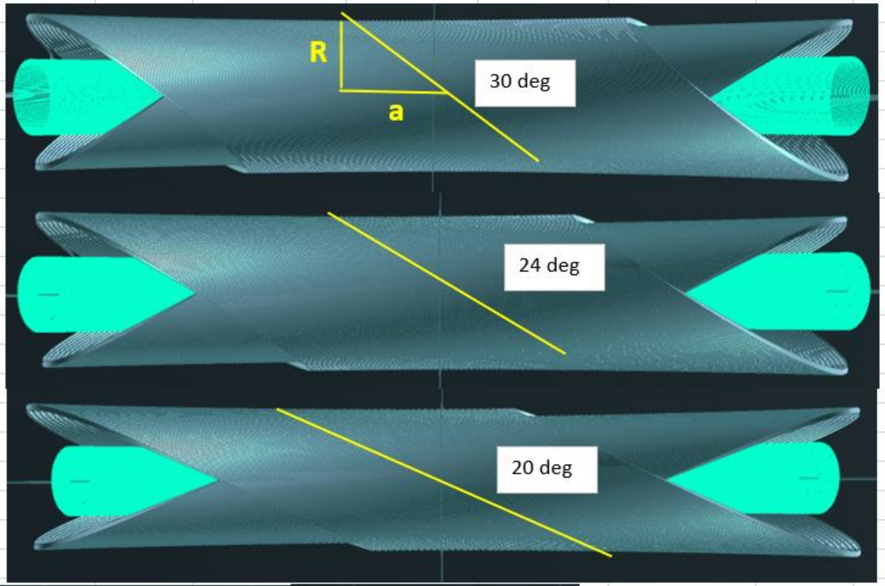
# Initial optimization of angle to maximize B.dL

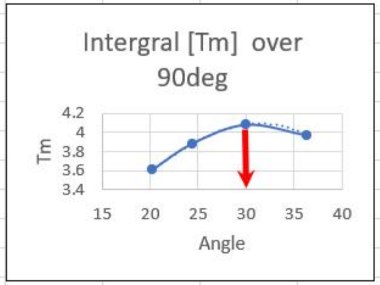
| R | a | r/a | Bend angle | CCT Angle | SS % | I [A] | Min wall thk | Peak in coil [T] | Beam field [T] | Peak/Beam Ratio | turns | Conductor [km] | Channel turns | [Tm] over 90deg | Inductance [H] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 118 | 160 | 0.7375 | 90 | 36.41 | 91.3 | 360 | 0.3 | 4.938 | 3.21 | 1.538 | 40 | 15.1 | 176 | 3.97 | 8.078 |
| 118 | 204 | 0.57843 | 90 | 30.05 | 91.08 | 360 | 0.3 | 4.918 | 3.504 | 1.404 | 40 | 13.64 | 142 | 4.083 | 8.484 |
| 118 | 260 | 0.453846 | 90 | 24.41 | 90.9 | 360 | 0.3 | 4.904 | 3.76 | 1.304 | 40 | 11.67 | 106 | 3.884 | 8.052 |
| 118 | 320 | 0.36875 | 90 | 20.24 | 90.91 | 360 | 0.3 | 4.903 | 3.96 | 1.238 | 40 | 10 | 80 | 3.607 | 7.256 |

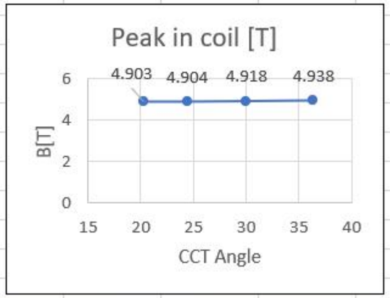


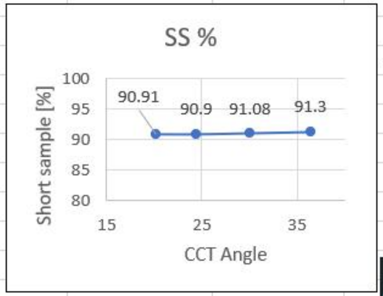



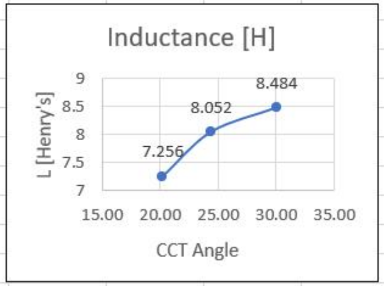



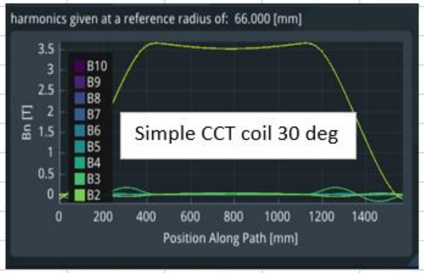



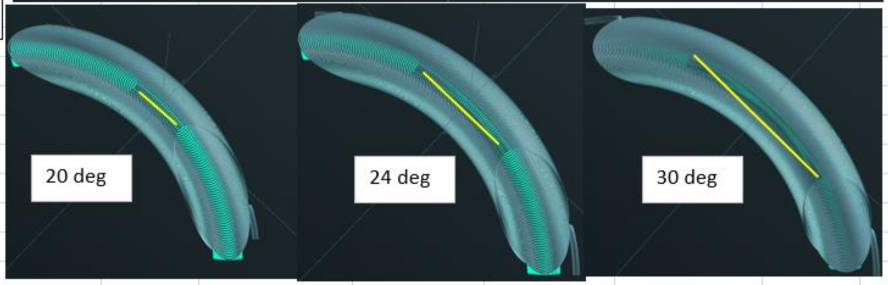



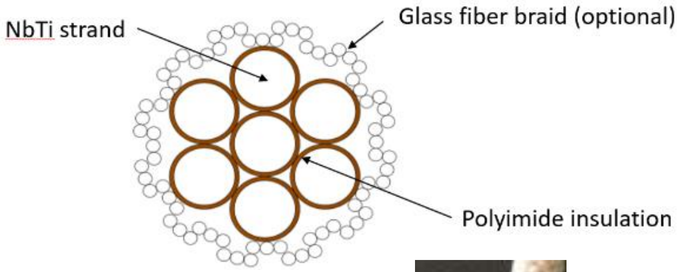



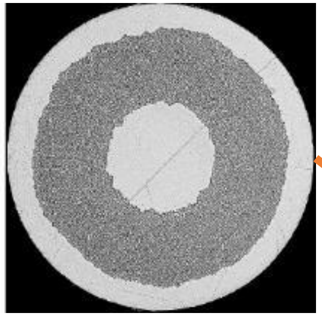



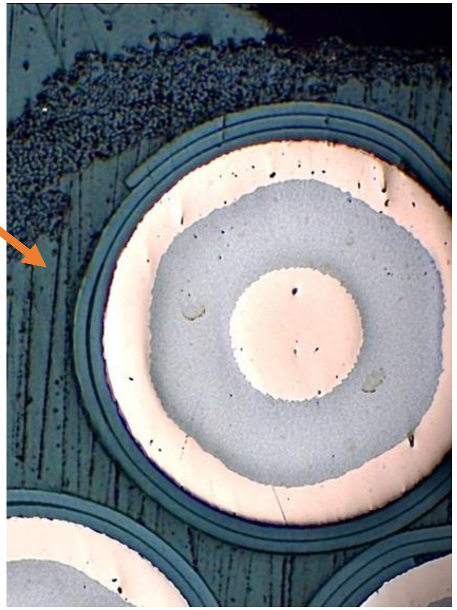
# Cable

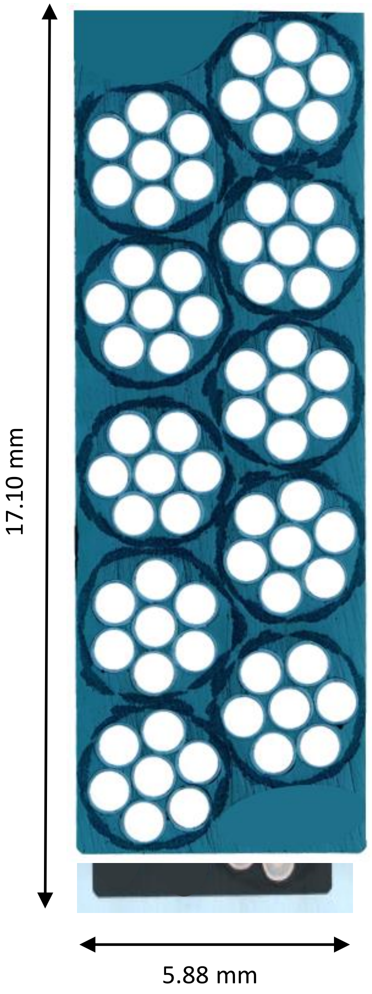
| Strand Parameters | Values |
|---|---|
| Strand diameter | 0.8250 ± 0.0025 mm |
| Filament diameter | 6.0 ± 0.1 µm |
| Nominal number of filaments | (6300 – 6550) ± 20 |
| Minimum critical current at 4.2 K and 6 T | 387 A |
| Copper to superconductor ratio | 1.90 – 2.00 |
| RRR | 150 |
| Coating | none |

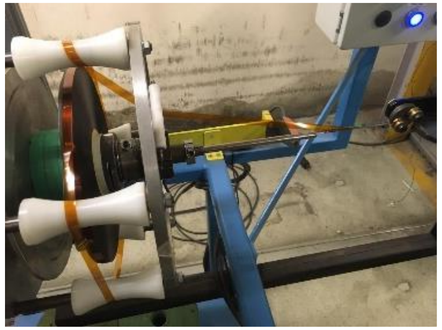
| Cable Parameters | Values |
|---|---|
| Type of cable | Rope type |
| Conductor | 0.825 mm Nb-Ti strand |
| Wire insulation | Polyimide tape (25 µm) with FEP glue (2.5 µm)<br>overlapping: 52 ± 2 %; t: 70 µm<br>insulation: 5000 V DC |
| Insulated wire diameter | 0.97 mm |
| Assembly | 7 wires, helicoidal twist<br>Pitch 45 ± 2 mm |
| Cable diameter | 2.91 mm |
| Cable insulation (optional) | Glass fibre braid, S2, 33 Tex, ens. 493<br>16 bobbins of 2 yarns<br>Pitch: 9.4 ± 0.5 mm ; Covering: almost 100 %;<br>t: 100 µm |
| Insulated cable diameter | 3.1 mm |
| Cable twist pitch | 45 mm |



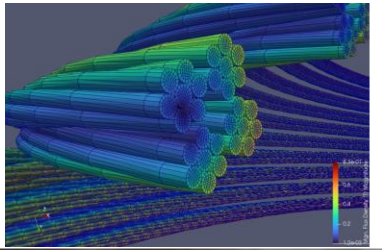


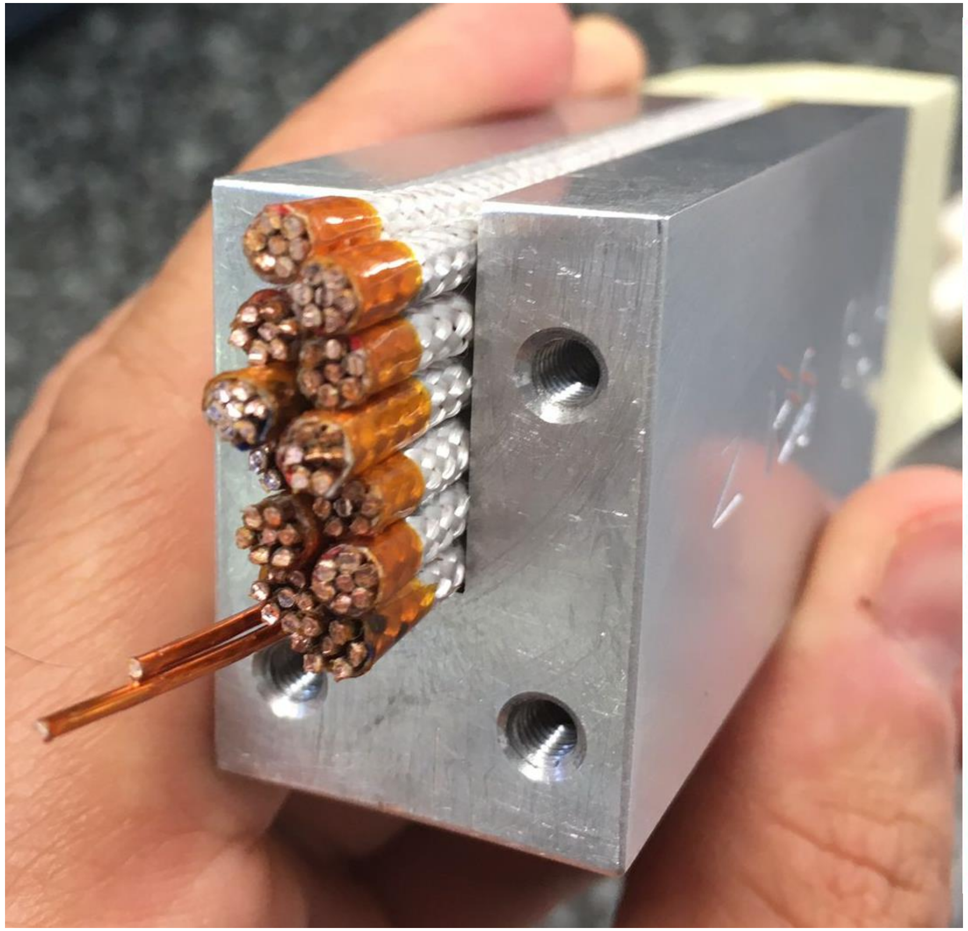


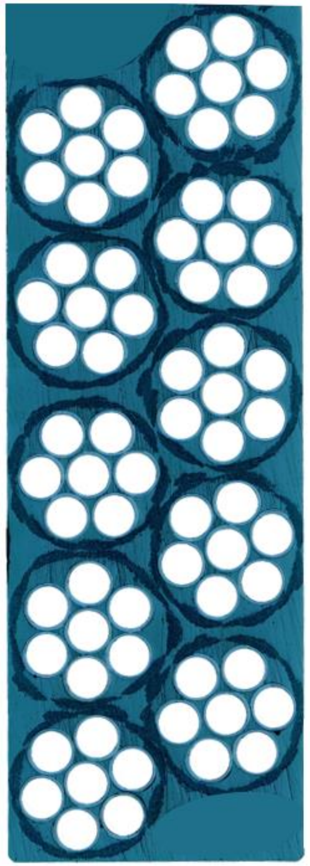



# Fusillo rope cable in channel tests

Channel tests → 77K then cut polish measure → Re polish design coil with final sizes

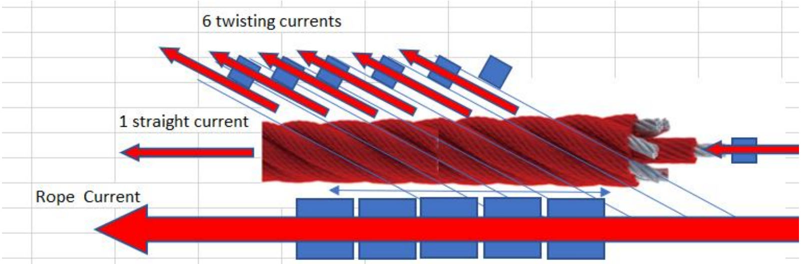


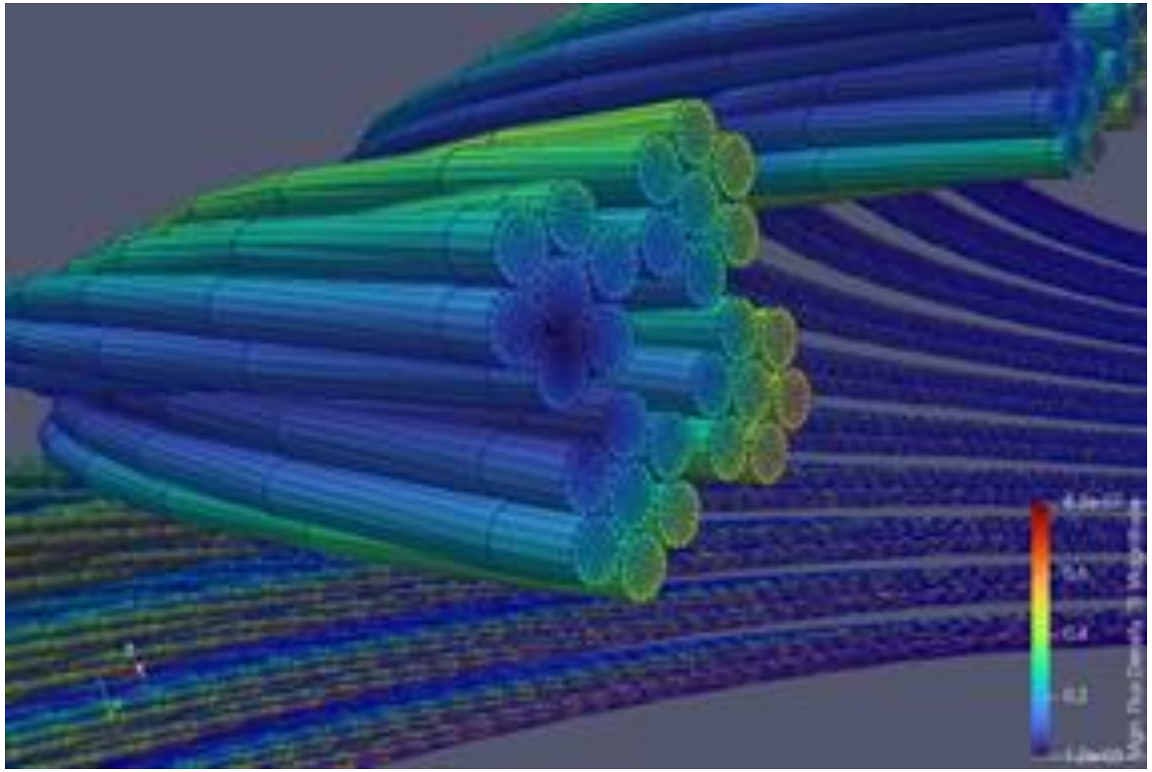


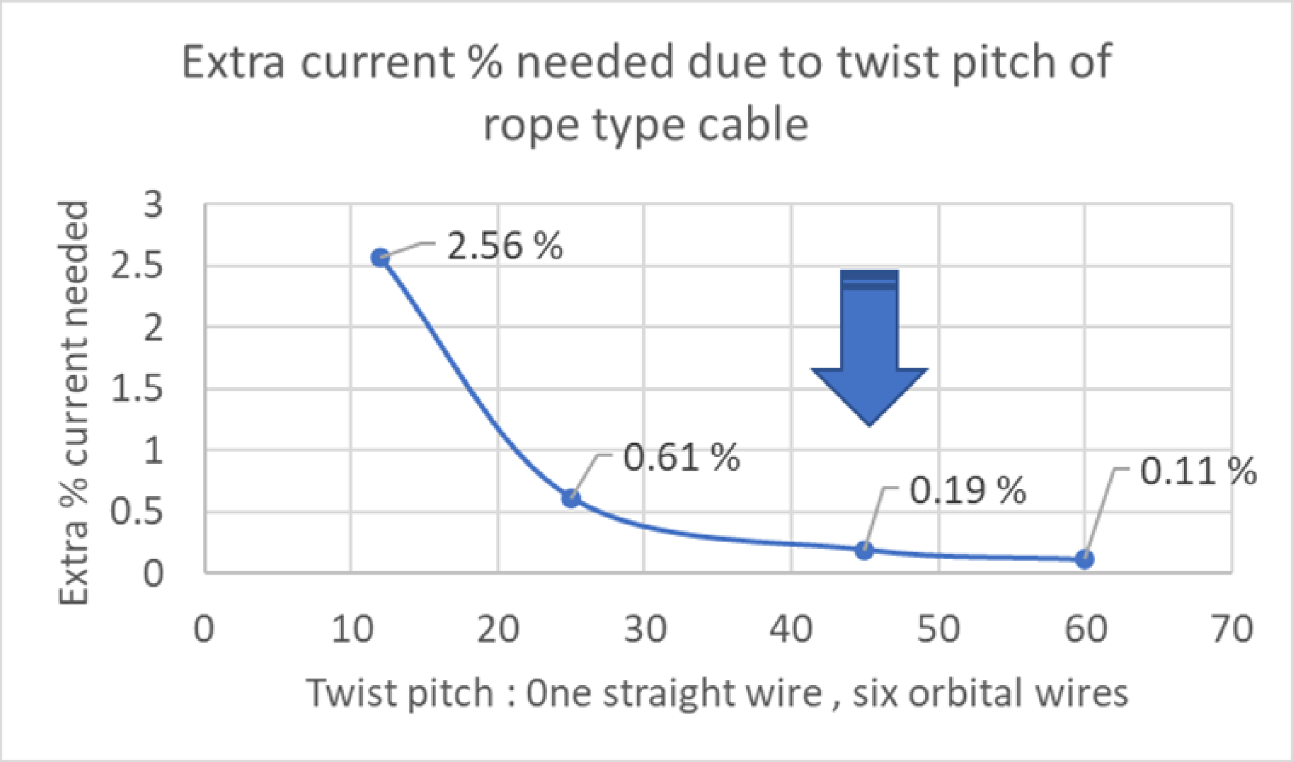


**The tests check: the cable positioning in channel , resin fill, thermal cycle looking for cracks, electrical insulation between turns and ground**

# Rope cable current offset



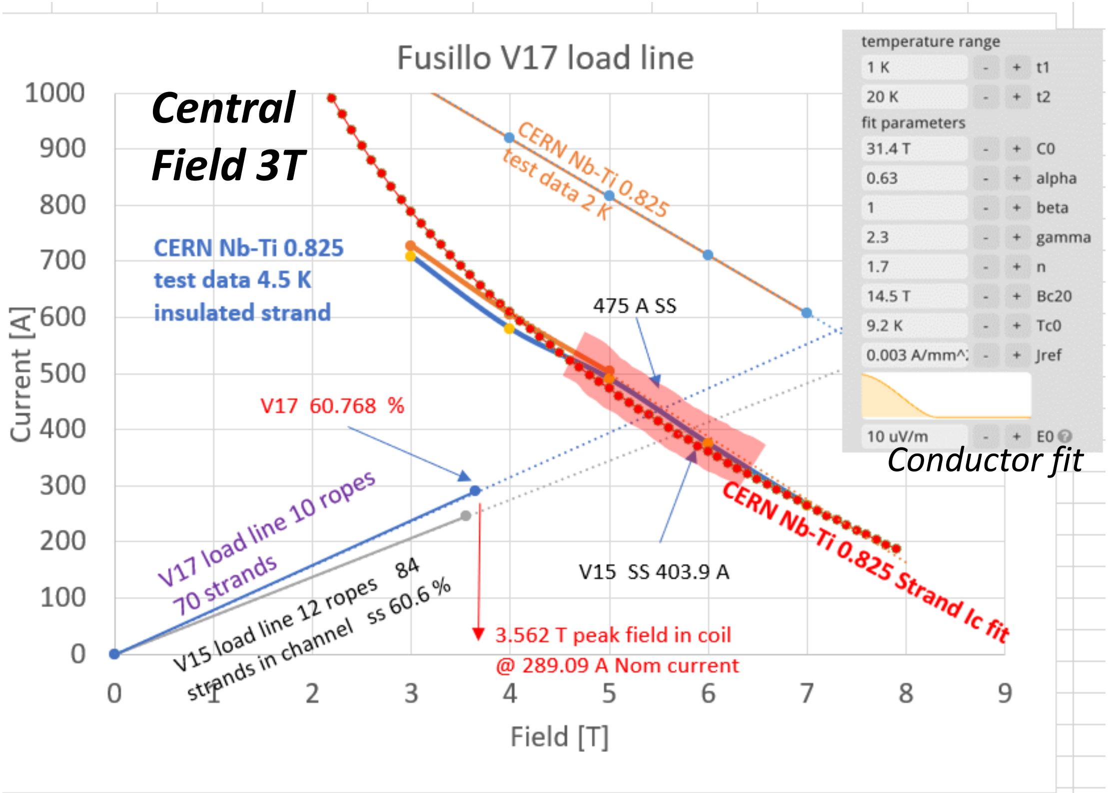



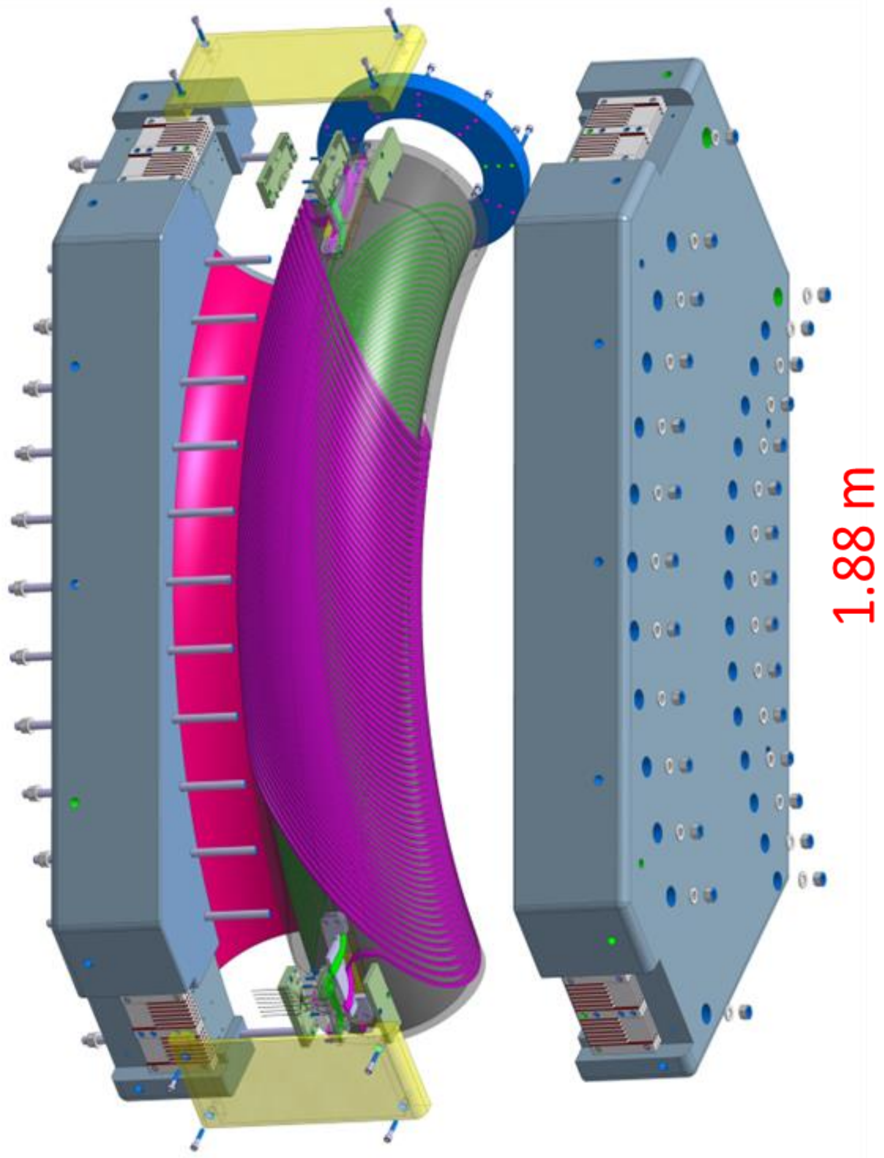



The six round one cable has the effect to loos a small amount of effective field generating current! Due to the vector that the orating strand take. Its only small! The central insulated wire contributes 100% the not the others. We set the pitch so that the cable is stable with a pitch of ~ 45 mm. We will measure the small off set in the sub scale magnets.

# Coil design V17 cold.

***Short sample 60.7 %LL***
***Operating current at 3.000 T = 289.09 A***
***Mass 1000 Kg***

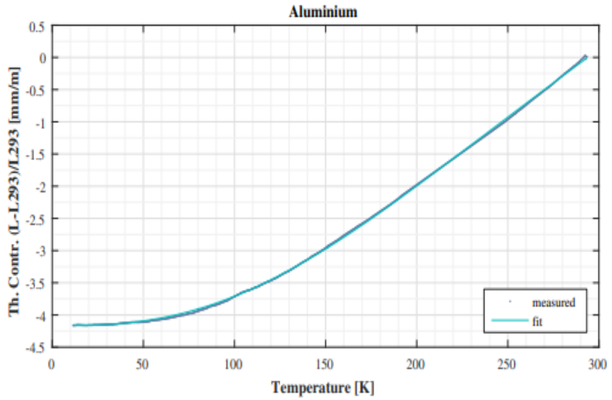



Conductor is from the LHC dipole cable strand, 10 strands per rope cable , 7 strands in each rope.
Margin allows for the addition on a set of quads later to focus the beam. The flat field design allows for easy measurement.

# Warm to cold design for contraction

## The Aluminum former




$$\frac{L - L_{293}}{L_{293}} = a + bT + cT^2 + dT^3 + eT^4 + fT^5$$

| Coeff | Value |
|---|---|
| a | -4.16e+00 |
| b | -4.48e-04 |
| c | 1.25e-05 |
| d | 5.74e-07 |
| e | -2.31e-09 |
| f | 2.68e-12 |

Measured values for material contraction

The contraction of the aluminum former from room temperature to 4.5K means that we design the magnet at cold, then warm it up to room temperature.
One important change is the radius! Room temperature it is at 1004.16 mm Rad.

**Inner radius at centre= 129.3 mm with a 5 mm taper from one end to the other on radius**

| | sDp A1 | nDp B1 | sQ A2 | nQ B2 | sSex A3 | nSex B3 | sOct A4 | nOct A$ |
|---|---|---|---|---|---|---|---|---|
| Z offest cold | -0.003 | 211.793 | -0.050 | -3.038 | 0.010 | 0.080 | 0.000 | 0.010 |
| Z offset warm | -0.003 | 212.64 | -0.05 | -3.05 | 0.01 | 0.08 | 0 | 0.01 |
| Diff | 0.0000 | 0.8472 | -0.0002 | -0.0122 | 0.0000 | 0.0003 | 0.0000 | 0.0000 |

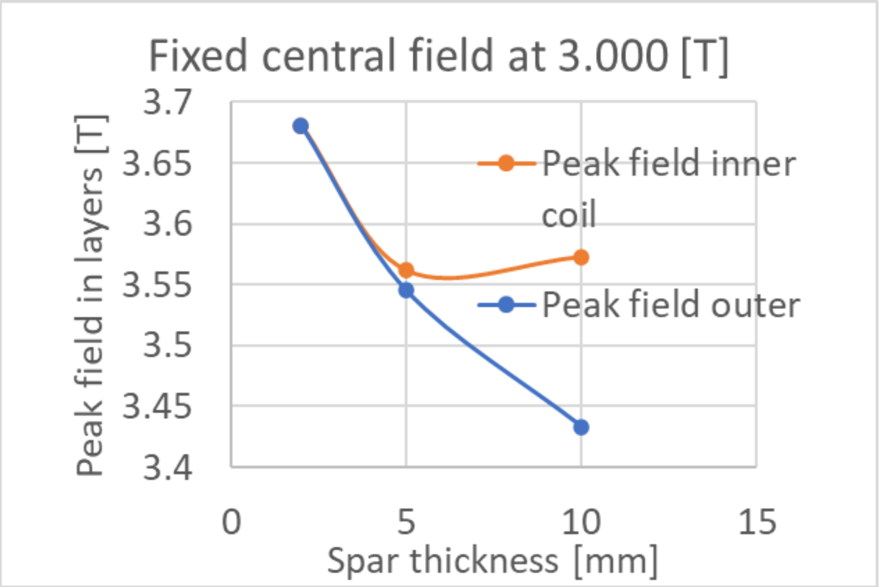
Starting point

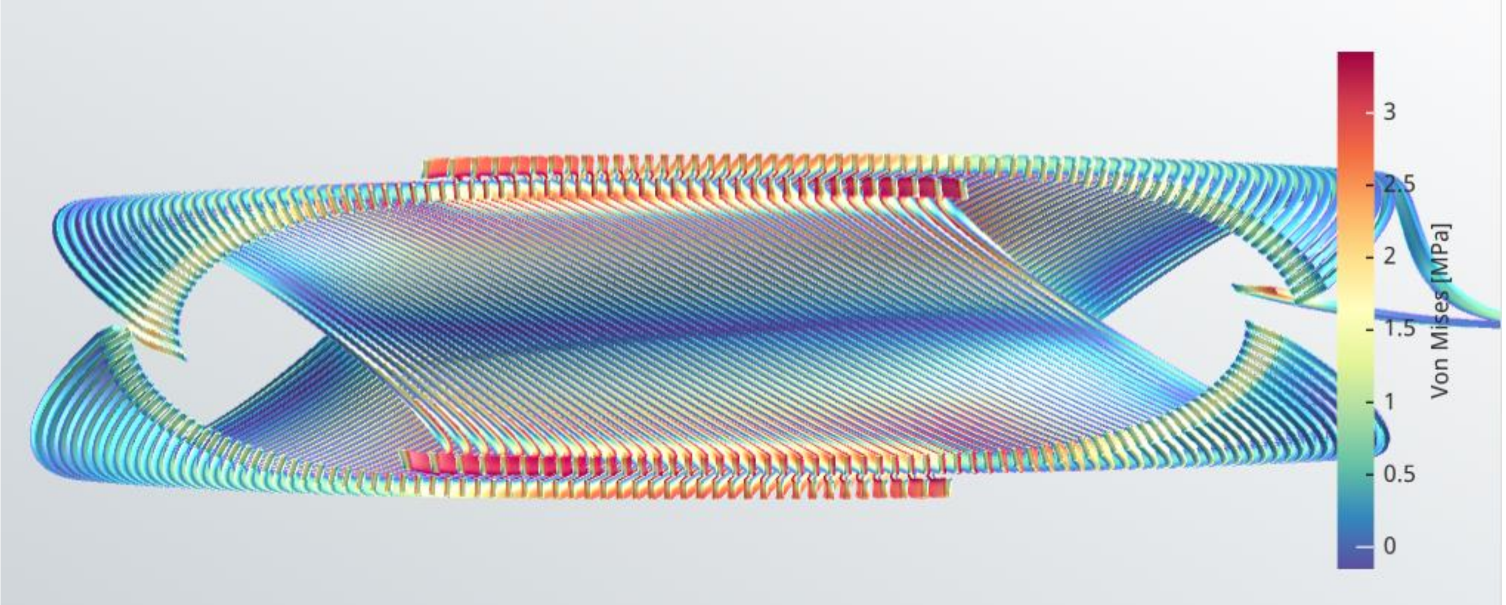
| | Cold | Warm | diff |
|---|---|---|---|
| Outer former dia | 167.131 | 167.8 | -0.668526 |
| Channel Hight | 17.032 | 17.1 | -0.068127 |
| Inner channel radius | 150.100 | 150.7 | -0.600398 |
| Former inner radius | 145.120 | 145.7 | -0.580478 |
| | 144.024 | 144.6 | -0.576096 |
| Channel Hight | 17.032 | 17.1 | -0.068127 |
| coil inner radius | 126.992 | 127.5 | -0.507968 |
| Former inner radius | 120.020 | 120.5 | -0.48008 |
| Channel width | 5.857 | 5.88 | -0.02343 |

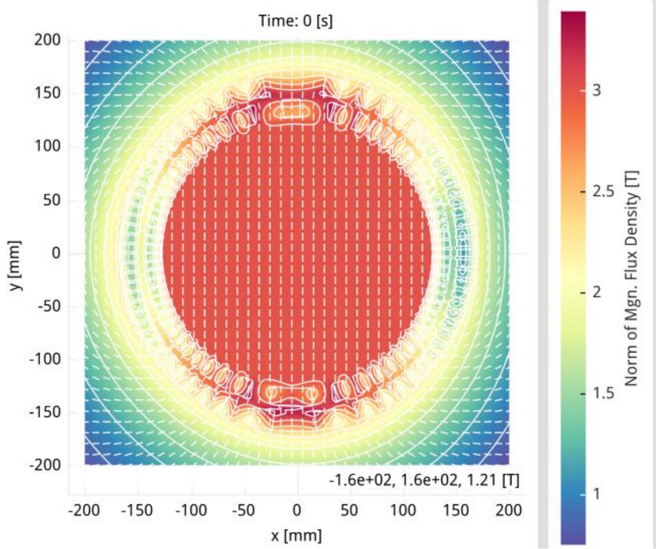


| | | | |
|---|---|---|---|
| distance between coils | 23.10757 | 23.2 | -0.09243 |
| pitch | 6.358566 | 6.384 | -0.02543 |
| W/2 | 2.928287 | | |

# Optimizing the gap between coils for max fields

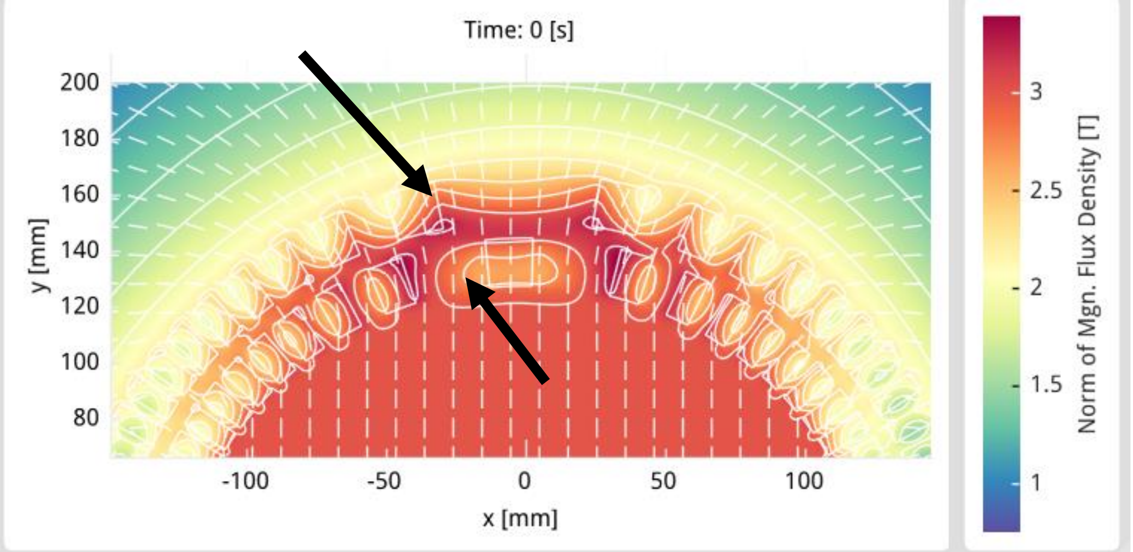


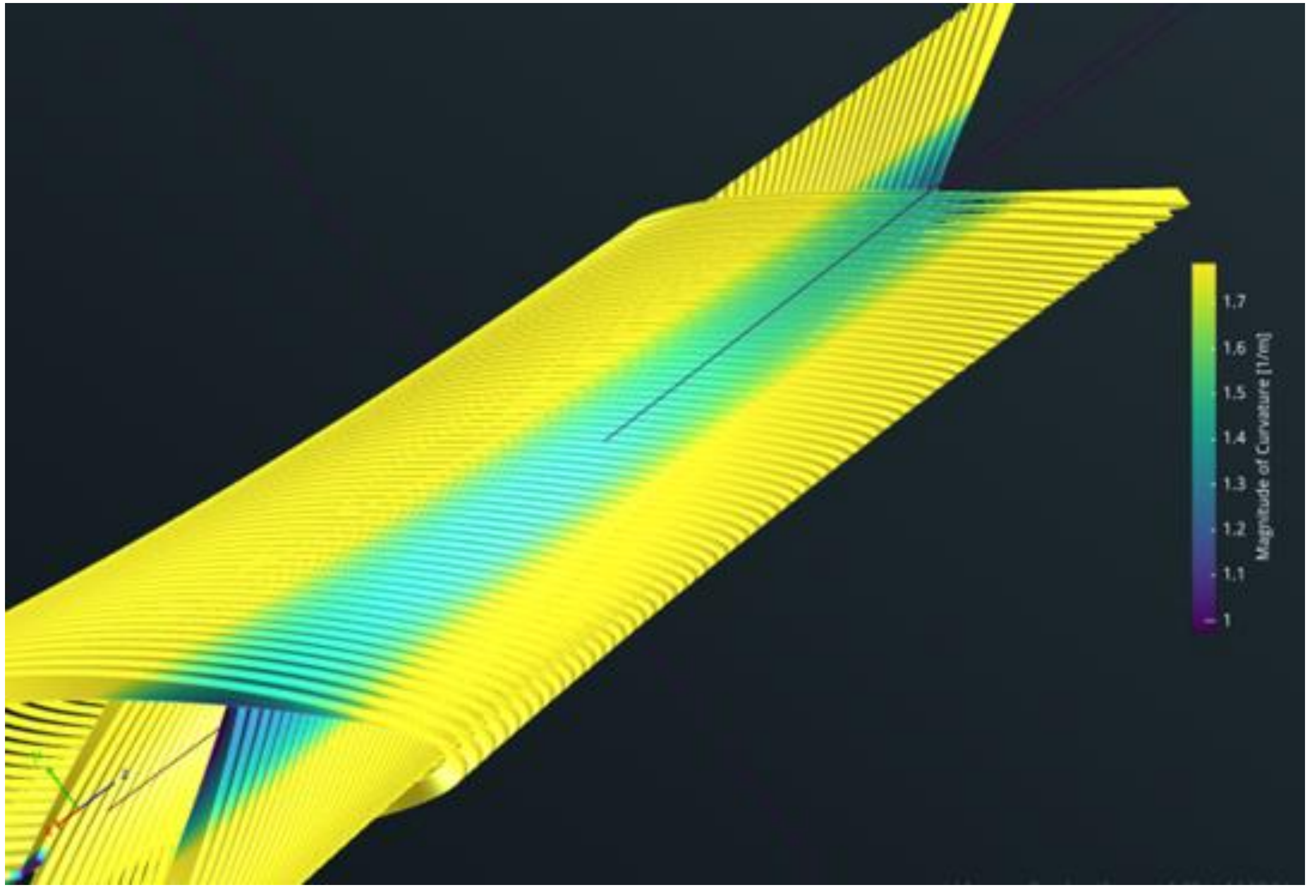

***Optimizing the gap between coils***

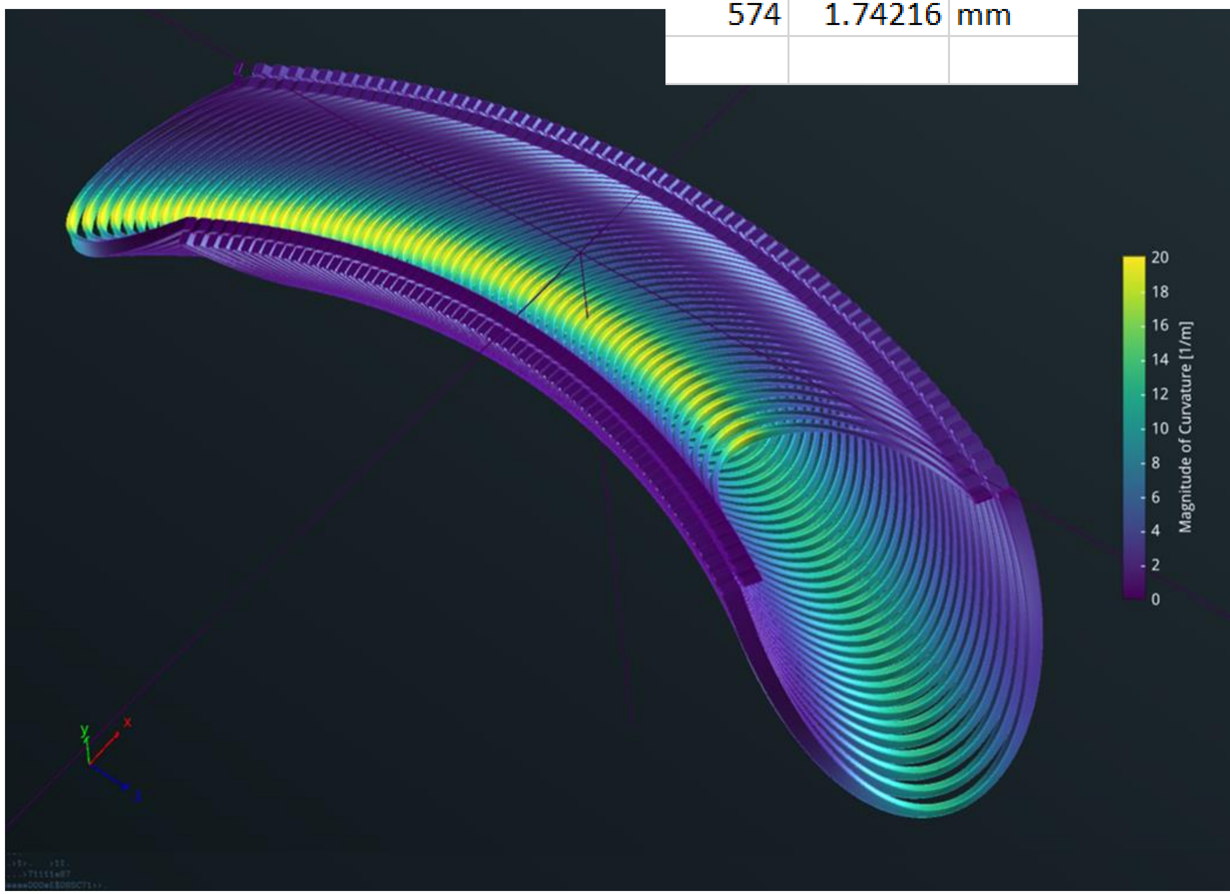
As the gap between the coils reduces the peak fields converge then at 5 mm both start increasing



# Minimum cable radii in coil

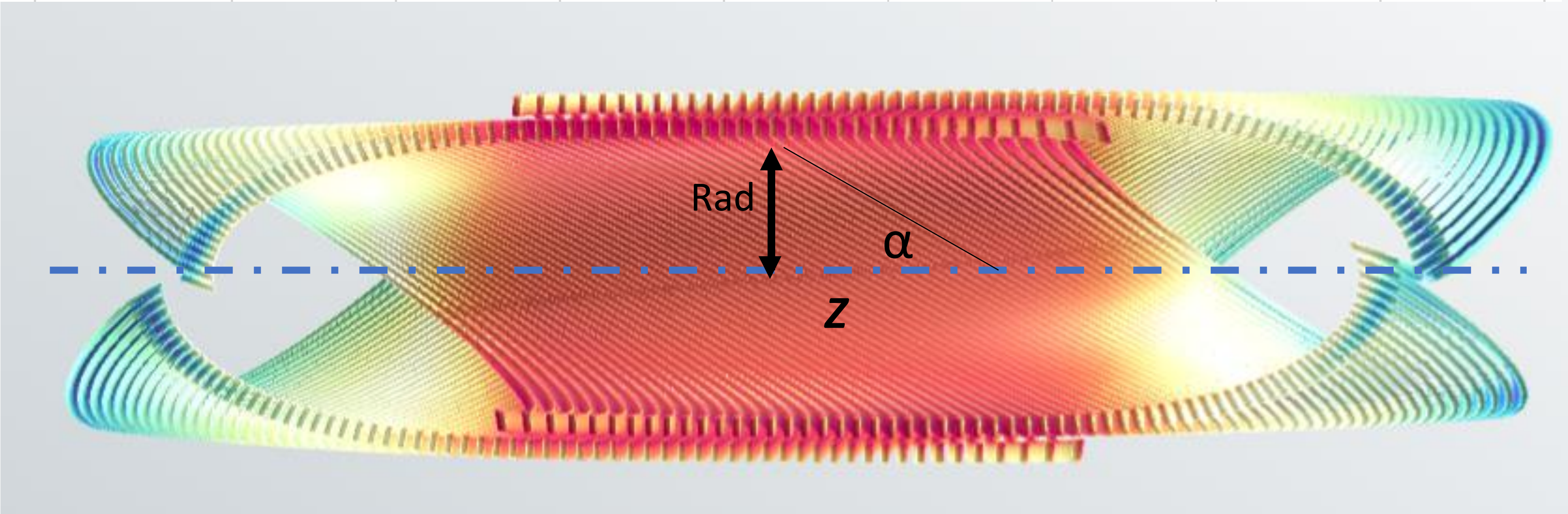
| | Rad ofCurvituer | |
|---|---|---|
| 0.4 | 2500 | mm |
| 1 | 1000 | mm |
| 5 | 200 | mm |
| 10 | 100 | mm |
| 15 | 67 | mm |
| 20 | 50 | mm |
| 25 | 40 | mm |
| 574 | 1.74216 | mm |
| | | |



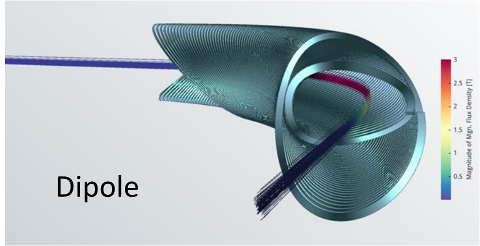



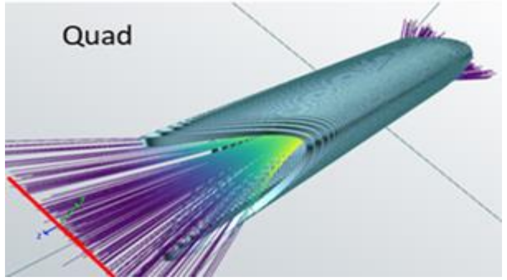
# Coil design multi harmonics correction

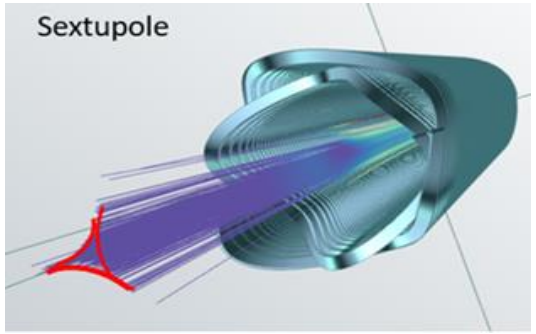
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A1 = Skew Dipole B1= normal dipole torough to | | | | | | | |
| **Inner radius at centre= 129.3 mm with a 5 mm taper from one end to the other on radius** | | | | | | | | |
| | Dipol A1 | Dipole B1 | Quad A1 | Quad B2 | Sext A3 | Sext B3 | Oct A3 | Oct B4 |
| Z off set | -0.00299 | 211.7928 | -0.0498 | -3.03785 | 0.00996 | 0.079681 | 0 | 0.00996 |
| CCT Angle Deg | 90.0013 | **31.40** | 90.02 | 91.35 | 90.00 | 89.96 | 90.00 | 90.00 |

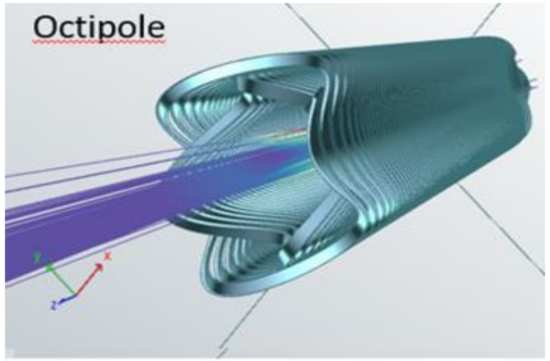



Higher order corrections

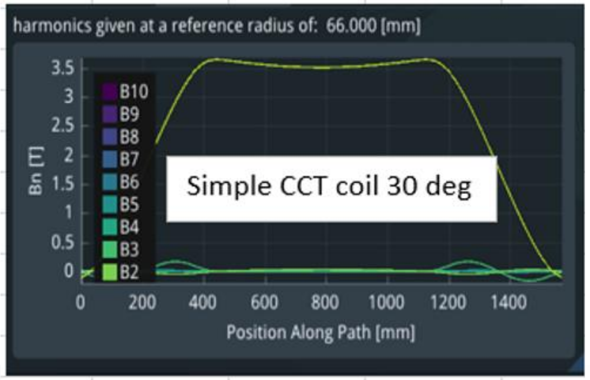


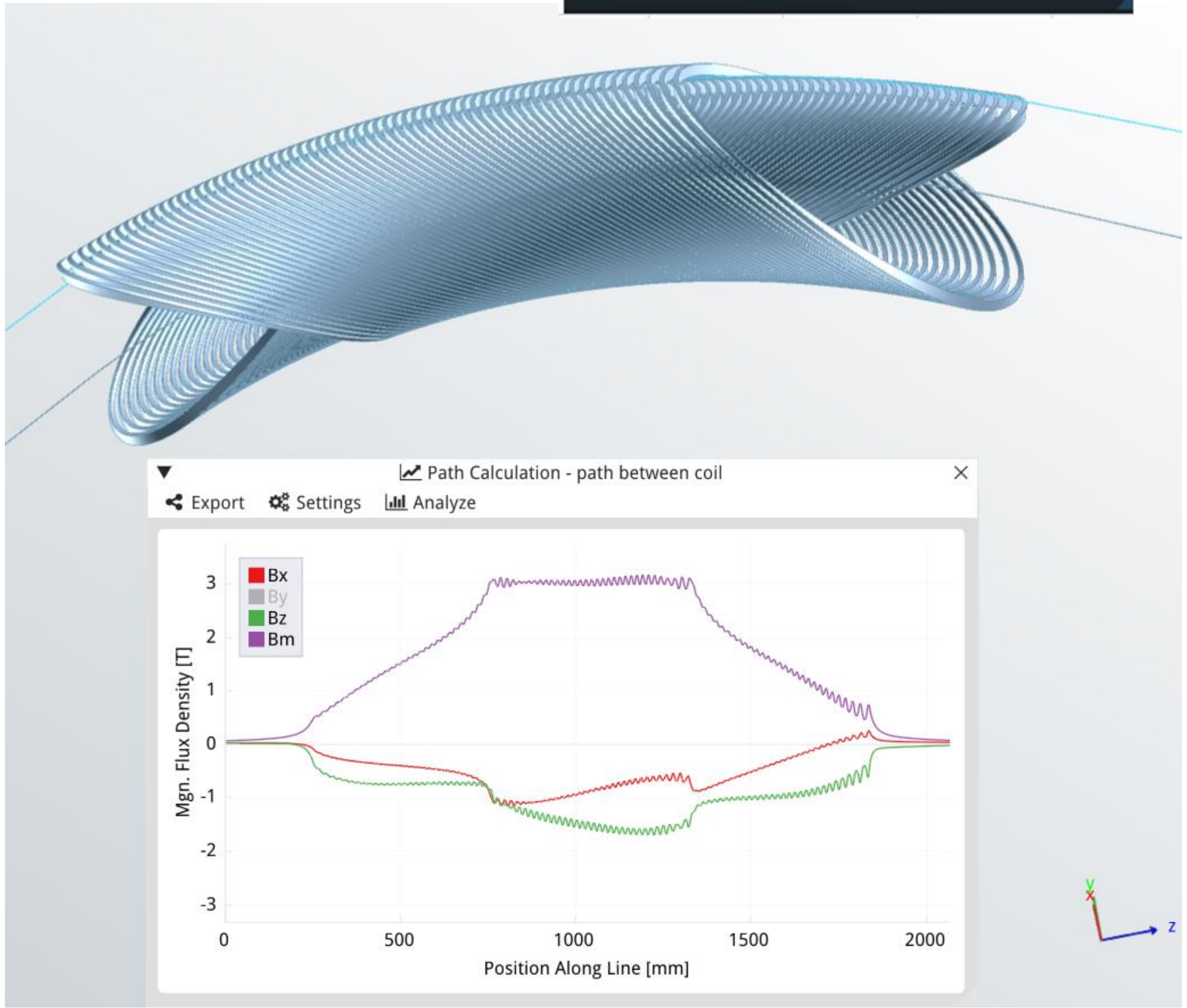



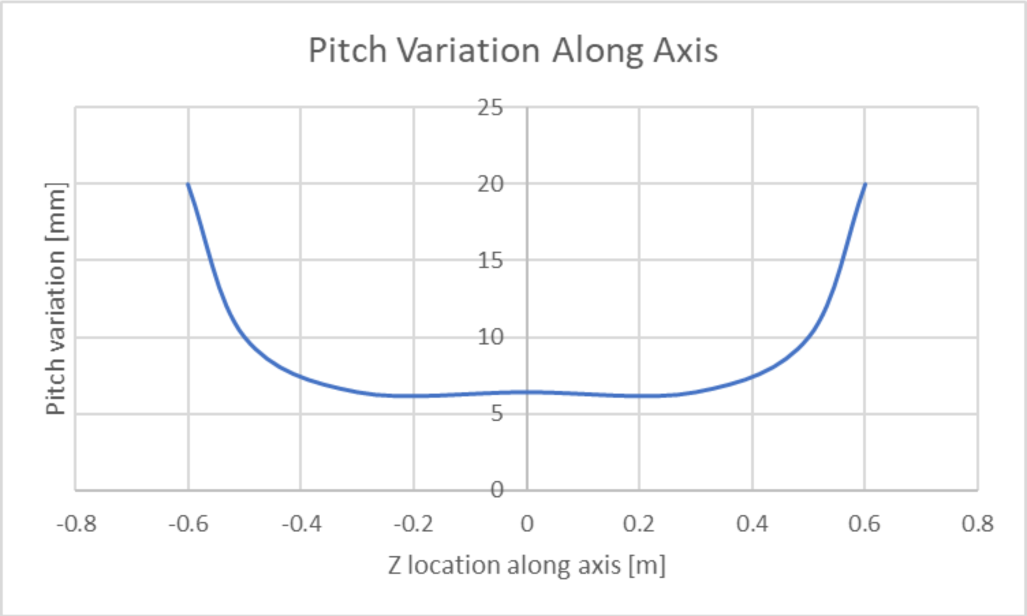



# Pitch correction to reduce peak field



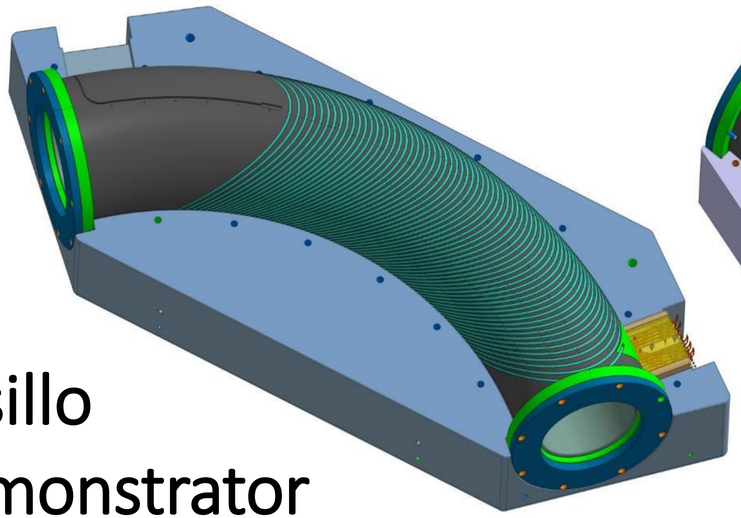

The pitch of the cable channel is gradually increased at both ends to remove the peak field bump that occurs due to the coil end geometry effect. It difficult to see the image.  See the flat B(mod) [T] plot through that runs between the two coils.

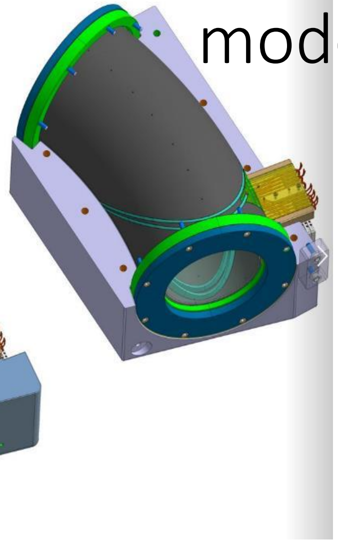


# Sub-Scale v Demo

Fusillo subscale model

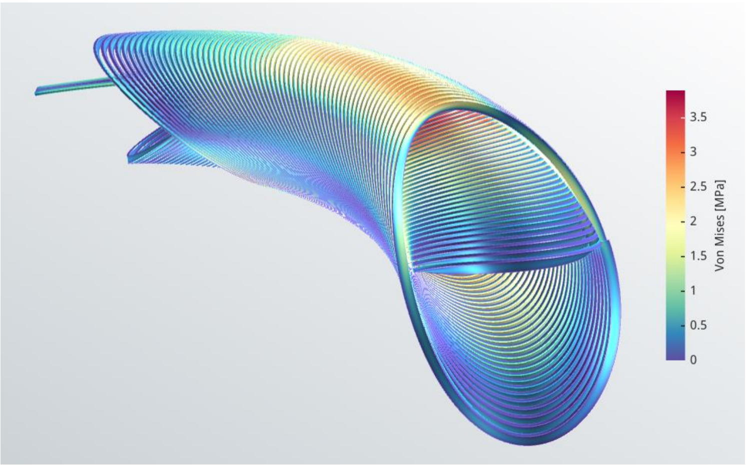


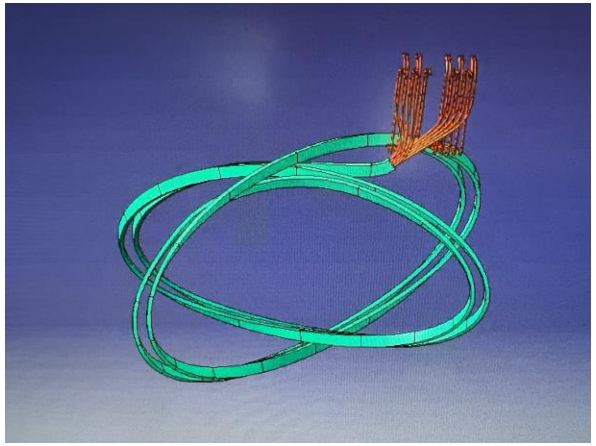


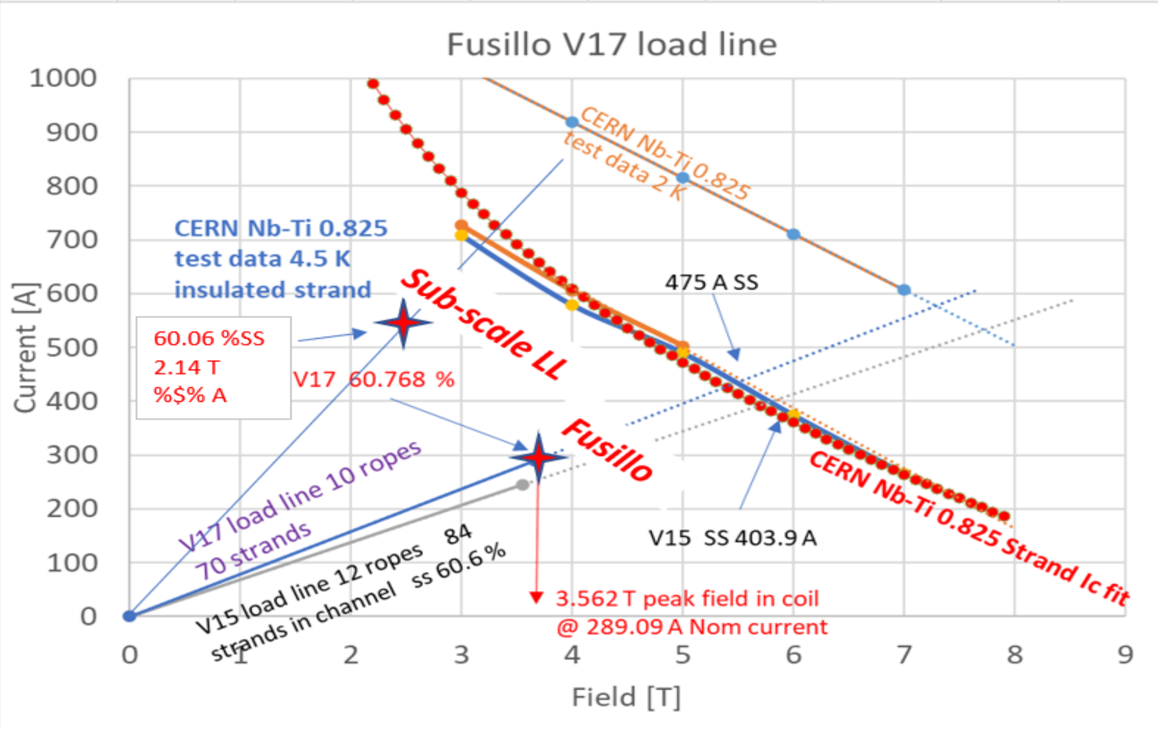
Fusillo demonstrator

The set of 2 or 3 Sub Coils will test :

1) Winding test of a section of the Demo fusillo coil
2) By powering to higher current, the ***subscale can match stress*** **and** ***short sample.***
3) Several impregnation materials / processes are planned to test quench levels

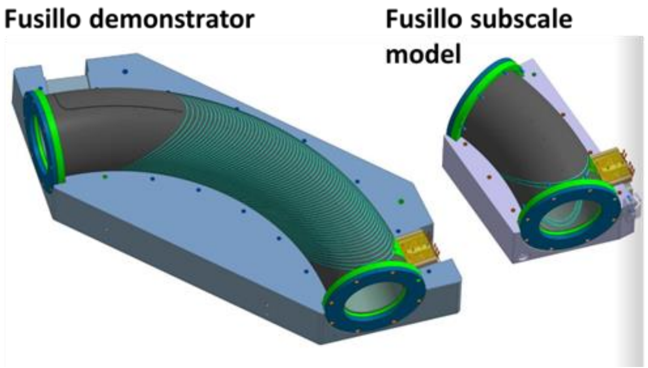


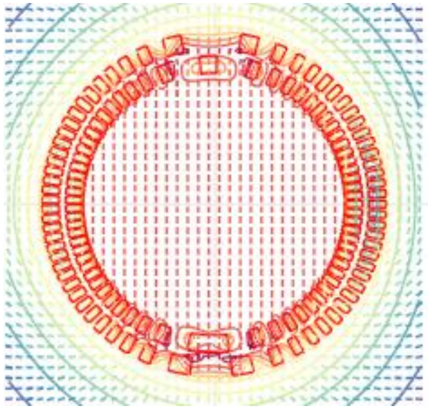



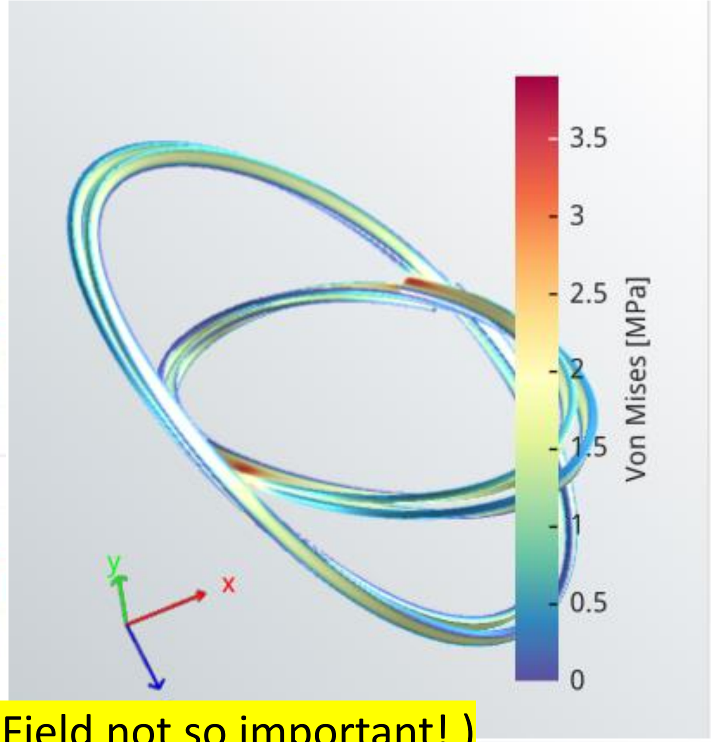


# Sub-Scale Stress and SS% matching to full Fusillo

289 A
3.9 MPa
60% SS
3.6 T



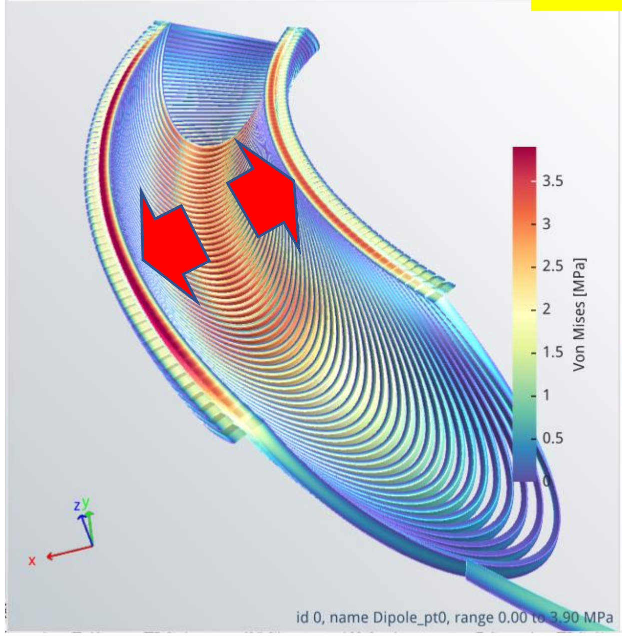


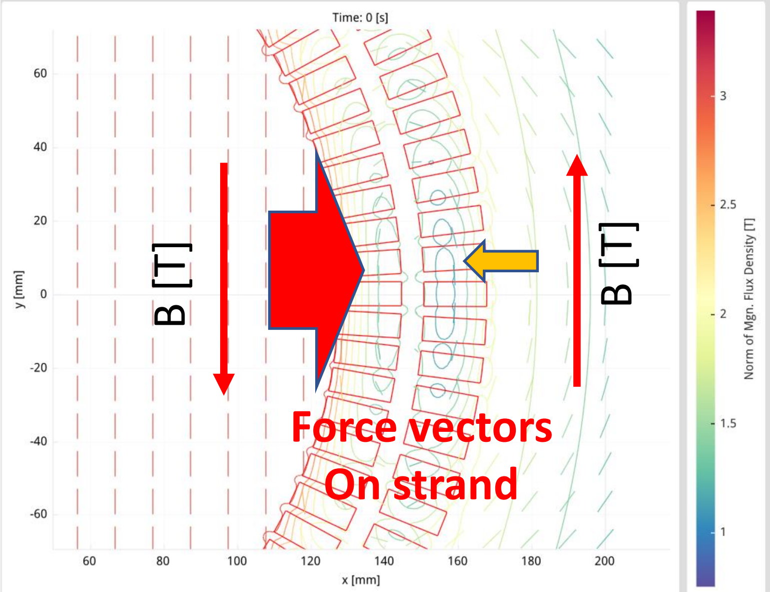

Von Mises [MPa]

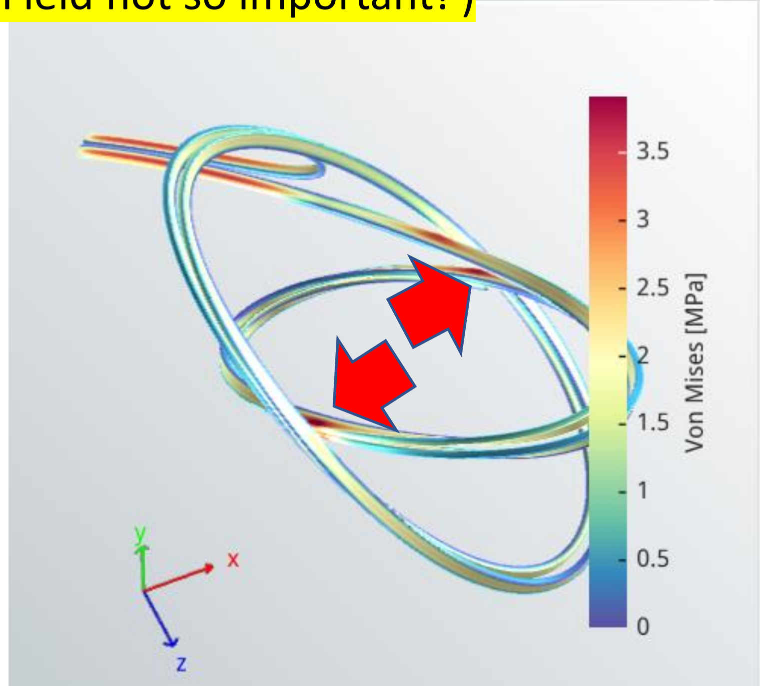
| Name | vmax [MPa] |
| --- | --- |
| Dipole_pt0 | 3.900 |
| Dipole_pt1 | 2.415 |

535 A
3.9 MPa
60 % ss
2.14 T

Stress = Movement-Cracks, % SS = stability , (Field not so important! )



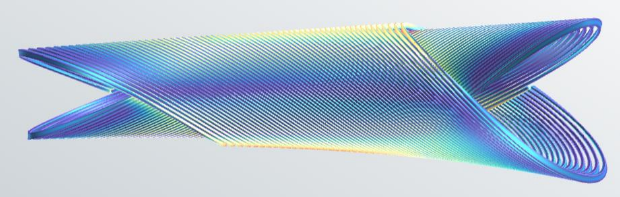




Von Mises [MPa]

| Name | vmax [MPa] |
| --- | --- |
| Dipole_pt0 | 3.906 |
| Dipole_pt1 | 3.474 |

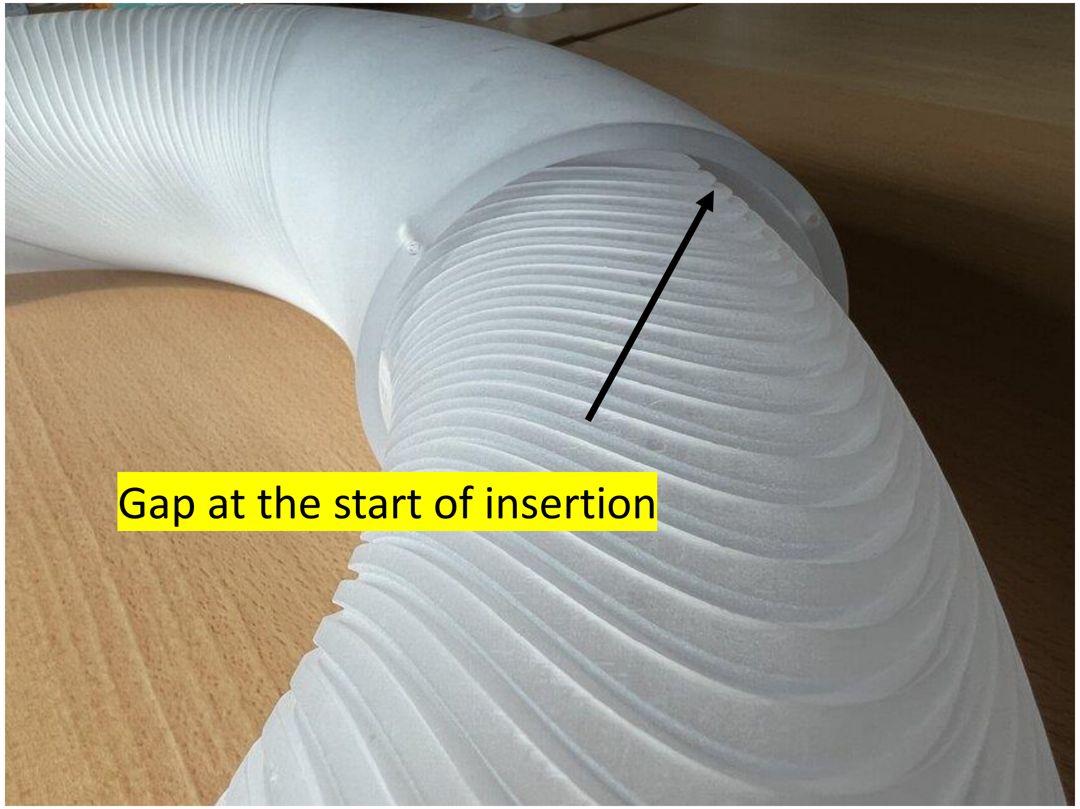
578 A
3.9 MPa
63.4 % ss
2.1 T

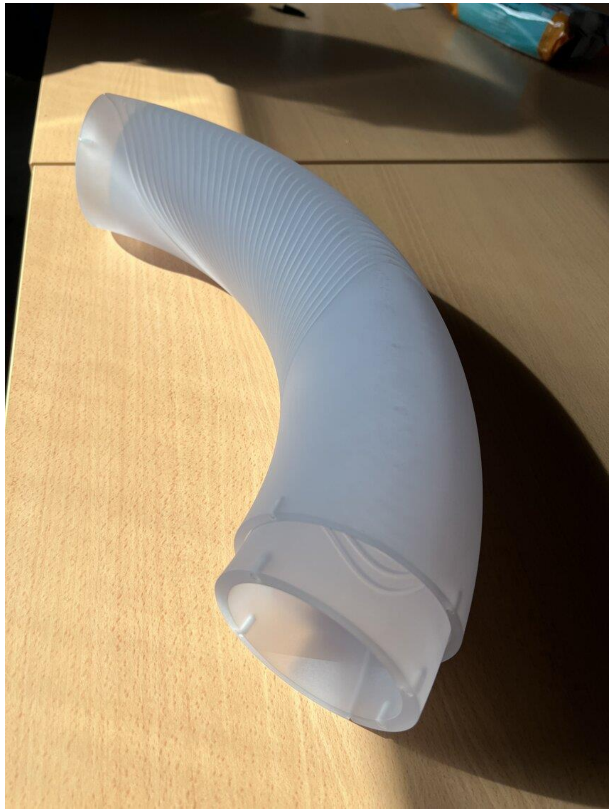
# Test Taper with printed curved formers



The taper allows the two coils' formers to slide together with a gradually reducing gap until aligned in the good Z dimension?
The curved coil forces the azimuthal alignment of the two formers !

A new opportunity for CCT using the taper will be can we apply a radial pre-stress?

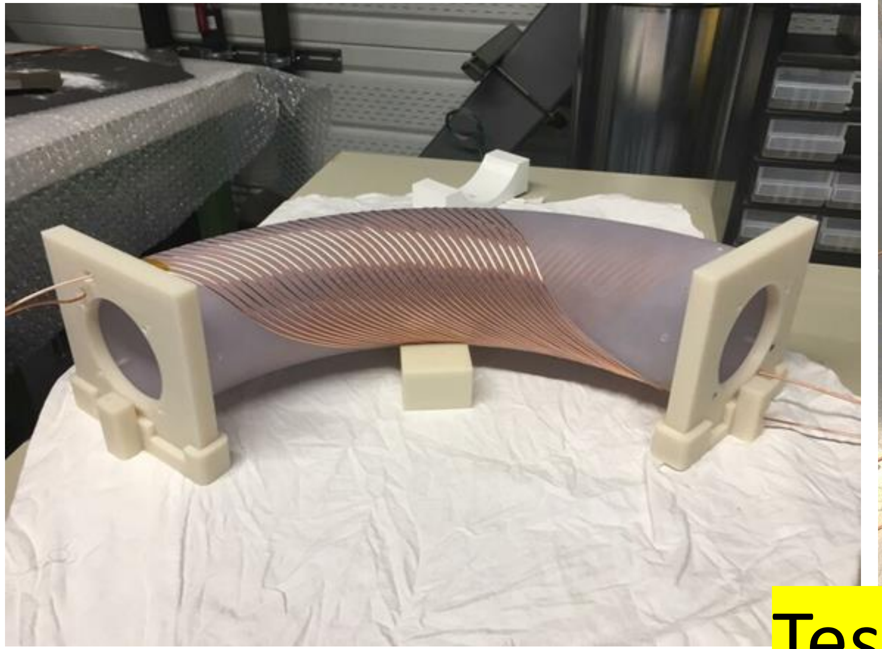



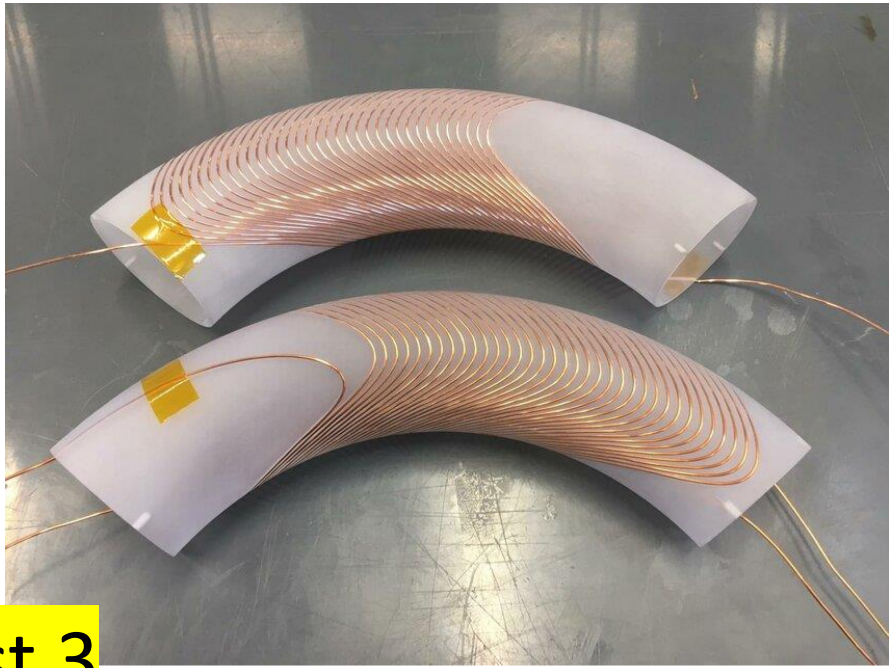



# Pulse tests

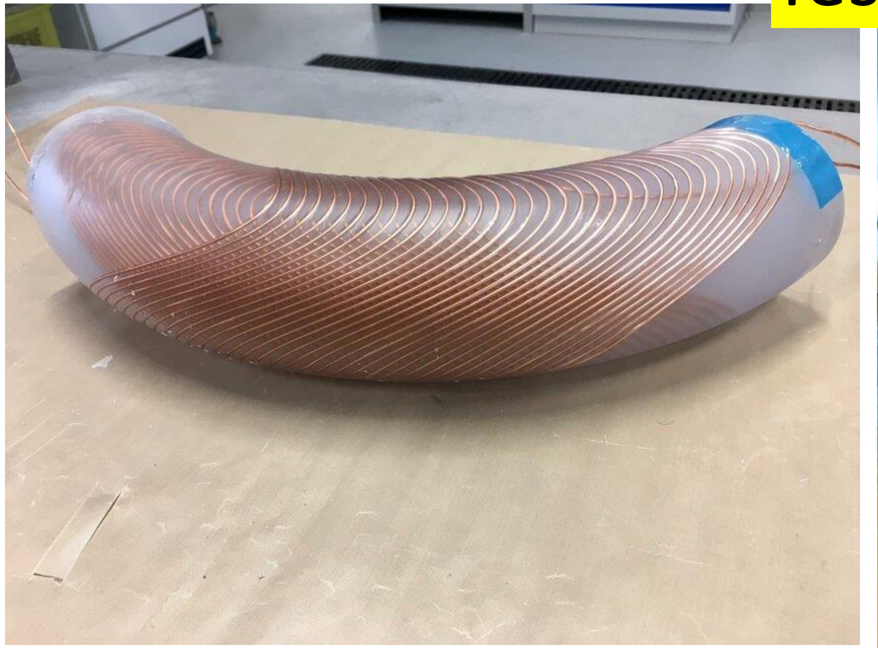
## Set of pulse tests coils

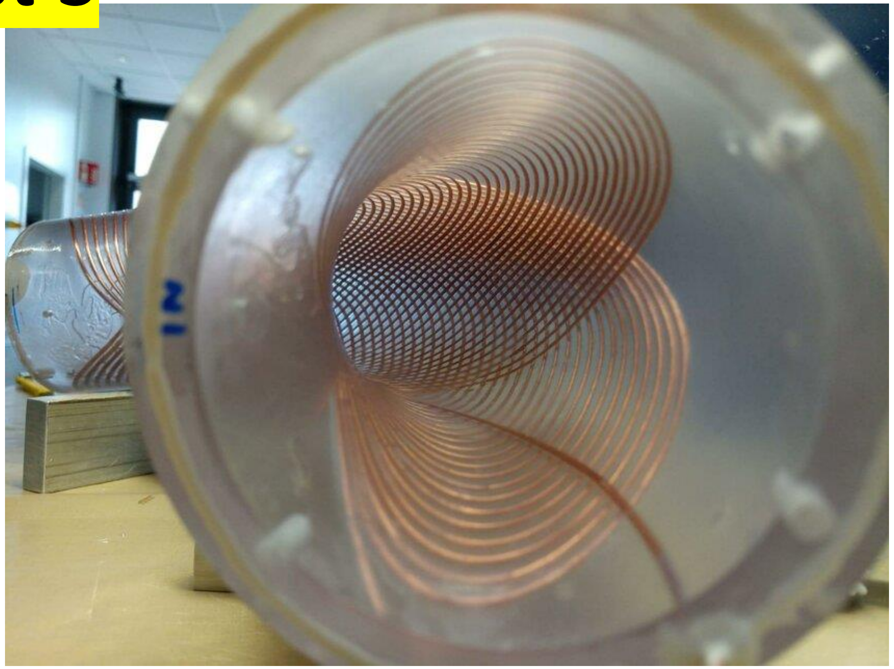
0) Short straight winding test.
1) Straight
2) Curved with no harmonic correction
3) This coil with flat field like fusillo with harmonic corrections
4) The 4th puled coil will be a fully accelerator with < 1-unit errors.





Test 3





# Pulse designs 0 to 3 a field measurements tests

The pulse achieves approximately 1300 A
Field measurements match calculations



## 2. MEASUREMENT PROCEDURE

The magnets were measured using a translating fluxmeter in pulsed field mode. The fluxmeter consists of a stack of two PCB coil arrays, as shown in Fig. 4, each with five coils in a radial configuration [1,2].

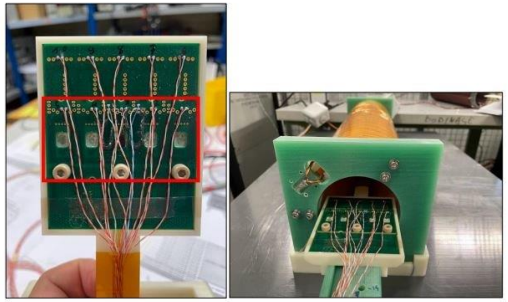


Fig.4 – Left) PCB arrays were used for the measurement. Only the array highlighted in red was used to perform the measurement. Right) Assembly within the long prototype.

The short PCB array has five coils with a rectangular shape, 11.9 mm × 20.2 mm, with a nominal area of 0.01865 mm2. The long PCB array is similar but has a size of 11.9 mm × 66.6 mm, with a nominal area of 0.06319 mm2. A distance of 12.5 mm separates the coil centers. Given the limited number of acquisition channels available on the acquisition board and considering problems of ADC saturation observed during preliminary tests, only the short PCB array was used. The acquisition board is a NI DAQ USB-6356 [3]. The PCB array was installed on a guiding rail, with pin-holes to keep track of the nominal position with respect to the magnet center.

The translating fluxmeter was used in pulsed field mode. At each measurement position, the magnet was pulsed with a current ranging from 800 A to 1200 A. As these current levels are much higher than the nominal current (40 A), the pulses have a 20-30 ms duration to avoid damaging the magnet coils. Such fast pulses were obtained through capacitive discharge. Fig. 5 shows an example of test current and its corresponding field values, measured by the coils.



## 3. RESULTS

### 3.1 CRMRDFUSR001-CR000001

The following figures and tables report the measurement results for the short straight prototype.

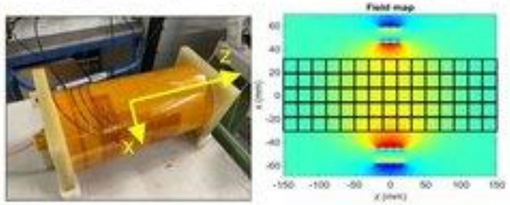



Fig. 6 – Left) A photograph of the short prototype with the reference frame. Right) $B_y$ component of the field at y=0. The grid represents the PCB array positions during the measurement.

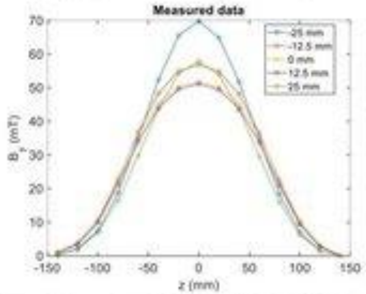



Fig. 7 – Measured field map as a function of the longitudinal position for different x values.



| z [mm] | B [mT] | | | | | I [A] |
|---|---|---|---|---|---|---|
| | x=-25 mm | x=-12.5 mm | x=0 mm | x=12.5 mm | x=25 mm | |
| -140 | 0.23 | 0.75 | 1.078 | 0.794 | 0.043 | 830.2 |
| -120 | 2.09 | 3.13 | 3.936 | 3.463 | 1.848 | 832.6 |
| -100 | 7.41 | 10.07 | 11.010 | 9.924 | 6.802 | 831.4 |
| -80 | 18.66 | 22.32 | 23.024 | 21.348 | 16.361 | 832.4 |
| -60 | 35.08 | 36.73 | 35.924 | 34.011 | 29.759 | 830.2 |
| -40 | 52.34 | 48.26 | 45.310 | 43.919 | 43.645 | 830.1 |
| -20 | 65.46 | 54.91 | 50.308 | 49.524 | 54.190 | 830.5 |
| 0 | 69.86 | 56.81 | 51.718 | 51.122 | 57.882 | 833.0 |
| 20 | 64.78 | 54.77 | 50.236 | 49.377 | 53.730 | 829.9 |
| 40 | 51.67 | 48.60 | 45.174 | 43.722 | 43.294 | 832.7 |
| 60 | 34.61 | 36.38 | 35.648 | 33.607 | 29.416 | 829.4 |
| 80 | 18.33 | 21.97 | 22.644 | 20.766 | 15.874 | 831.4 |
| 100 | 6.98 | 9.58 | 10.477 | 9.353 | 6.256 | 832.5 |
| 120 | 1.41 | 2.55 | 3.113 | 2.717 | 1.373 | 831.9 |
| 140 | 0.02 | 0.03 | 0.049 | 0.012 | 0.015 | 827.5 |

Tab. 1 – Measured field values for the short prototype as a function of the longitudinal position

### 3.2 CRMRDFUSR002-CR000001

The following figures and tables report the measurement results for the long straight prototype.

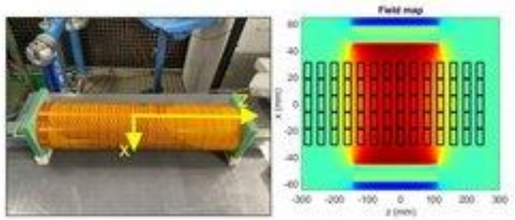



Fig. 9 – Left) A photograph of the short prototype with the reference frame. Right) $B_y$ component of the field at y=0. The grid represents the PCB array positions during the measurement.



### 3.3 CRMRDFUSR003-CR000001

The following figures and tables report the measurement results for the curved prototype.

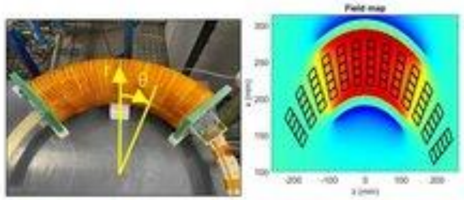



Fig. 12 – Left) A photograph of the curved prototype with the reference frame. Right) $B_y$ component of the field at y=0. The grid represents the PCB array positions during the measurement.

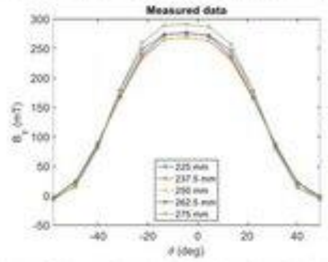
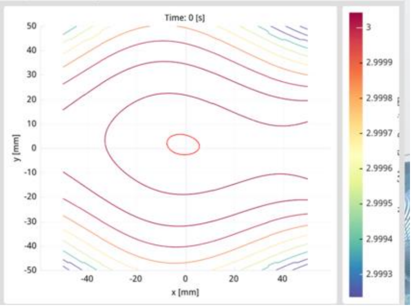
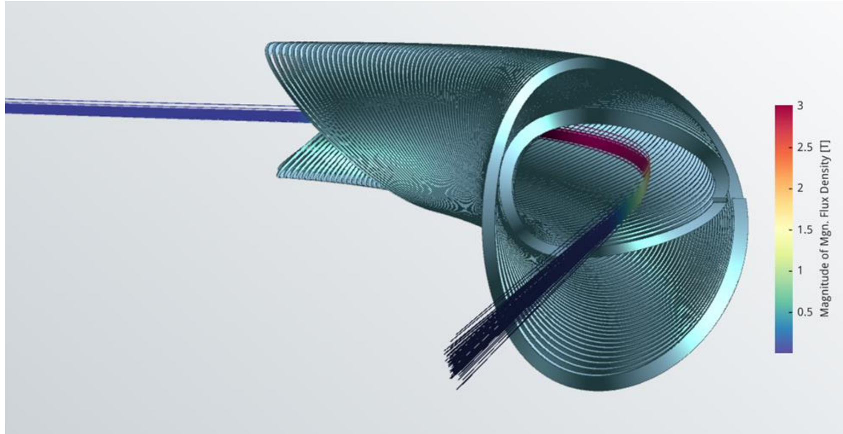



Fig. 13 – Measured field map as a function of the angular position for different r values.

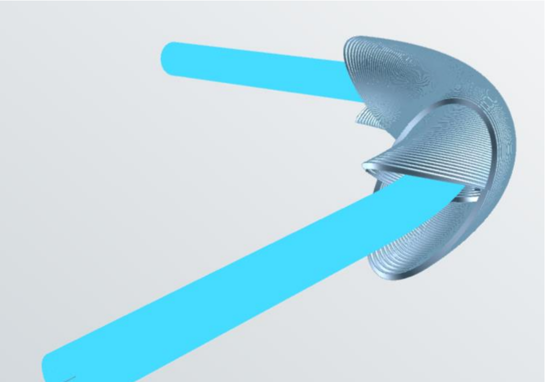
# V 17 Harmonics table




See slide 21, central field errors 1 unit




At 3.000 T and a Beam energy calc 1.12 GeV 100 partials, 5mm x 5mm Sigmax from Emitter 90 deg bend,



Harmonic calculation rings on curved 1 m radius path with 1 m straight sections.

Harmonics Calculation - Aperture Harmonics 1

Export

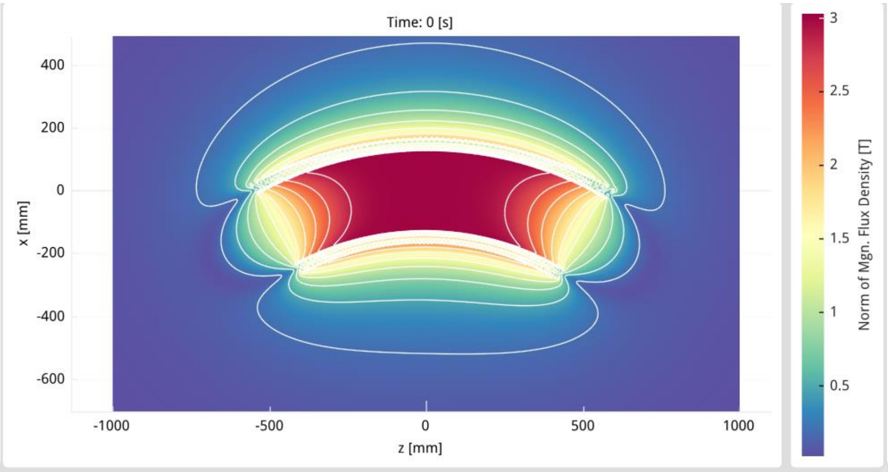
Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

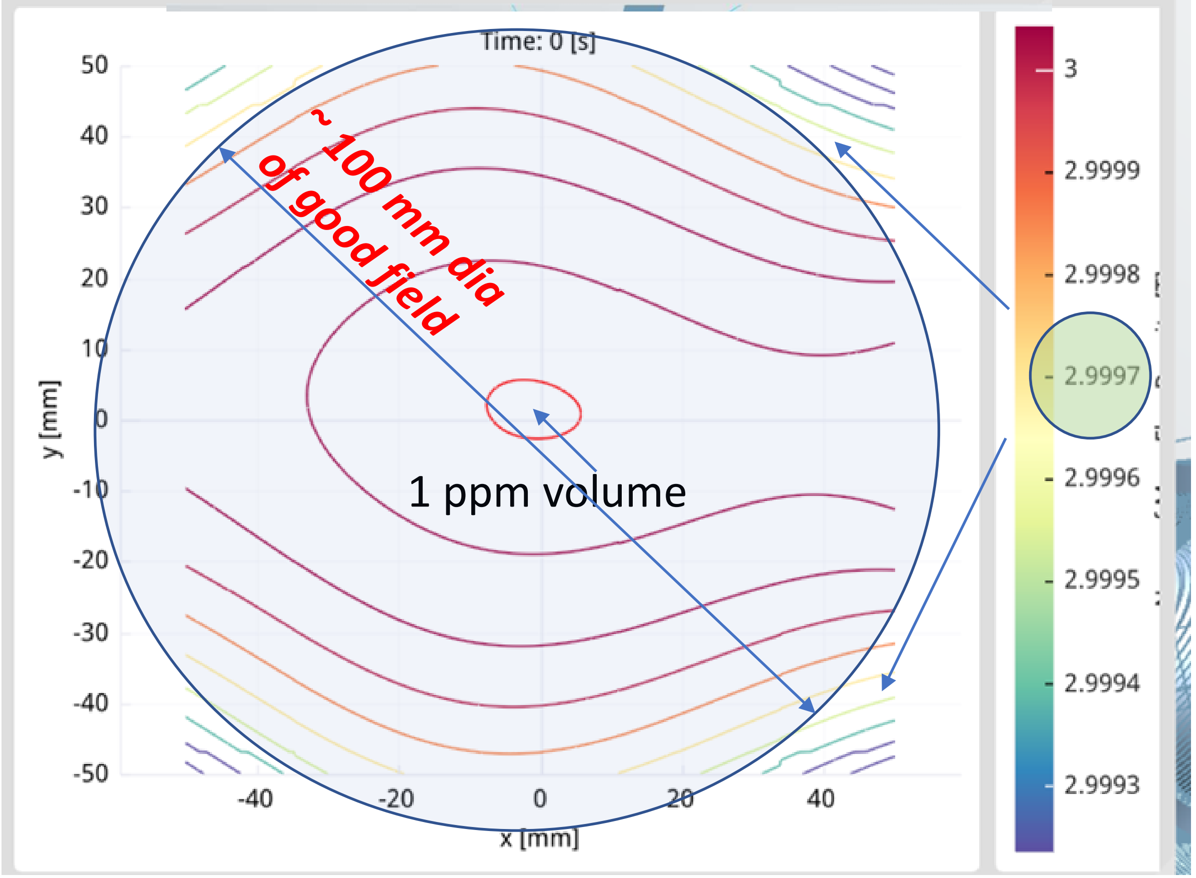
harmonics given at a reference radius of: 66.000 [mm]

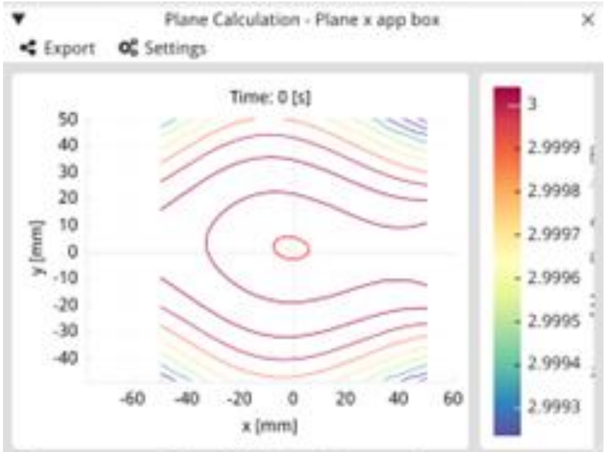
| Order | An [T.m] | an | Normalized Shape | Order | Bn [T.m] | bn | Normalized Shape |
|---|---|---|---|---|---|---|---|
| A1 | 6.42e-05 | -0.22 | | B1 | -2.87e+00 | 10000.00 | |
| A2 | -1.62e-03 | 5.65 | | B2 | -1.04e-01 | 363.46 | |
| A3 | 5.65e-05 | -0.20 | | B3 | 1.33e-03 | -4.64 | |
| A4 | 5.07e-05 | -0.18 | | B4 | -9.00e-05 | 0.31 | |
| A5 | 2.35e-05 | -0.08 | | B5 | -7.14e-06 | 0.02 | |

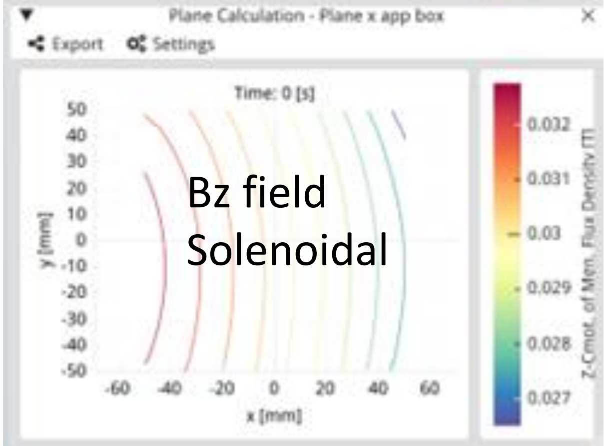
Harmonics Calculation
- Appearance
  - Aperture Harmonics 1 — name
  - ✓ visibility
- Geometry
  - ✓ compensate curvature
  - 66 mm — radius
  - 64 — ntheta
  - 10 — nmax
- CUDA Settings
  - ✓ NVIDIA GeForce GTX 107...
- MLFMM Settings
  - direct Biot Savart
  - ✓ ext. interaction list
  - 7 — num exp
  - 400 — nrefine

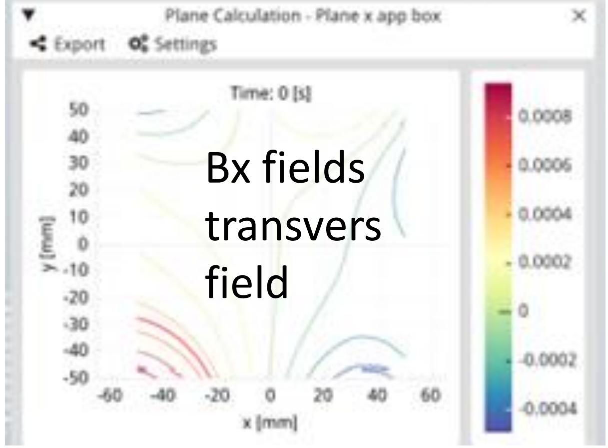
# Magnetic field at center



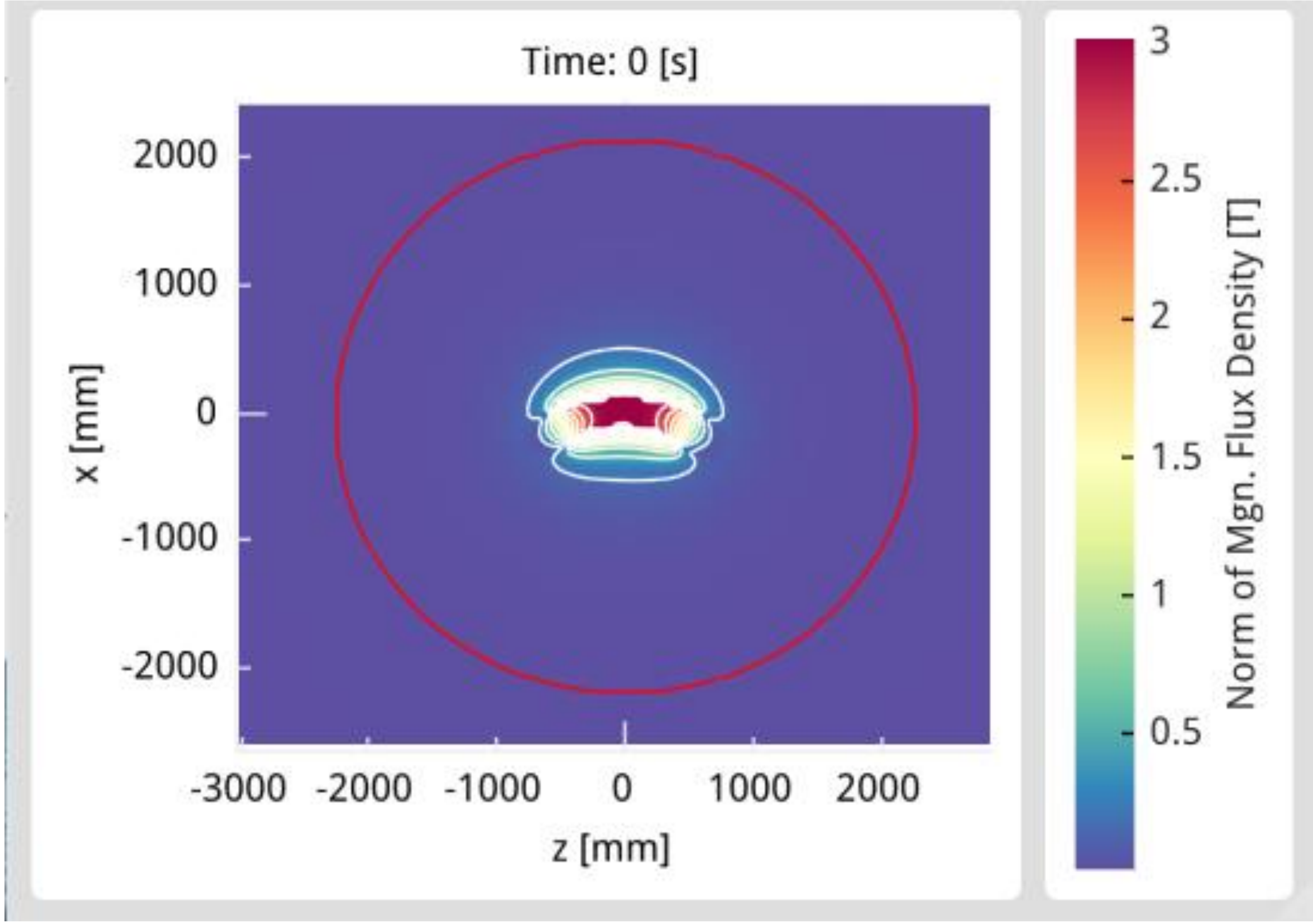



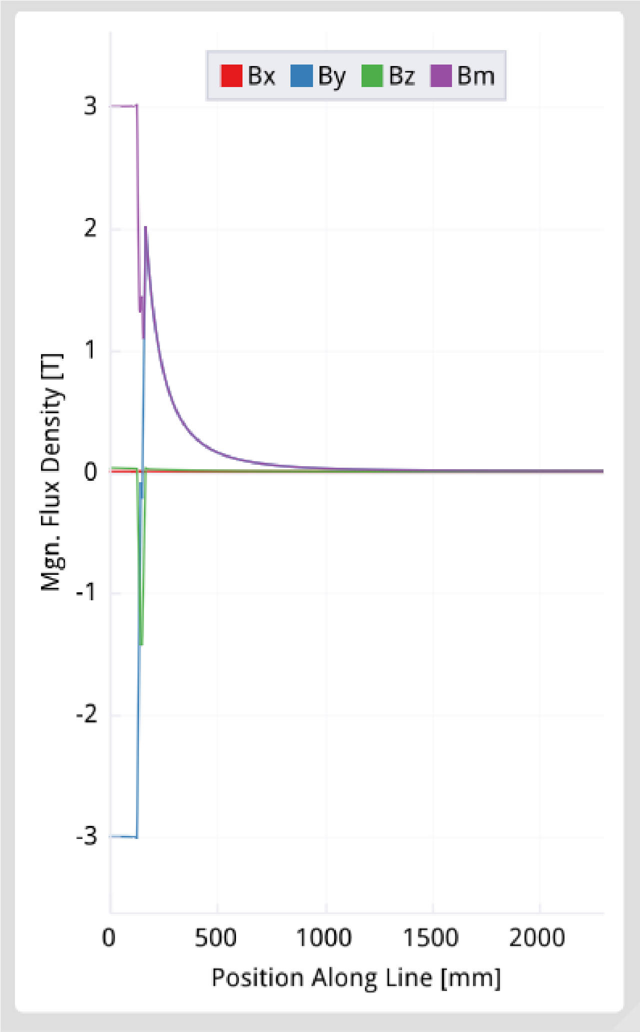




The central field is designed to have a large volume of 3 Tesla.

3 gauss variation from center! = 1 unit over ~ 80mm dia.

# Stray fields

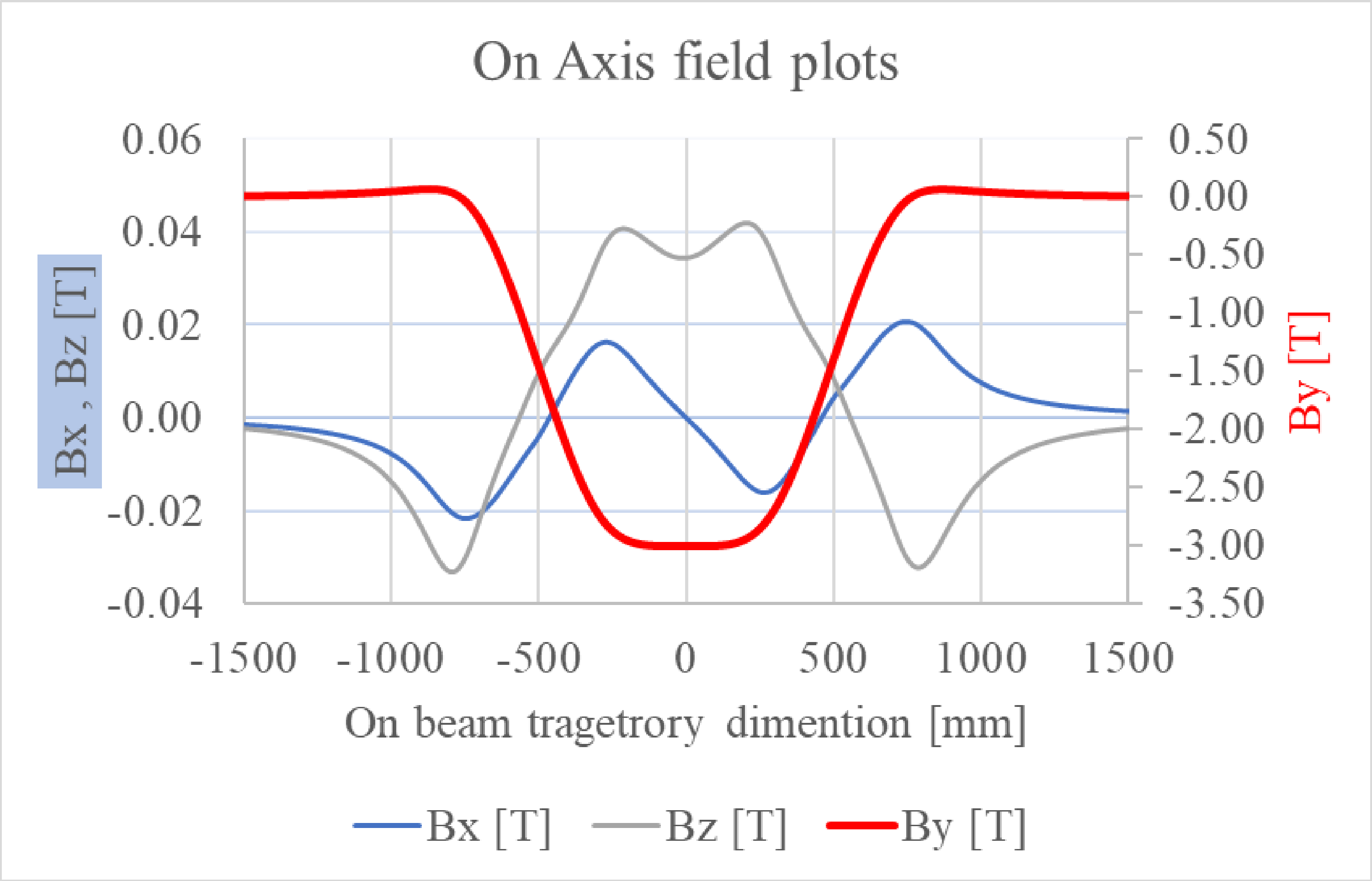


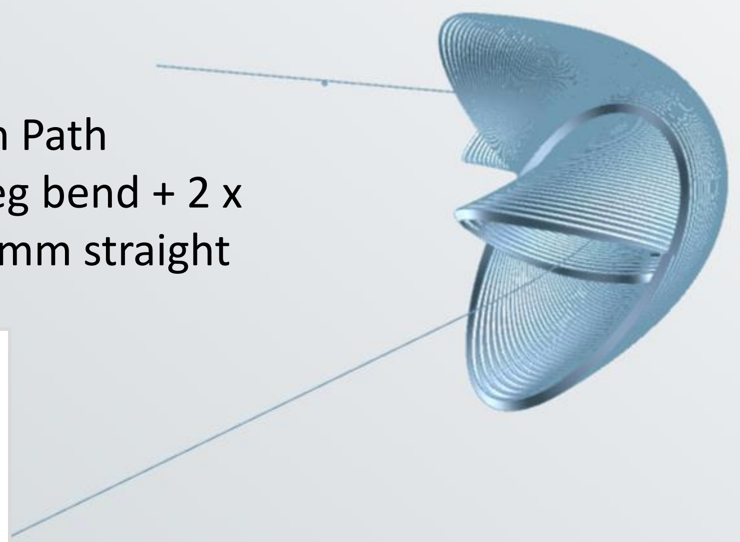

30 gauss line at 2.2 m from center of magnet, About 1.72 m from the outside of the cryostat in X direction

# On axis field

Fields along the beam path




Beam Path
90 deg bend + 2 x
1000mm straight



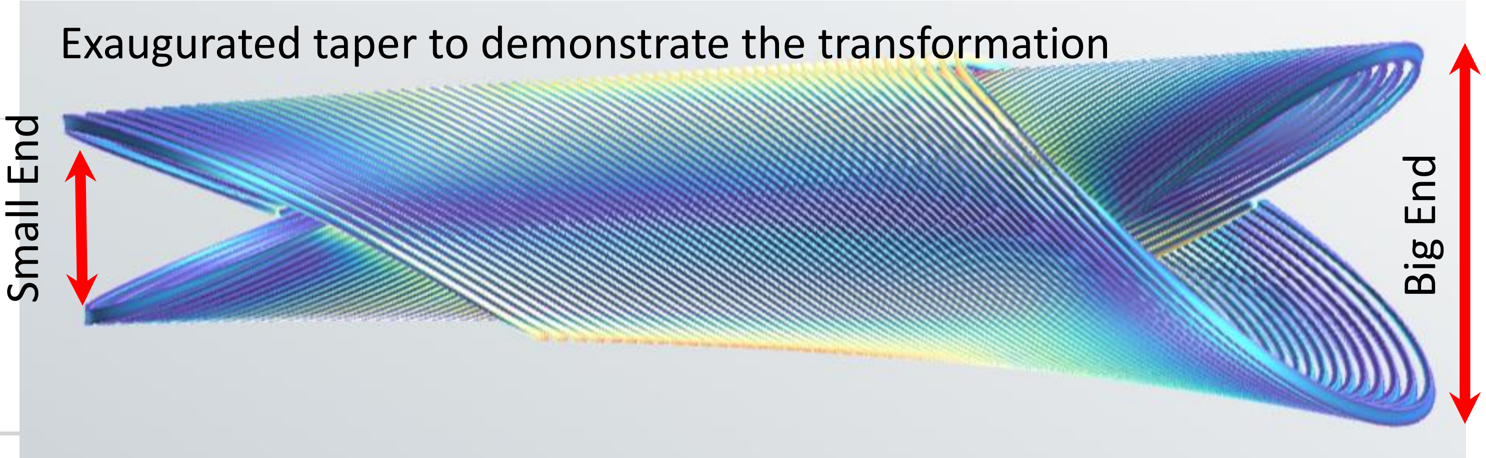
Line Integral

Export Settings

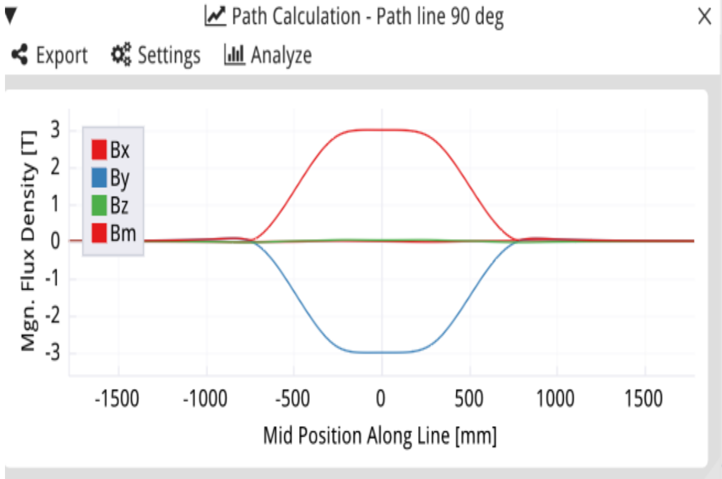
field integral in [Tm]

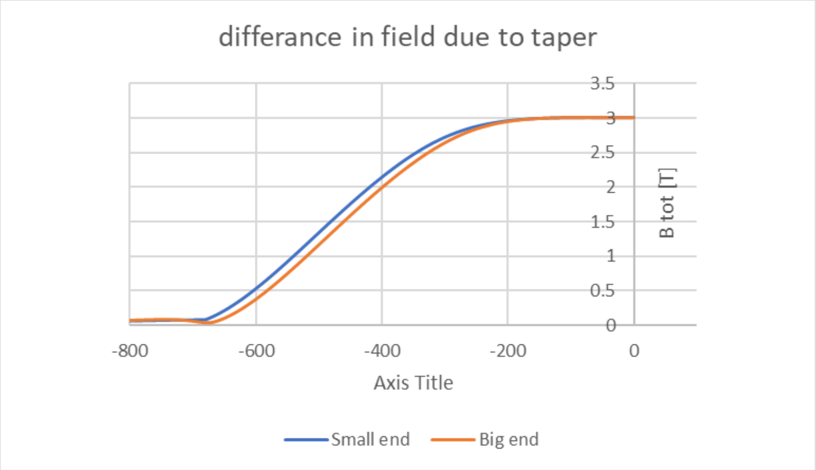
| field | Bx | By | Bz |
|---|---|---|---|
| integral | -3.668e-04 | -2.867e+00 | 8.127e-03 |

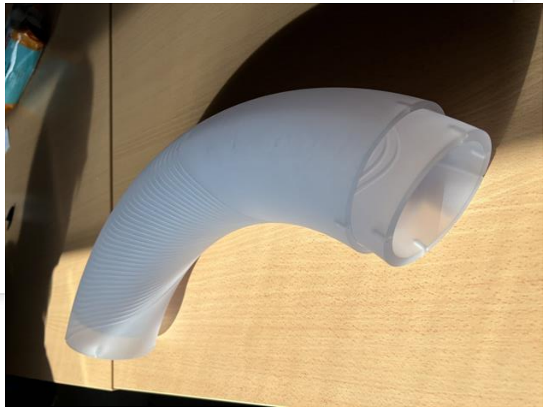
# Effect of taper on the on-axis field

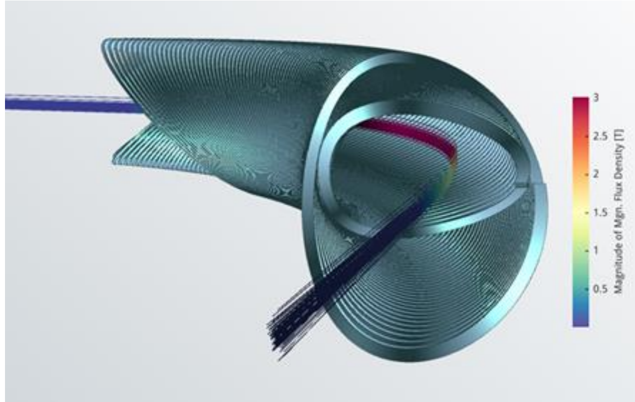


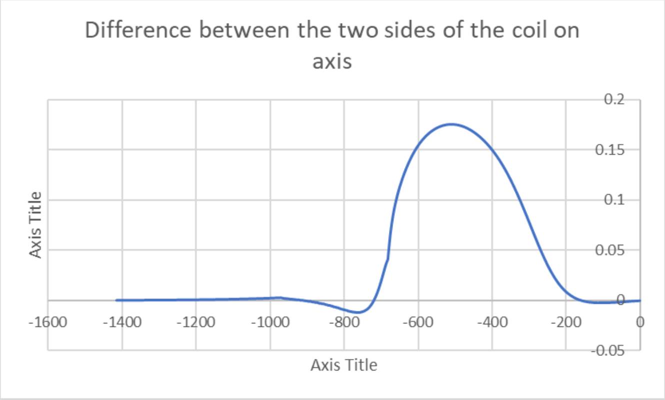

As the aperture reduces, the field increases! The plot shows the additional field in the smaller side of the coil. This could be corrected; however, it would just talk integral field away from bend. So, the beam would be bent less! We don't need to correct this effect.



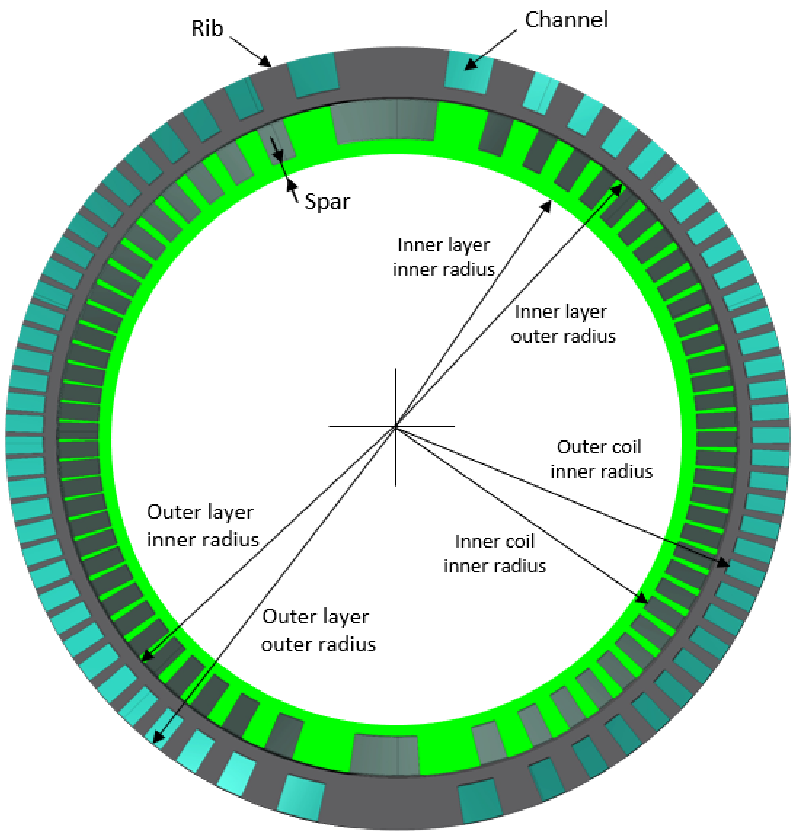



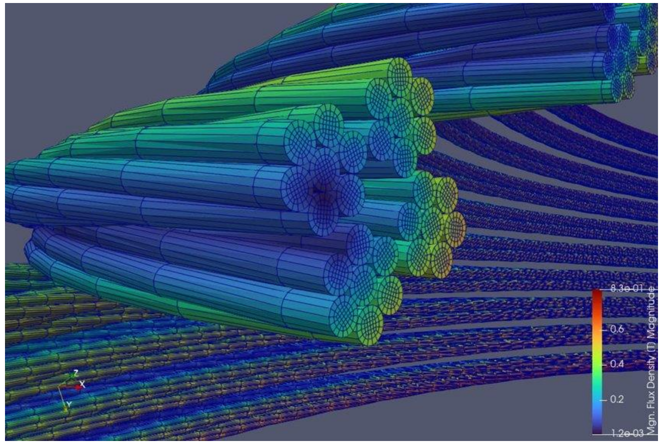



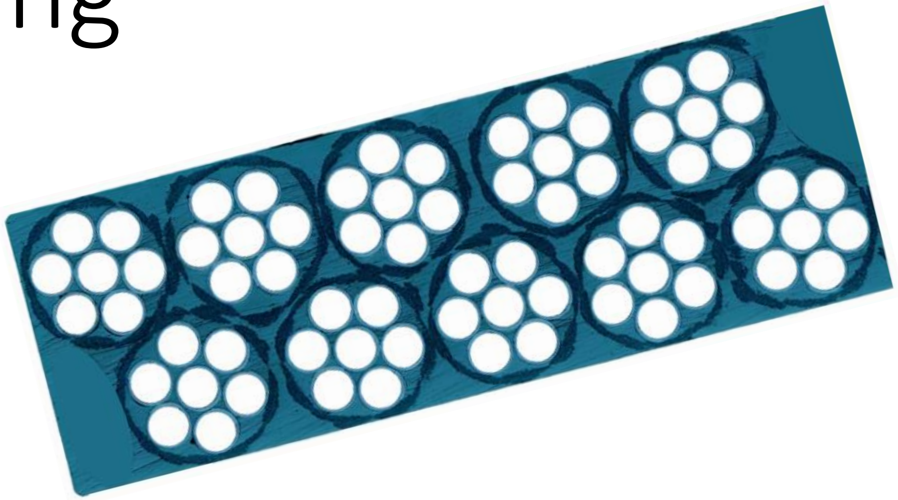


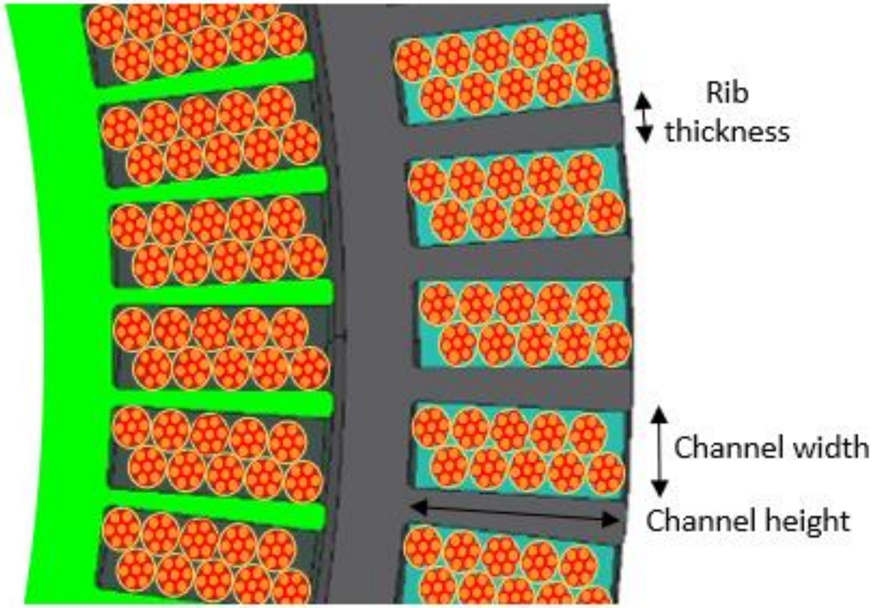


# Coil cross section and cable stacking







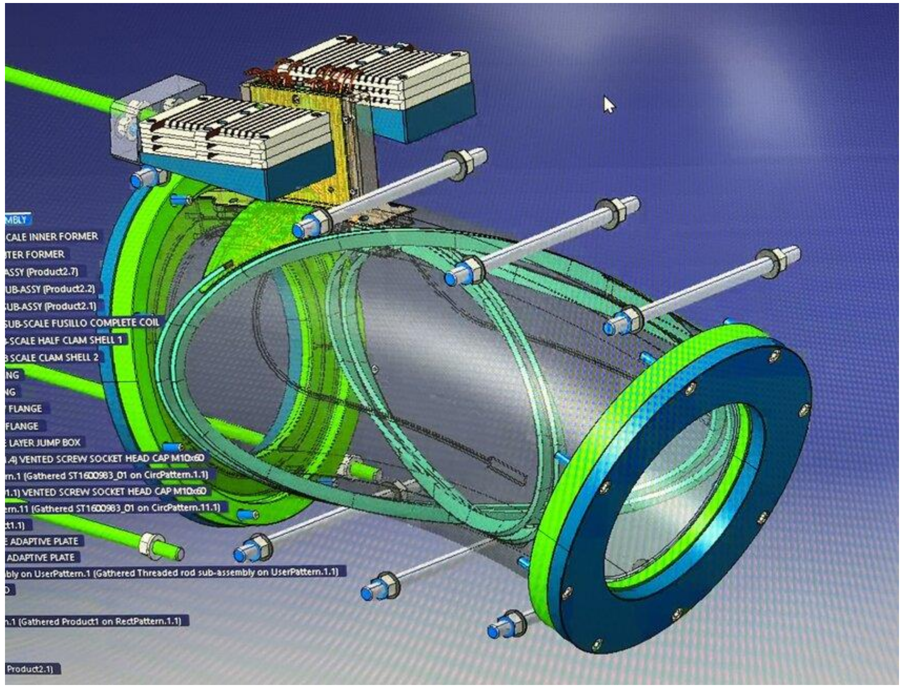

The rope cable enables us to wind 70 strands in one pass. Also, the rope transposition helps with quench propagation, the **log stacking** layout **reduces resin volume** and makes the coil pack **mechanically more stable** !,

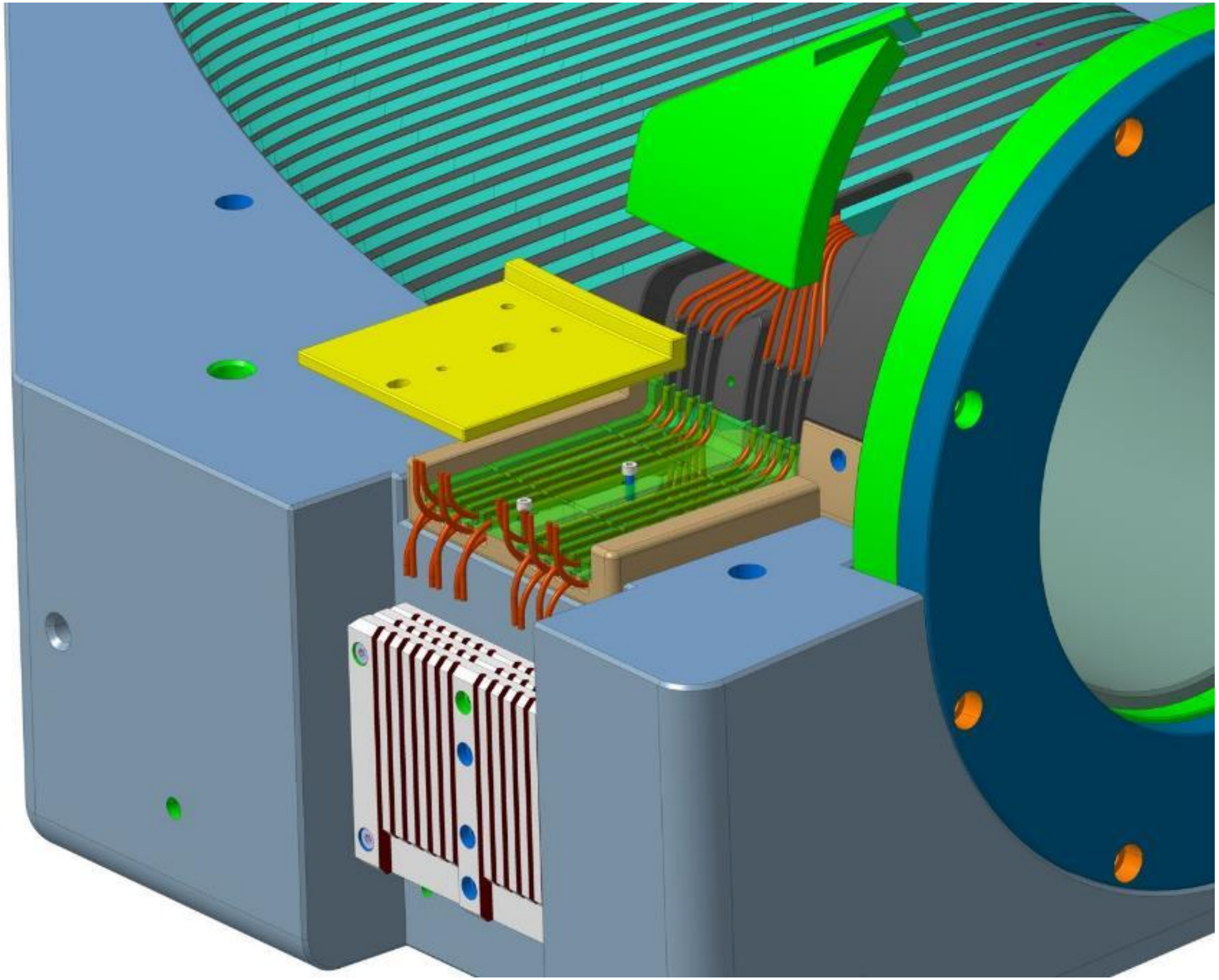
# Joint box

**Electrical connections**

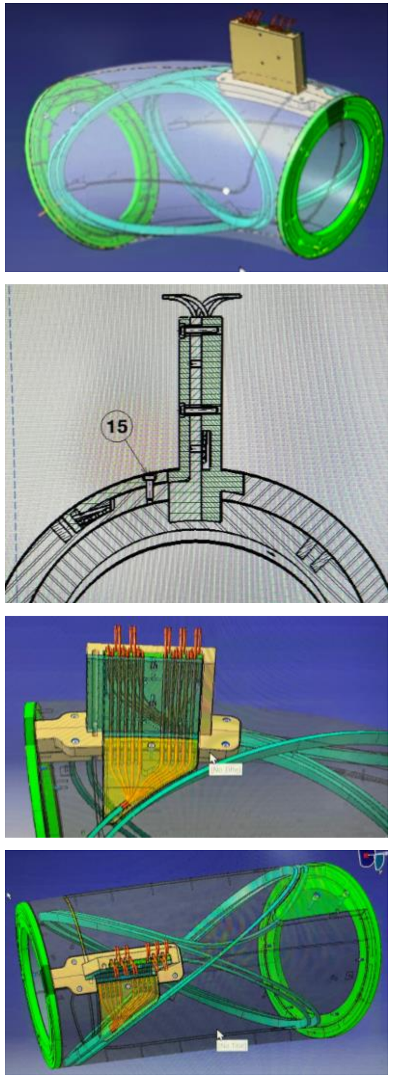
- 69 connections to make between wires
- A guiding box allow a controlled separation of the different cables
- The cables are then untwisted before connection

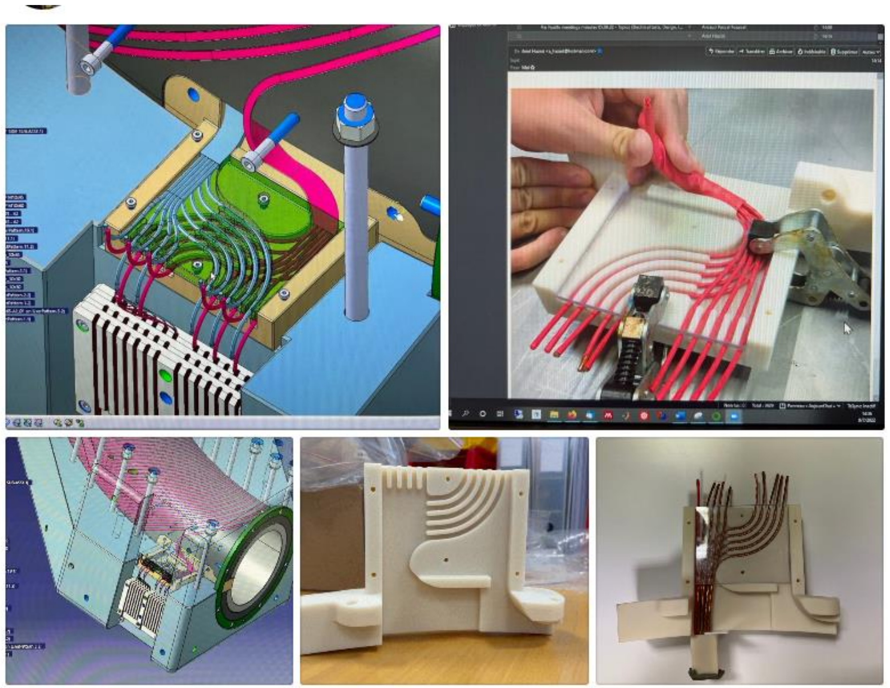
**Box is waiting for inputs to be as practical as possible**



# Joint box development



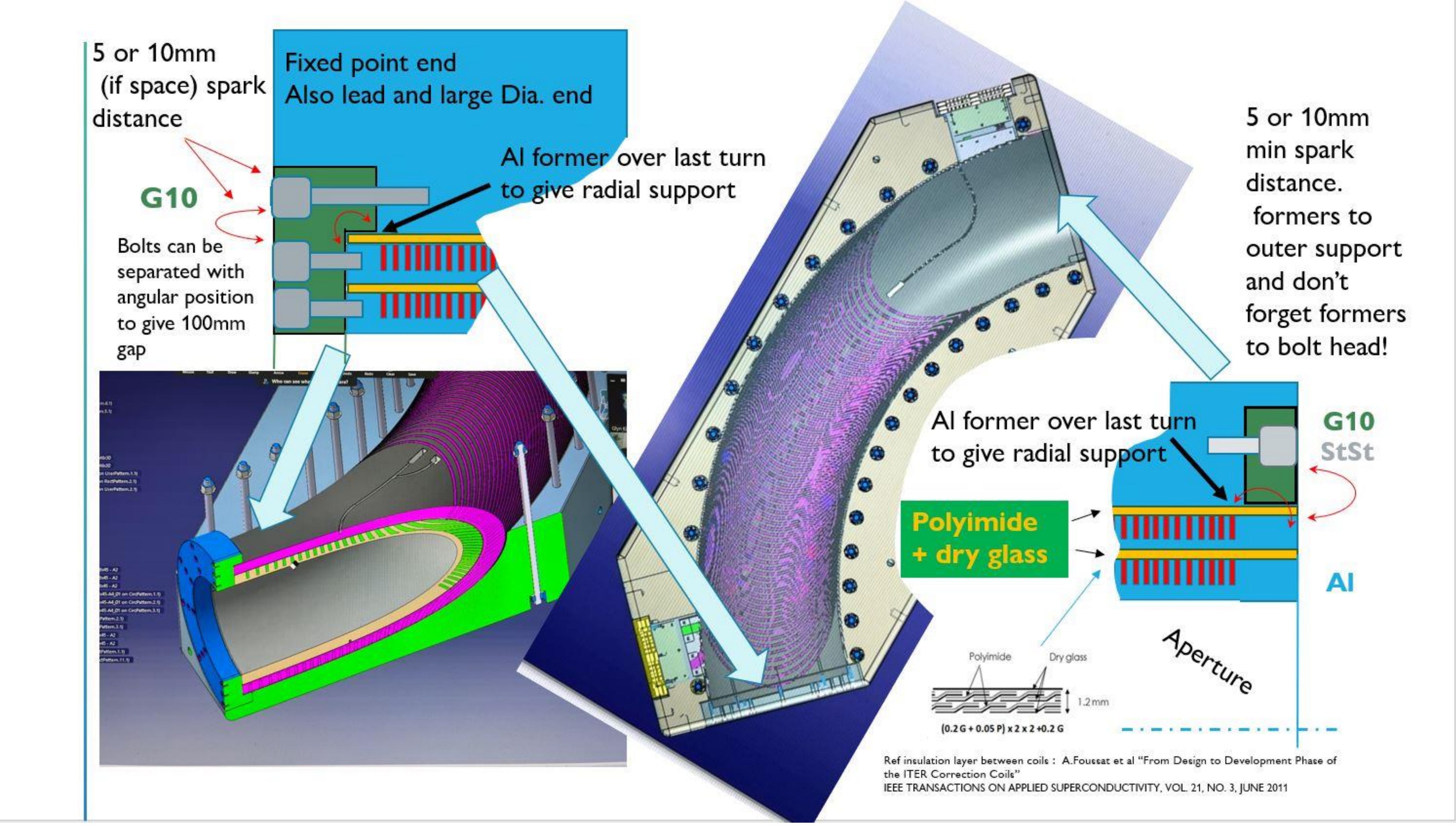



## Ongoing joint box development

We added individual guiding channels to the box. However the angle that the ropes enter the box made placing the ropes difficulty, with a high strain that could damage the insulation, so we are redesigning the path that the rope takes into the box. We will add clamping in stages to hold the ropes. The test box will now be modified. So the images above are now out of date. The box will have several stages. A sealing zone, a zone where the ropes are unwound , joint box volume, cooling , insulation!

The Gif shows the support that is fixed to the formers and supports the joint box that moves with the coil former and not the outer support.

# Ground insulation




Two layers of 125 um polyimide sheets and spark backdown distance > 5 mm !

# Impregnation

- Impregnation of both layers together with MY-750
- Impregnation directly in mechanical shell
- Curing temperature ~80 degrees

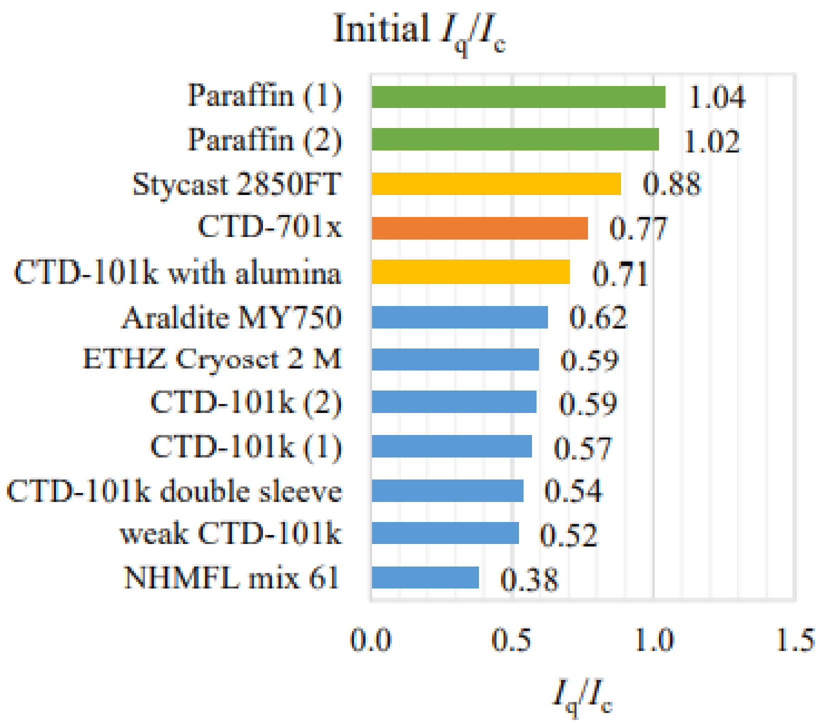
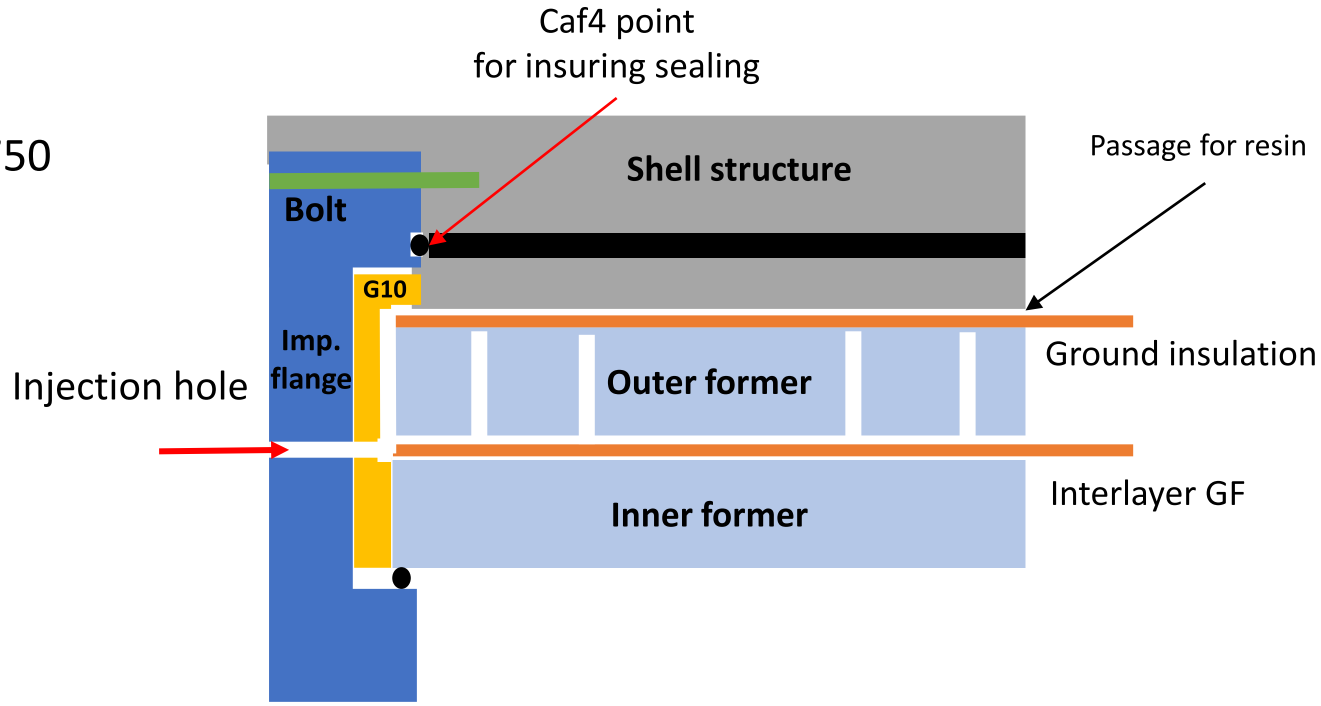
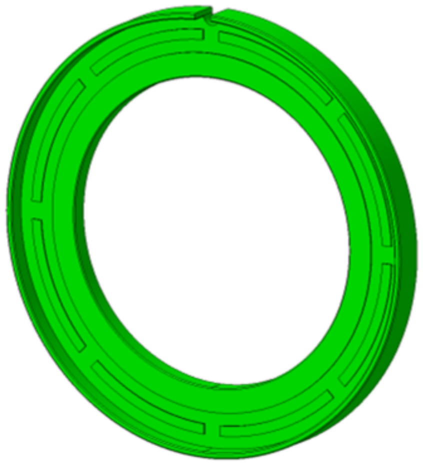
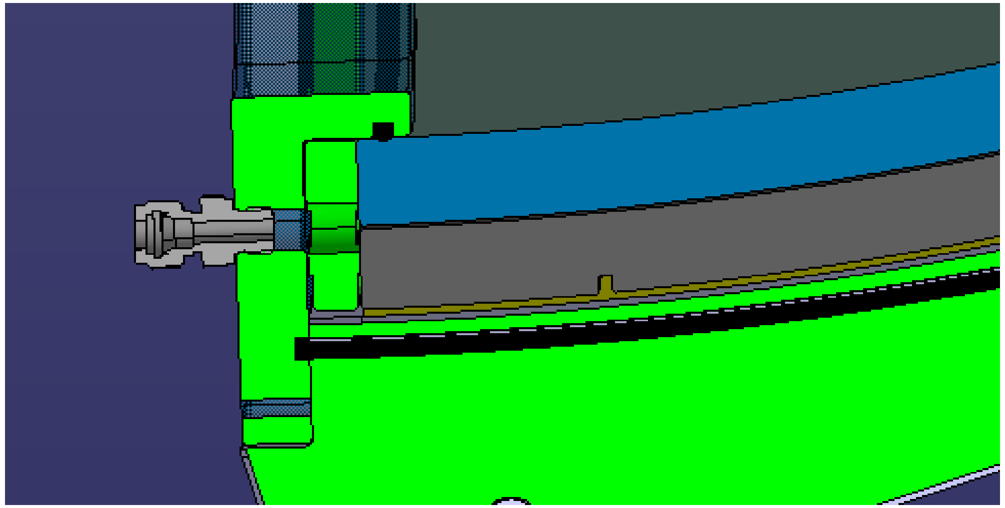


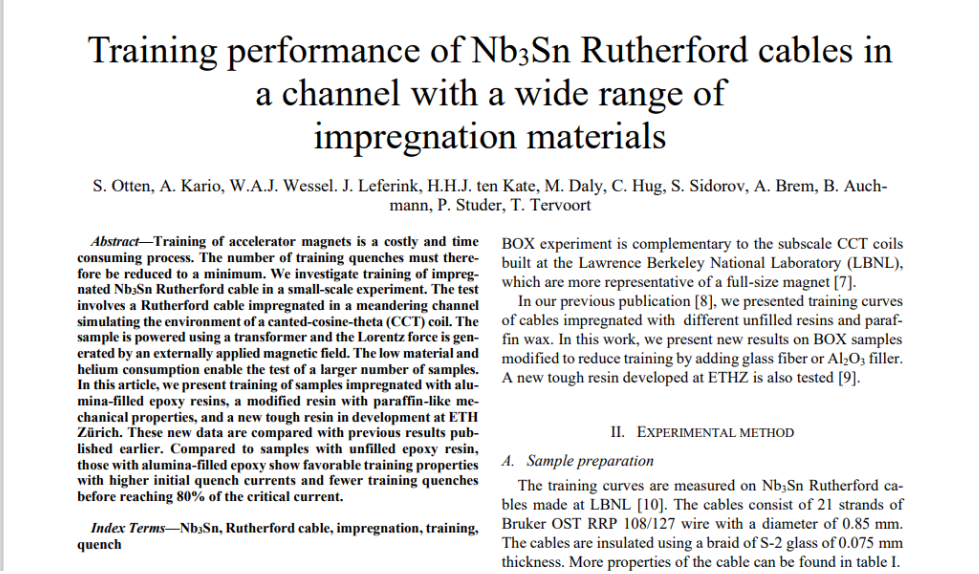

Fig. 5. Initial quench current normalized to the critical current for impregnated samples. Unfilled epoxies are shown in blue, alumina-filled epoxies in orange, polyolefin resin in red, and paraffin in green.





ASC 2022 paper Honolulu



3LOr2B-06 1

# Training performance of $Nb_3Sn$ Rutherford cables in a channel with a wide range of impregnation materials

S. Otten, A. Kario, W.A.J. Wessel. J. Leferink, H.H.J. ten Kate, M. Daly, C. Hug, S. Sidorov, A. Brem, B. Auchmann, P. Studer, T. Tervoort

*Abstract*—**Training of accelerator magnets is a costly and time consuming process. The number of training quenches must therefore be reduced to a minimum. We investigate training of impregnated $Nb_3Sn$ Rutherford cable in a small-scale experiment. The test involves a Rutherford cable impregnated in a meandering channel simulating the environment of a canted-cosine-theta (CCT) coil. The sample is powered using a transformer and the Lorentz force is generated by an externally applied magnetic field. The low material and helium consumption enable the test of a larger number of samples. In this article, we present training of samples impregnated with alumina-filled epoxy resins, a modified resin with paraffin-like mechanical properties, and a new tough resin in development at ETH Zürich. These new data are compared with previous results published earlier. Compared to samples with unfilled epoxy resin, those with alumina-filled epoxy show favorable training properties with higher initial quench currents and fewer training quenches before reaching 80% of the critical current.**

***Index Terms*—$Nb_3Sn$, Rutherford cable, impregnation, training, quench**

BOX experiment is complementary to the subscale CCT coils built at the Lawrence Berkeley National Laboratory (LBNL), which are more representative of a full-size magnet [7].

In our previous publication [8], we presented training curves of cables impregnated with different unfilled resins and paraffin wax. In this work, we present new results on BOX samples modified to reduce training by adding glass fiber or $Al_2O_3$ filler. A new tough resin developed at ETHZ is also tested [9].

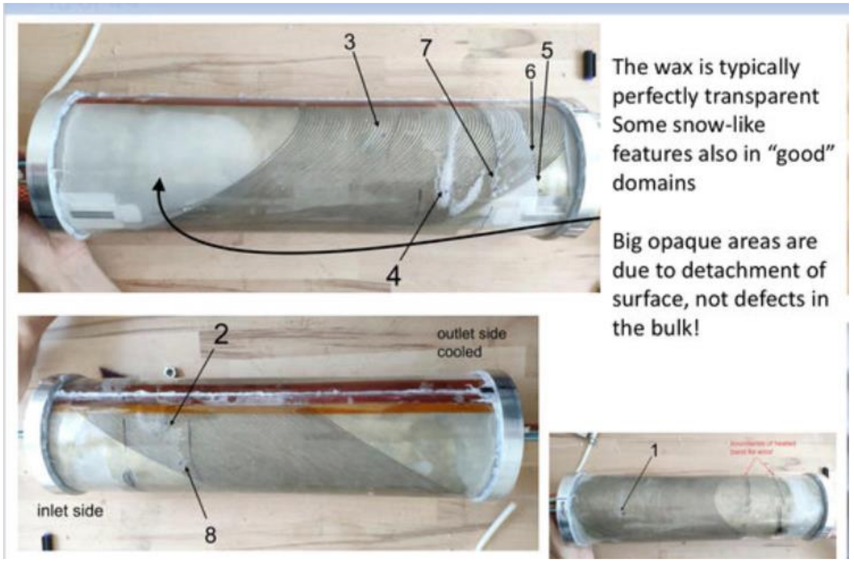
II. EXPERIMENTAL METHOD

*A. Sample preparation*

The training curves are measured on $Nb_3Sn$ Rutherford cables made at LBNL [10]. The cables consist of 21 strands of Bruker OST RRP 108/127 wire with a diameter of 0.85 mm. The cables are insulated using a braid of S-2 glass of 0.075 mm thickness. More properties of the cable can be found in table I.

https://youtu.be/jziguNhHCg8

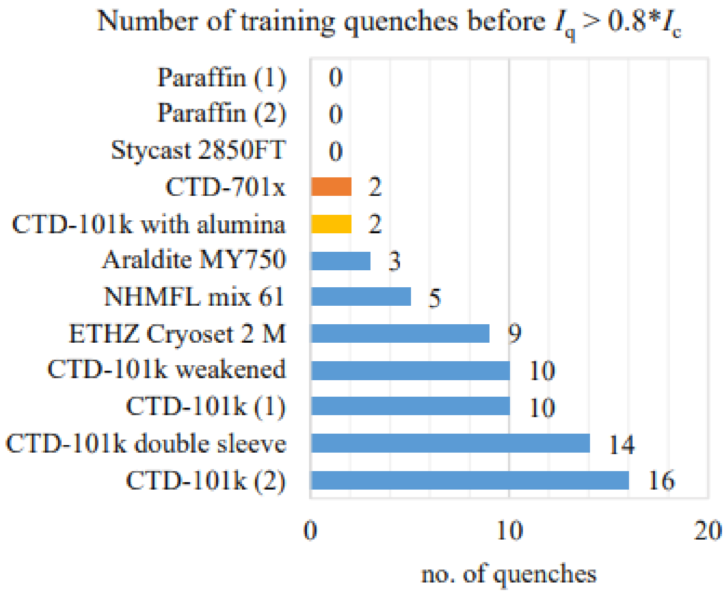
WAX Magnet test due 2023

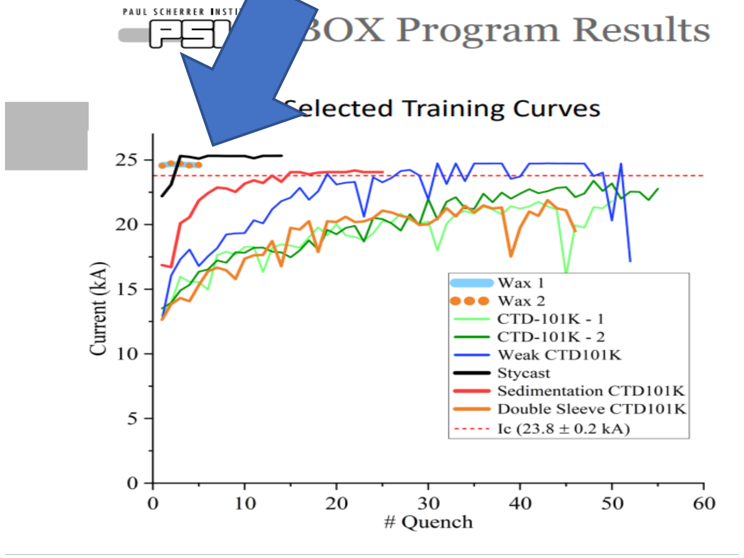



The wax is typically perfectly transparent
Some snow-like features also in "good" domains

Big opaque areas are due to detachment of surface, not defects in the bulk!

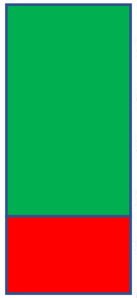
No quenching

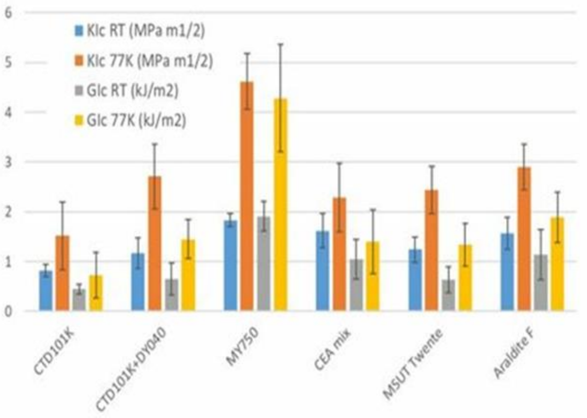



Wax has no quenches

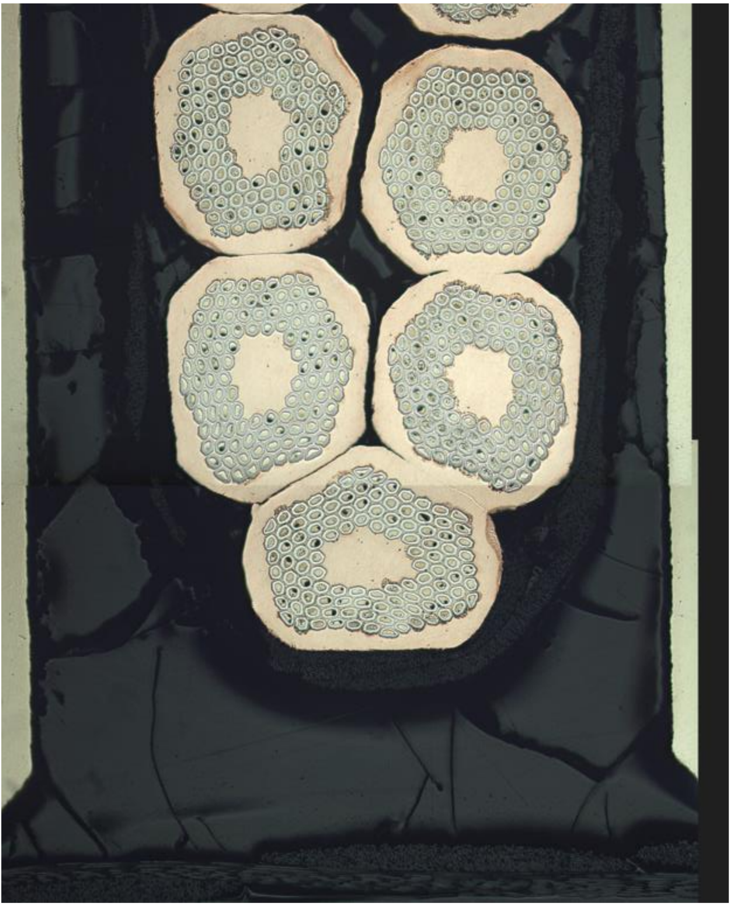
Thanks to D. Barna



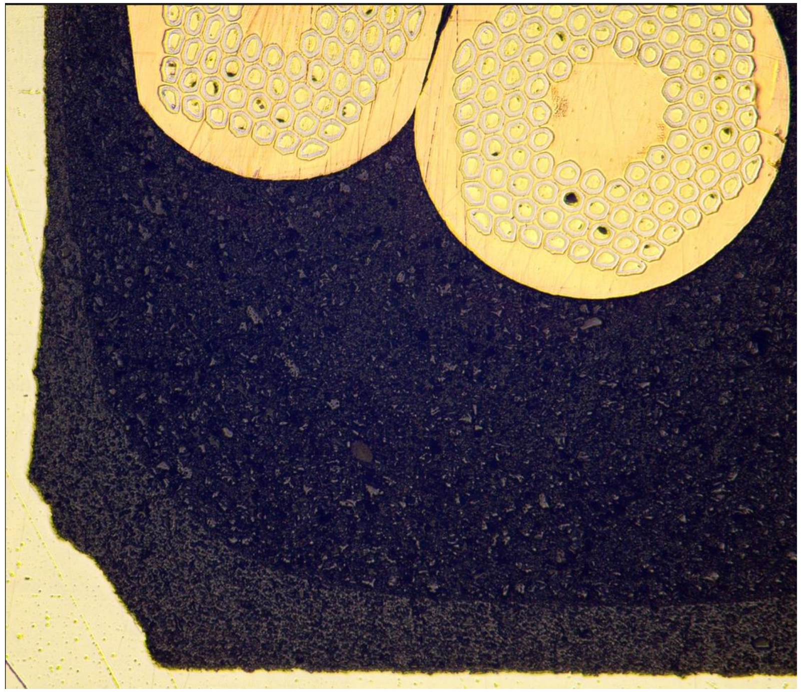



Fracture turfiness of resins above 1.5 would have a large advantage !

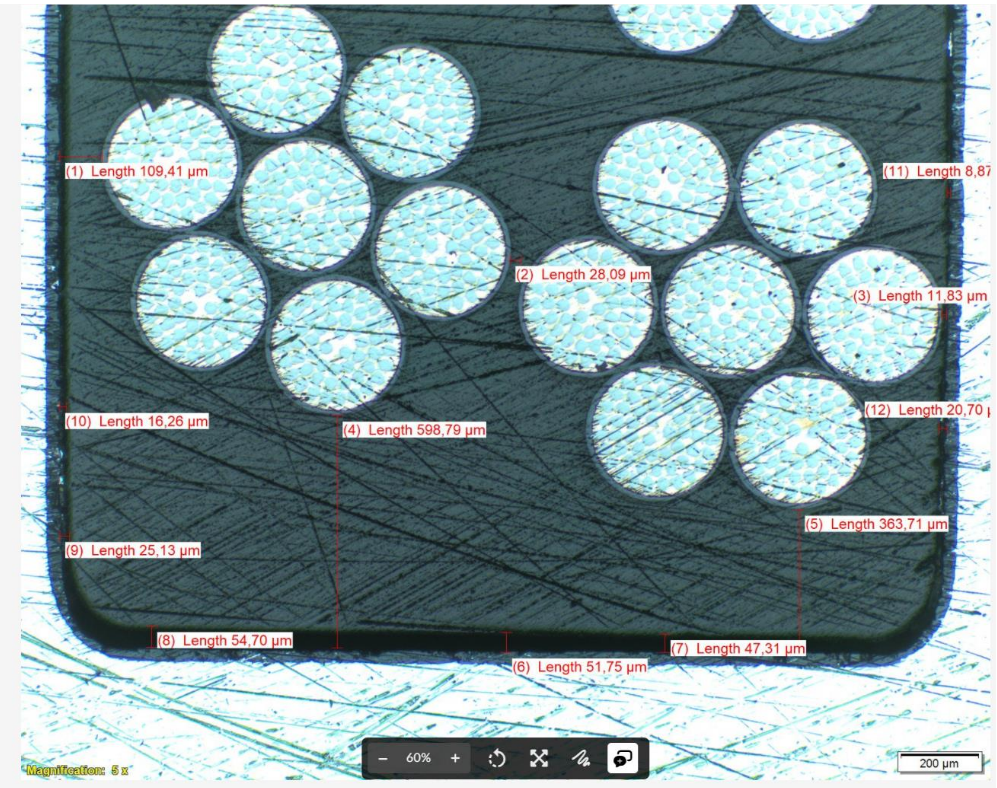
# Impregnation testing



CTD 101K
Many cracks in resin and poor magnet performance 60% after long training

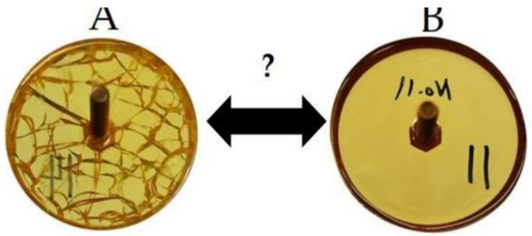


StyCast
No cracks , matches thermal contraction
But difficult to inject ! Again low number of quenches



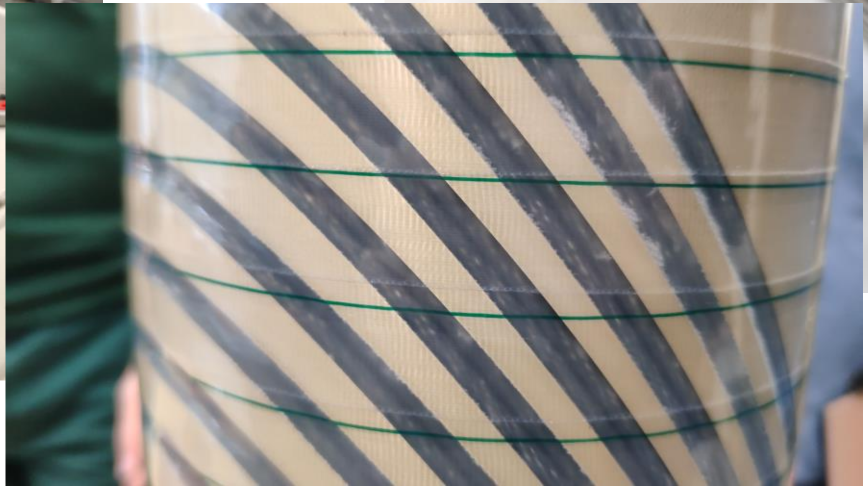

MY750
Classical NMR resin system for 40 + years
De-bonded at edges preferred material !

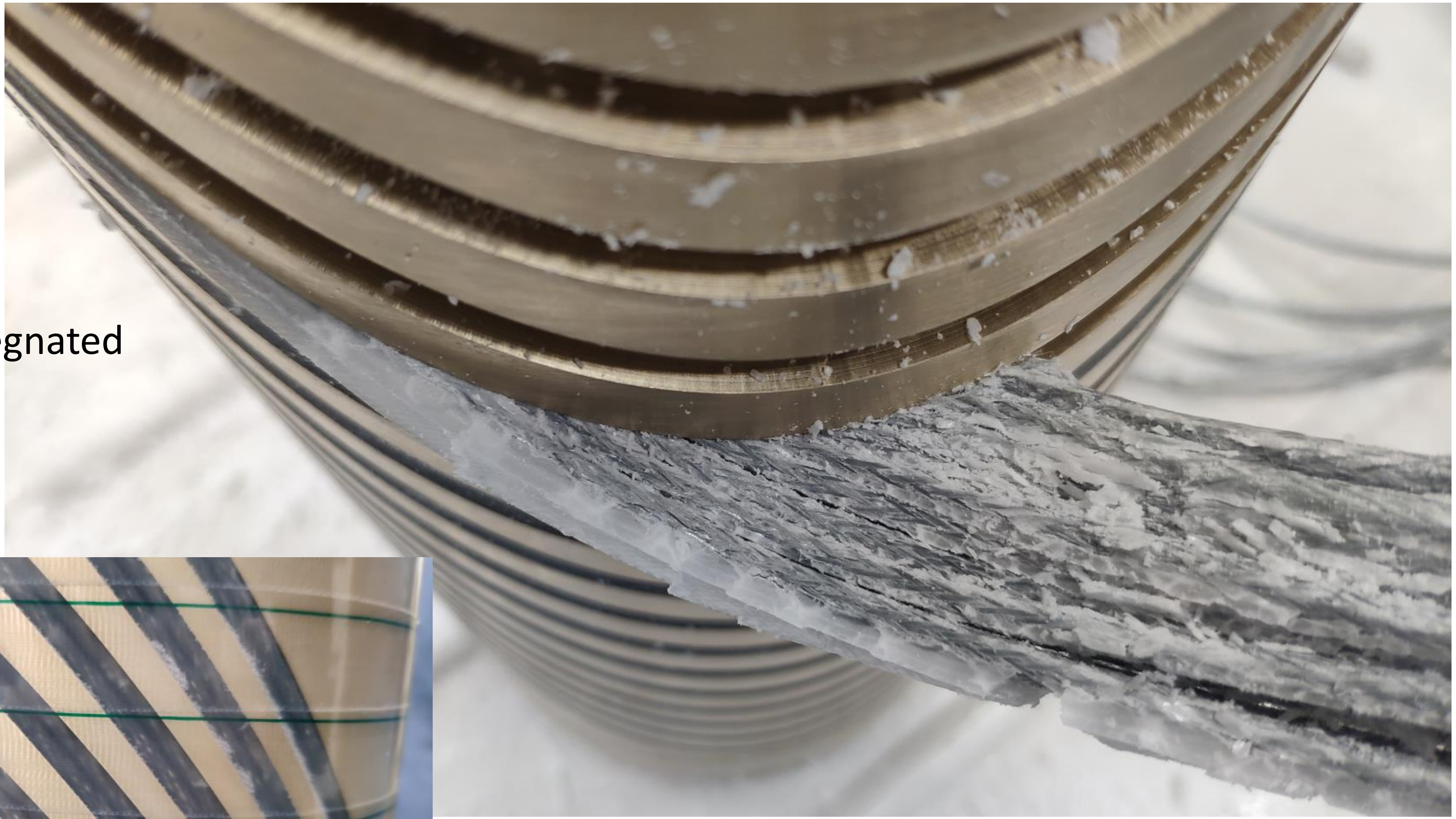
If wax is not possible for some reason



# Wax impregnation test in CCT coil

Fully impregnated with WAX !

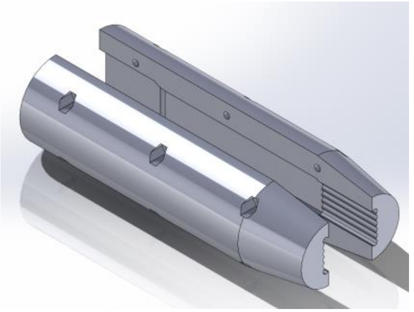


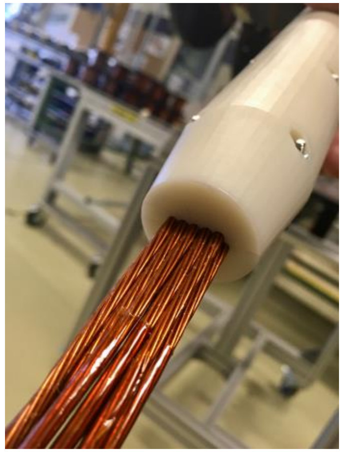


7 strand cable with

Thanks to INFN and Ernesto De Matteis

# Fast 3D printed subscale Winding tests.





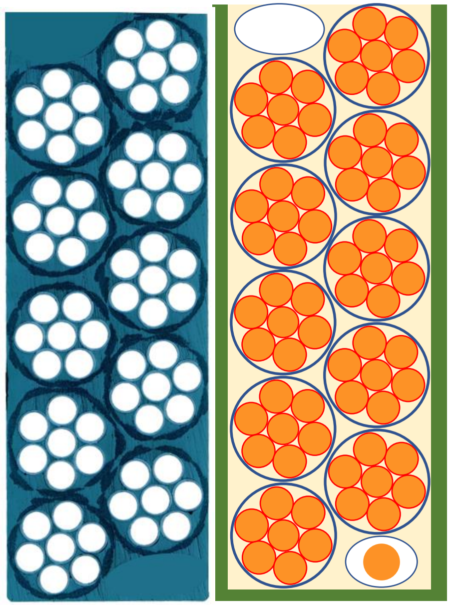
**Winding**

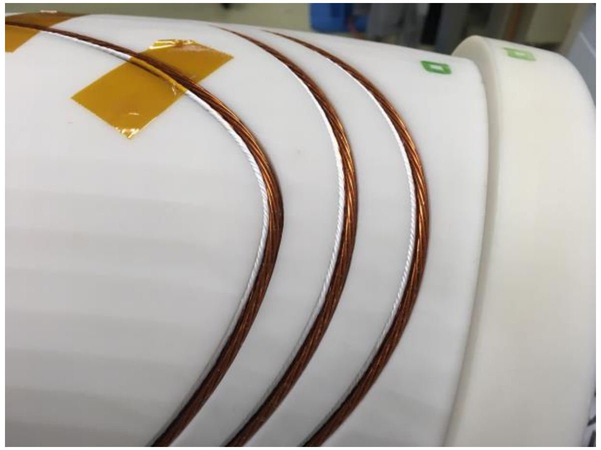
- Dedicated winding machine
  - Enough clearance for curved former
  - Ability to rotate on 2 axes

- Dedicated spool holder (maybe with tension)

- Development of specific tools

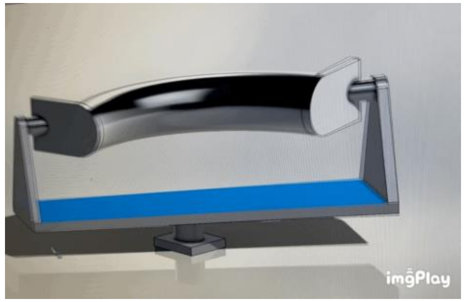
Winding trials are on-going (waiting for the cable sample to validate the development of the tools

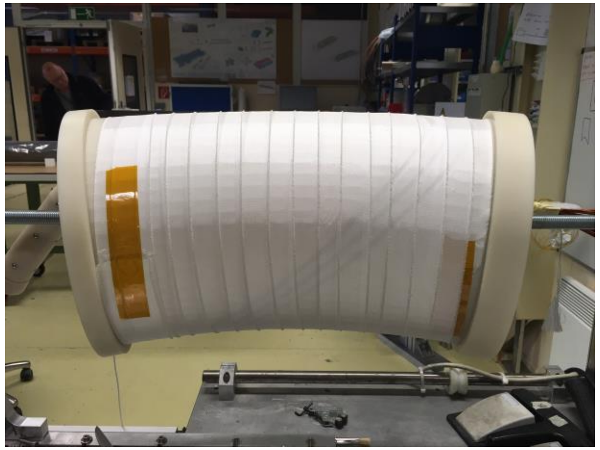


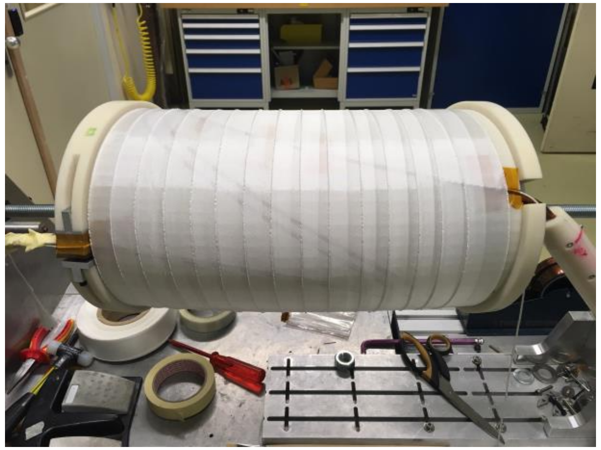


**Insulation wrapping**

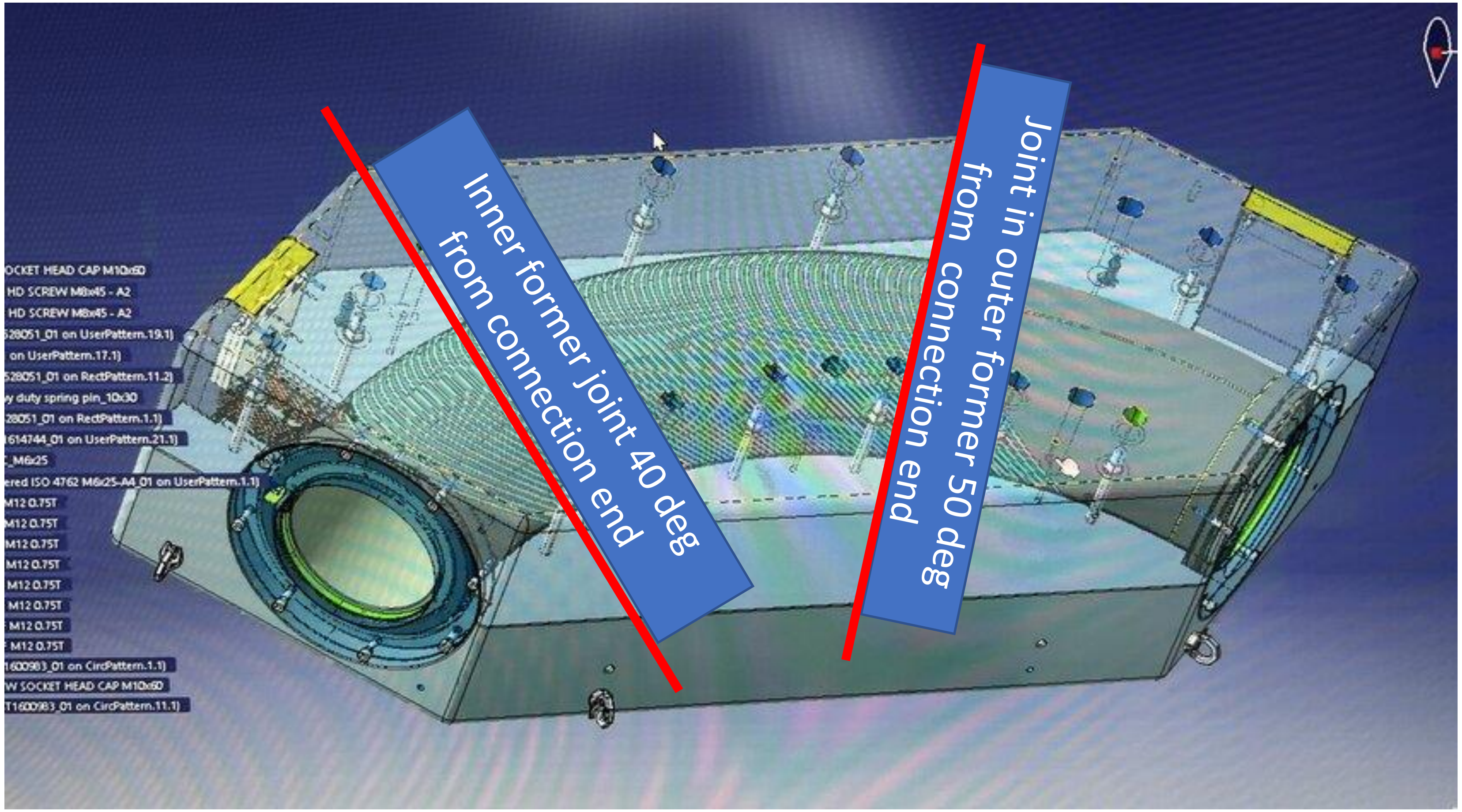
Developing tools and maybe a semi-automatic



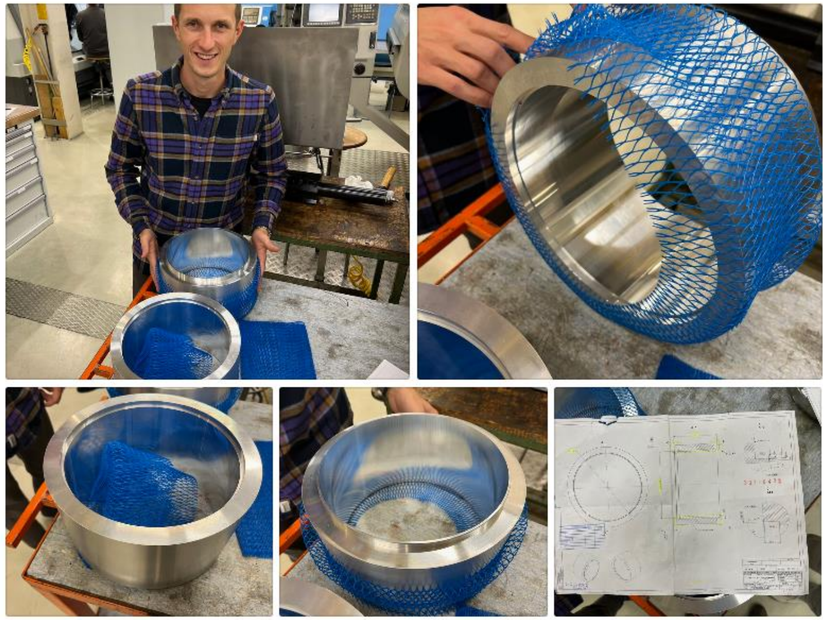




# Joints in former

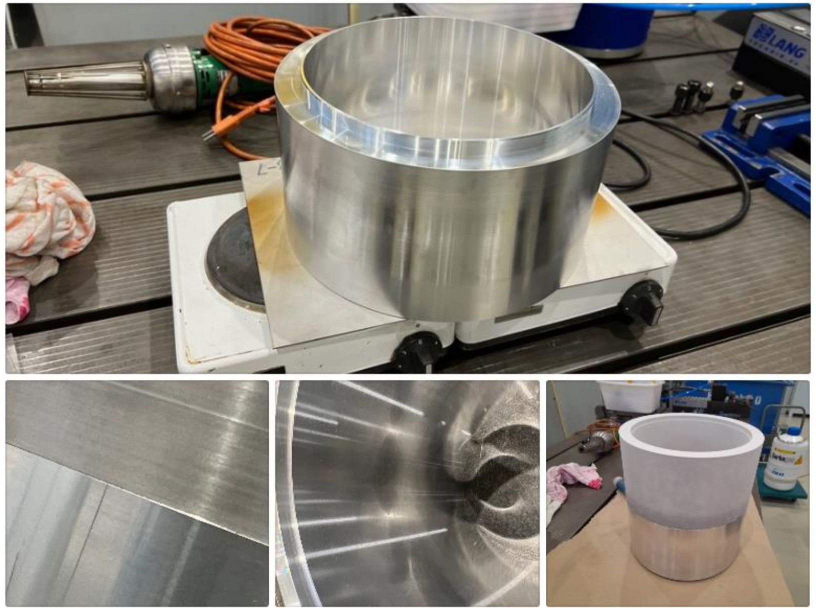


# Fusillo former assembly and joint tests



## Curved former joining tests

As we can only machine the inner aperture of the curved formers over about 60 deg. We need to joint to curved tubes. The idea is two make an interference fit with about 0.1 mm interference. A 1 deg negative taper. Leading to a pressure of about 3 MPa After joining the tubes we will machine several CCT channels through the joint to test if the joint remans smooth through the joint. Assembly of the set of joints it's Friday.



## Joining the aluminum tube for the curved CCT

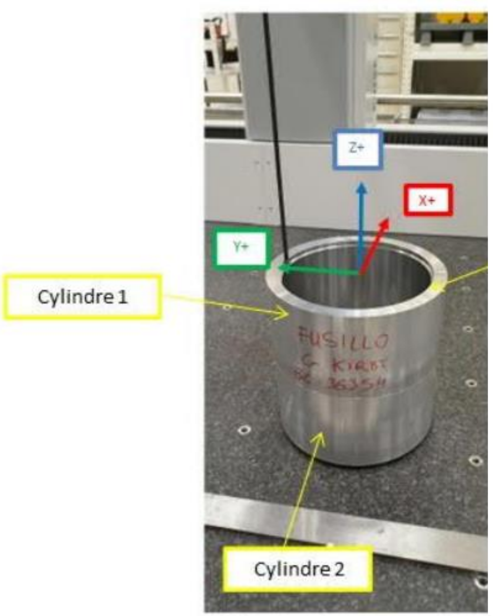
Heating one ring to 200C on a hot plate and cooling the other in liquid Nitrogen made the assembly easy. The difference in dia was about 0.5 mm. there was time to rotate the tubes for alignment, however we plan to add a key. Next steps machine the channels at about 30 deg.

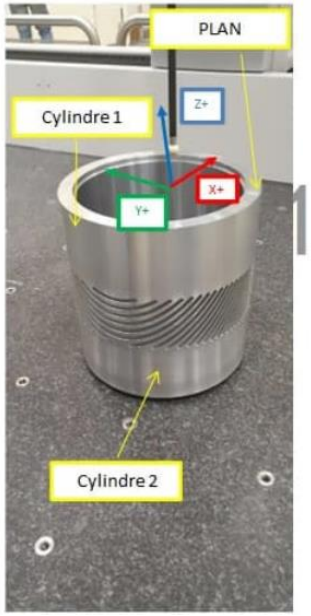
anodize to see if we get sharp edges. Cold traction test to see how strong the joint is.

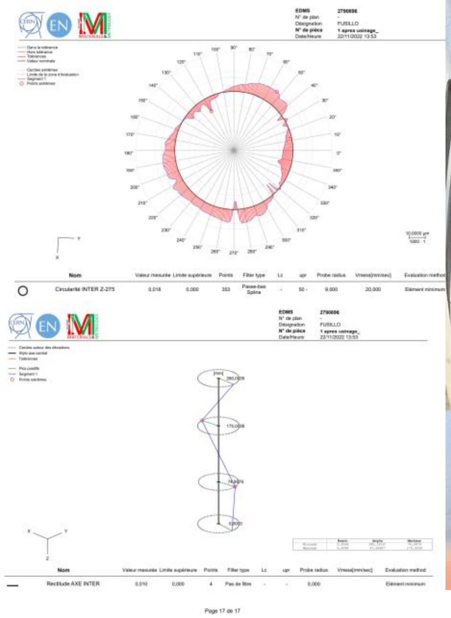
we see about 0.05 mm deformation into the bore at the joint. It leaves a small step. We can think to adjust this before assembly So that it ends up with no step.

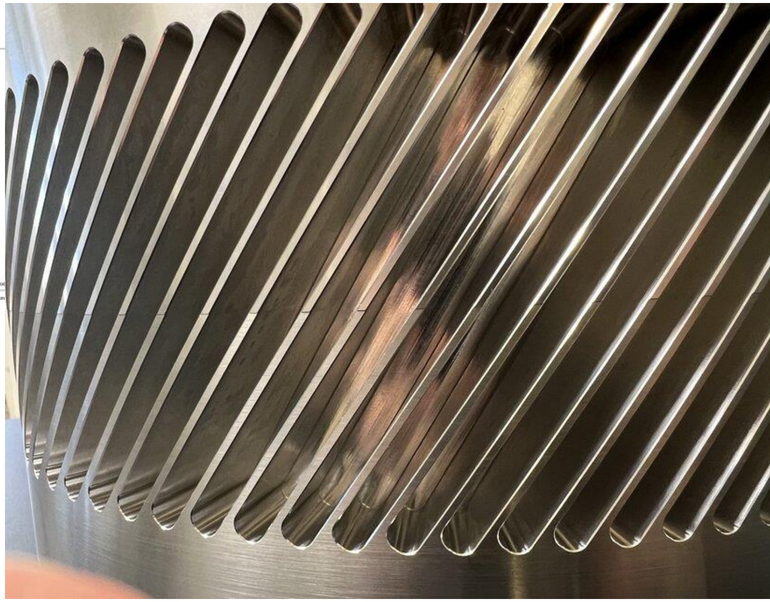
## Cold assembly test

First cold assembly test. Its not so easy ! We need to cool all of the part, not just the joint area. Second attempt one ring was heated to 200C and the parts went together easily . We see that the outer edge will need some carful design. Thinking about how the channel passes the joint. This test highlights that when we joint the large curved tubes. 64kg each combine, We will need tooling to lift and align. also we will add a key feature to precisely aline azimuthally the two tubes. more testing next week.



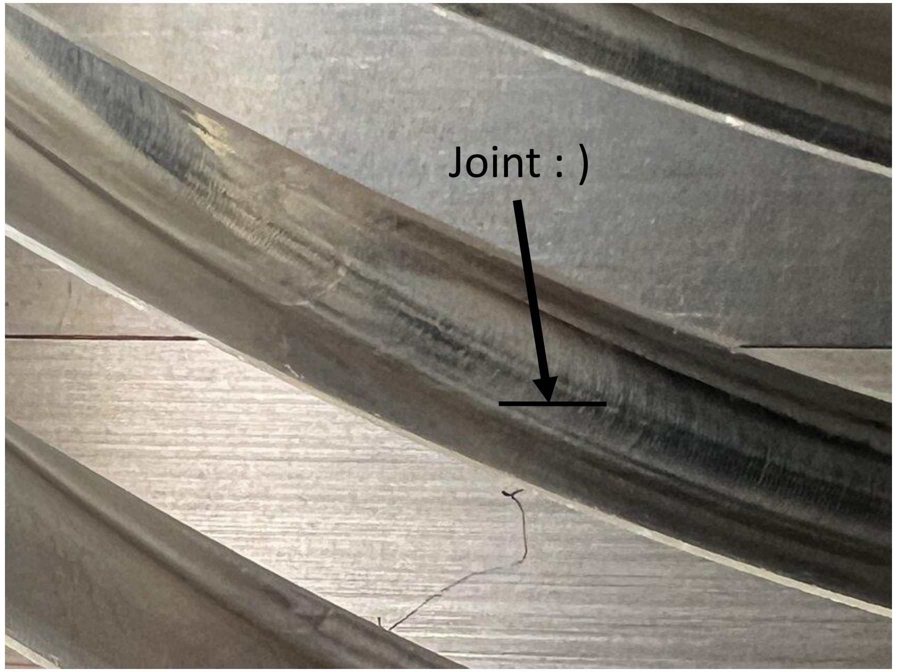



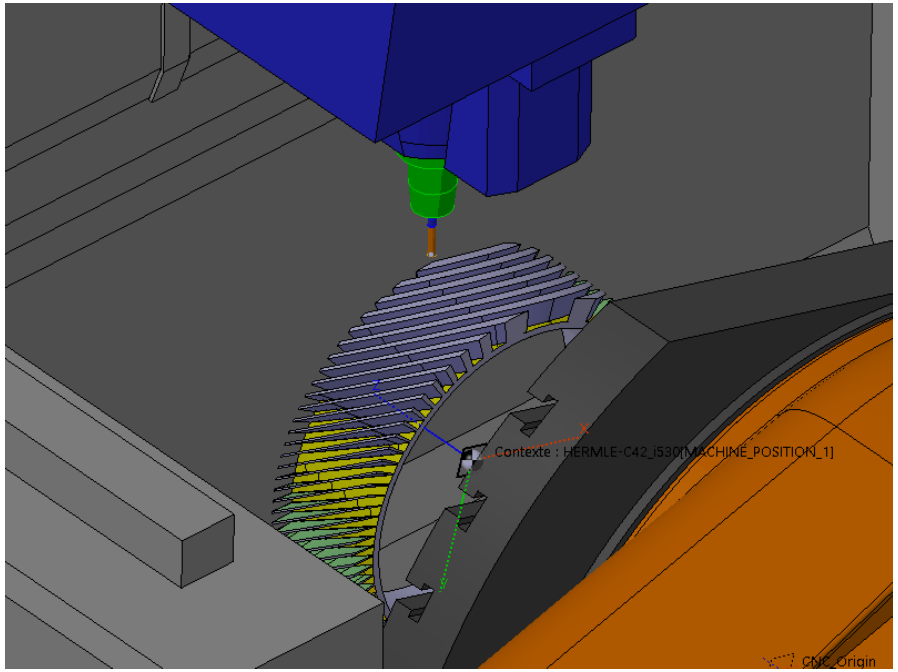


1)Thermal connection
2)Measured alignment
3)Machines channels
4) Measured alignment

5)Next steps anodize and check for sharp edges that can damage insulation!

6) Test strength of joint with bend test!

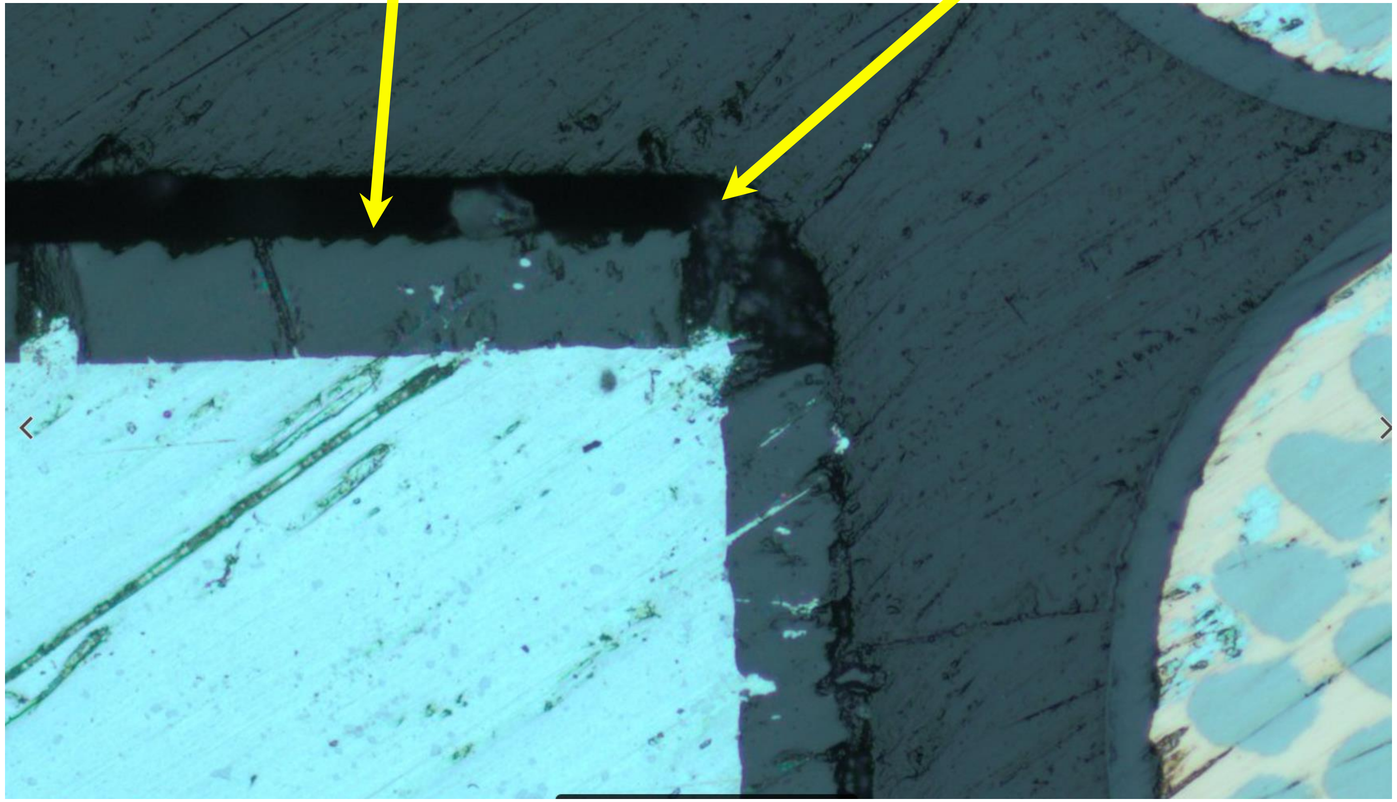


# Rounded edges on the former are important

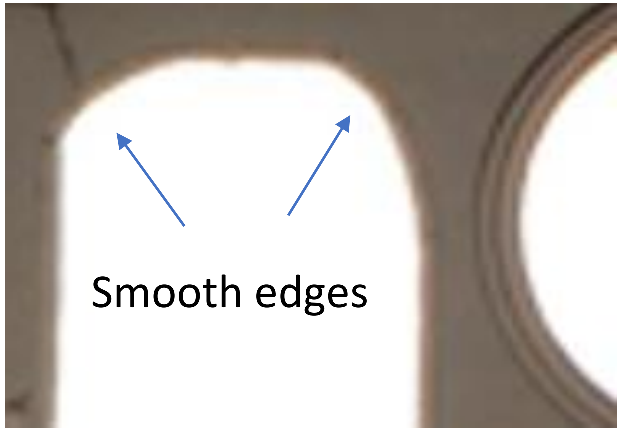
0.04 mm thick anodizing layer

Sharp edges to anodizing layer



Ae anodize the former to help give a hard surface to help protect the thin walls of the CCT channels , it also gives electrical insulation on the flat surfaces up to 2 kV,

But if the edges are sharp! The anodizing can curt the insulation, and open the insulation layer



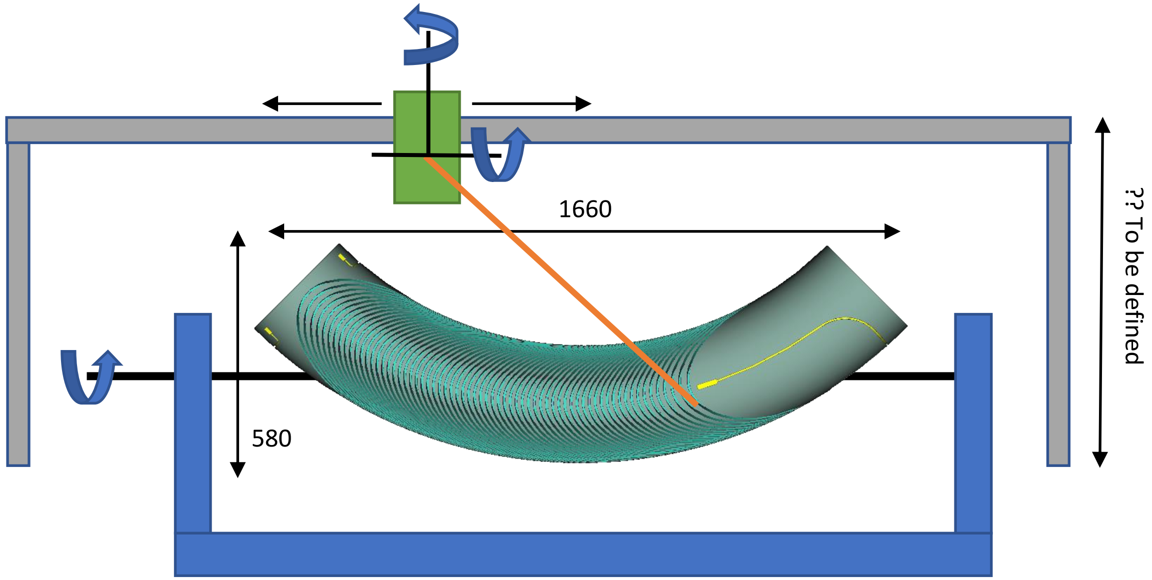
# Fabrication

**Winding machine proposal concept**

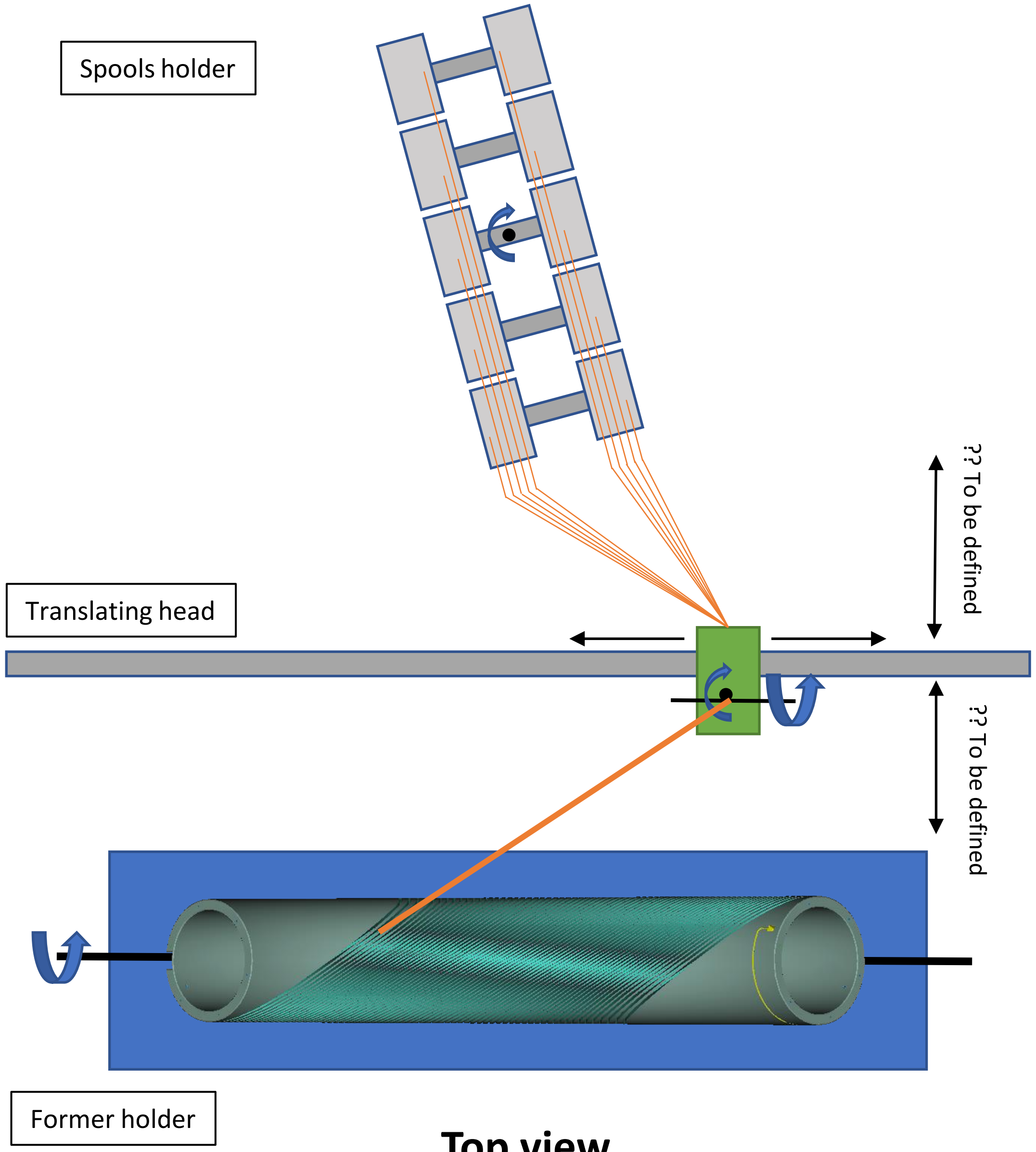
- The former rotates horizontally (fixed position)
- The former holder is adjustable for different projects (MCBRD, Fusillo,…)
- A head is feeding the cable pack
    - 1 translation, motorised, enslaved
    - 2 rotations, free movements
- The head is fed with cables by the spools holder (fixed position, 1 rotation)

**Optional requirements**

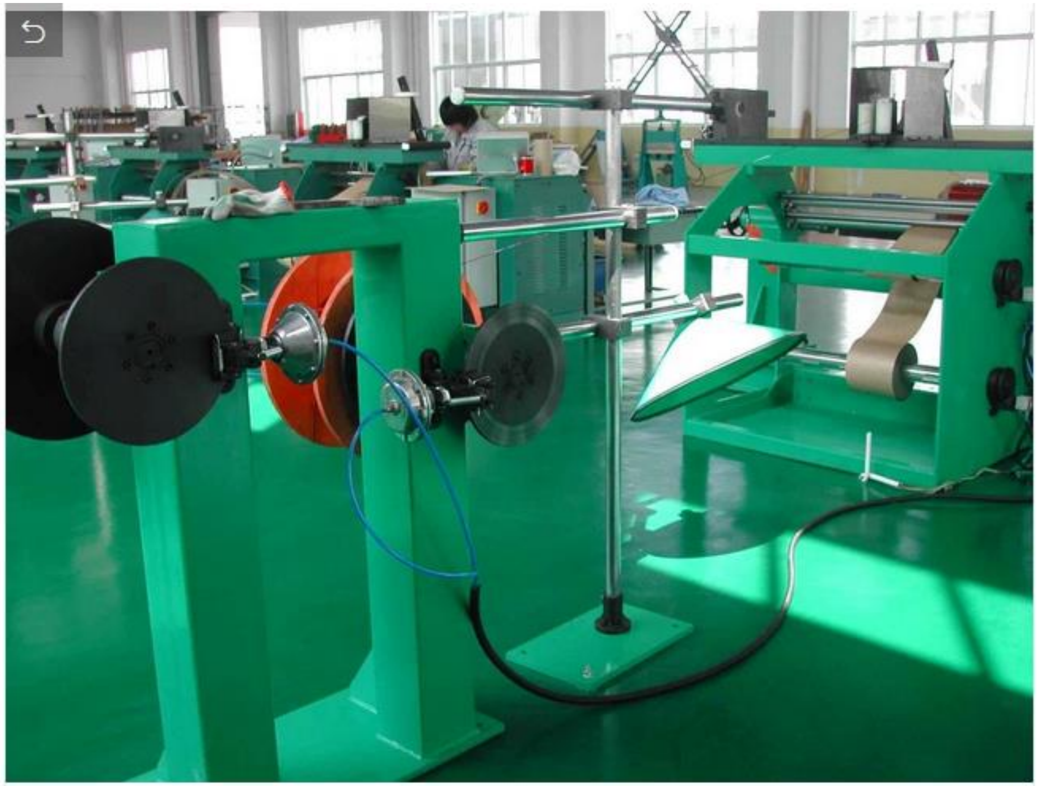
- The head has a tensioning mechanism (10-20 kg)
- The head could also be fed with tape
- The head could be motorised and enslaved to the rotation (programming)



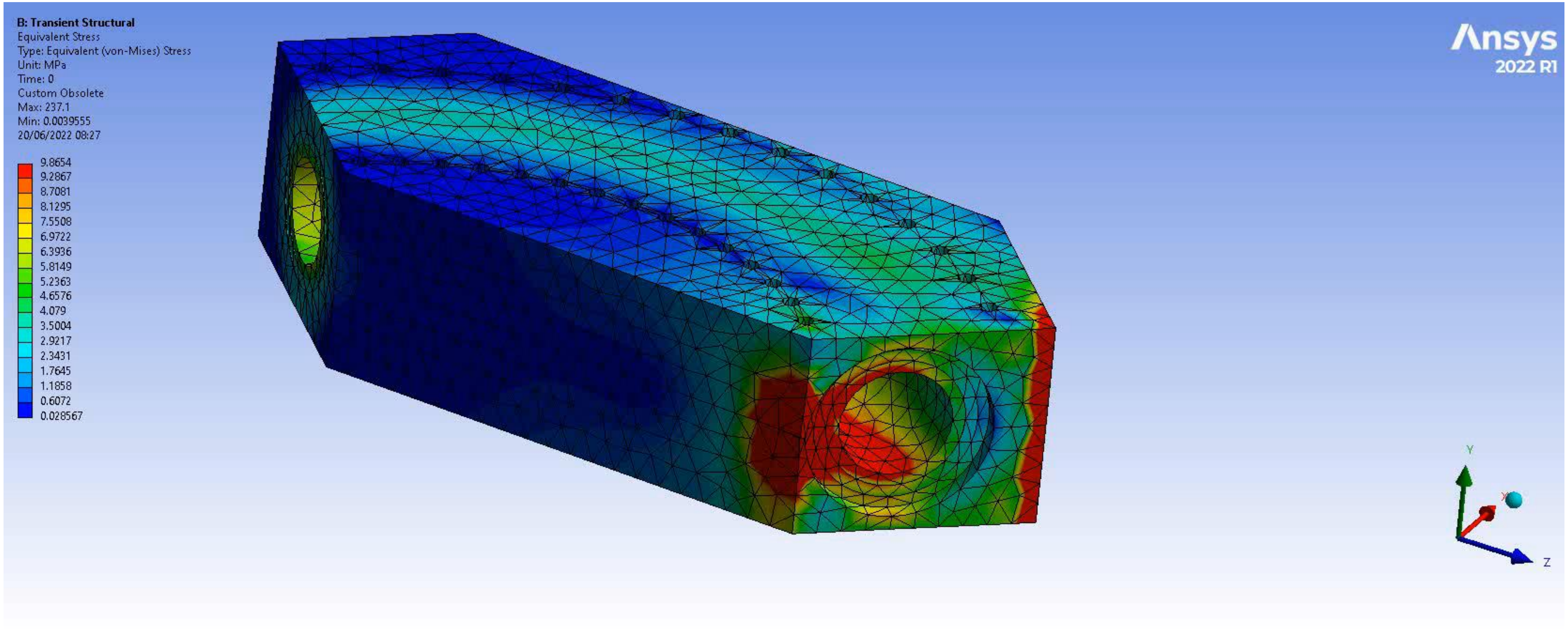

**Front view**



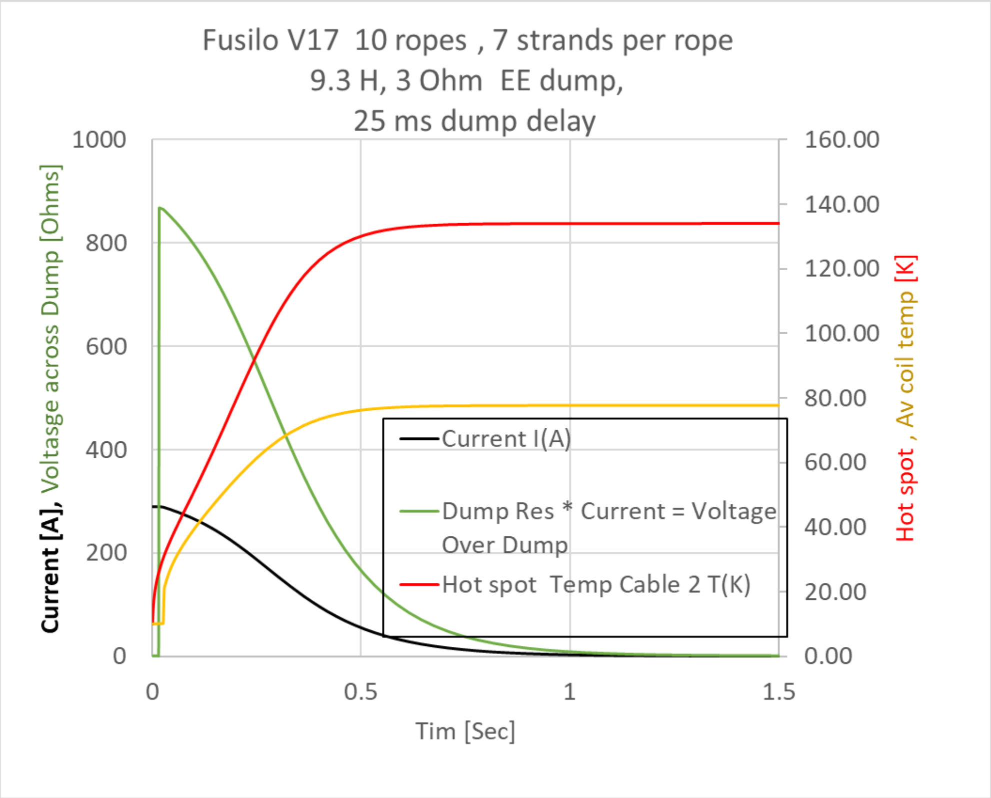

**Top view**

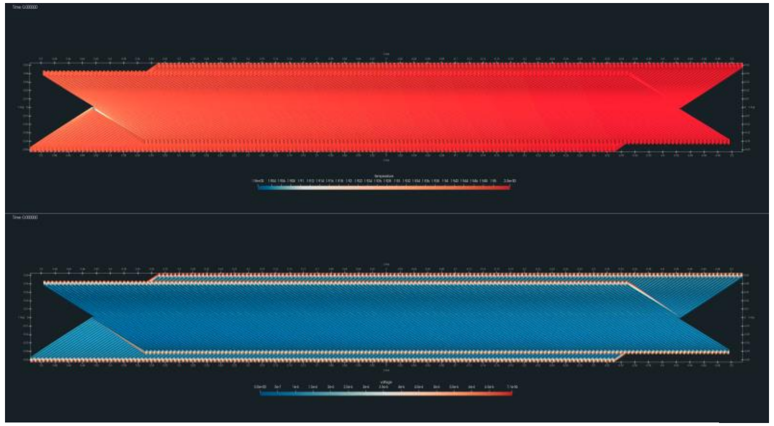


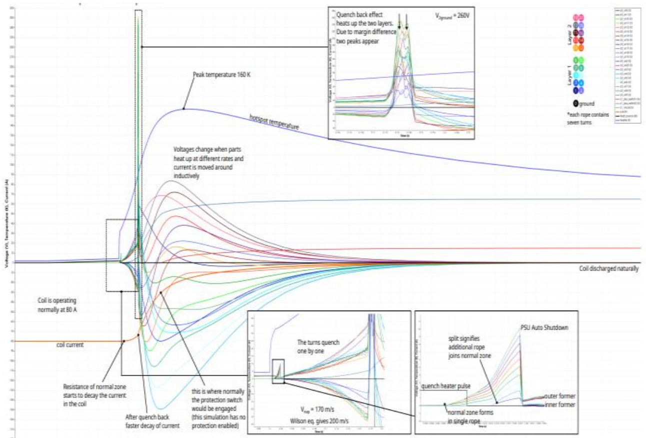
# Final FEA for coil and support in progress

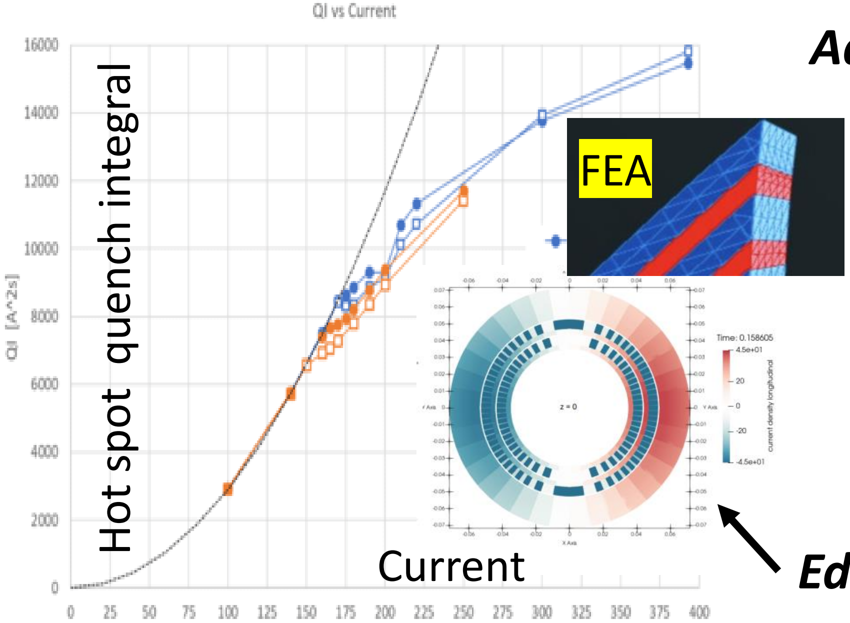


# Quench Simulations








***Advanced quench simulations*** in progress

***Quench back*** may offer the opportunity to have a passive protection of the magnet with no active system

***Eddy current heating*** in former

***Initial quench simulation*** inducts that the magnet can be protected with std energy extraction

Still need to check internal voltages !

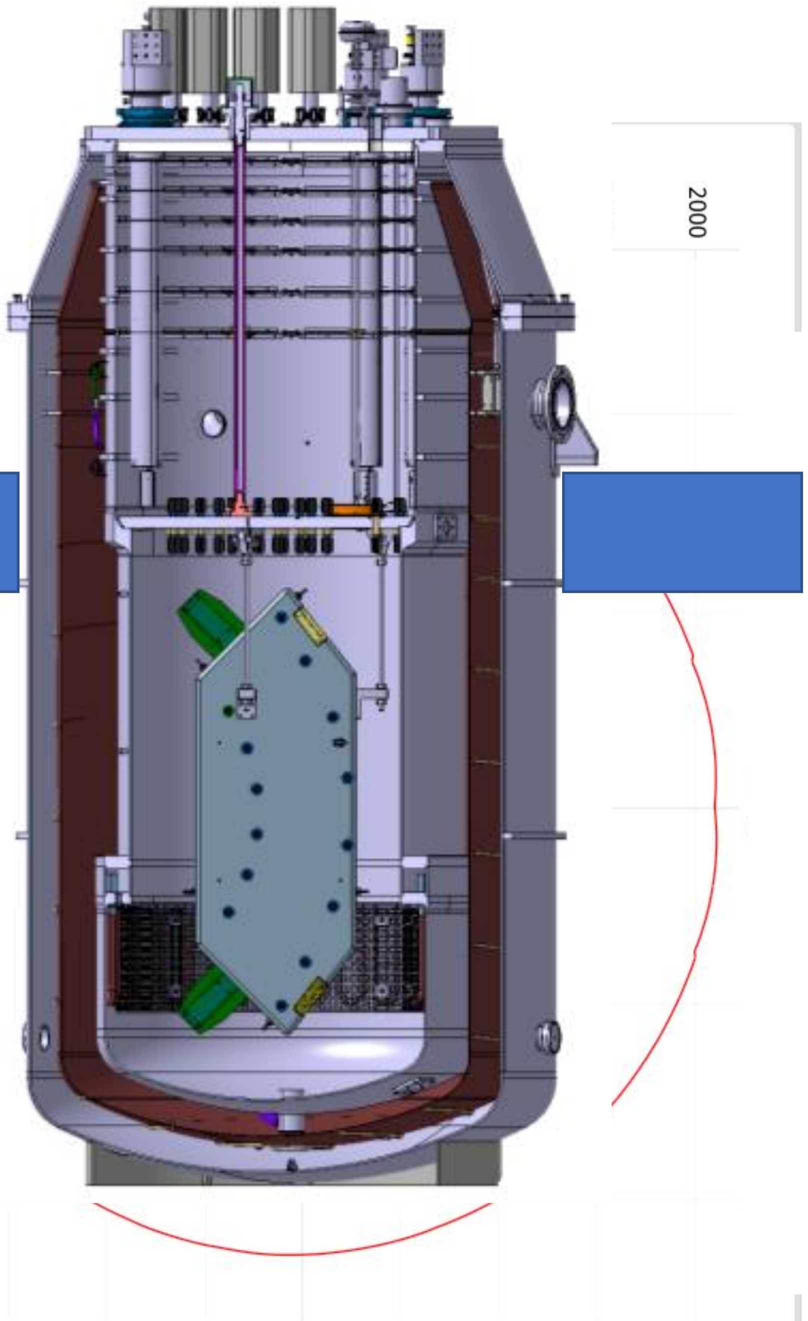
Target values **hot spot < 200 K , Voltage to ground < 1 kV**

***Quench Back is when*** the aluminum former picks up eddy currents that heat the former resulting in a faster quench and lower quench values up to – 30% in some cases

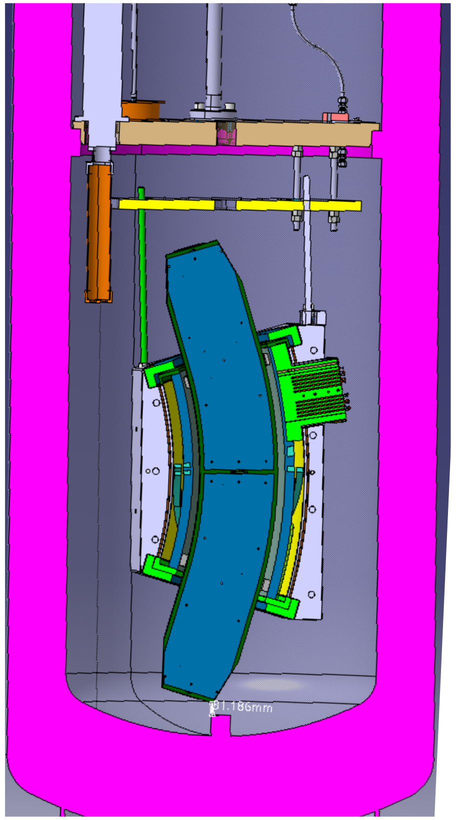
# Cold tests

**Cryostat**
- Fusillo in HFM cryostat
- Subscale in Siegtal cryostat

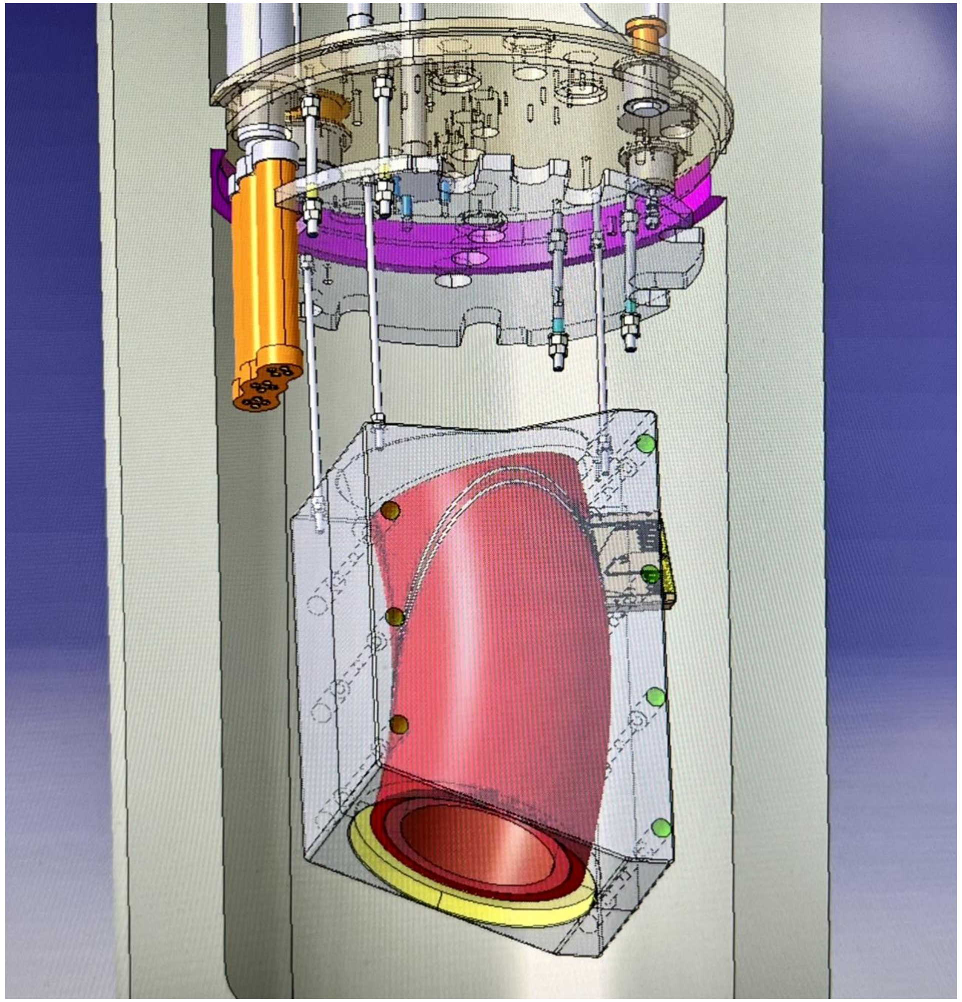
**Instrumentation**
- Magnetic measurements
  - Fixed PCB (midplane + 2 layers)
  - Set of pick-up coils
  - Adaptable from Fusillo to subscale
- Acoustic measurements

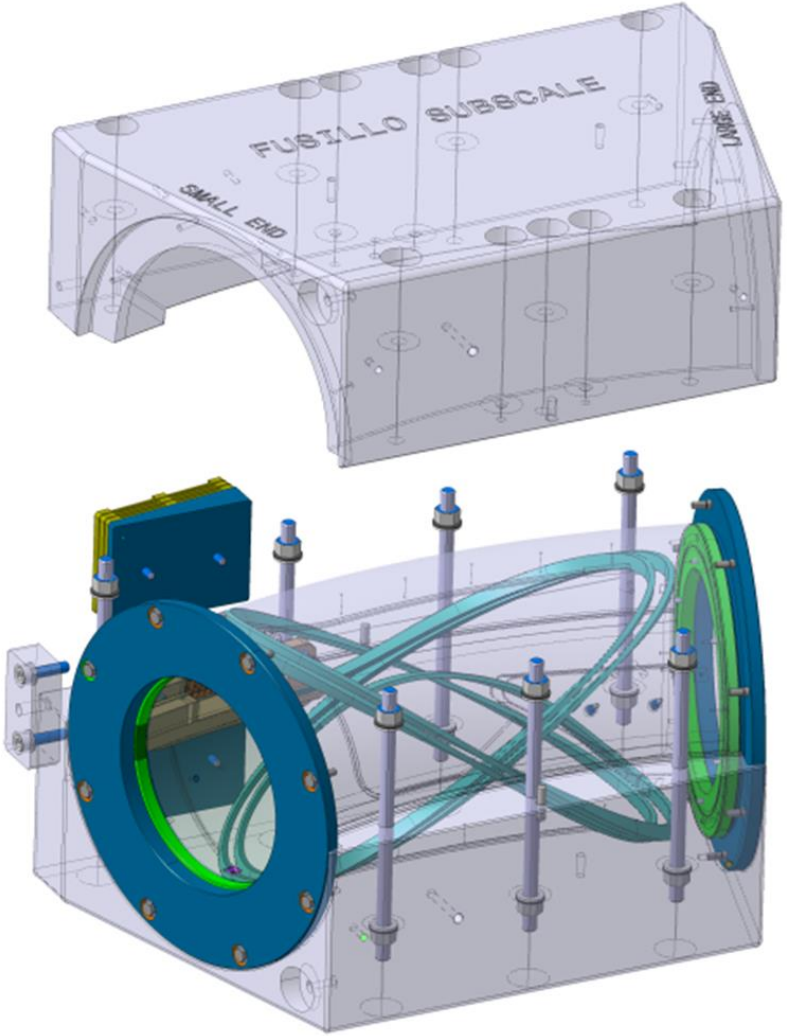



30 Gauss stray field
Is under ground



# Magnetic field measurement , Sub Scale





# Timeline - Fusillo in 927

## Q4 2022 | Q1 2023 | Q2 2023 | Q3 2023 | Q4 2023

**October 2022**
**subscale drawing review**
Start parts procurement at AP (2x)

**Q4 2022 – technology tests**
- electrical tests on cable (box samples)
- winding trials
- bag impregnation tests

**January 2023**
**Subscale part reception (927)**

**Q1 2023 – Subscale assembly & impregnation**
- cable
- insulation
- winding tools and procedure (CAD 927)
- impregnation tools and procedure (CAD 927)

Making the joints + Electrical tests

Milestone M2.1

**March 2023 - Subscale test**
- Magnetic meas. structure
- Siegtal cryostat integration parts

**Q3-Q4 – 1-2 Subscales Assemblies and tests to be foreseen**

## Q1 2024 | Q2 2024 | Q3 2024

**January 2024**
**Fusillo part reception**
- transport crate for formers
- handling structure for formers
- handling tools

**Q1-Q2 2024 – Fusillo assembly & impregnation**
- cable
- winding machine
- 927 integration of winding + platform (CAD 927)
- Spool holder (tension?)
- insertion tool (rail)
- insulation wrapper (structure on rail)
- Impregnation tools and holding structure

Making the joints + Electrical tests

Milestone 3.4

**May 2024 - Fusillo demonstrator test**
- Magnetic meas. structure
- HFM cryostat integration parts

# Conclusions

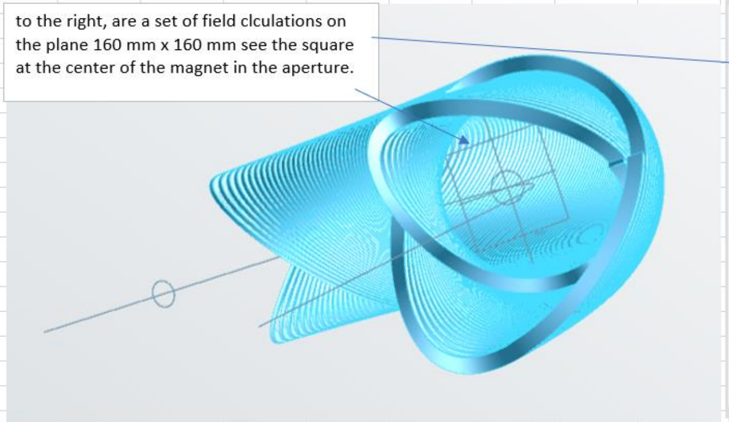
- Design of this novel magnet is at the fine tuning / polishing stage
- Sub-scale models to test impregnation systems are lunched
- We hope to cold test the sub-scales and 

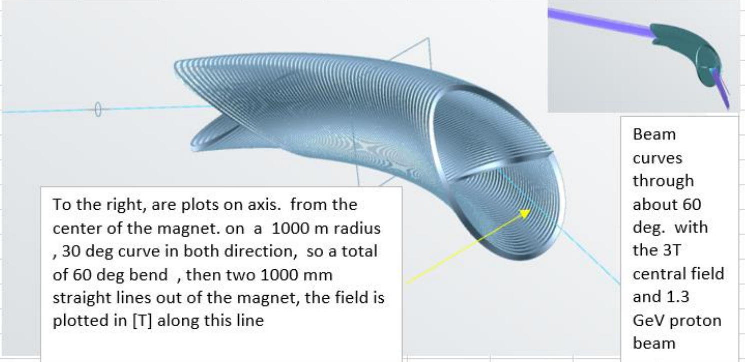
demonstrator in 2023
- Development at CERN , most manufacturing of components are being sourced in Spain.

# THE END


Follow the development on my ReserchGate project Log

to the right, are a set of field clculations on the plane 160 mm x 160 mm see the square at the center of the magnet in the aperture.





To the right, are plots on axis. from the center of the magnet. on a 1000 m radius , 30 deg curve in both direction, so a total of 60 deg bend , then two 1000 mm straight lines out of the magnet, the field is plotted in [T] along this line

Beam curves through about 60 deg. with the 3T central field and 1.3 GeV proton beam