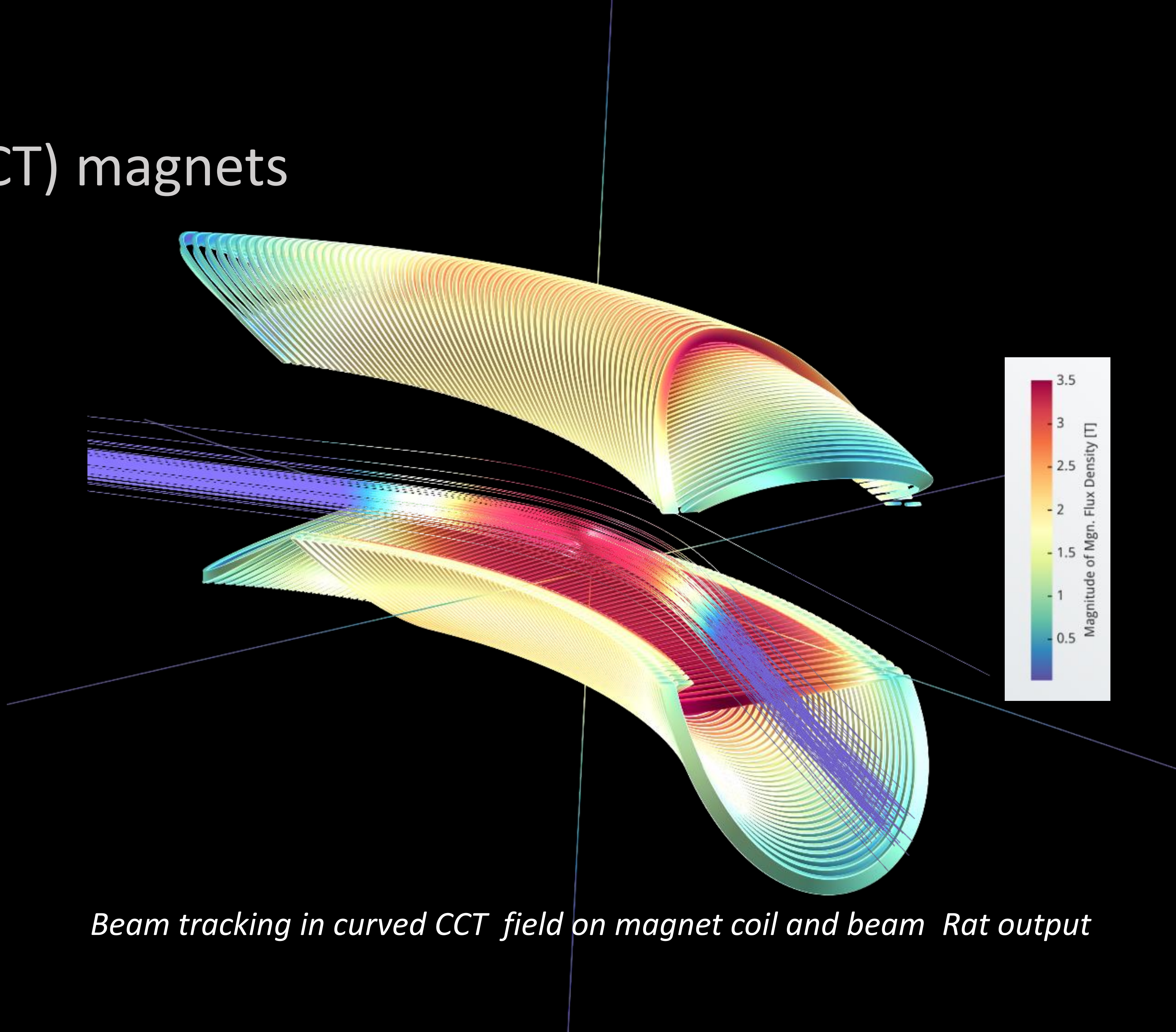
The State of The Art
Canted Cosine Theta (CCT) magnets

Glyn Kirby

May 19th 2022



Beam tracking in curved CCT field on magnet coil and beam Rat output

Talk Overview

- CCT history
- What are CCT's
- Some of the magnets built and under construction.
- A look at CCT designs features and idea's 2014 to today

1st CCT to go into LHC MCBRD CCT at CERN

HISTORY First CCT papers in the late 1960’s

NUCLEAR INSTRUMENTS AND METHODS 80 (1970) 339–341; © NORTH-HOLLAND PUBLISHING CO.

A NEW CONFIGURATION FOR A DIPOLE MAGNET FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

The magnetic field configuration obtained when an ordinary circular solenoid is skewed looks very promising for use as a dipole magnet. The field inside is uniform and $\int B dl$ including end effect is independent of position across the magnet.

At the high fields now attainable with superconducting materials the support of the long narrow coils which are needed in bending magnets for high energies becomes a problem. In addition considerable rather difficult coil placement must be done to attain uniform fields. I suggest here a configuration which eliminates both of these problems.

Consider a long circular solenoid skewed at an angle θ as shown in fig. 1. On analysis of the field pattern it is found that the field inside such a configuration is completely uniform and makes an angle of $\theta/2$ with the z' axis. Details of this analysis are given in the appendix. The magnitude of the z' component of the magnetic field is the same as that of an unskewed solenoid with the same current and turn spacing in the z direction.

If we now send a beam of particles through along the skewed axis they will be bent perpendicular to the plane of the paper by the component $B_{x'}$ of the field. Thus the effective bending will be $B \sin \frac{1}{2} \theta$. We may however improve on this configuration by the method illustrated in fig. 2. Place two skewed solenoid windings on top of each other but skewed in opposite direction. Then by applying currents as shown the z' field components cancel but the x' components add. Thus we have ellipsoidal cross sections with a completely uniform field perpendicular to the axis in the x' direction.

Clearly since we are cancelling one field component there is some effective loss of ampere turns. Approximately twice as much wire is needed as in a standard cosine dipole for a given field. However for a superconducting magnet this is not too serious and is compensated for by four factors.

1. The field is completely uniform and the $\int B \cdot dl$ through the magnet including end effects is independent of lateral position.

2. The field volume is used very effectively. The aperture viewed along the beam line is elliptical with the long axis of the ellipse in the direction of bend. For 60° skew for example the aperture for 10 cm diameter rings would be 10 cm in the direction of bend and 5 cm perpendicular to this direction.

A uniform field of elliptic cross section can be generated by the proper distribution of current ($J \propto y'/a$) in wires run along the x' direction however the end effects are not so neatly handled.

3. The mechanical construction is much simplified over that of a cosine dipole from the standpoint of properly placing the wires. The circular coils and compact structure simplify the handling of magnetic stresses.

4. The configuration lends itself very well to being made in modules which can then be stacked end to end to provide any desired bending. This could add

* Work performed under the sponsorship of the U.S. Atomic Energy Commission.

Fig. 1. Diagram for calculating the magnetic field at the point x_0, y_0.

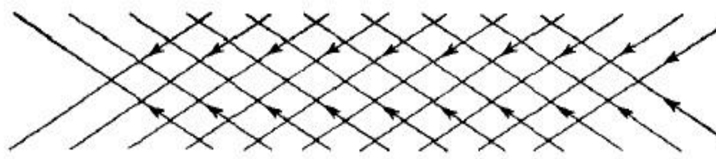
Fig. 2. Two superimposed coils with opposite skew.

D. I. Meyer and R. Flasck, “A new configuration for a dipole magnet for use in high energy physics applications,”Nucl. Instrum. Method, vol. 80,no. 2, pp. 339–341, Apr. 1970.

1970, I was playing football

A bit of Background

- Idea originates from 1960’s [1]
- Two nested canted solenoids

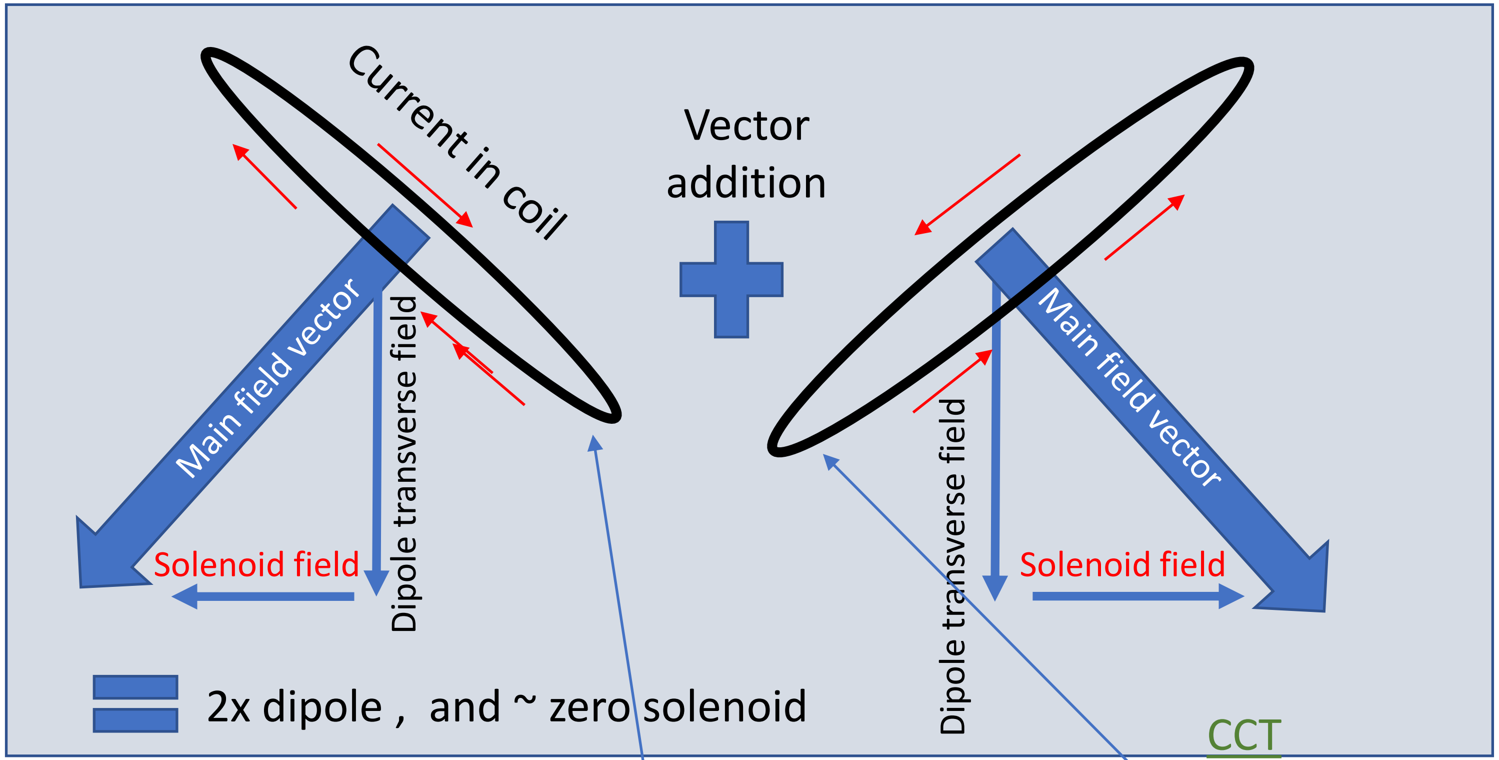


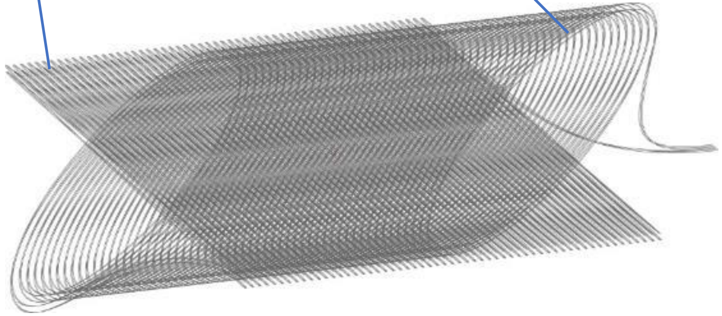
[1]

- Axial field components cancel
- Dipolar field components add up

- Visit Shlomo Caspi LBNL before Christmas
- Sparked renewed interest in CCT design

- Why now?
  - Advancements in Rapid Prototyping
  - Advancements in Computing



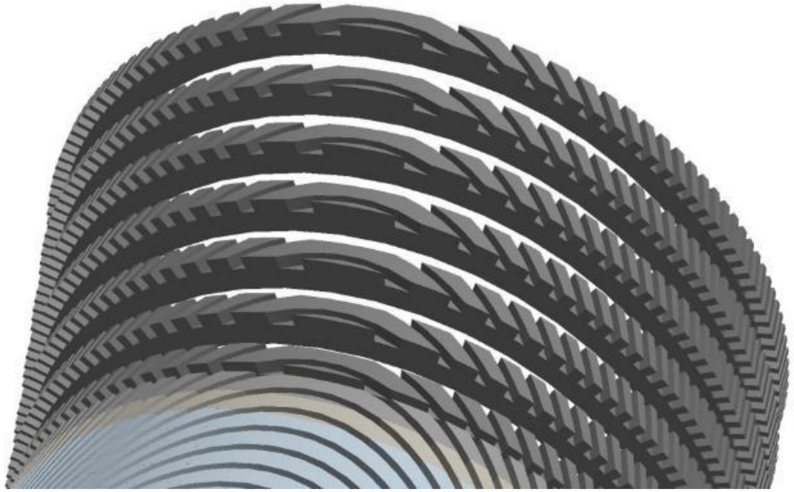


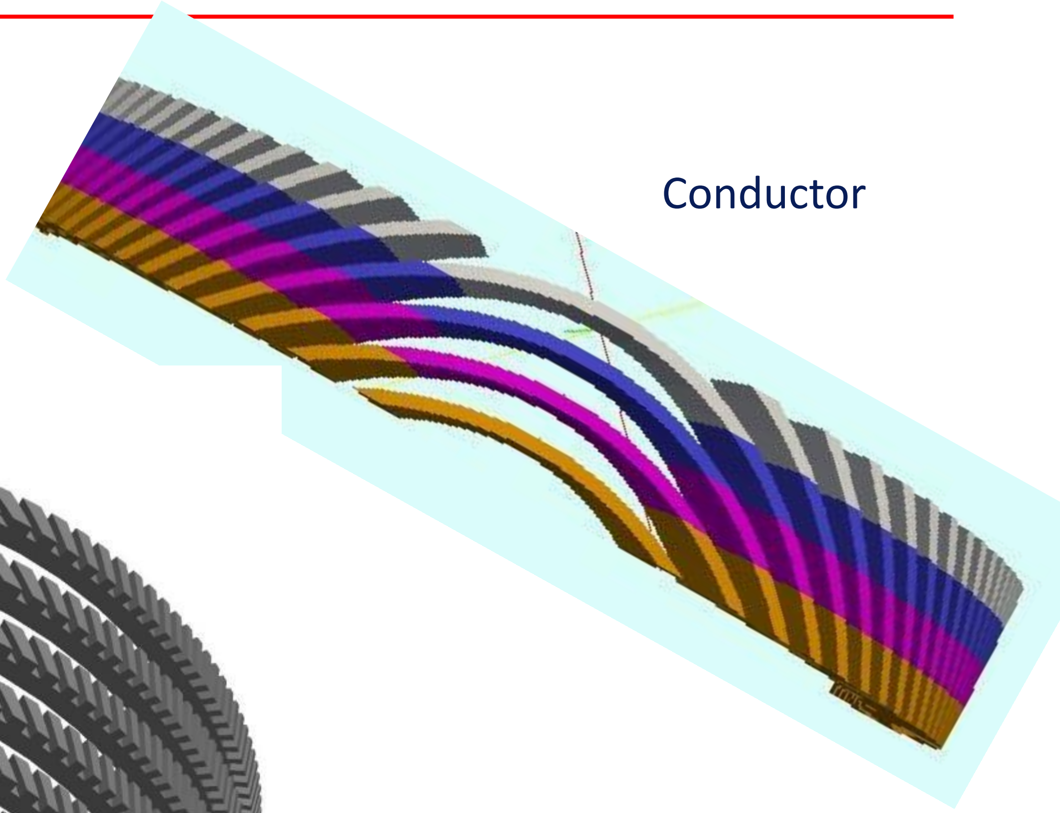
[1] D. Meyer and R. Flasck, A new configuration for a dipole magnet for use in high energy physics applications, Nuclear Instruments and Methods, no. 80, pp. 339-341, 1970.

Slide from 2013

Repeating geometry

Shlomo Caspi led the CCT program in LBNL and lit my interests in CCT's





Lamination can simplify analysis
Reduce cost
Reduce losses

INFN CCT 2012! *Stefania Farinon*

2LPC-02

Compact Superconducting High Gradient Quadrupole Magnets for the Interaction Regions of High Luminosity Colliders

Filippo Bosi, Pasquale Fabbricatore, Stefania Farinon, Umberto Gambardella, Riccardo Musenich, Roberto Marabotto, Eugenio Paoloni

Abstract— Recent developments in the high luminosity e^+e^- colliders are based on a collision scheme with a large Piwinski angle, a vertical beta function β_y much smaller than the bunch length and a crab waist transformation. This scheme is being adopted in the SuperB asymmetric collider, to be built in Italy, with a design peak luminosity of 10^{36} $cm^{-2}sec^{-1}$. A crucial role is played by the quadrupole doublets QD0/QF1 which are placed close to the interaction point and generate gradients close to 100 T/m. The available space for the doublets is very small, causing the magnets to be operated with a high engineering current density (2000 A/mm^2). Starting from the helical coil concept, an advanced design of the quadrupole has been developed. The paper discusses the basic design concepts and the development of a coil model aimed at assessing the design criteria and demonstrating the feasibility of the quadrupole. The successful test of the coil model opens the way to new compact superconducting high gradient quadrupole magnets for the interaction regions of high luminosity colliders.

Index Terms—Superconducting quadrupole, helical coils.

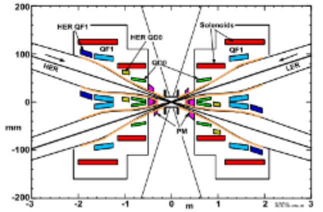


Fig. 1. Top view of the IR layout. The PM and the cold masses of the SC magnets are represented together with the horizontal LER and HER beam stay clear.

1AO-1

Design, Construction and Test of a Model Superconducting Quadrupole for the Interaction Region of Super$B$ Factory

Filippo Bosi, Eugenio Paoloni, Pasquale Fabbricatore, Stefania Farinon, Riccardo Musenich, Roberto Marabotto, Davide Nardelli

Abstract—Super$B$ is an asymmetric energy e^+e^- collider operating at the $\Upsilon(4S)$ peak ($\sqrt{s} \sim 10.58$ GeV) to be built in Italy, with a design peak luminosity of 10^{36} Hz/cm^2. In order to get the required high luminosity, a novel collision scheme, the so called "large Piwinski angle and crab waist", has been designed. This scheme requires that two doublets of high gradient superconducting quadrupoles (denominated in the Super$B$ naming scheme as QD0 and QF1) are placed as close as possible to the interaction point. This layout is critical because the space allowed to the doublets is very small. An advanced design of the quadrupole has been developed, based on the so-called helical coil concept. The paper discusses the design and construction concept of a model of the superconducting quadrupole based on NbTi technology.

Index Terms—Helical coils, Superconducting coils, Quadru-

showed that it is reasonable to revise the *Snowmass Year* definition to $1.5 \cdot 10^{36}$ s.

II. The Collider And Its Interaction Region (IR)

Super$B$ is designed as an High Energy Ring (HER) and a Low Energy Ring (LER) storing respectively positrons at 6.7 GeV and electrons at 4.18 GeV injected at nominal energy by a linac. The Super$B$ collision scheme requires a short focus final doublet to reduce the vertical beta function down to $\beta_y^* = 0.2$ mm at the Interaction Point (IP). The final doublet (see Fig. 1) will be composed by a set of permanent samarium cobalt magnets (PM) and superconducting (SC) quadrupoles.

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. 25 (2012) 065006 (10pp) doi:10.1088/0953-2048/25/6/065006

Refined modeling of superconducting double helical coils using finite element analyses

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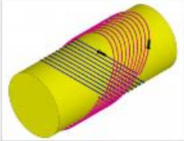


Figure 2. Two layers of tilted elliptical turns wound onto a cylindrical mandrel with opposite angles with respect to the central axis, showing the current flow directions.

Abstract
Double helical coils are becoming more and more attractive for accelerator magnets and other applications. Conceptually, a sinusoidal modulation of the longitudinal position of the turns allows virtually any multipolar field to be produced and maximizes the effectiveness of the supplied ampere turns. Being intrinsically three-dimensional, the modeling of such structures is very complicated, and several approaches, with different degrees of complexity, can be used. In this paper we present various possibilities for solving the magnetostatic problem of a double helical coil, through both finite element analyses and direct integration of the Biot–Savart law, showing the limits and advantages of each solution and the corresponding information which can be derived.

(Some figures may appear in colour only in the online journal)

References

[1] Meinke R B, Ball M J and Goodzeit C L 2003 Superconducting double-helix accelerator magnets *Proc. 2003 Particle Accelerator Conf. (Portland, OR, May 2003)* pp 1996–8 http://accelconf.web.cern.ch/AccelConf/p03/PAPERS/WPAE025.PDF
[2] Goodzeit C L, Ball M J and Meinke R B 2003 The double-helix dipole—a novel approach to accelerator magnet design *IEEE Trans. Appl. Supercond.* 13 1365–8
[3] Meinke R B, Goodzeit C L and Ball M J 2003 Modulated double-helix quadrupole magnets *IEEE Trans. Appl. Supercond.* 13 1369–72
[4] Goodzeit C, Meinke R and Ball M 2007 Combined function magnets using double-helix coils *Proc. 2007 Particle Accelerator Conf. (Albuquerque, NM, June 2007)* pp 560–2 http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/MOPAS055.PDF
[5] Meinke R B, Lammers J, Masson P J and Stelzer G 2009 Direct double-helix magnet technology *Proc. 2009 Particle Accelerator Conf. (Vancouver, May 2009)* pp 229–31 http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/mo6pfp041.pdf
[6] Paoloni E, Bettoni S, Biagini M E and Raimondi P 2009 Magnetic design studies for the final focus quadrupoles of the super B large crossing angle collision scheme *Proc. 2008 Particle Accelerator Conf. (Genoa, June 2008)* pp 2401–3 http://accelconf.web.cern.ch/AccelConf/e08/papers/wepd002.pdf
[7] *ANSYS Multiphysics* Release 11, ANSYS Inc.
[8] Paoloni E, Bettoni S, Biagini M E, Raimondi P and Sullivan M 2009 Advances in the studies of the magnetic design for the final focus quadrupoles of the superB *Proc. 2009 Particle Accelerator Conf. (Vancouver, May 2009)* pp 238–40 http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/mo6pfp045.pdf
[9] Paoloni E *et al* 2011 Advances in the design of the superB final doublet *Proc. 2011 Int. Particle Accelerator Conf. (New York, Mar.–Apr. 2011)* pp 2454–6 http://accelconf.web.cern.ch/AccelConf/IPAC2011/papers/wepo026.pdf
[10] Jain A K 1998 Basic theory of magnets *CERN Yellow Report* 98–05 http://cdsweb.cern.ch/record/1246515/files/p1.pdf

Fig. 1. Top: winding of a double helical coil for generating a quadrupolar magnetic field. Bottom: a winding test with a dummy wire.

2

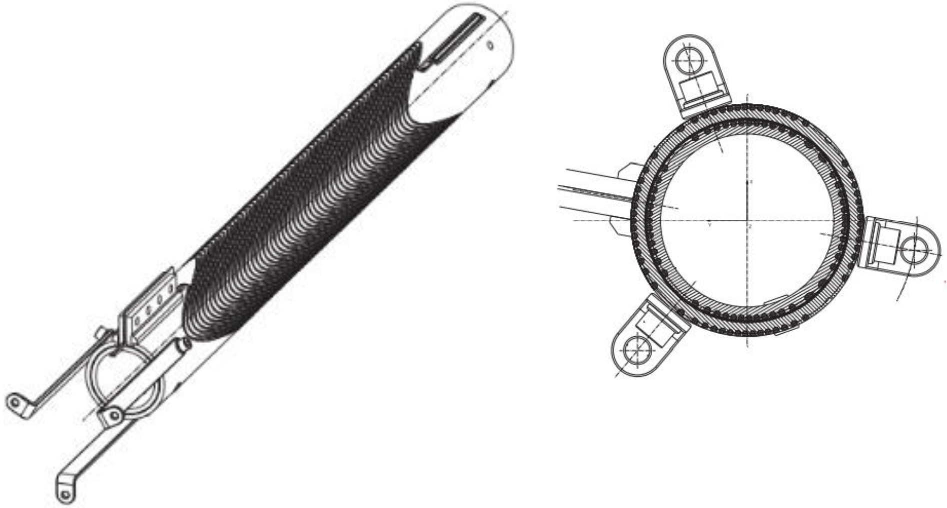
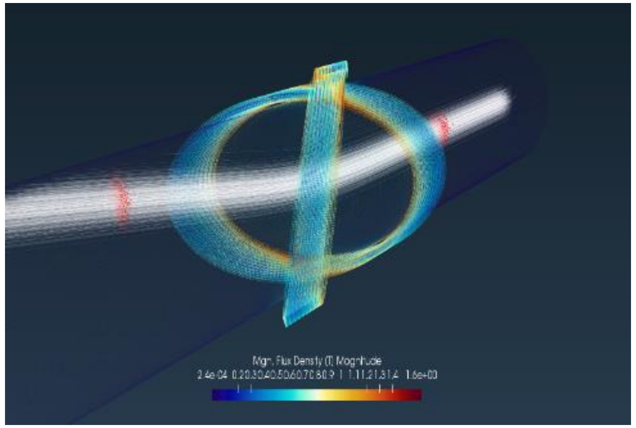
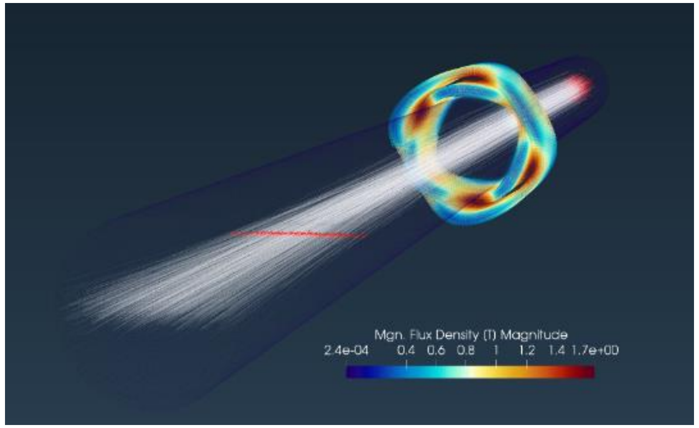
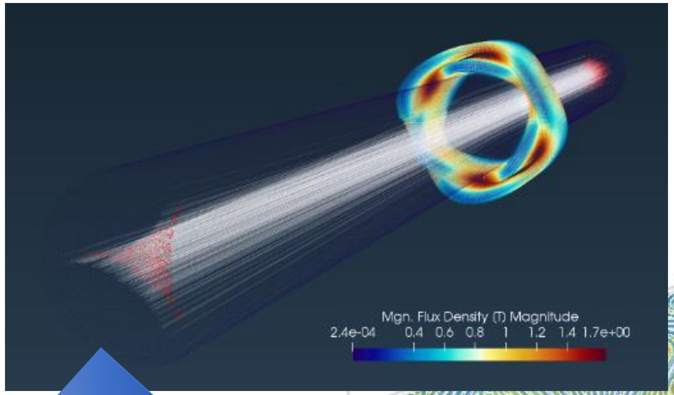


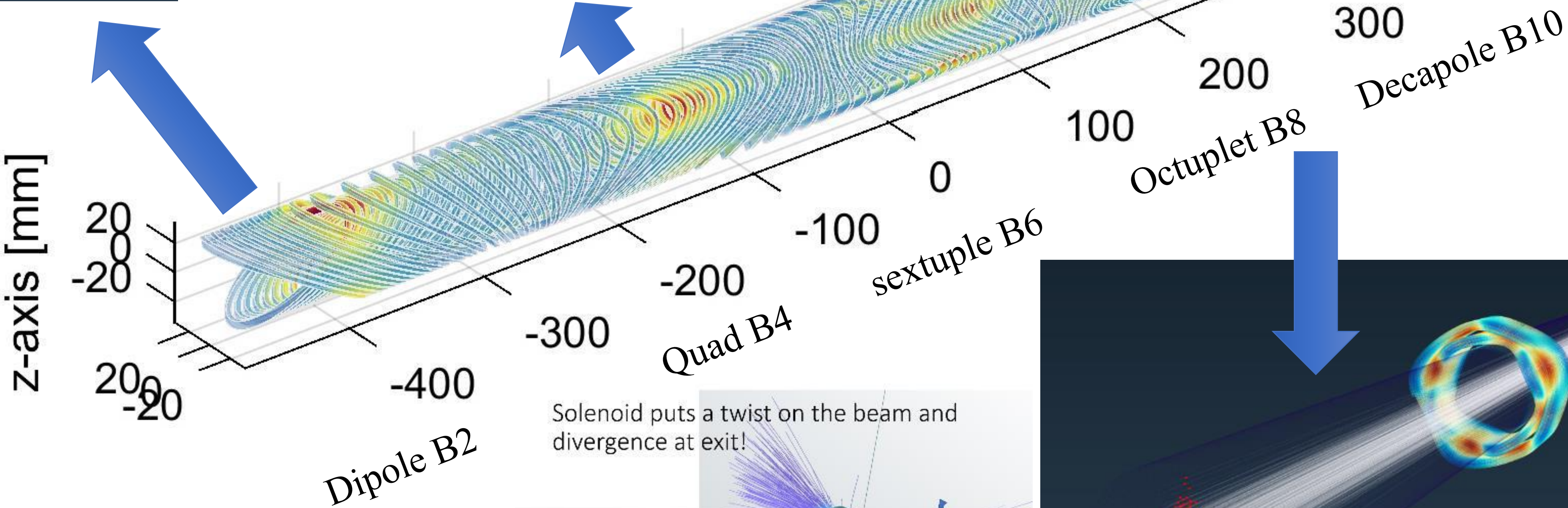
Fig. 3. Assembly view of the SC quadrupole prototype. The current feeders and the mechanical fixture are on the bottom left side and the junction is on the top right side.

CCT coil possibilities

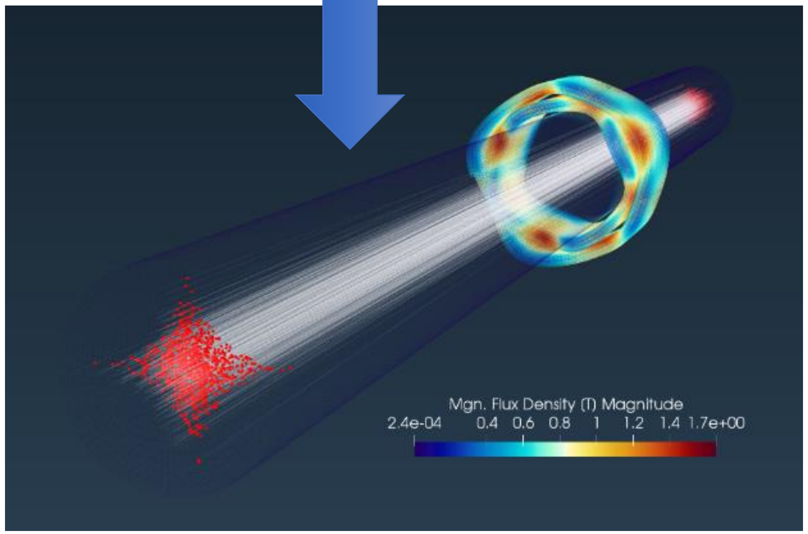


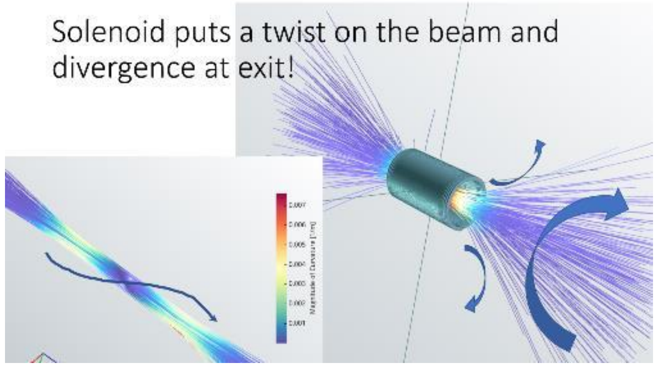






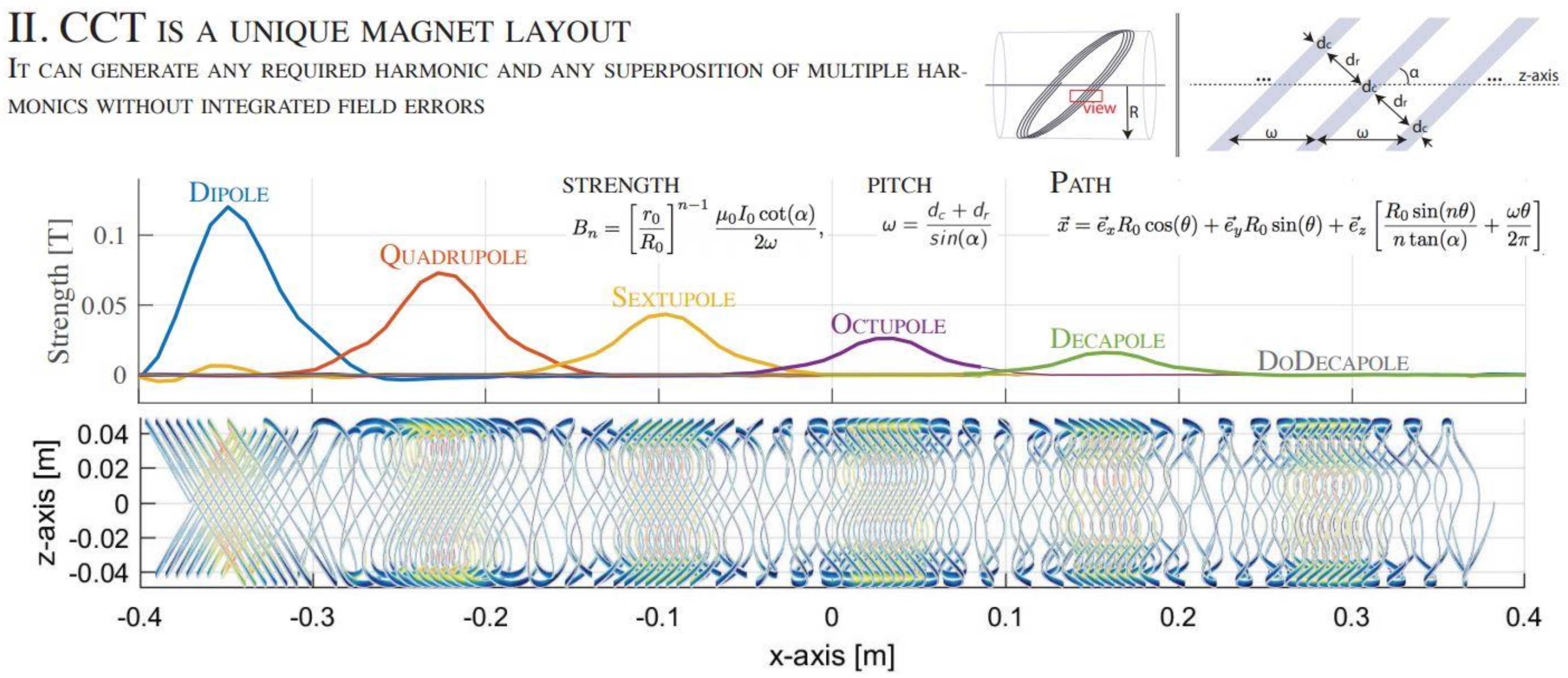
Its even possible to combine the coil shapes to have multi function





Thanks to JvN

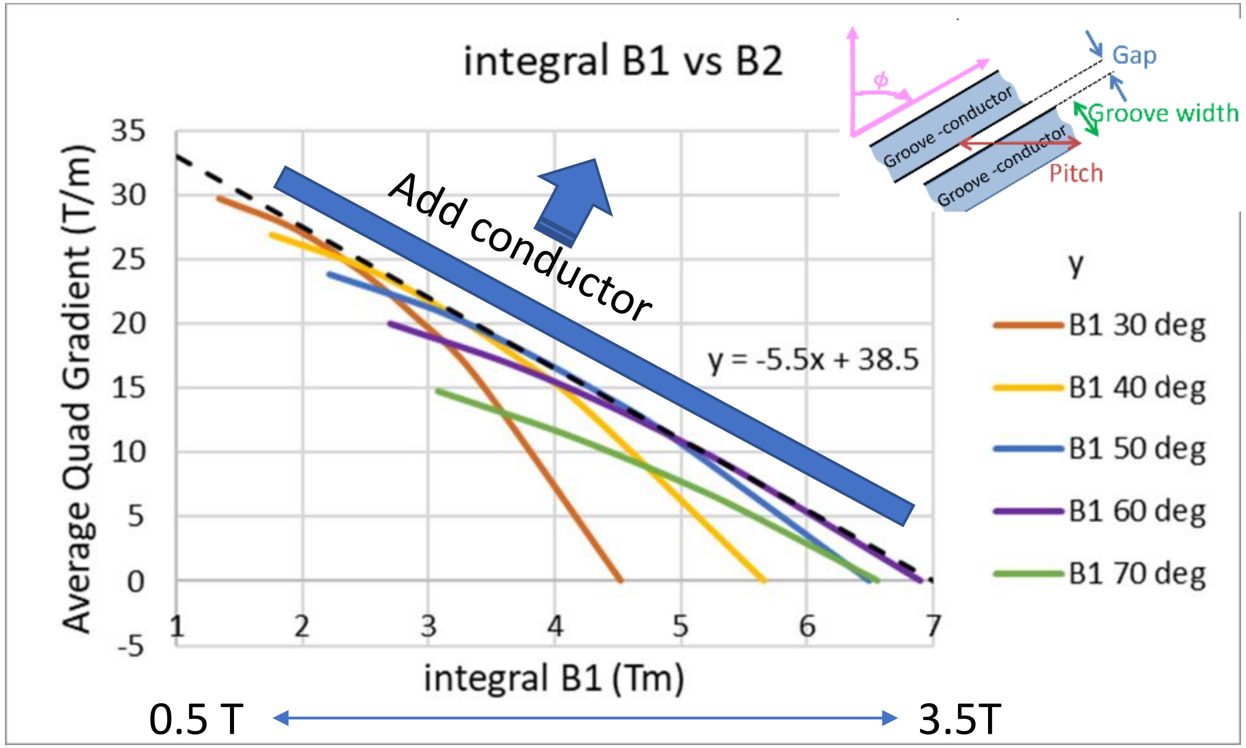
A few CCT Harmonic Coil Layouts

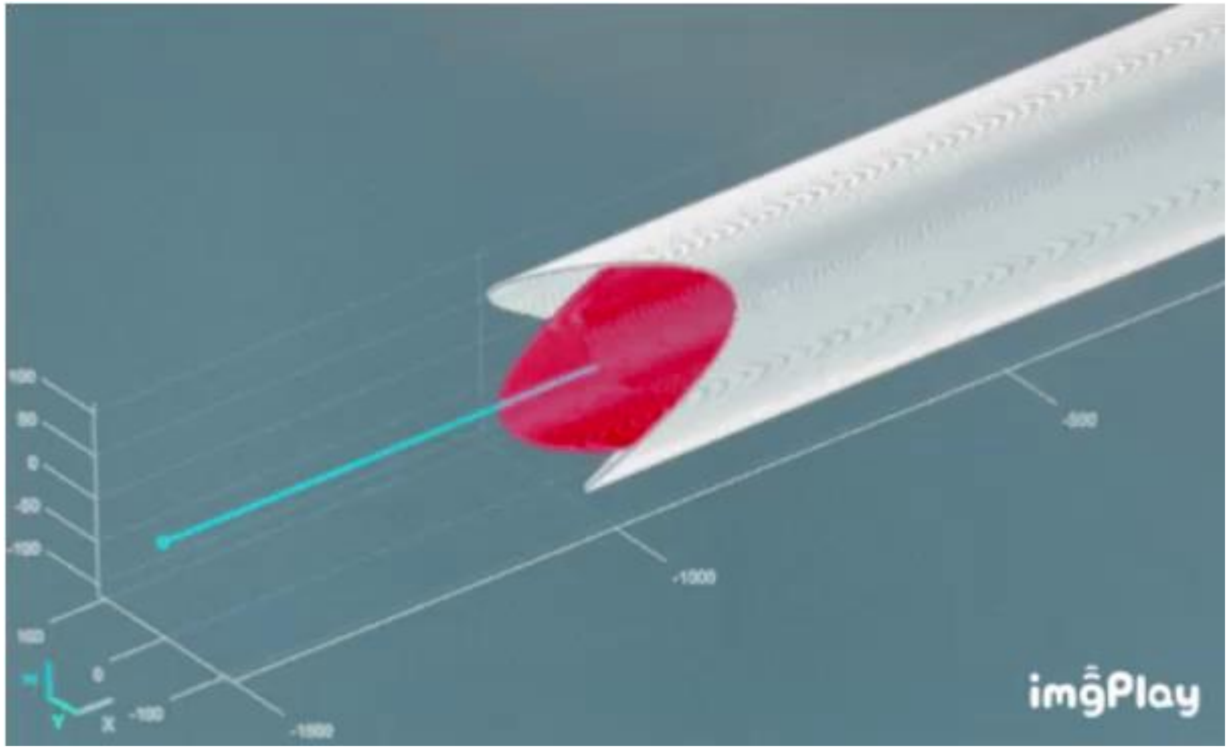


Morphing between Dipole and Quad Combined function strengths

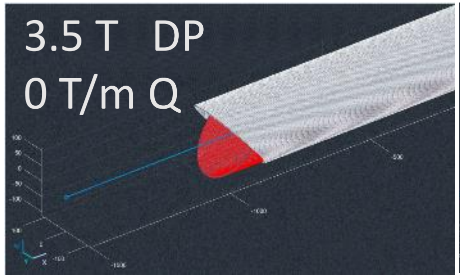
Thanks to Mike K & JvN's & his Field program

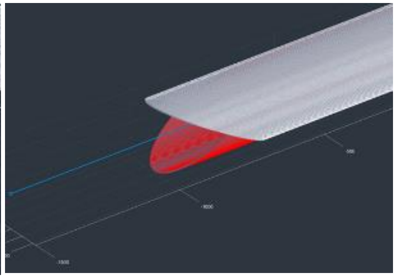
We can also set all the other harmonics if needed

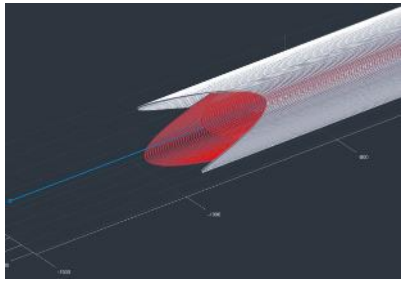


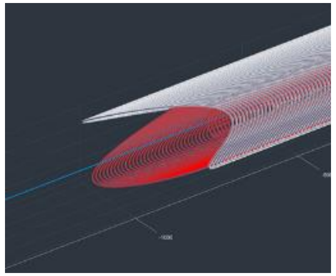


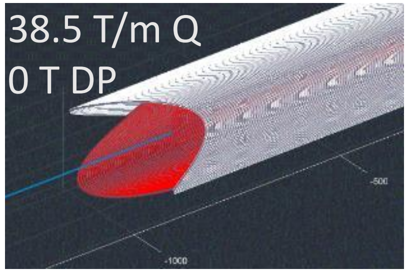
200 mm aperture
2 m long
Two layers
2x10 mm channel
95 A/mm



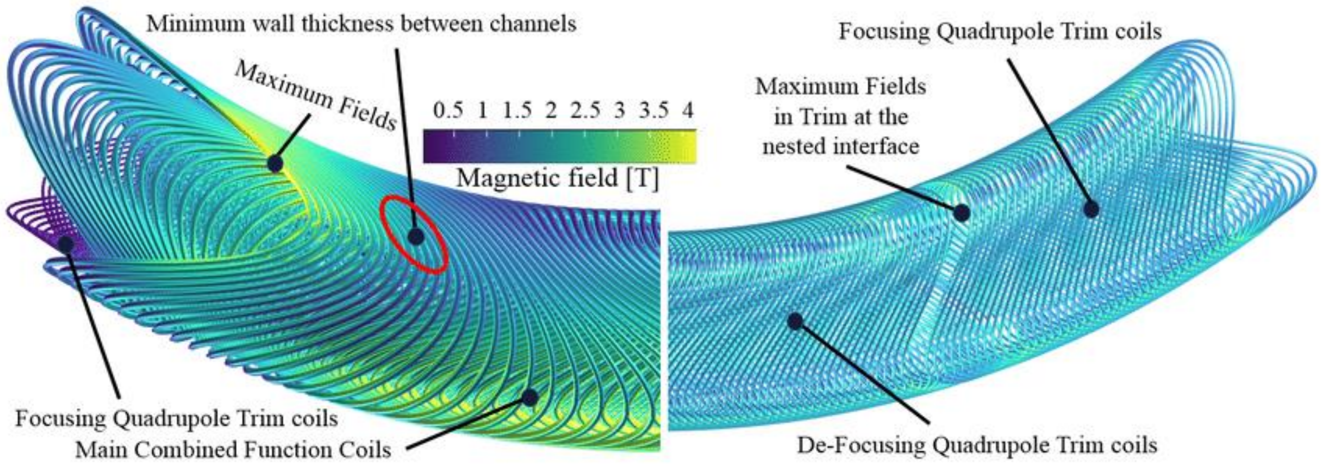


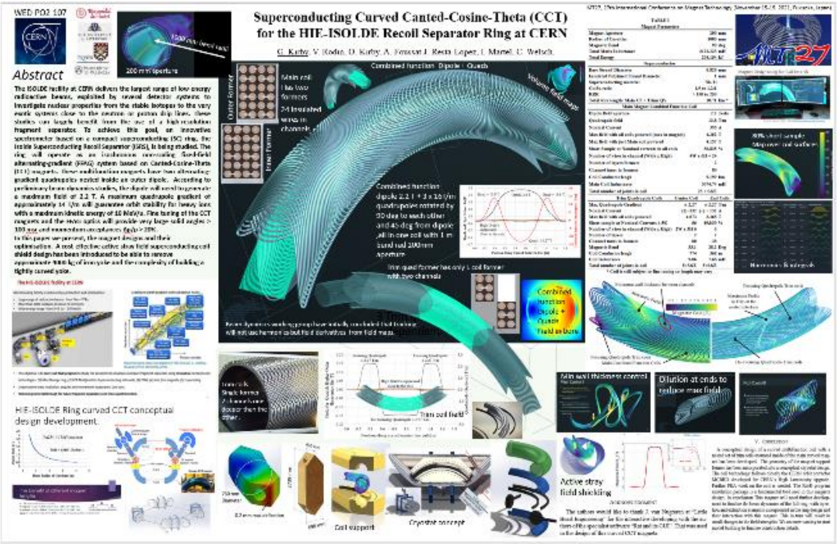


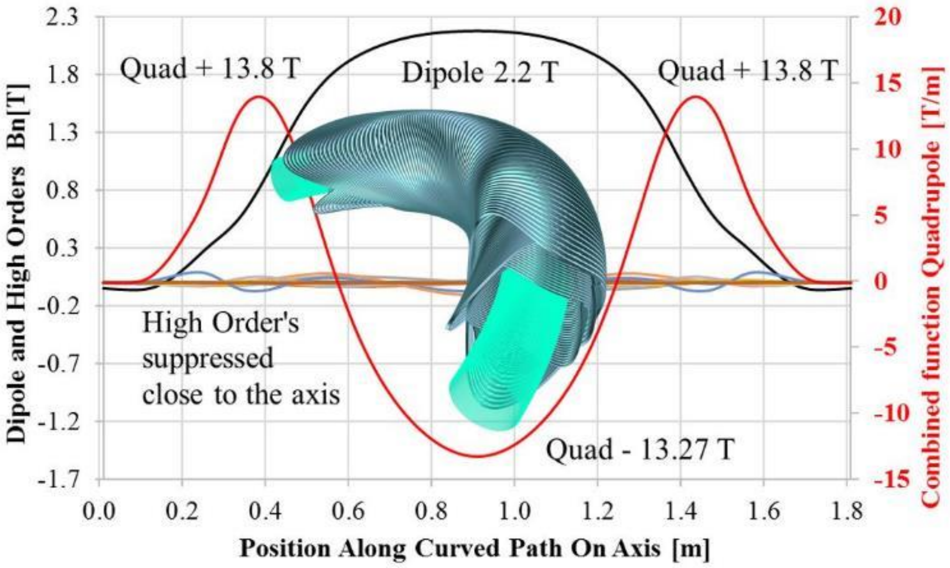


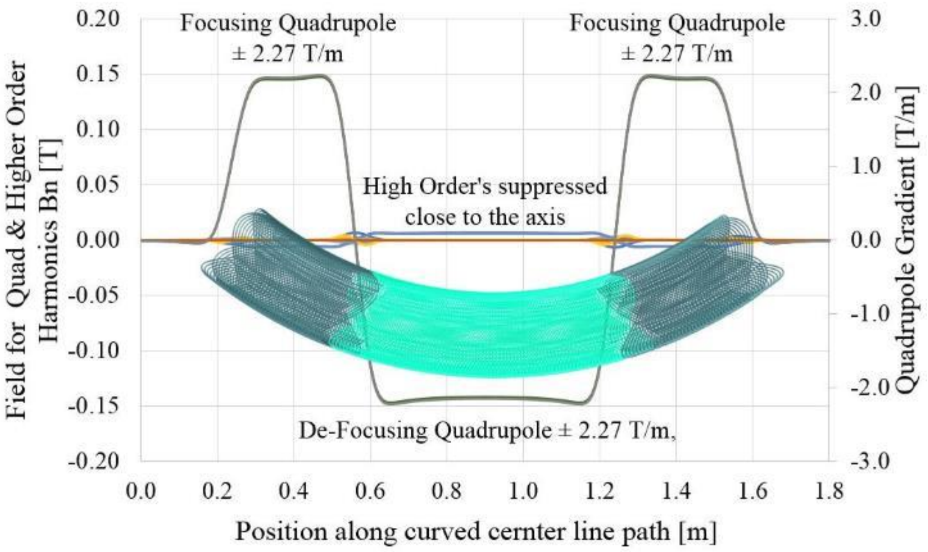


Multi harmonic coil adds all functions together

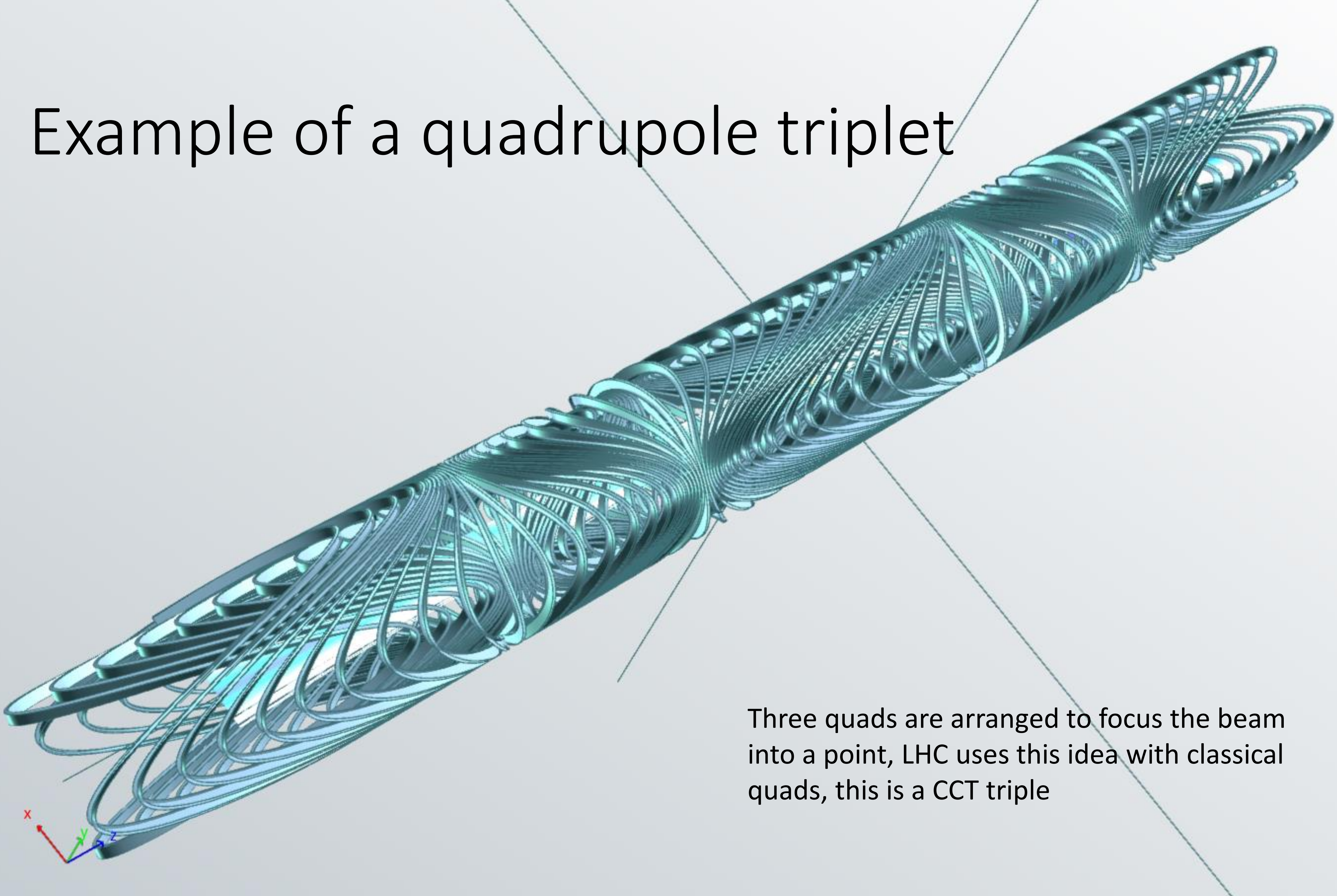




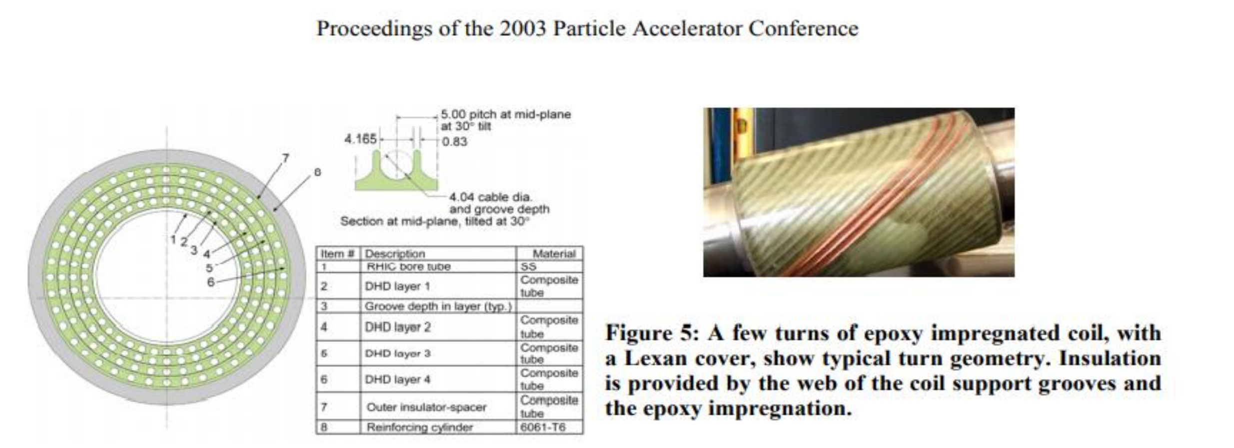




Example of a quadrupole triplet



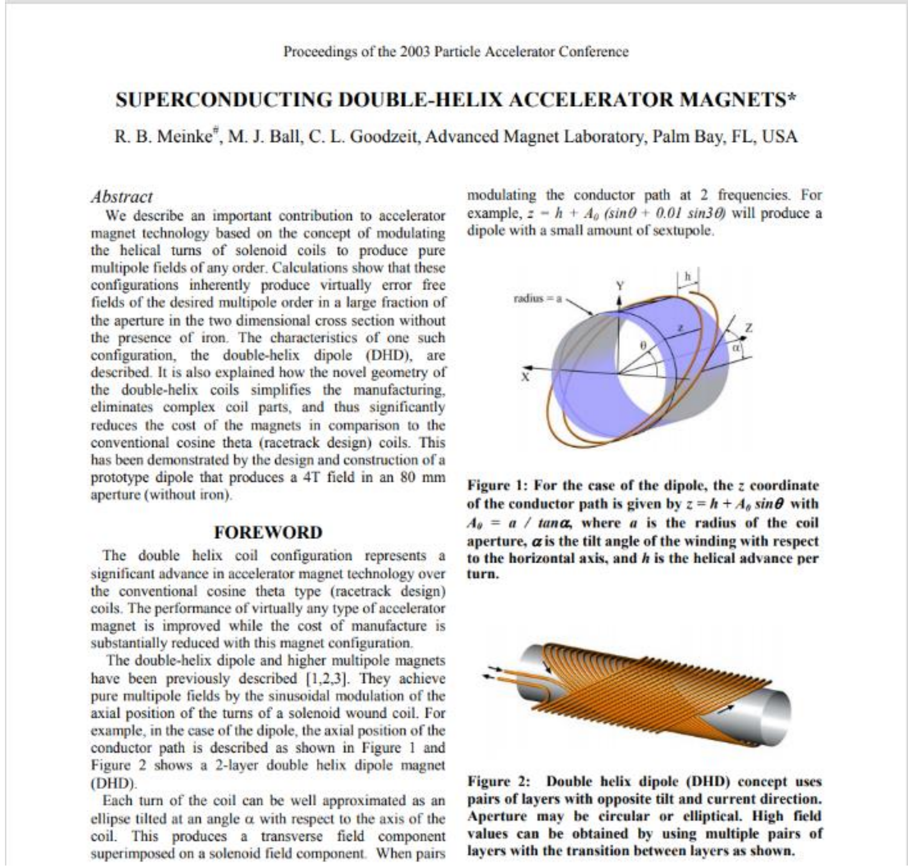
Three quads are arranged to focus the beam into a point, LHC uses this idea with classical quads, this is a CCT triple



Proceedings of the 2003 Particle Accelerator Conference

Item #	Description	Material
1	RHIC bore tube	SS
2	DHD layer 1	Composite tube
3	Groove depth in layer (typ.)	
4	DHD layer 2	Composite tube
5	DHD layer 3	Composite tube
6	DHD layer 4	Composite tube
7	Outer insulator-spacer	Composite tube
8	Reinforcing cylinder	6061-T6

Figure 5: A few turns of epoxy impregnated coil, with a Lexan cover, show typical turn geometry. Insulation is provided by the web of the coil support grooves and the epoxy impregnation.



Proceedings of the 2003 Particle Accelerator Conference

SUPERCONDUCTING DOUBLE-HELIX ACCELERATOR MAGNETS*

R. B. Meinke#, M. J. Ball, C. L. Goodzeit, Advanced Magnet Laboratory, Palm Bay, FL, USA

Abstract

We describe an important contribution to accelerator magnet technology based on the concept of modulating the helical turns of solenoid coils to produce pure multipole fields of any order. Calculations show that these configurations inherently produce virtually error free fields of the desired multipole order in a large fraction of the aperture in the two dimensional cross section without the presence of iron. The characteristics of one such configuration, the double-helix dipole (DHD), are described. It is also explained how the novel geometry of the double-helix coils simplifies the manufacturing, eliminates complex coil parts, and thus significantly reduces the cost of the magnets in comparison to the conventional cosine theta (racetrack design) coils. This has been demonstrated by the design and construction of a prototype dipole that produces a 4T field in an 80 mm aperture (without iron).

FOREWORD

The double helix coil configuration represents a significant advance in accelerator magnet technology over the conventional cosine theta type (racetrack design) coils. The performance of virtually any type of accelerator magnet is improved while the cost of manufacture is substantially reduced with this magnet configuration.

The double-helix dipole and higher multipole magnets have been previously described [1,2,3]. They achieve pure multipole fields by the sinusoidal modulation of the axial position of the turns of a solenoid wound coil. For example, in the case of the dipole, the axial position of the conductor path is described as shown in Figure 1 and Figure 2 shows a 2-layer double helix dipole magnet (DHD).

Each turn of the coil can be well approximated as an ellipse tilted at an angle α with respect to the axis of the coil. This produces a transverse field component superimposed on a solenoid field component. When pairs modulating the conductor path at 2 frequencies. For example, $z = h + A_0 (\sin\theta + 0.01 \sin 3\theta)$ will produce a dipole with a small amount of sextupole.

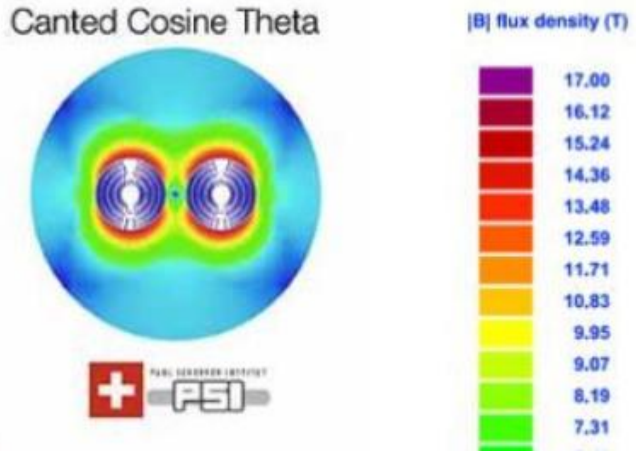
Figure 1: For the case of the dipole, the z coordinate of the conductor path is given by $z = h + A_0 \sin\theta$ with $A_0 = a / \tan\alpha$, where a is the radius of the coil aperture, α is the tilt angle of the winding with respect to the horizontal axis, and h is the helical advance per turn.

Figure 2: Double helix dipole (DHD) concept uses pairs of layers with opposite tilt and current direction. Aperture may be circular or elliptical. High field values can be obtained by using multiple pairs of layers with the transition between layers as shown.

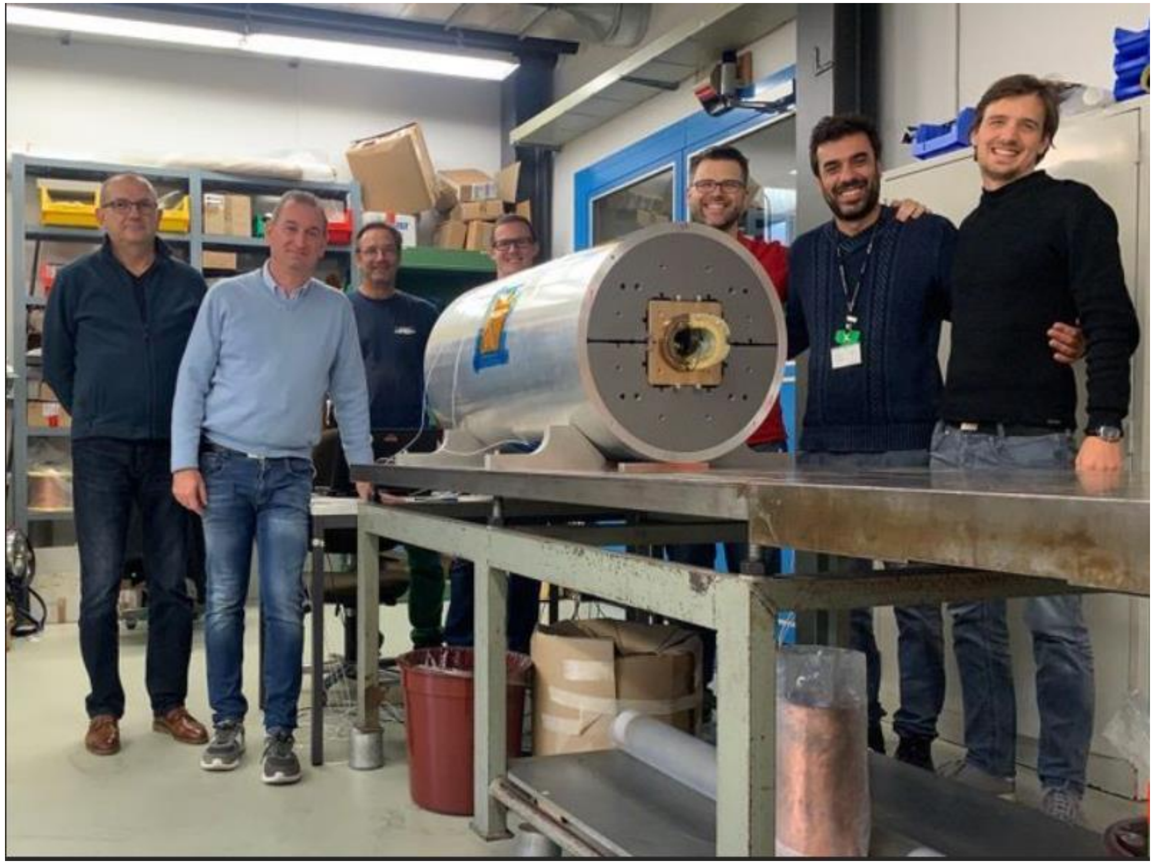
USA company specializing in CCT's AMLSuperconductivity.com

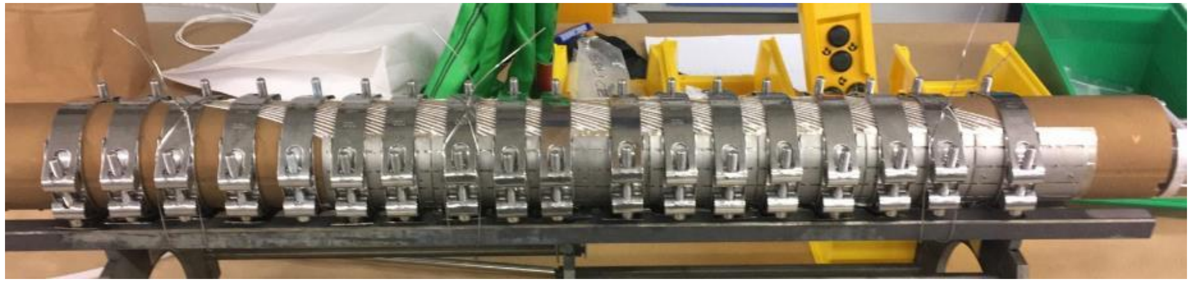
Nb3Sn dipole development at PSI

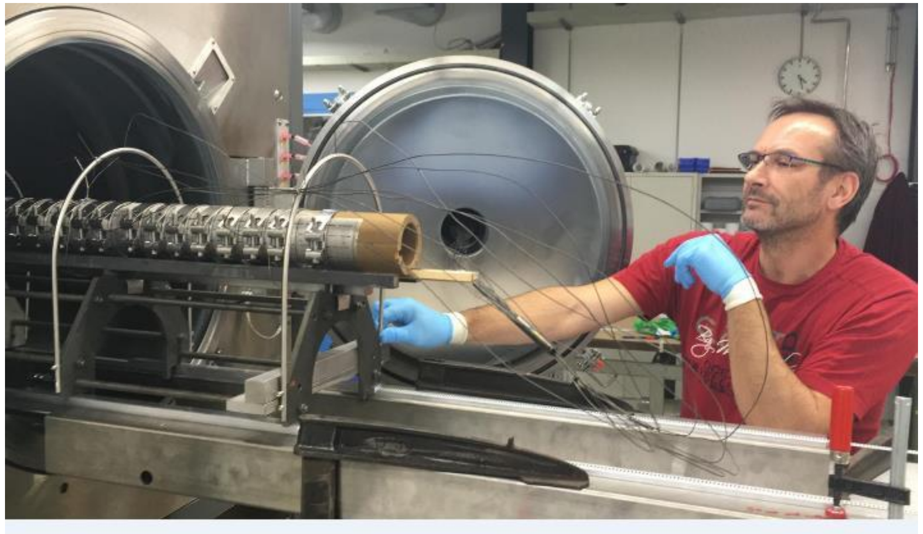
Bernhard Auchmann & team at (PSI)



Test halted due to liquefier problem at LBNL ! So far One quench, at 62% SS, 11 KA, ~6T……



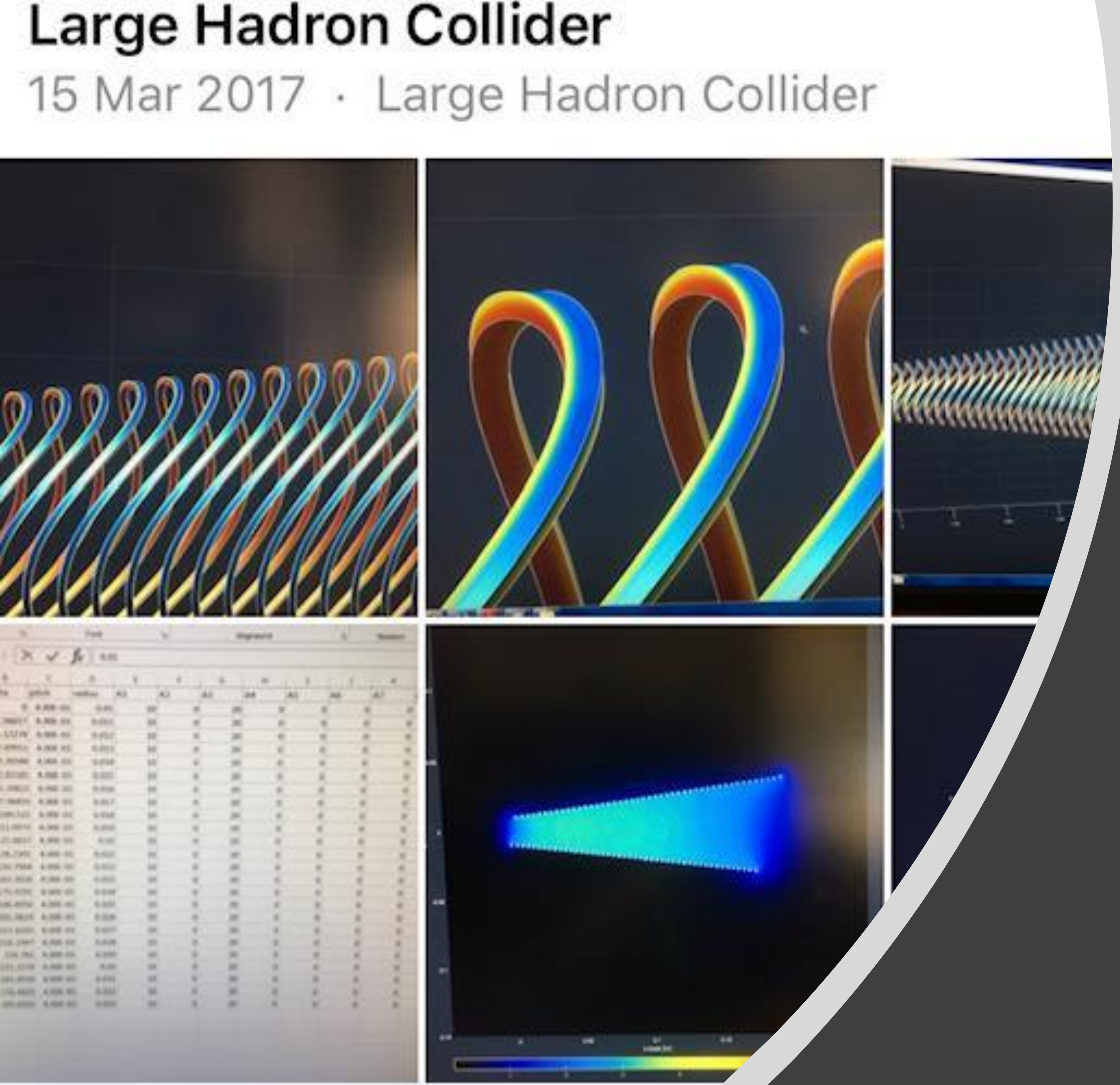




Our first CCT dipole 2014.

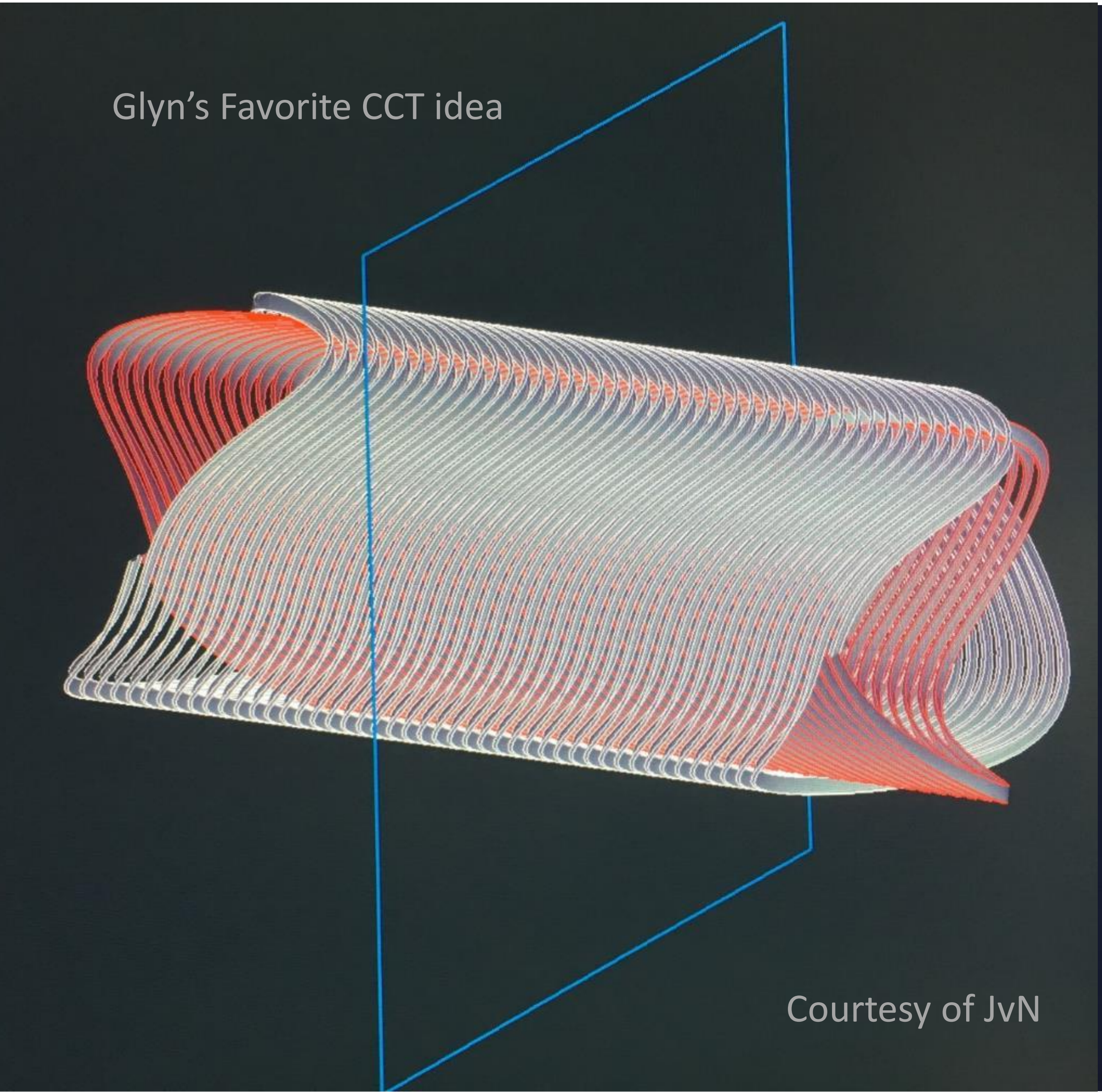
Built in my office.
Sadly, we never tested it.

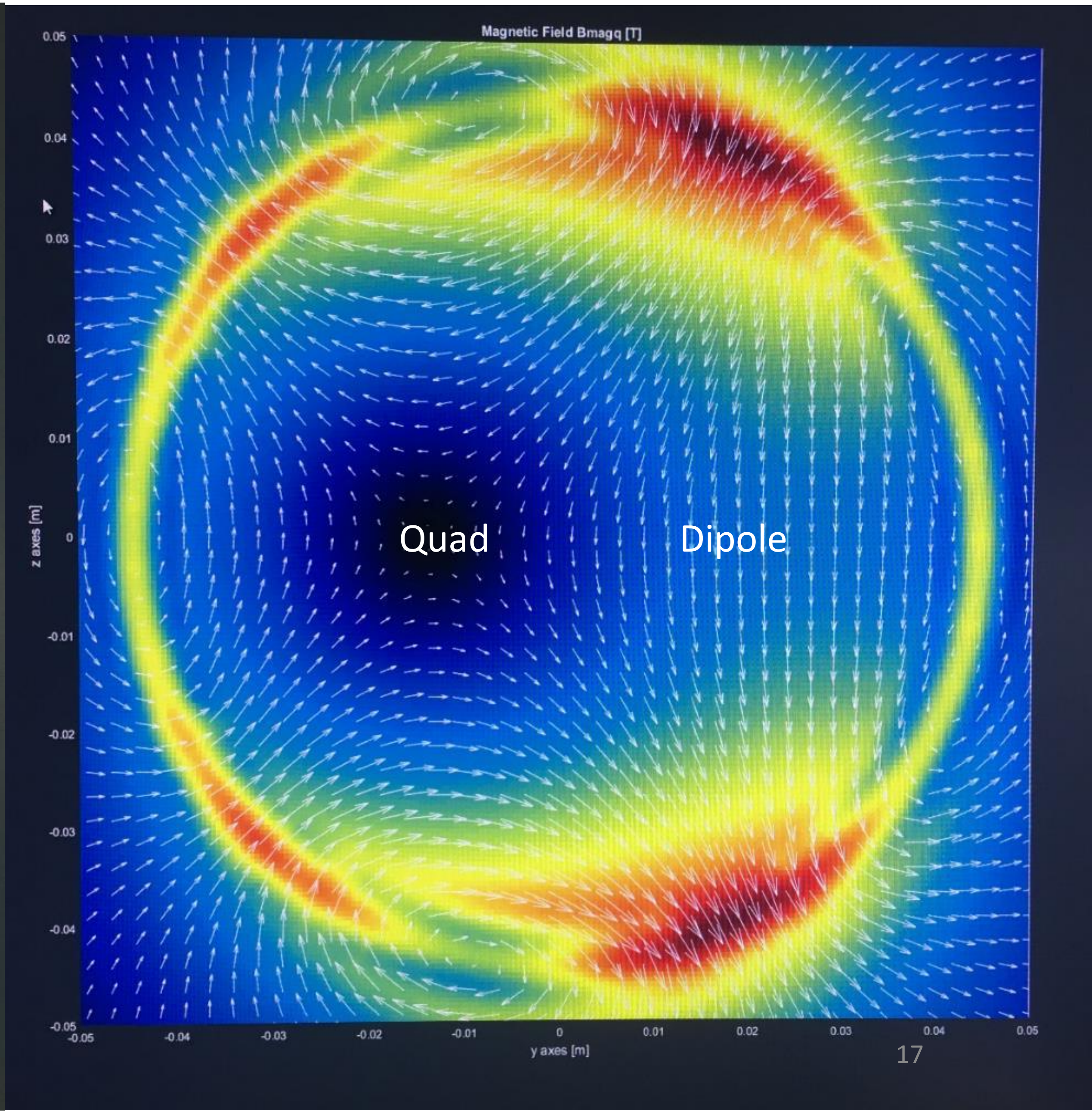
One of the first ideas wind on inside and outside of former.



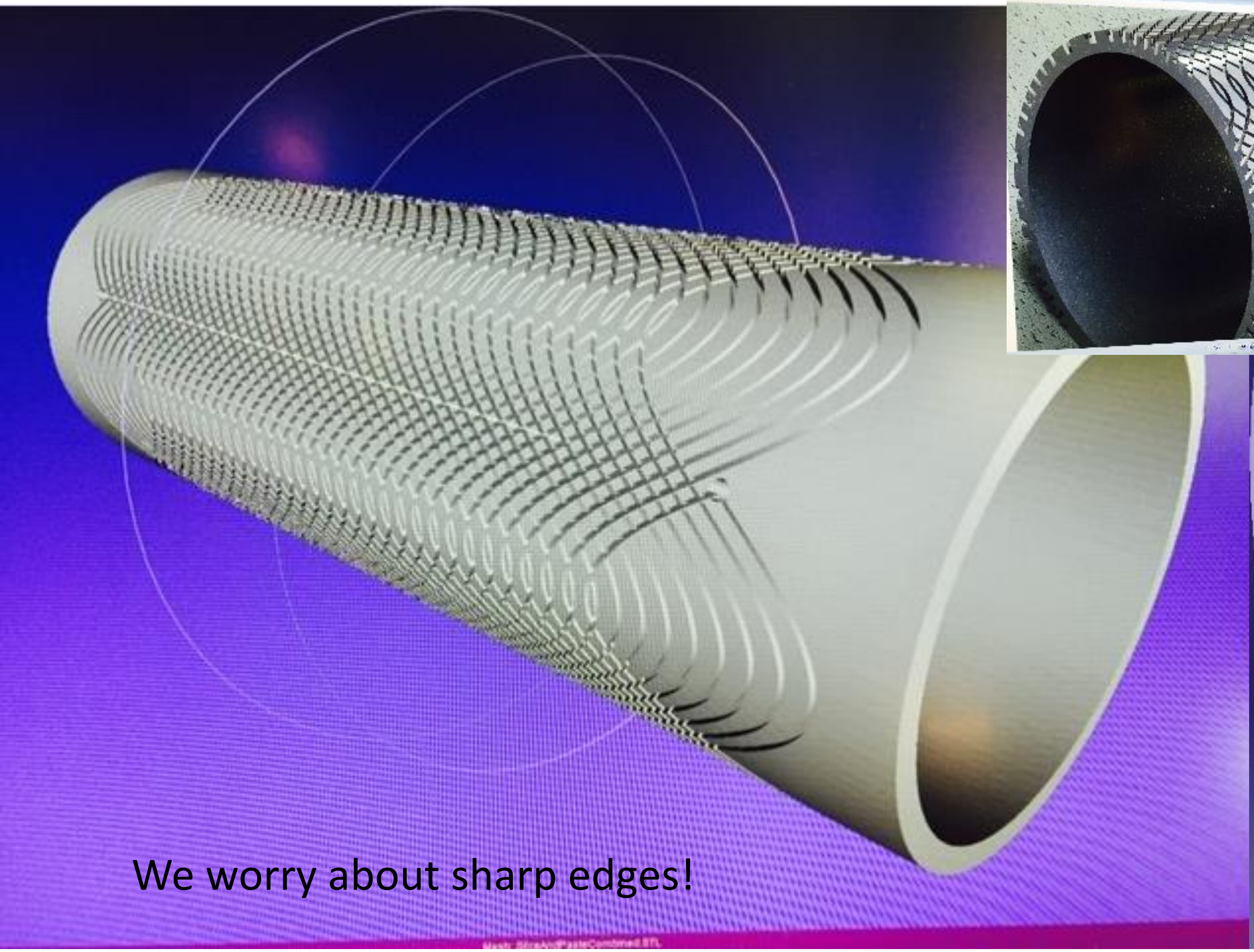
JvN’s field program advances Cone Quad

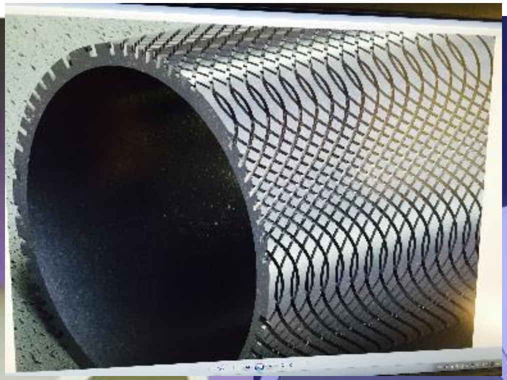
Flexibility of CCT designs combined function off axis

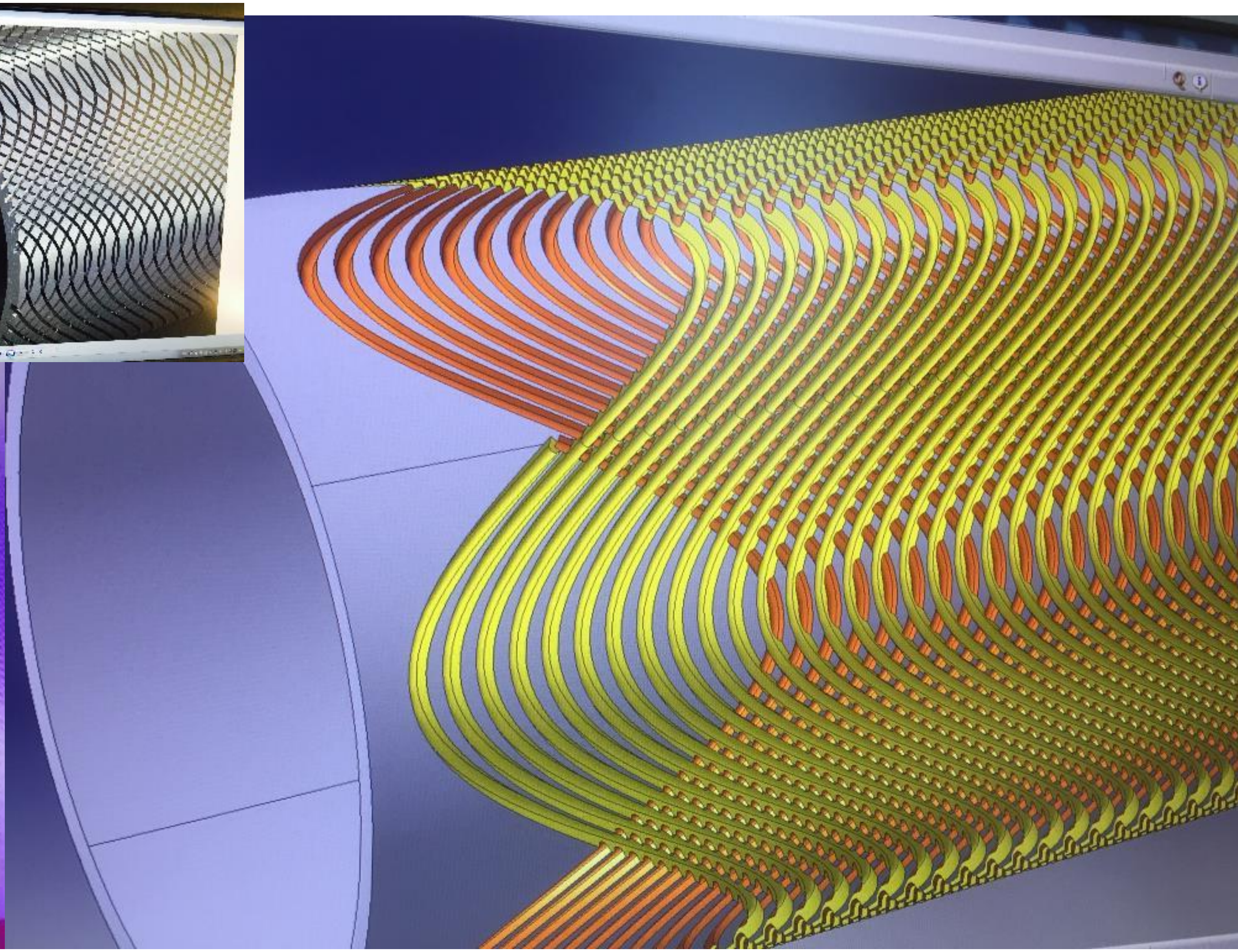




Former ideas
two layers wound onto a single tube
two channel depths in the single tube







Possible PhD idea

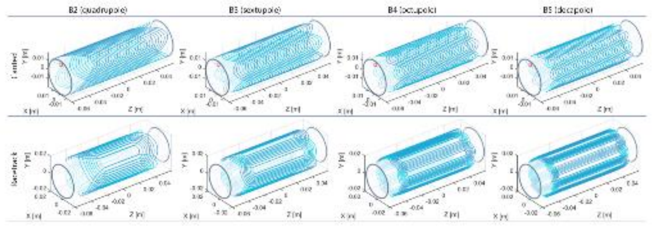
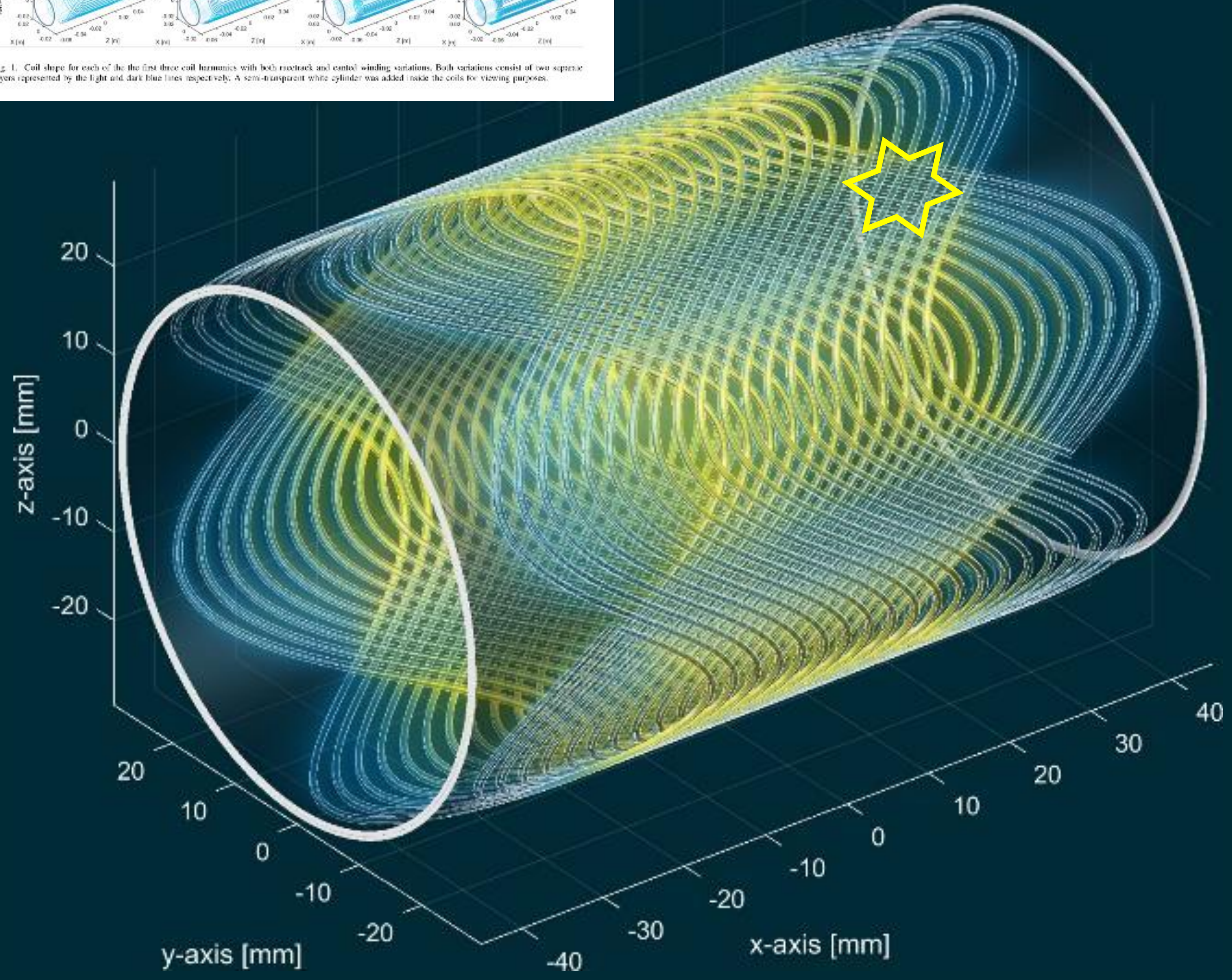


Fig. 1. Coil shape for each of the the first three coil harmonics with both racetrack and cantol winding variations. Both variations consist of two separate layers represented by the light and dark blue lines respectively. A semi-transparent white cylinder was added inside the coils for viewing purposes.



One more technology that may prove to be necessary for HTS

Persistent Current Shim Coils for Accelerator Magnets

-The Magic Magnet-

[1] J. van Nugteren et. Al. "Persistent Current Shim Coils for Accelerator Magnets", *Technical Report, CERN, 2016*
[2] J. van Nugteren, "High Temperature Superconductor Accelerator Magnets", PhD Thesis, University of Twente, 2016
[3] A. Dael et. Al., "Auto Correction des Harmonicques du champ Magnetique d'un multipole pulse par enroulements supraconducteurs," Particle Accelerators, vol. 4, pp. 145–150, 1973, in French.

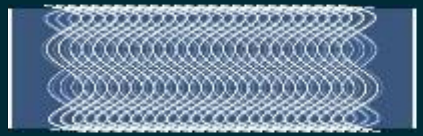
Shim Coil Numerical Analysis

- Shim corrects its integrated harmonic exactly over its magnetic length, local errors remain.
- Here is demonstrated on static field, but concept also works for dynamic

very crappy dipole (=

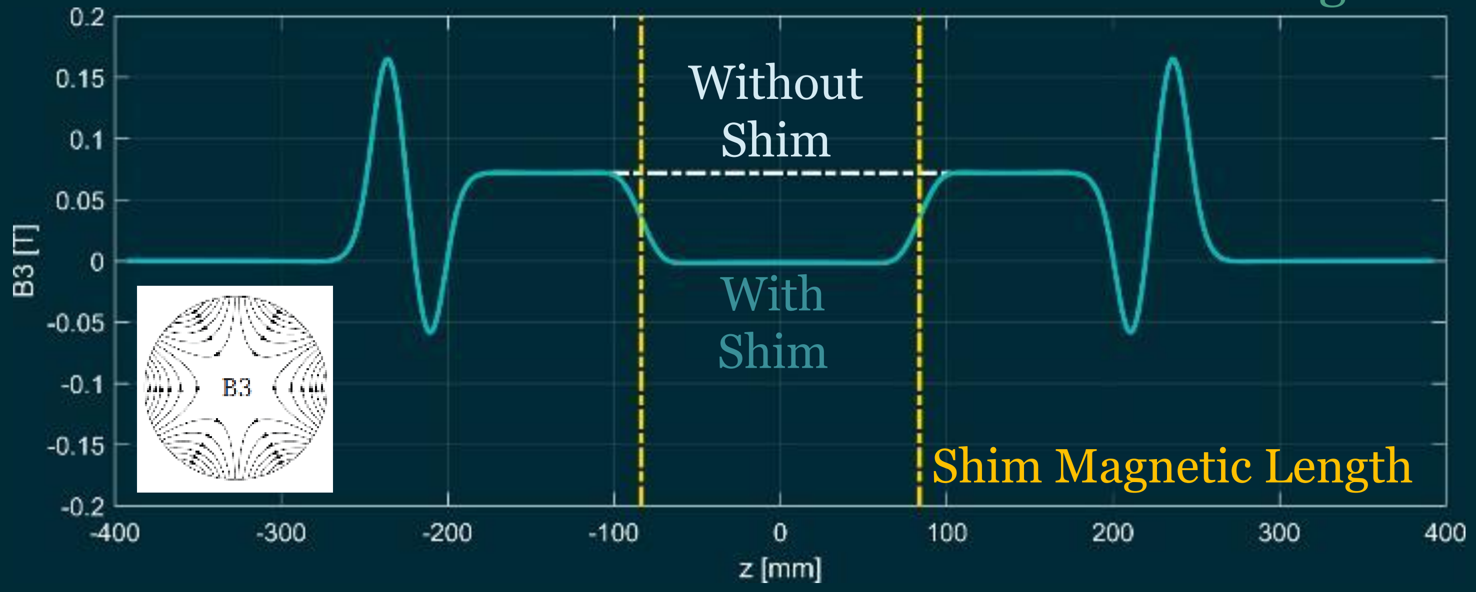
+

sextupole (B_3) shim coil

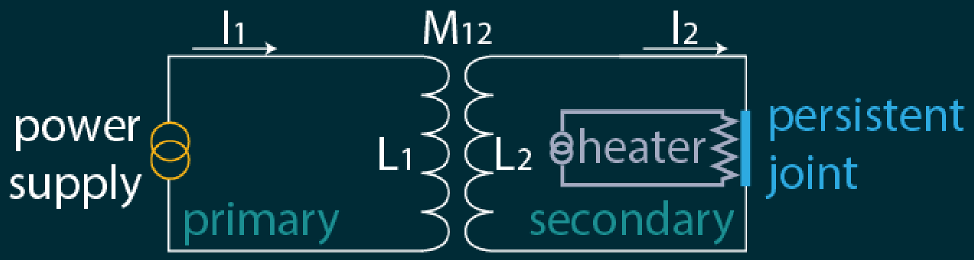


sextupole at 2/3 aperture along axis

=

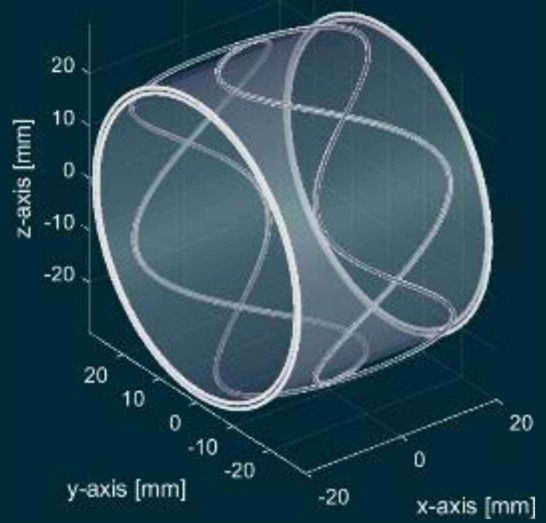


- The current in the shim can be calculated using the mutual inductance matrix of the system (as a transformer)

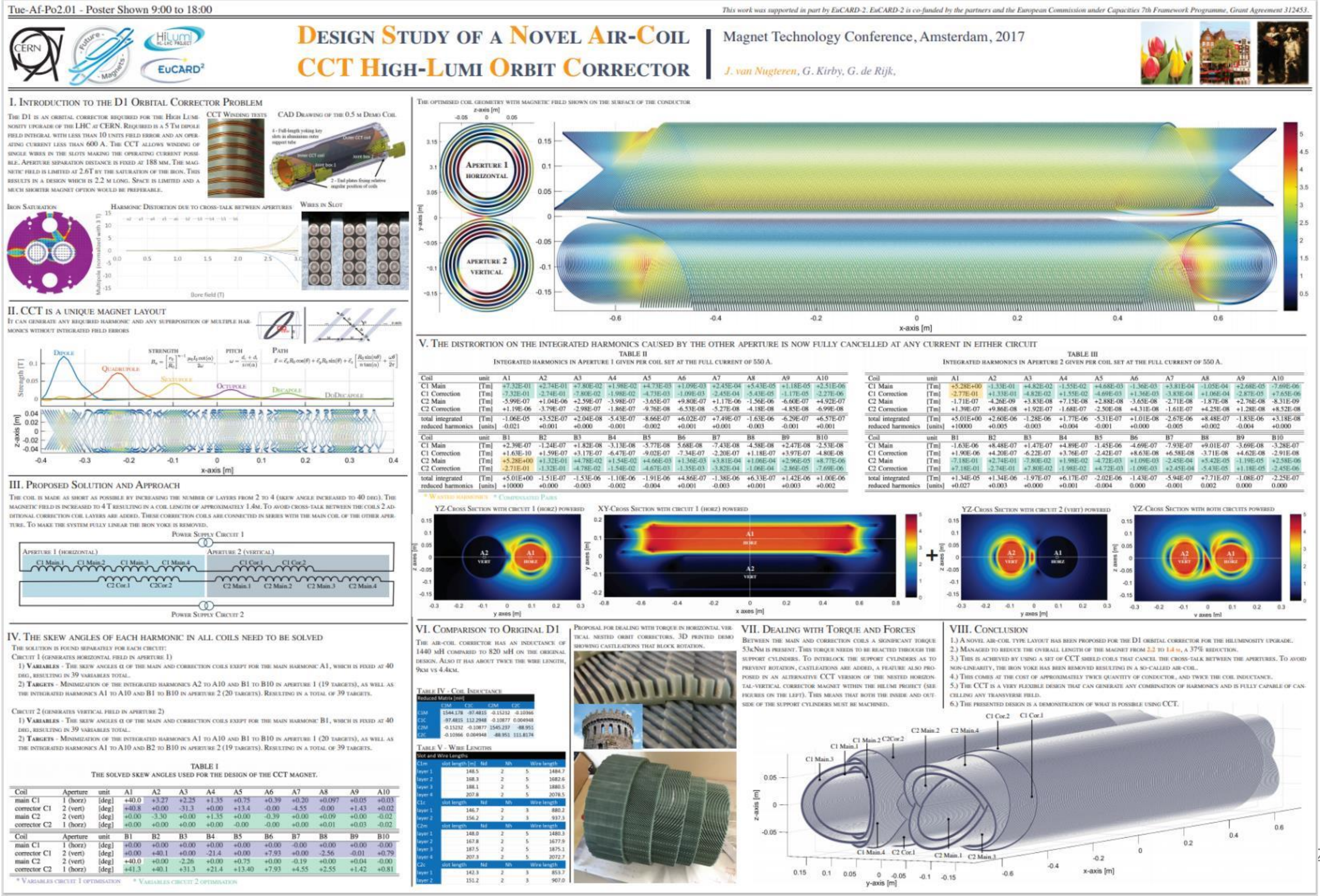


$$\frac{I_2}{dt} = \frac{M_{12}}{L_2}\frac{I_1}{dt}$$

- Where M_{12} and L_2 are calculated using *Field 2017* code

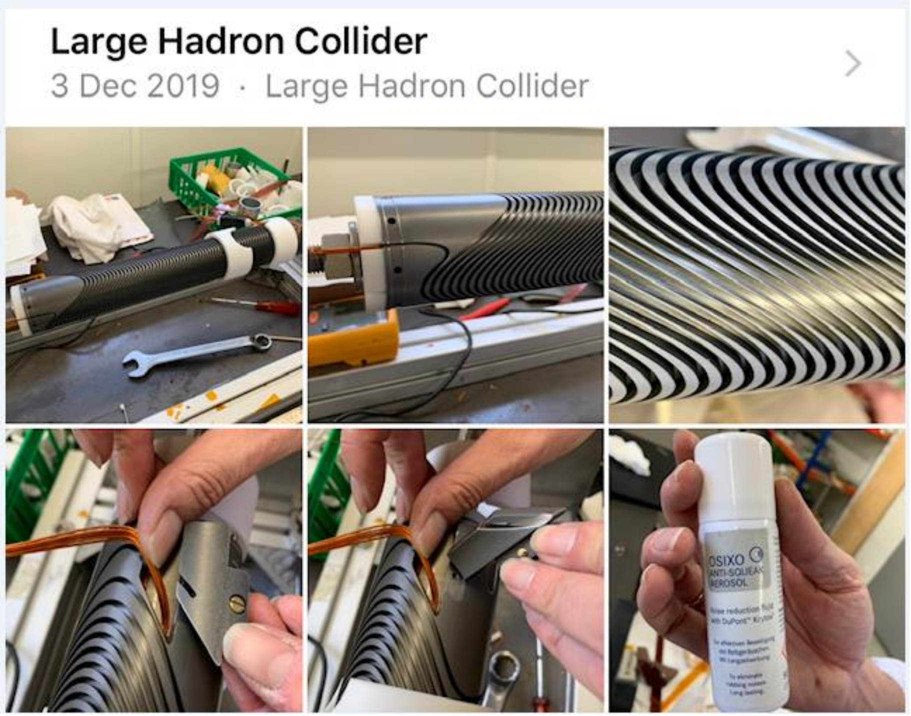


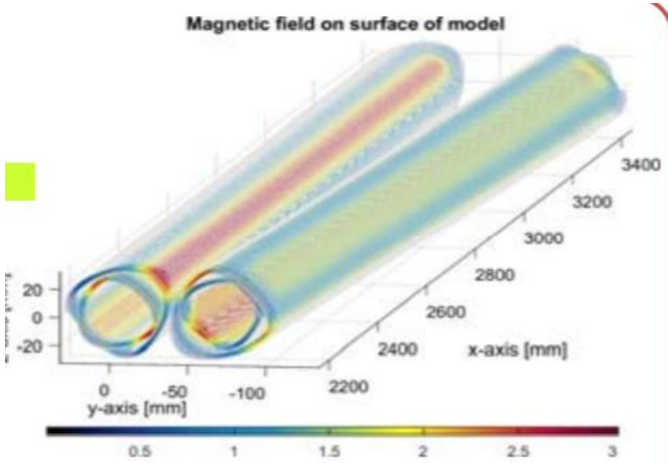
- A repeated pattern of single lanes also works due to mutual coupling
- Layers are not electrically connected
- Vapour deposition ReBCO on tube?

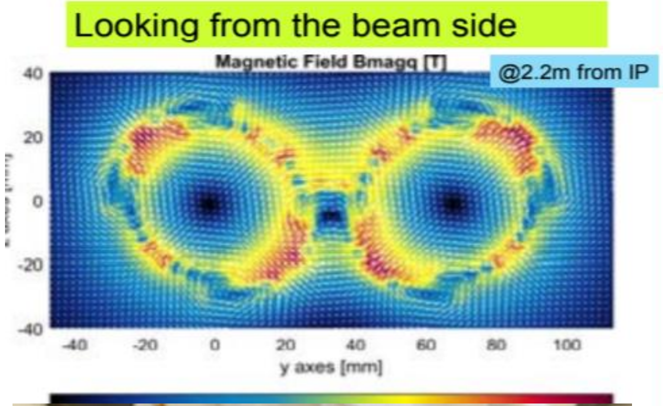


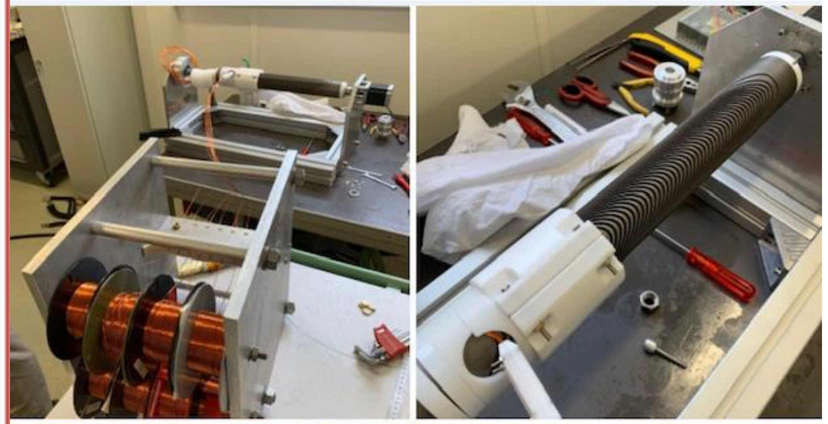
Tue-Af-Po2.01 - Poster Shown 9:00 to 18:00
This work was supported in part by EuCARD-2. EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453.
CERN
HiLumi
EuCARD²
Design Study of a Novel Air-Coil CCT High-Lumi Orbit Corrector
Magnet Technology Conference, Amsterdam, 2017
J. van Nugteren, G. Kirby, G. de Rijk,
I. Introduction to the D1 Orbital Corrector Problem
The D1 is an orbital corrector required for the High Luminosity upgrade of the LHC at CERN. Required is a 5 Tm dipole field integral with less than 10 units field error and an operating current less than 600 A. The CCT allows winding of single wires in the slots making the operating current possible. Aperture separation distance is fixed at 188 mm. The magnetic field is limited at 2.6T by the saturation of the iron. This results in a design which is 2.2 m long. Space is limited and a much shorter magnet option would be preferable.
CCT Winding tests
CAD Drawing of the 0.5 m Demo Coil
Iron Saturation
Harmonic Distortion due to cross-talk between apertures
Wires in Slot
II. CCT is a unique magnet layout
It can generate any required harmonic and any superposition of multiple harmonics without integrated field errors
Dipole
Quadrupole
Sextupole
Octupole
Decapole
DoDecapole
III. Proposed Solution and Approach
Power Supply Circuit 1
Aperture 1 (horizontal)
Aperture 2 (vertical)
Power Supply Circuit 2
IV. The skew angles of each harmonic in all coils need to be solved
TABLE I
The solved skew angles used for the design of the CCT magnet.
The optimised coil geometry with magnetic field shown on the surface of the conductor
Aperture 1 horizontal
Aperture 2 vertical
x-axis [m]
V. The distrortion on the integrated harmonics caused by the other aperture is now fully cancelled at any current in either circuit
TABLE II
Integrated harmonics in aperture 1 given per coil set at the full current of 550 A.
TABLE III
Integrated harmonics in aperture 2 given per coil set at the full current of 550 A.
YZ-Cross Section with circuit 1 (horz) powered
XY-Cross Section with circuit 1 (horz) powered
YZ-Cross Section with circuit 2 (vert) powered
YZ-Cross Section with both circuits powered
VI. Comparison to Original D1
The air-coil corrector has an inductance of 1440 mH compared to 820 mH on the original design. Also it has about twice the wire length, 9km vs 4.4km.
Table IV - Coil Inductance
Table V - Wire Lengths
Proposal for dealing with torque in horizontal vertical nested orbit correctors. 3D printed demo showing castleations that block rotation.
VII. Dealing with Torque and Forces
VIII. Conclusion

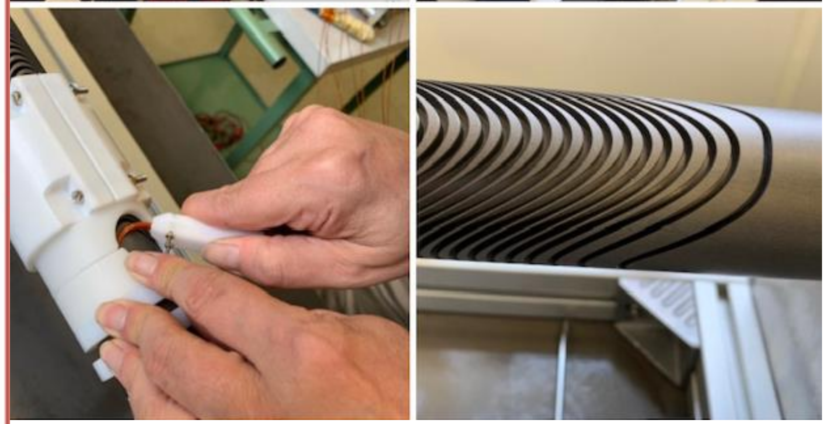
- FCC quad CCT
- Low-Cost Project 17 CHF

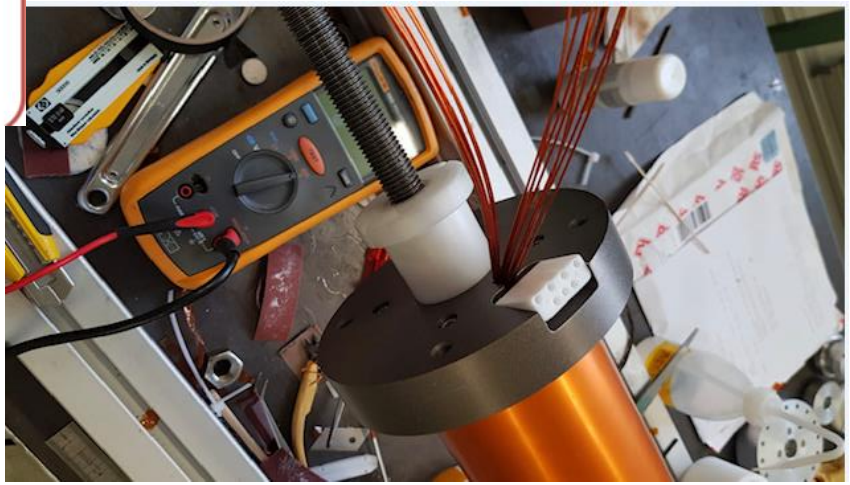










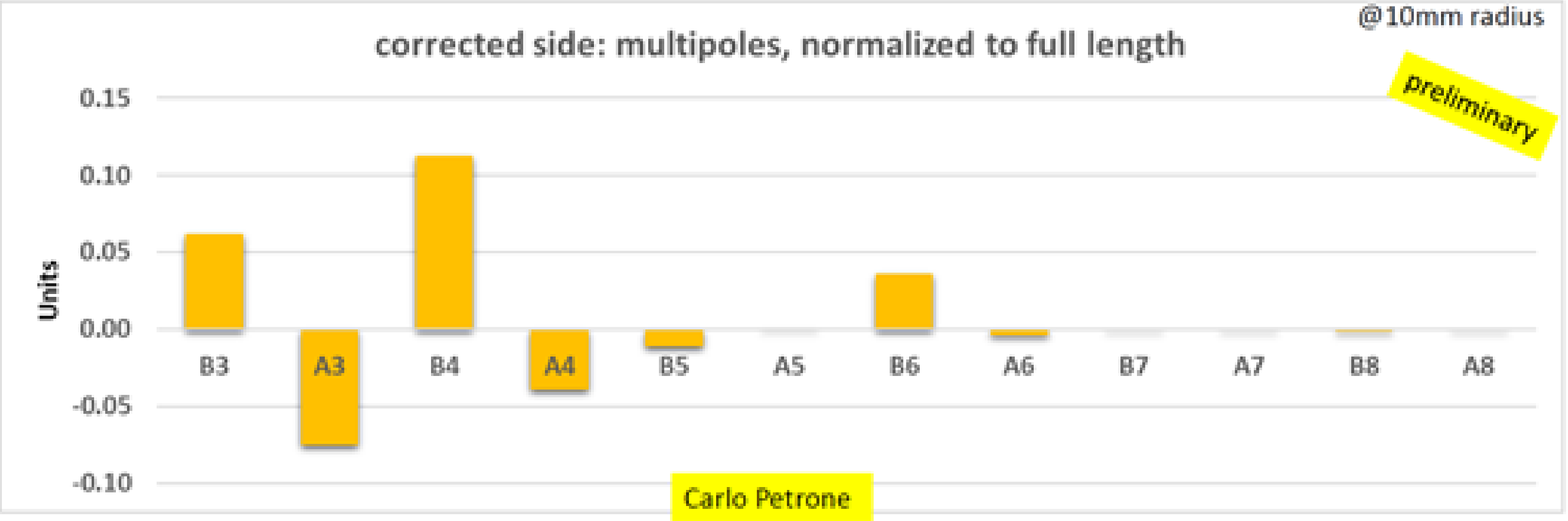


Design to CNC !!
How to transfer the geometry is important !!

Winding tool ideas

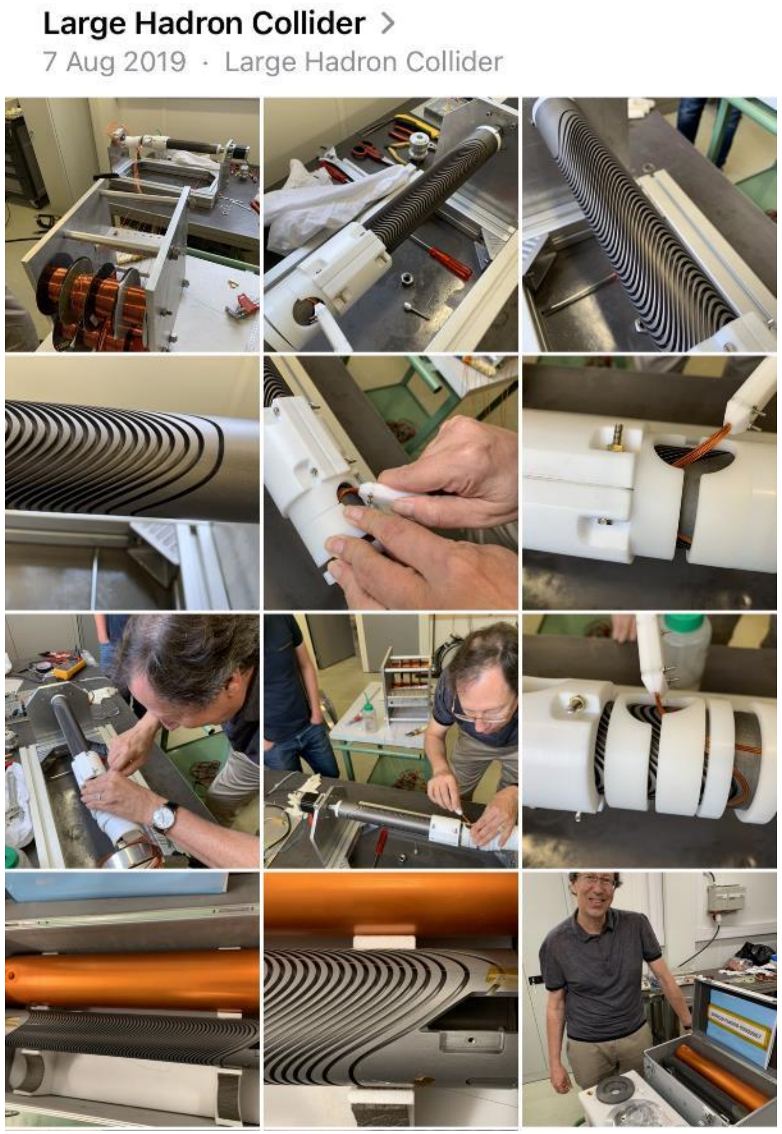
CCT FCC quad

Field quality at the edge, with correction



Multipoles calculated up to B15, A15, but are all zero

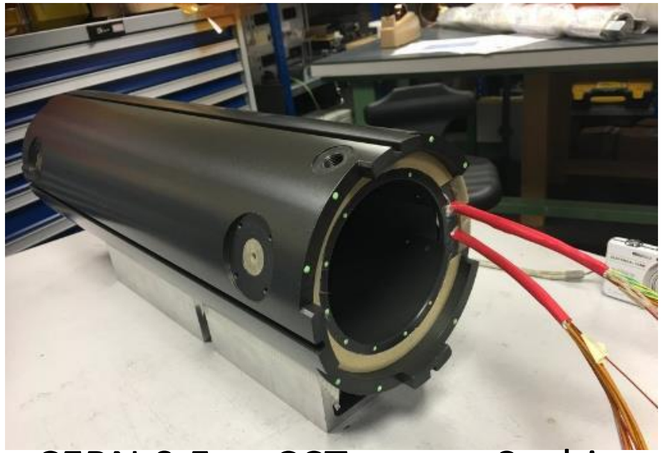
0.1 units maximum. An excellent result.



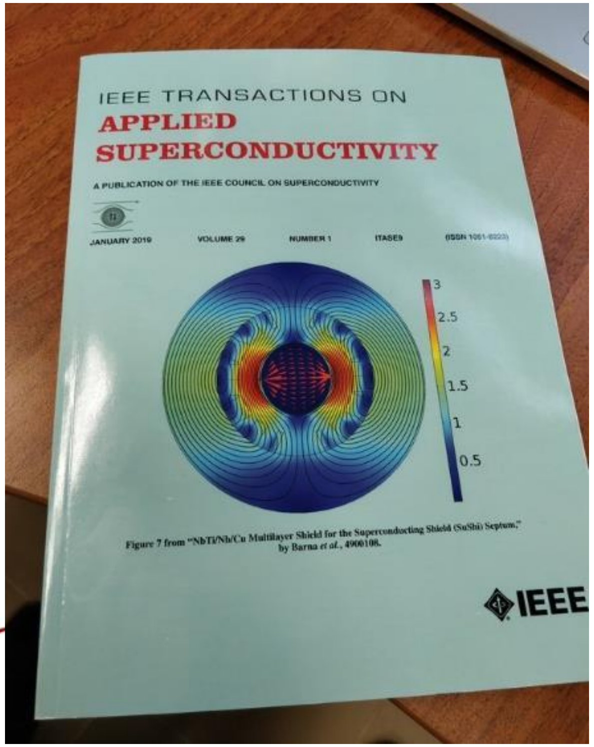
The coil had magnetic material near the aperture so it may be even better still working on it

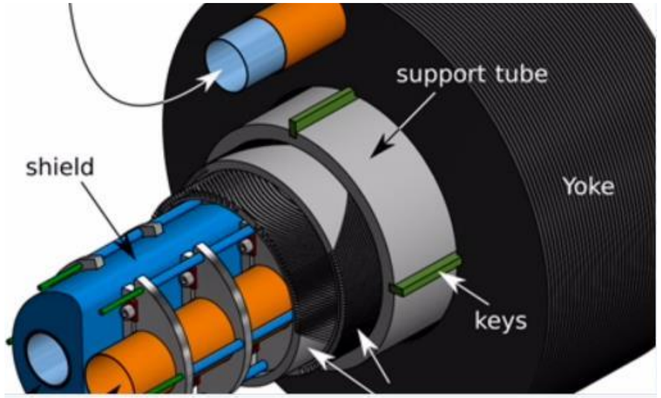
SuShi septum status report:
Testing the NbTi/Nb/Cu multilayer shield & update on the concept

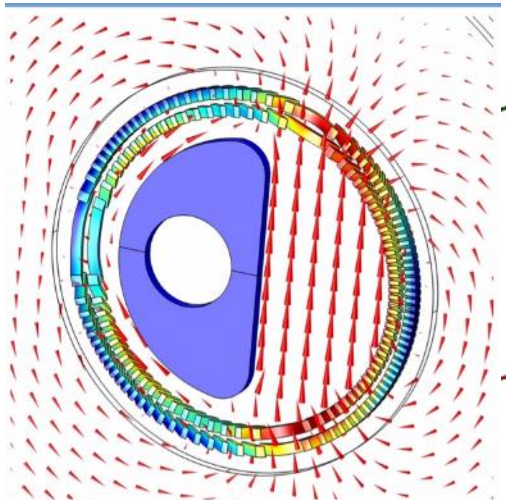
D. Barna, M. Novák, K. Brunner
Miro Atanasov, Carlo Petrone, Max Pascal, Jerome Feuvrier, Franco Mangiarotti, Frederic Rougemot, Yannick Thuau & the rest of the SM18 team

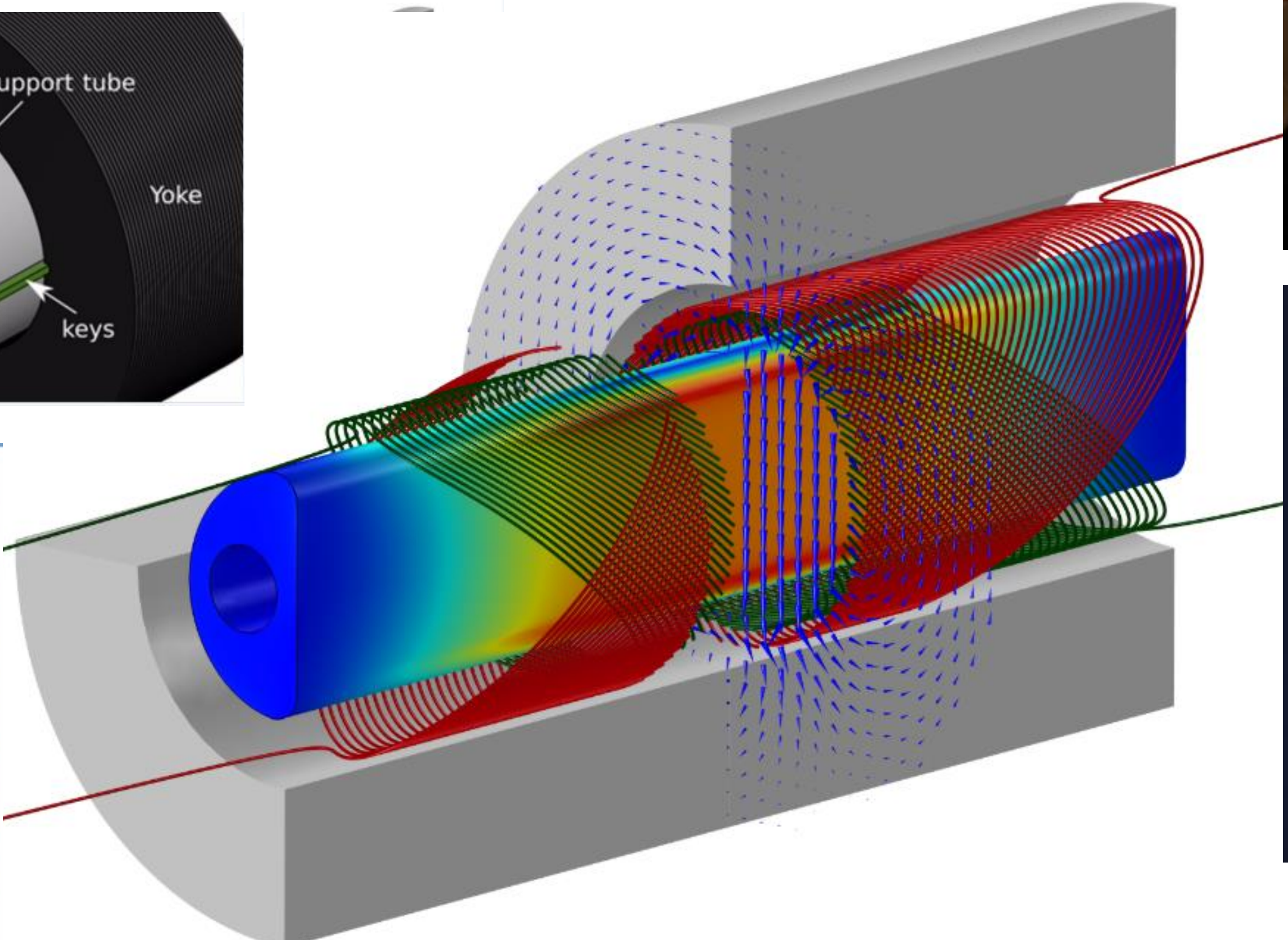


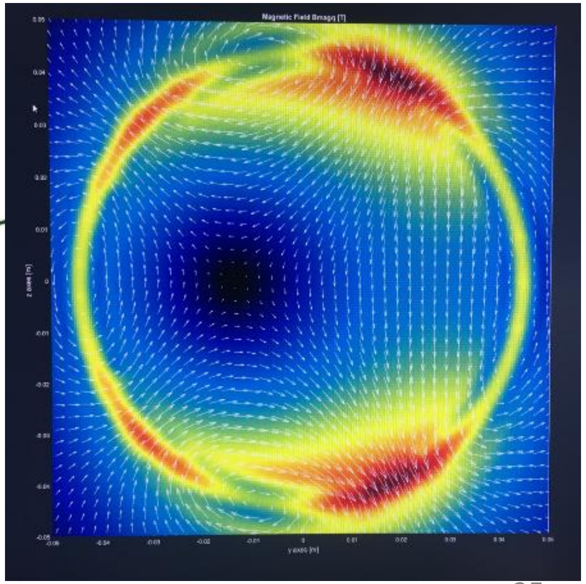
CERN 0.5 m CCT to test Sushi

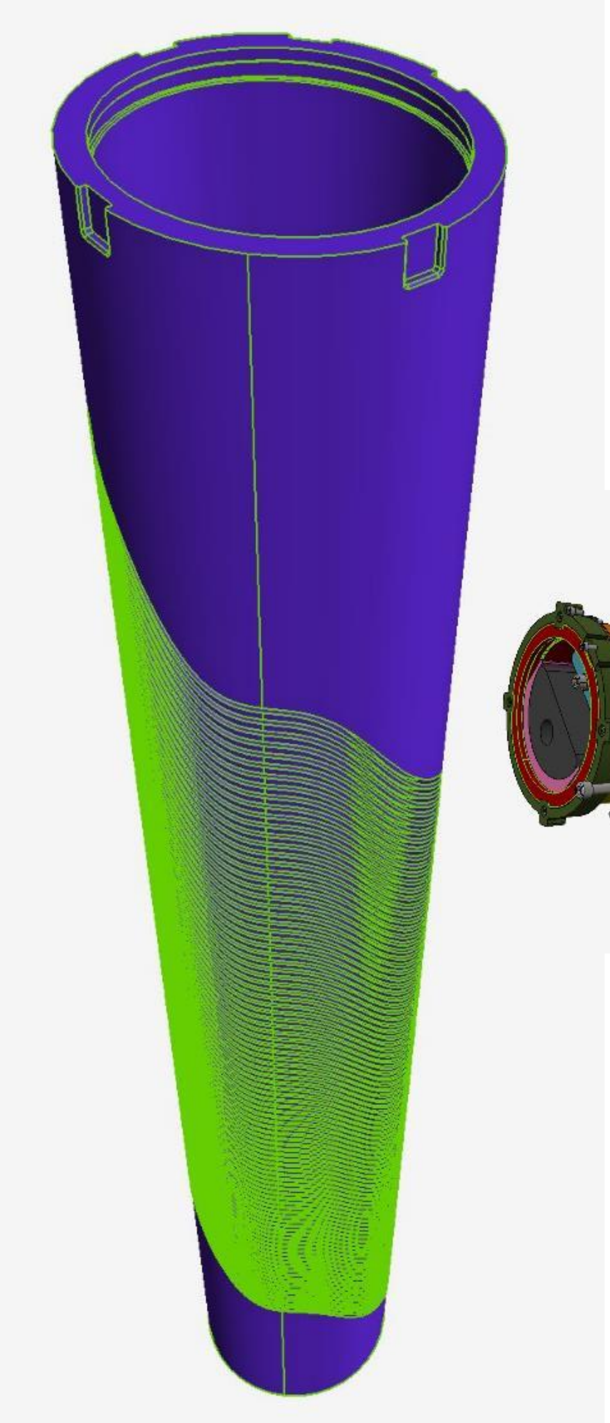


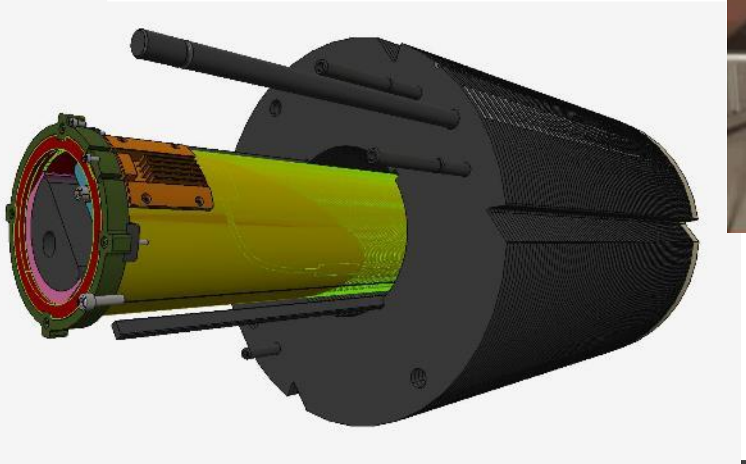




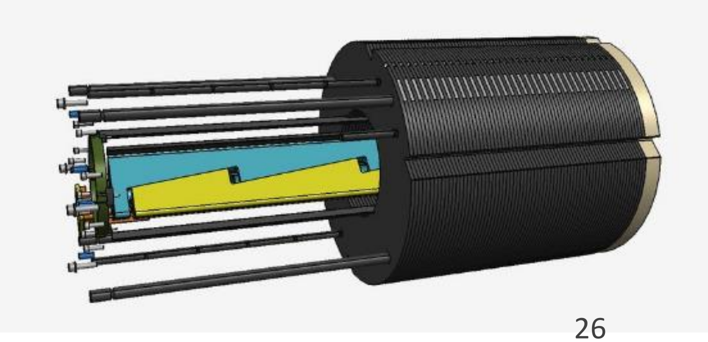








Sushi combined function First test wind



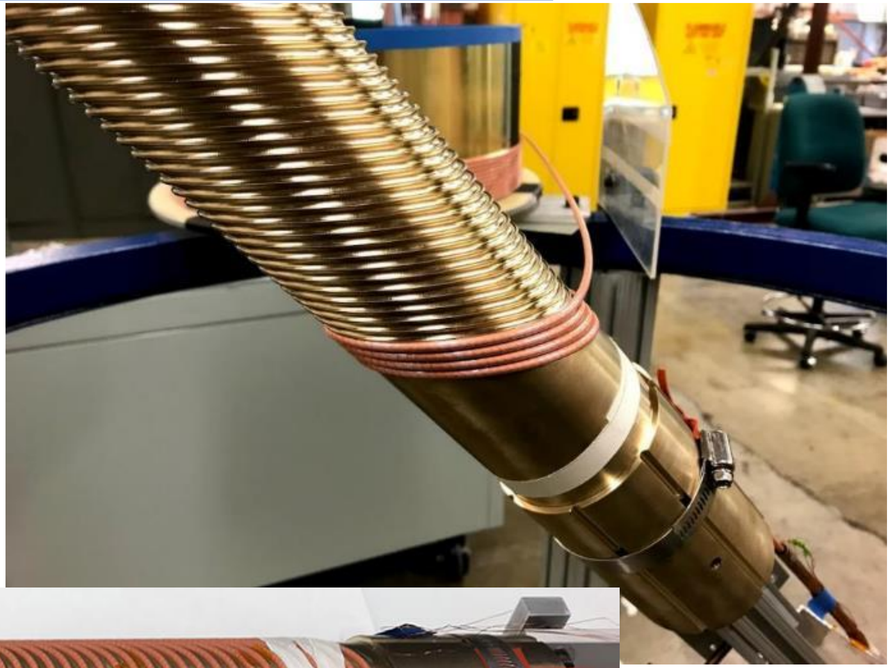
Manufacturing of CCT-C2 layer 1

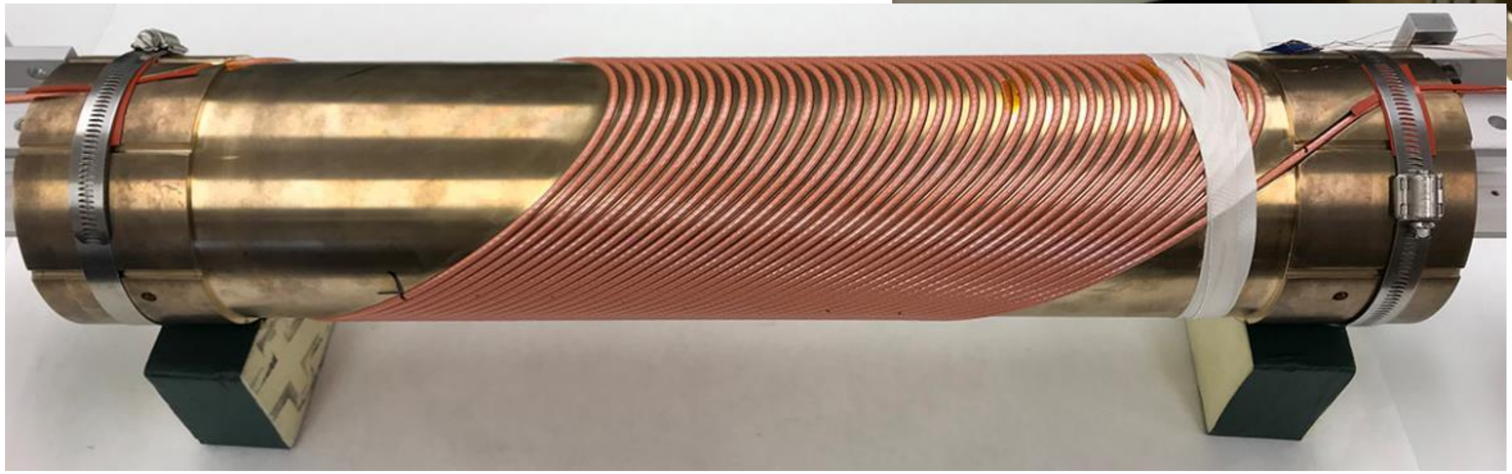
HTS quench energy equal to dropping a cannon ball 2 m !

LTS quench energy equal to dropping a pin 10 mm!

CCT-C2 layout

- 3 T at 4.2 K
- 4 Layers, 40 turns per layer
- 80 m of CORC® wire ordered by LBNL
- Aperture 85 mm
- Minimum bending diameter 60 mm





Advanced Conductor Technologies
www.advancedconductor.com

Thanks to Danko van der Laan and his team
See the full talk on my RG project log, or
https://indico.cern.ch/event/882979/

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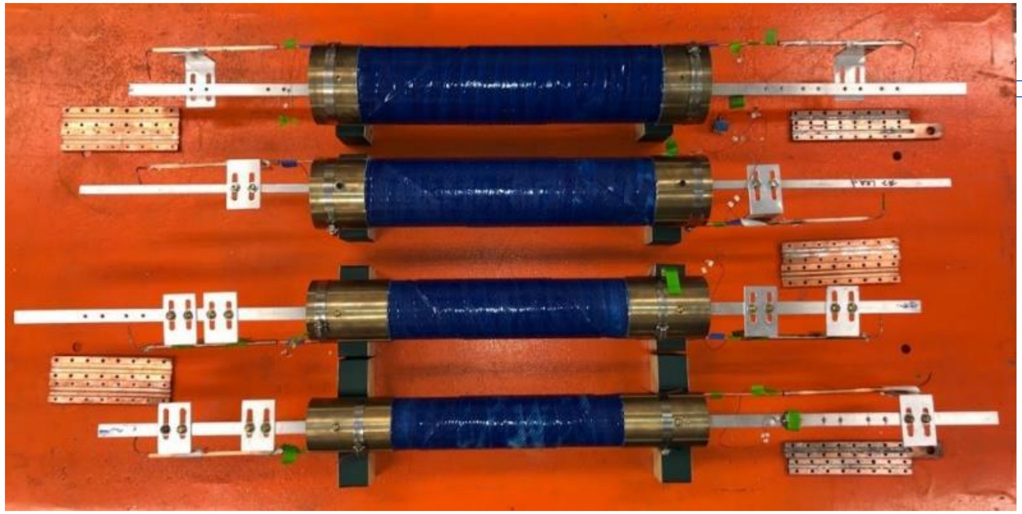
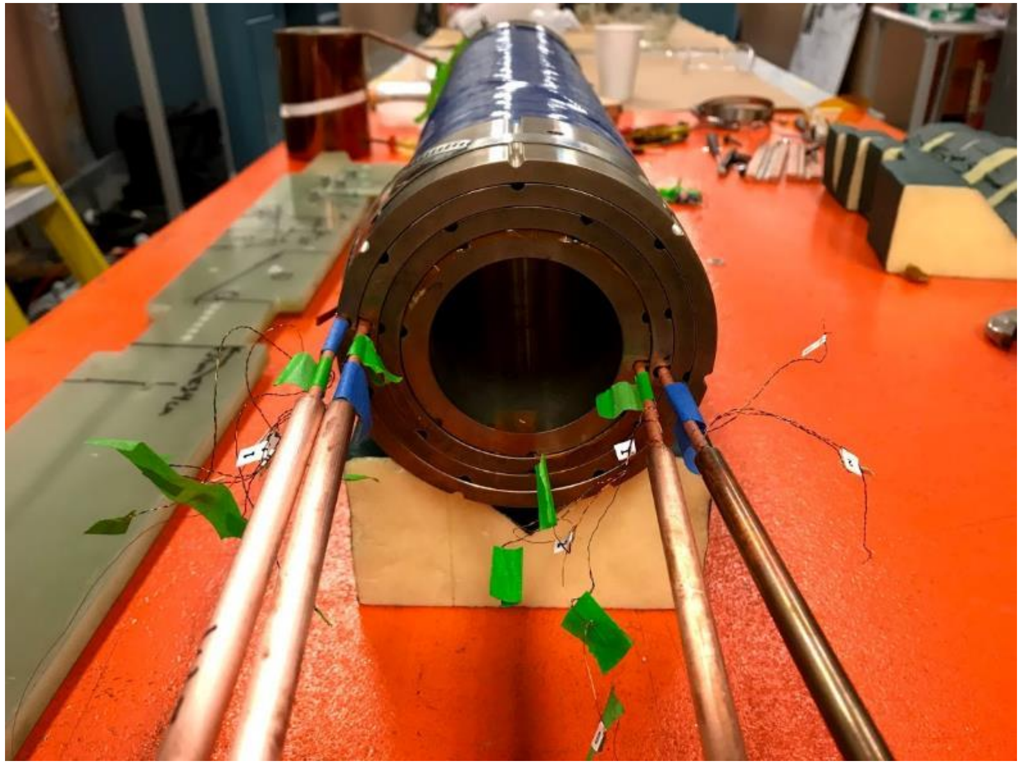
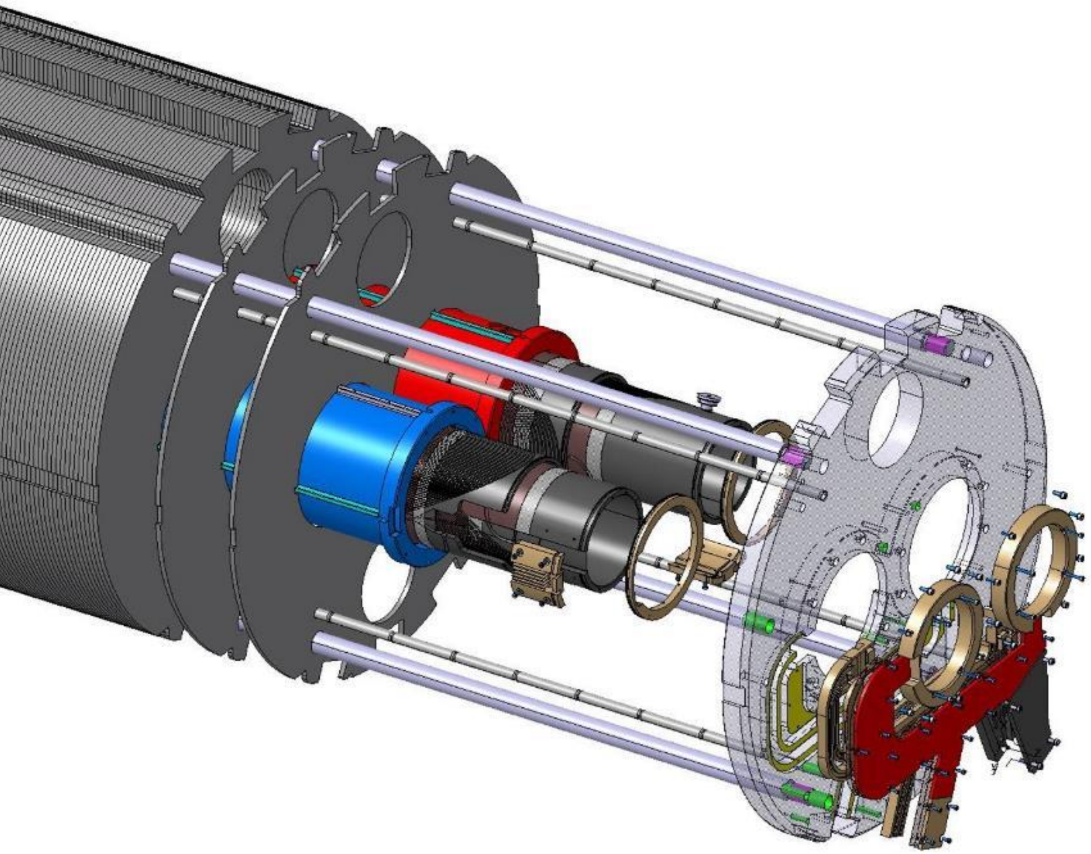
CCT-C2 Assembly





MCBRD LHC high-Lumi CCT



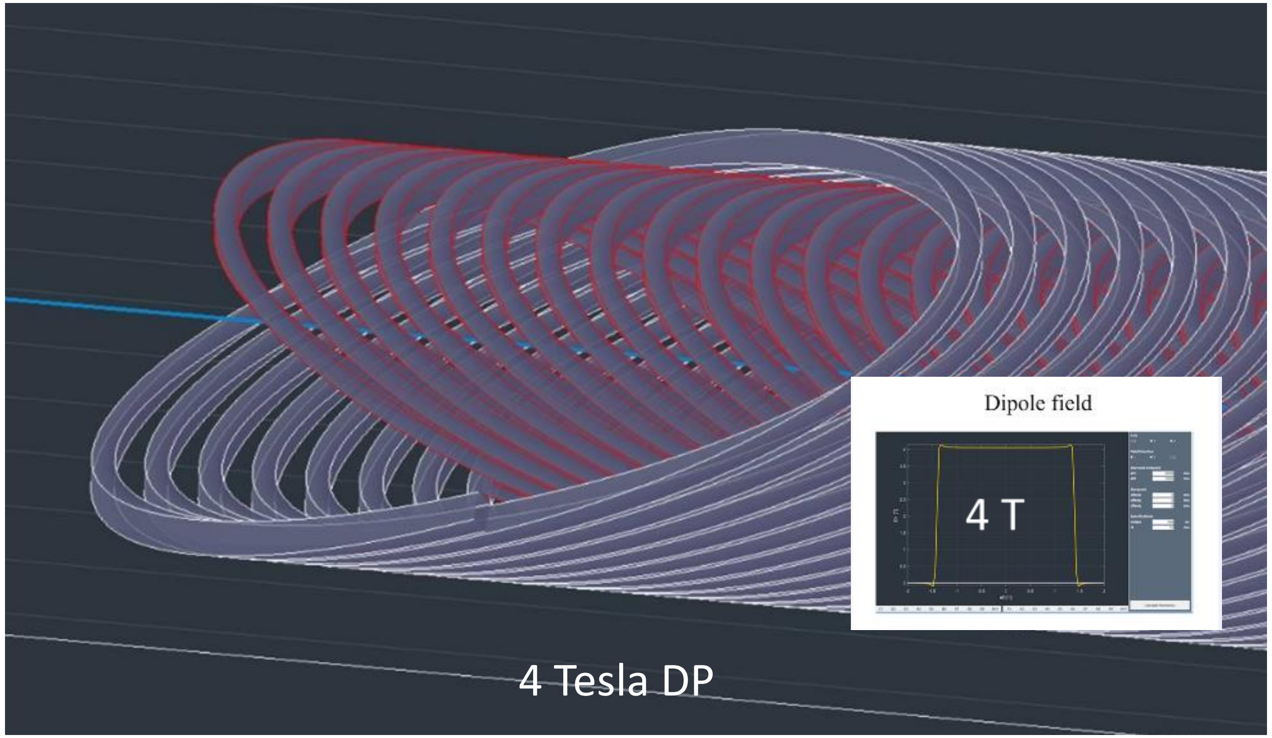
This week at CERN 16 May 2022

15 + apertures manufactured so far in the LHC Hi-LUMI project 9 at CERN 11 in China

LBNL curved dipole

MCBY update

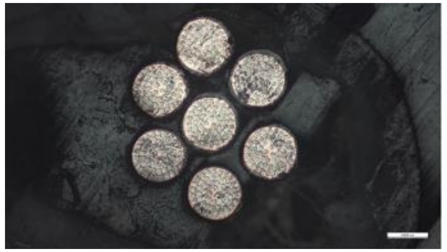
LHC need 20+ MCBC or MCBY magnet. To replace old magnets that are starting to fail due to radiation damage ! This was the first 600 A design from 2016 now the team in Sweden are building a 100 A rad hard design.



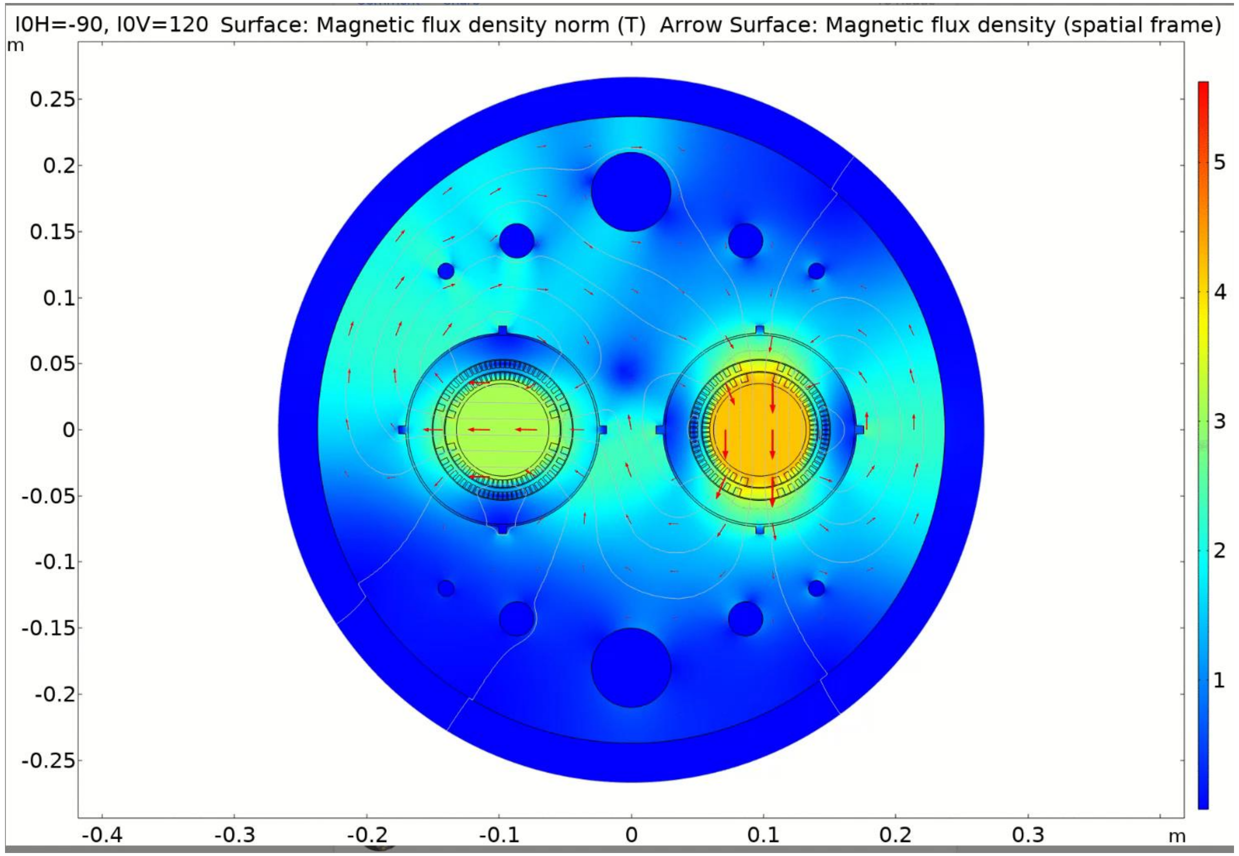
4 Tesla DP

MCBC / MCBY 400A LHC replacement

Swedish low current high radiation CCT



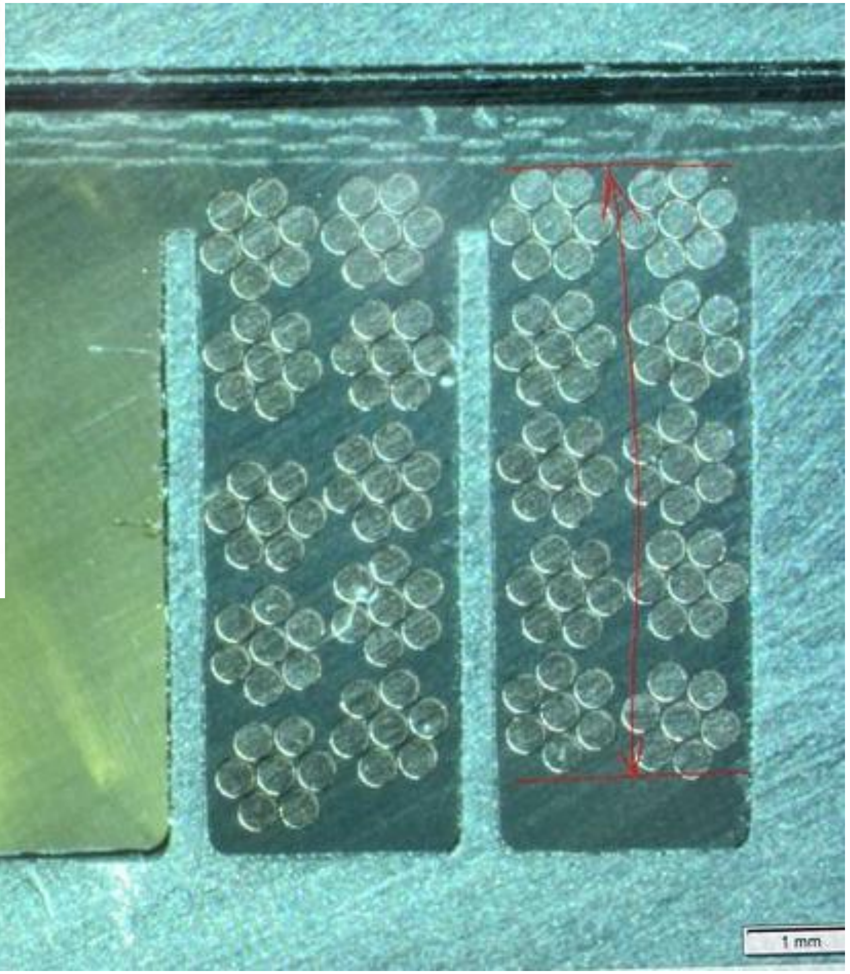
Uppsala University in Sweden leading the MCBY development.

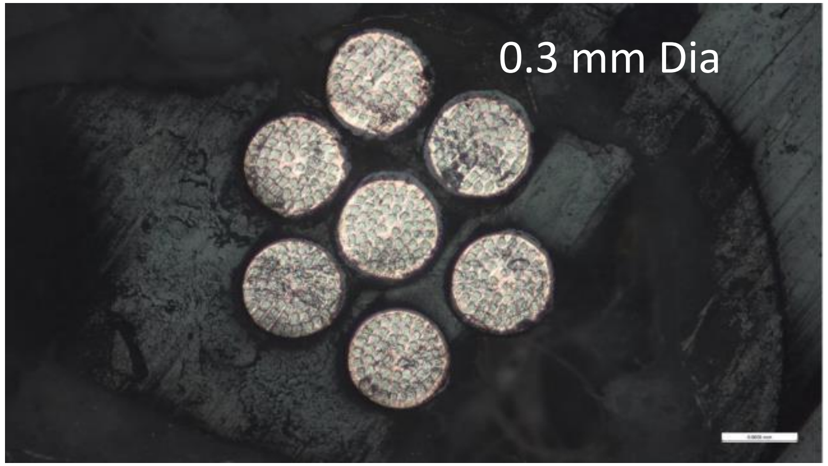


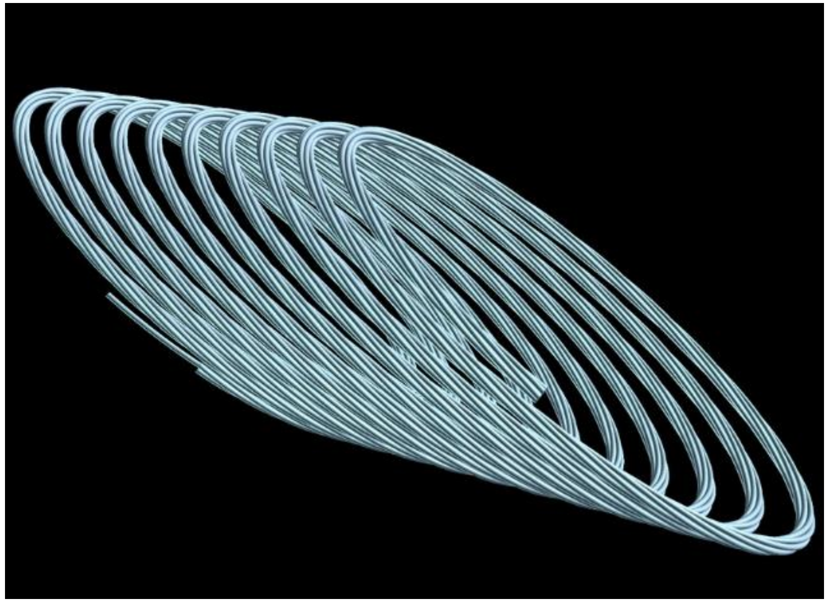
Thanks to Kevin for the MCBY CCT magnetic field model

Low current means: small wires and many turns so we selected a rope design

MCBY rope conductor using 7-0.3 mm strand

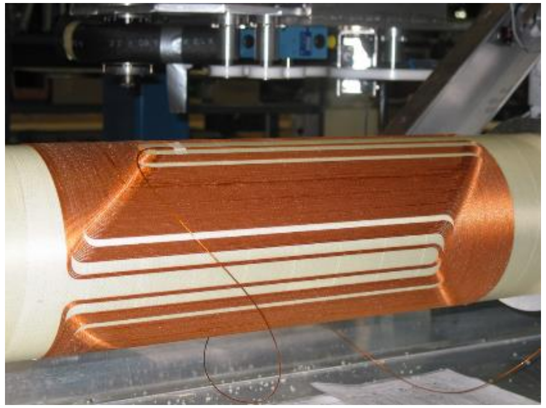


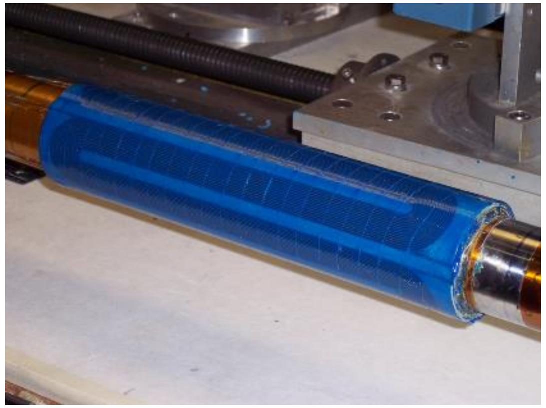


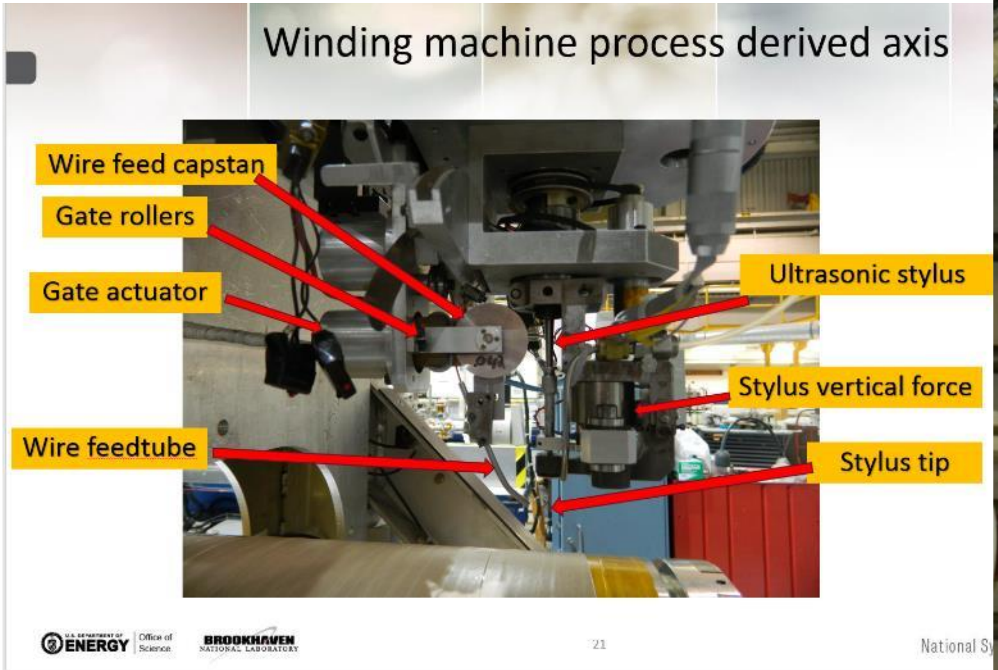


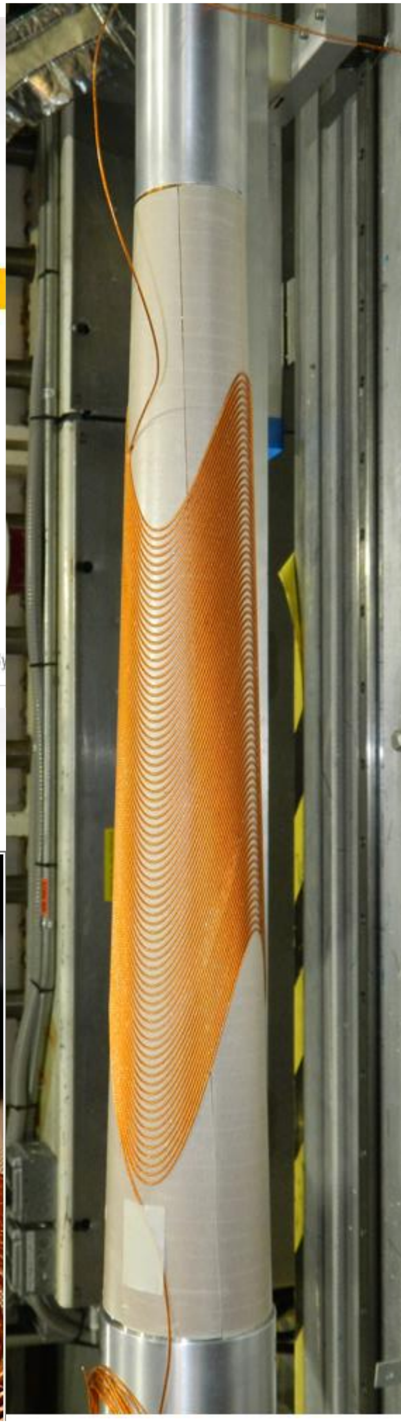
BNL Direct CCT winding

Stray field active shield idea

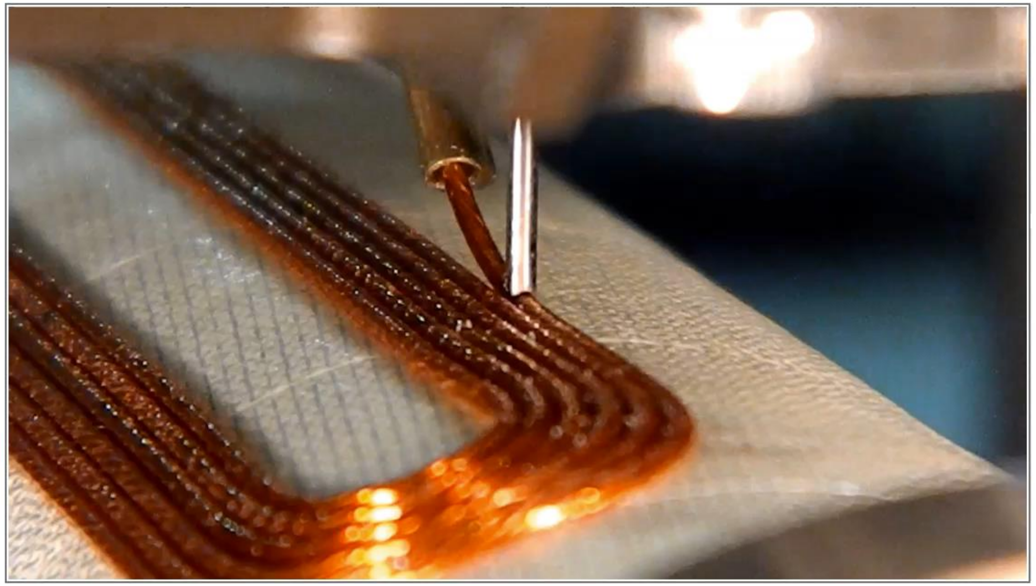




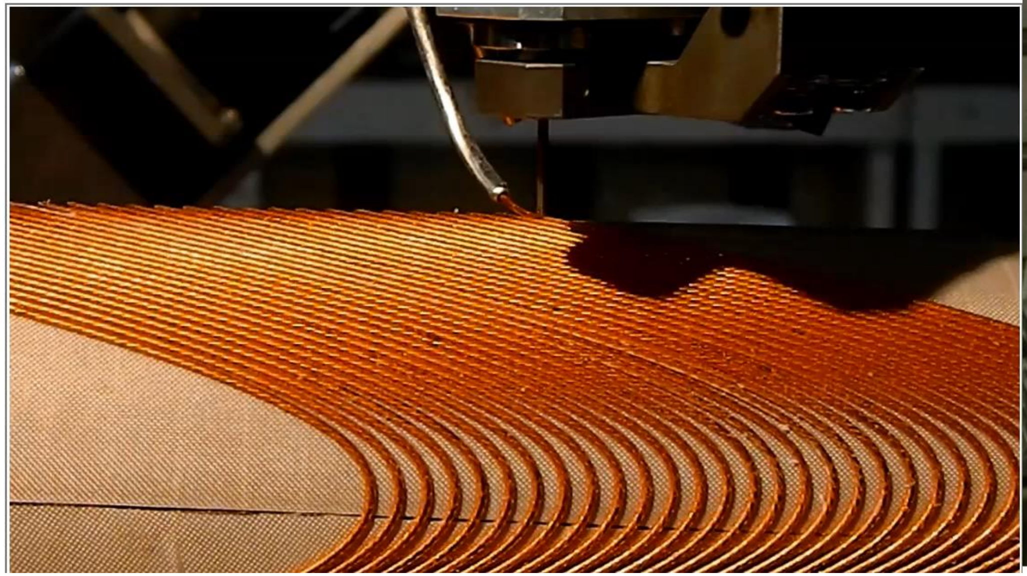




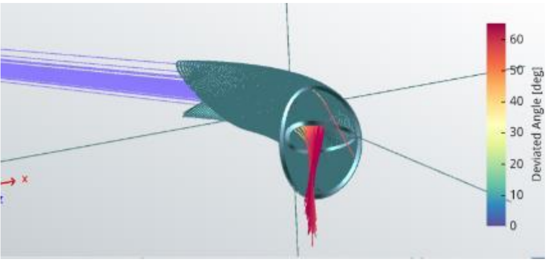
Alpha octupole winding

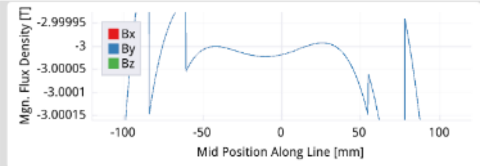


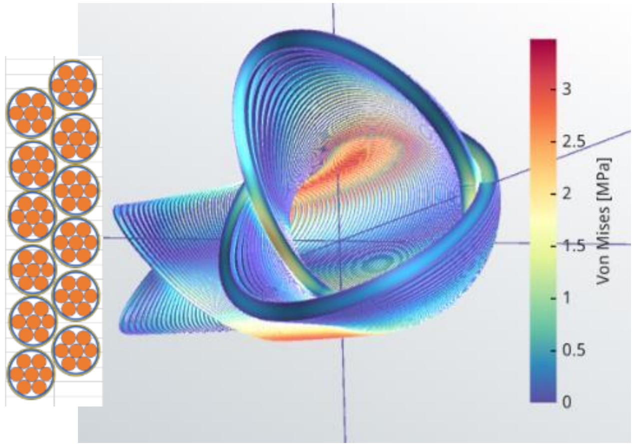
Canted cosine quadrupole direct winding

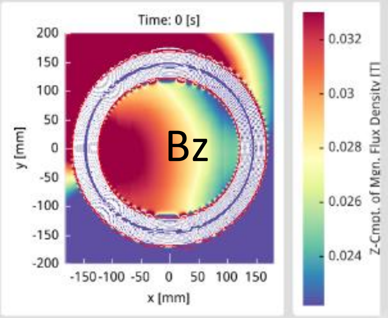


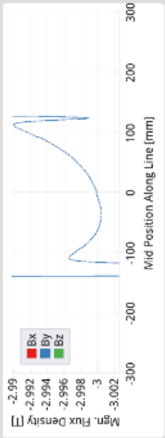
Fusillo curved CCT CERN project 2022 - 2024

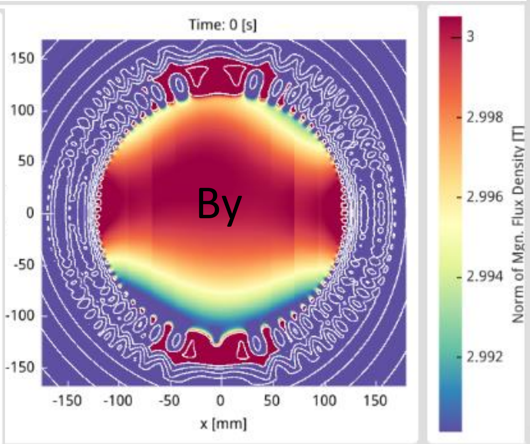


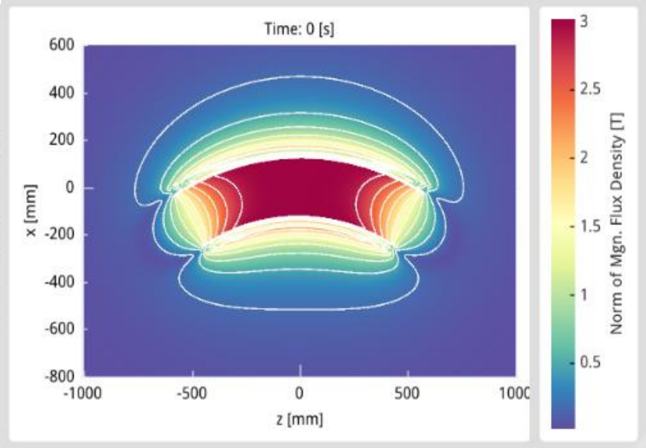


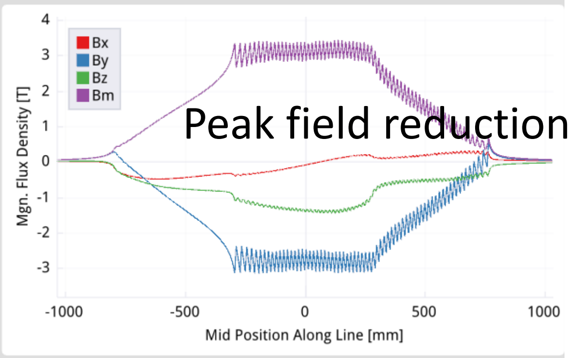


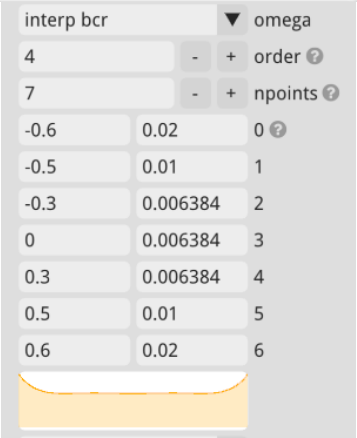


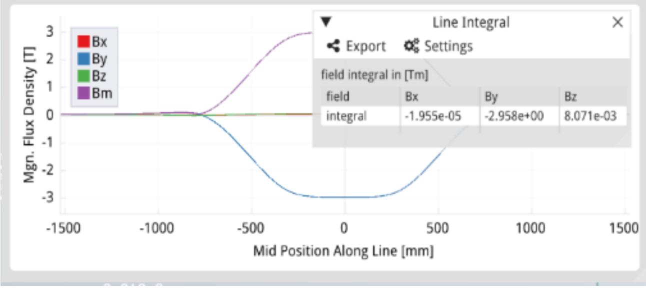












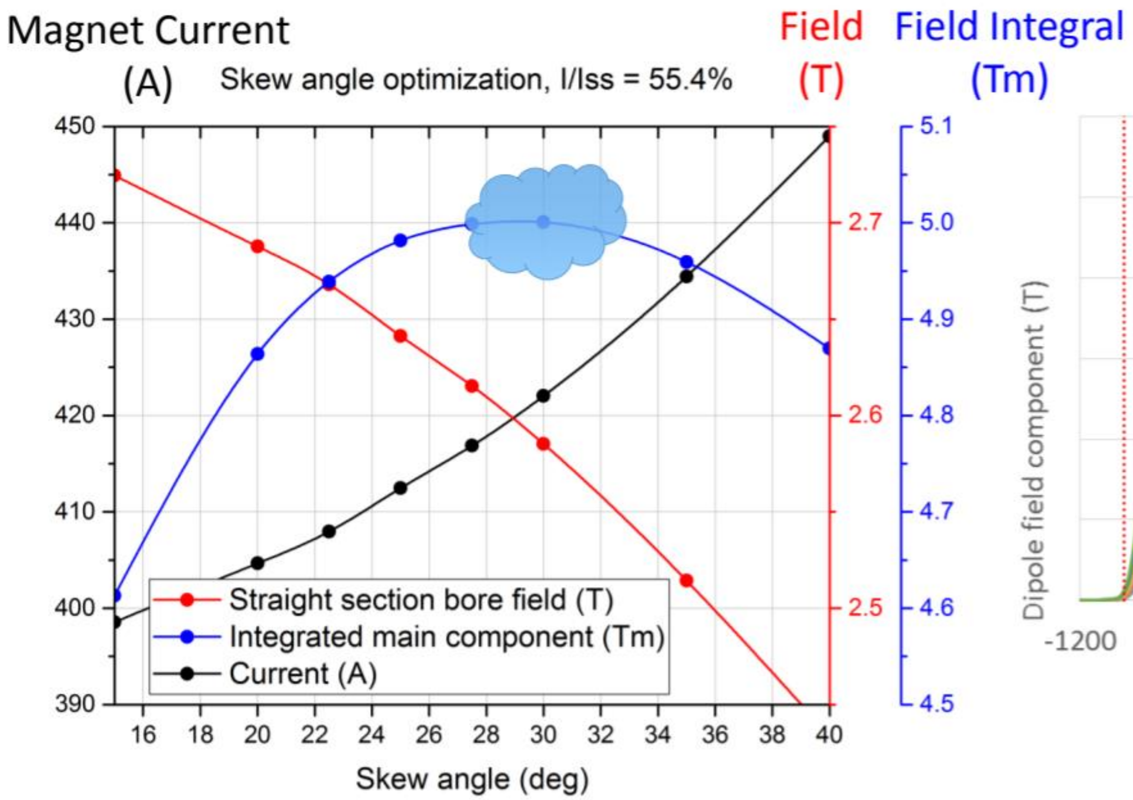
Nom current 244.457A
3.000 T, inner 3.500 T, outer3.397 T
Ss% inner 70.18 % & outer 69.018 %
2.958 Tm integral
15.57 km strand
2.224 km rope
84 strands in channel
Nom rope dia 3.1 mm
Channel size 5.884 x 20.15 mm
log-stacking lay out.
Pitch 6.384 mm
Min wall 0.5 mm
Gap between coil layers 5 mm
T margin 1.504 K to 3.807 K
Stress nom 3.493 MPa
Central inner coil rad 123 mm
DP 212.64 mm, Q 3.05 mm,
Skew Q 0.195 mm, Sextupole 0.1 mm,
Skew S 0.04 mm
Radius of curvature cold 1000 mm.
Inductance 12.359 H
Stored energy 369.141 kJ

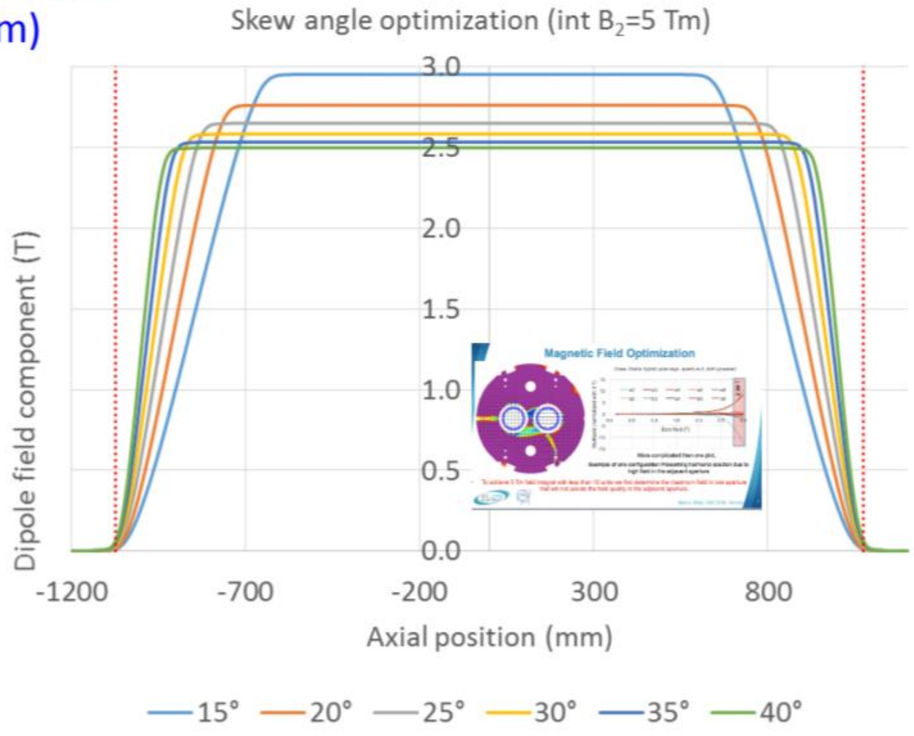
Channel step file

https://cernbox.cern.ch/index.php/s/JudKfM6sLcBMtDS

CCT Design features

- As we look at the designs, we find more and more features that can improve the magnet performance



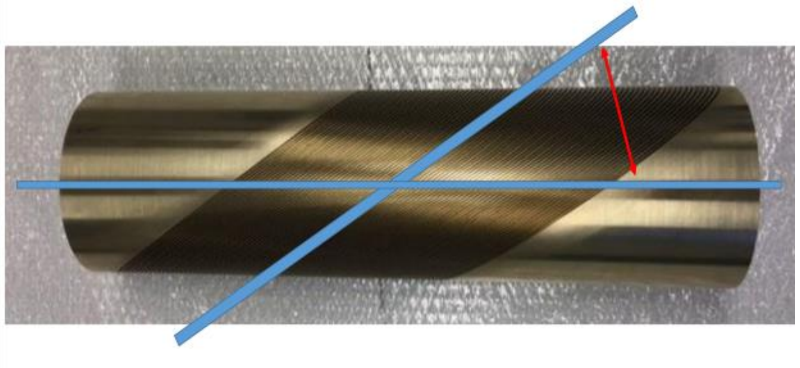


CCT skew angle optimisation

Due to the cross talk the max aperture field is set to ~2.7 T

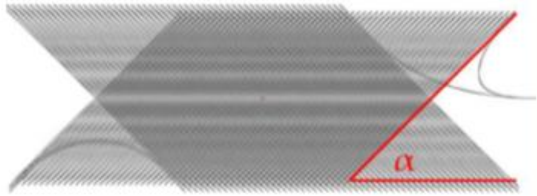
For a fixed 5 Tm integral & magnet length ~2m the optimum skew angle is 30 deg.

Lower skew angles give more field less conductor but have longer ends!

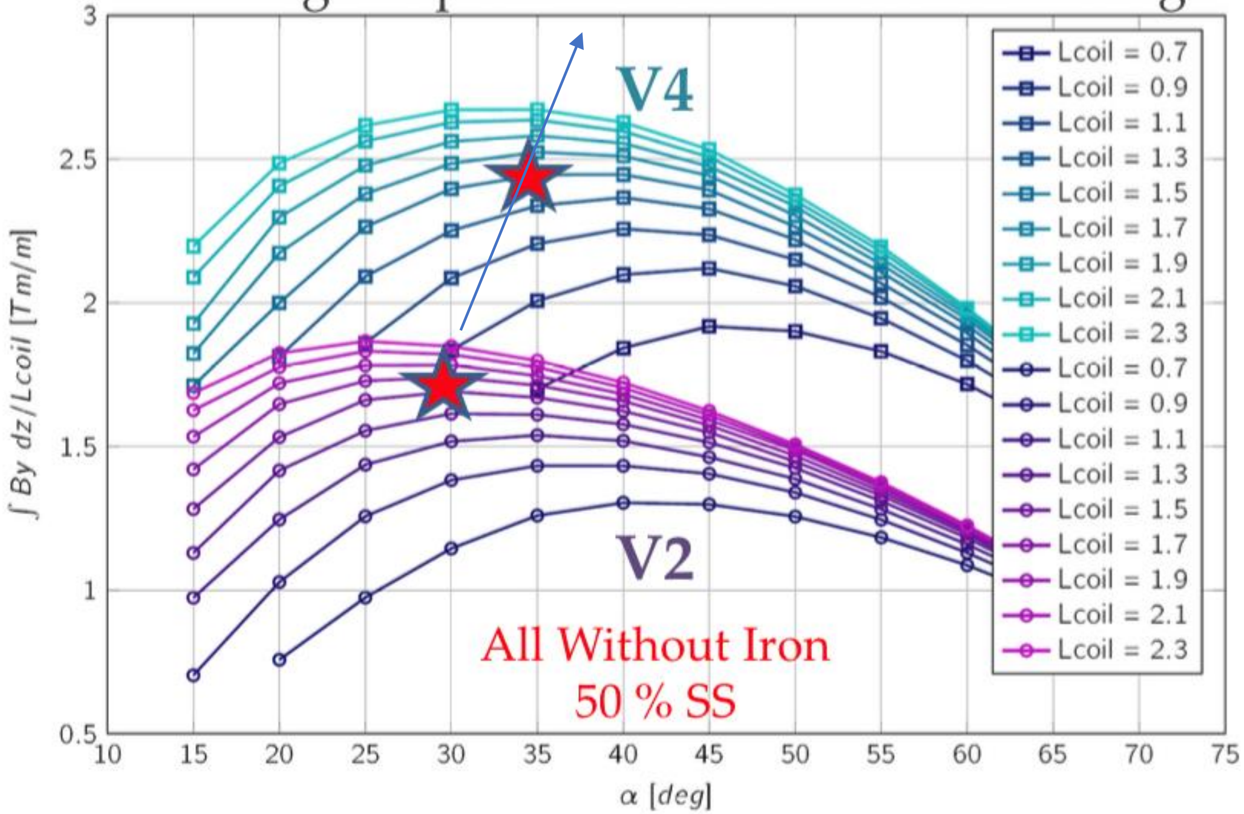


Glyn A. Kirby

Field Integral / Skew angle Optimization

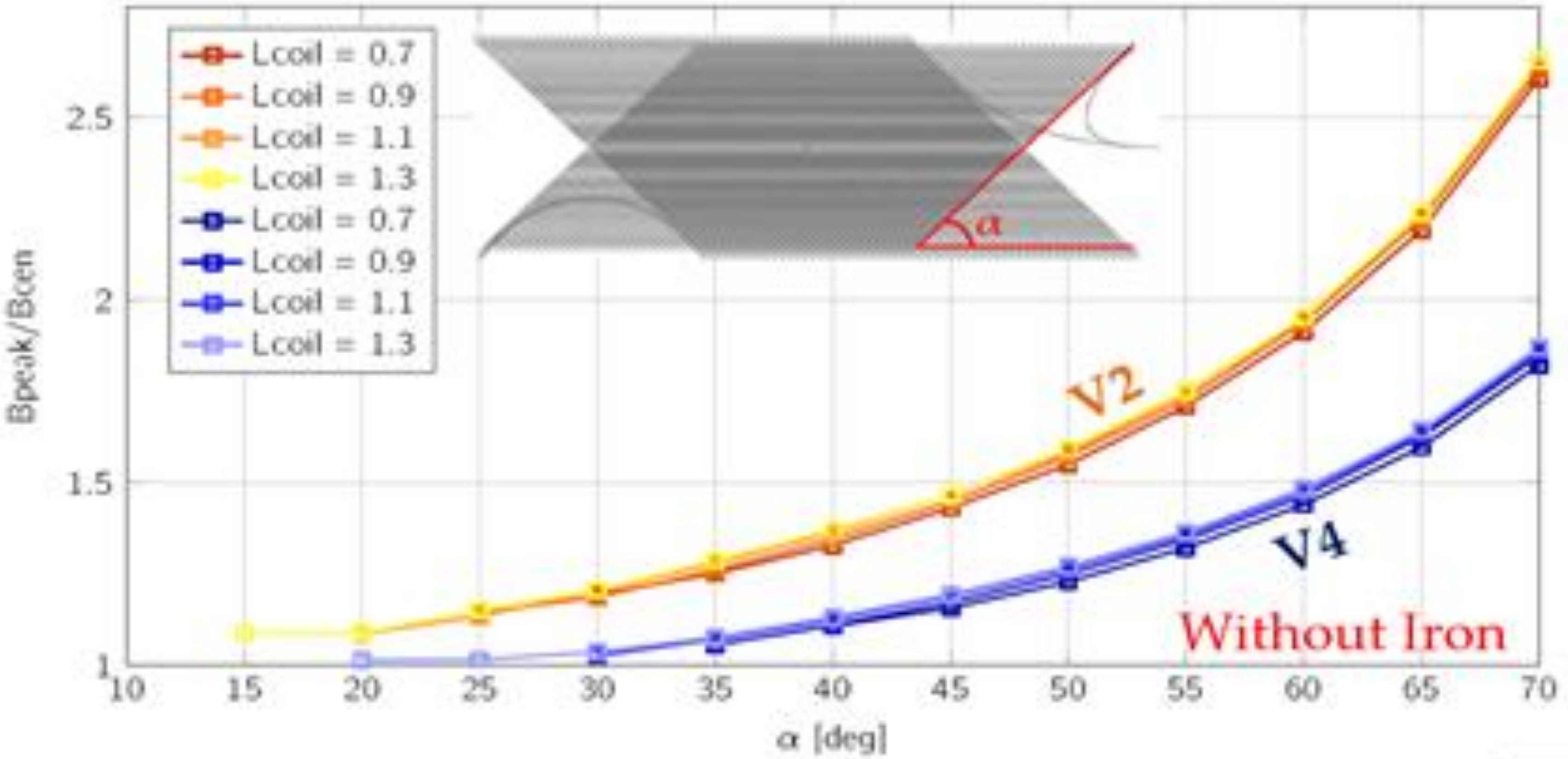


- Two counteracting processes
  - Higher skew angle increases Bpeak/Bcen
  - Lower skew angle increases length of coil ends
- Leads to a field integral optimized value for the skew angle



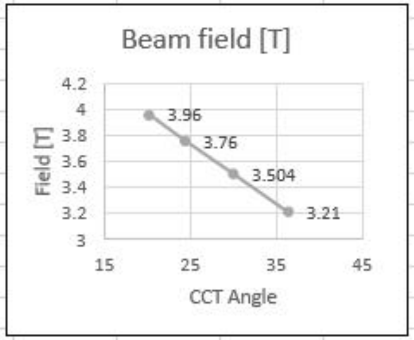
Skew Angle Influence

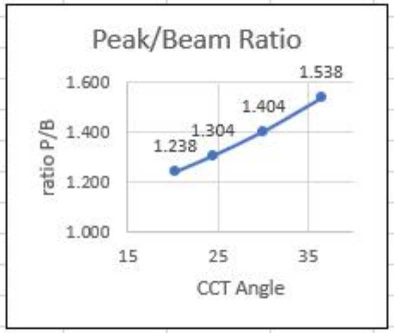
- Ratio Bpeak/Bcen depends on skew angle and # of layers

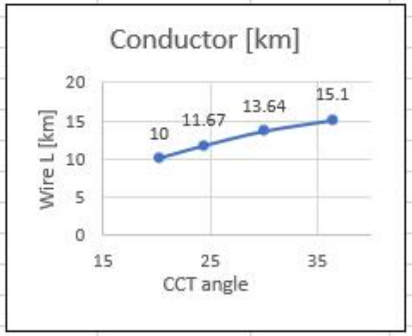


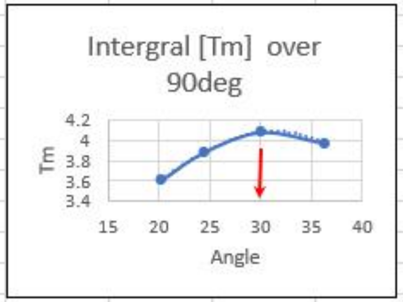
The basics of selecting the CCT angle

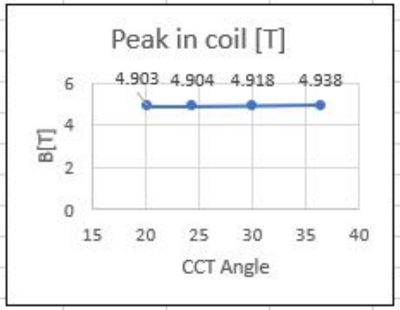
R	a	r/a	Bend angle	CCT Angle	SS %	I [A]	Min wall thk	Peak in coil [T]	Beam field [T]	Peak/Beam Ratio	turns	Conductor [km]	Channel turns	[Tm] over 90deg	Inductance [H]
118	160	0.7375	90	36.41	91.3	360	0.3	4.938	3.21	1.538	40	15.1	176	3.97	8.078
118	204	0.57843	90	30.05	91.08	360	0.3	4.918	3.504	1.404	40	13.64	142	4.083	8.484
118	260	0.45385	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

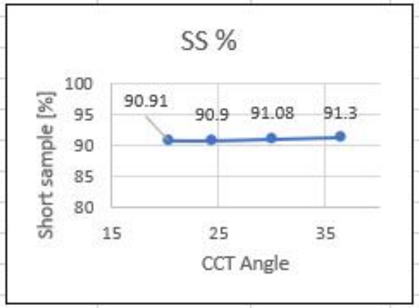


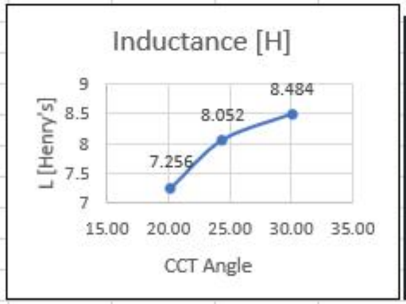


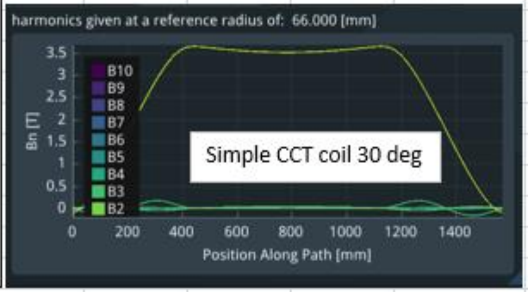


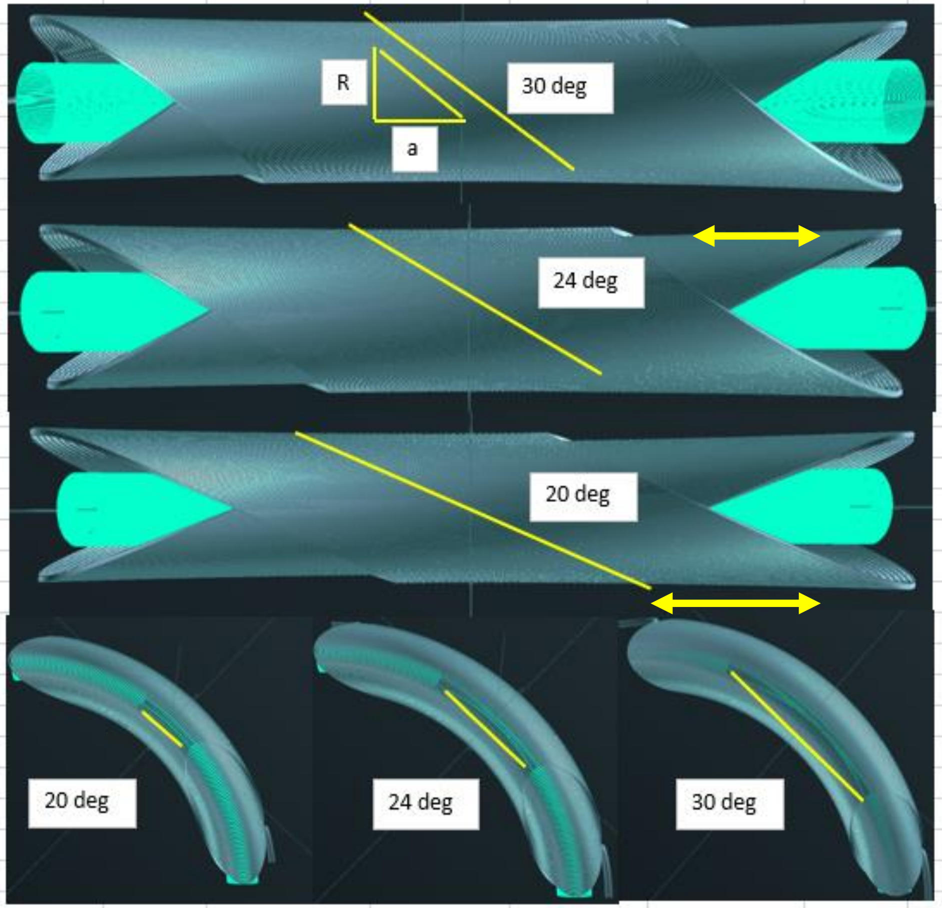




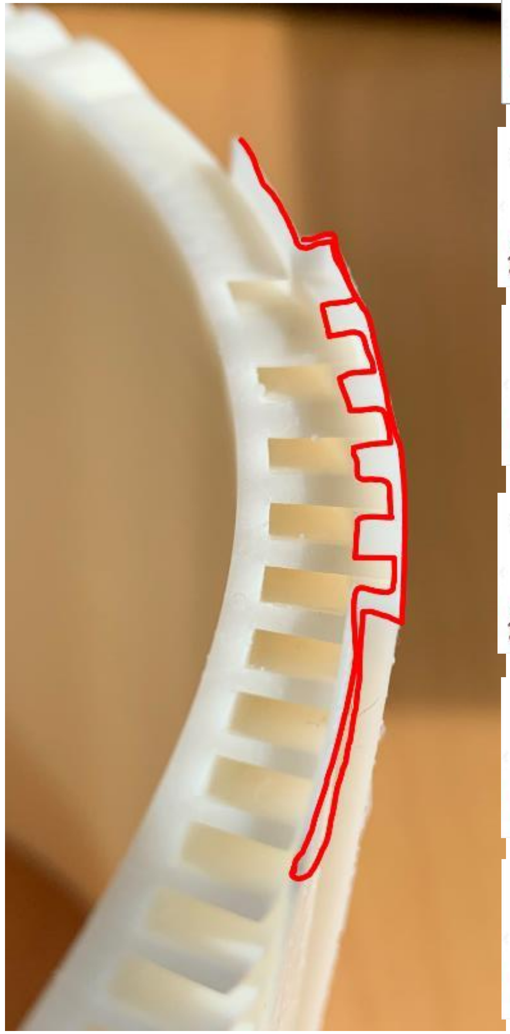








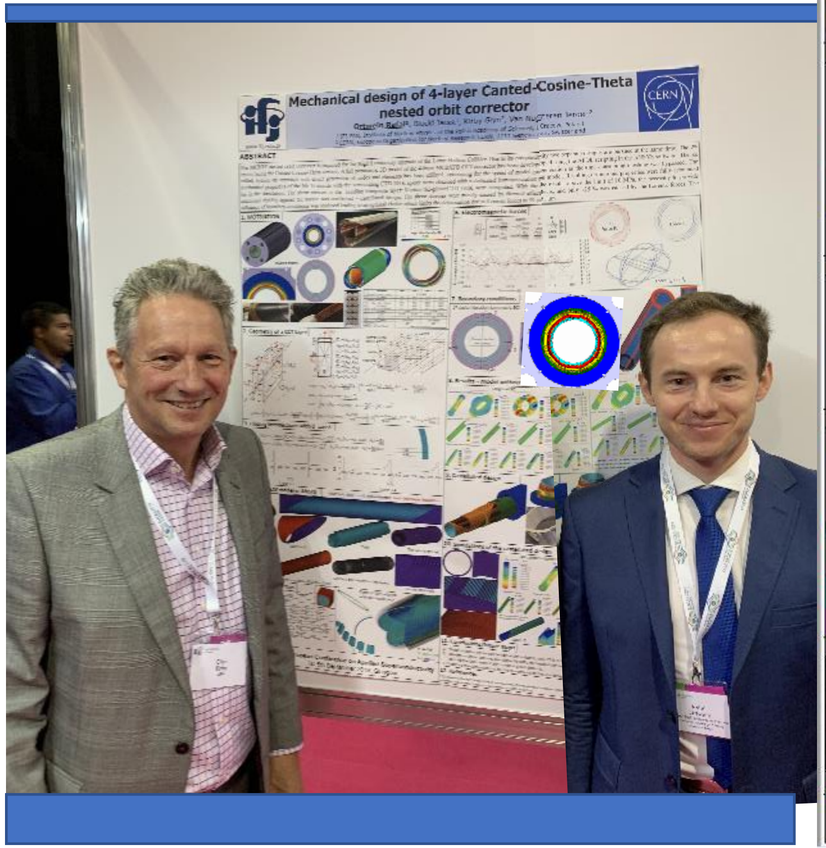
Nested castellated support between coil formers to support the very high torque

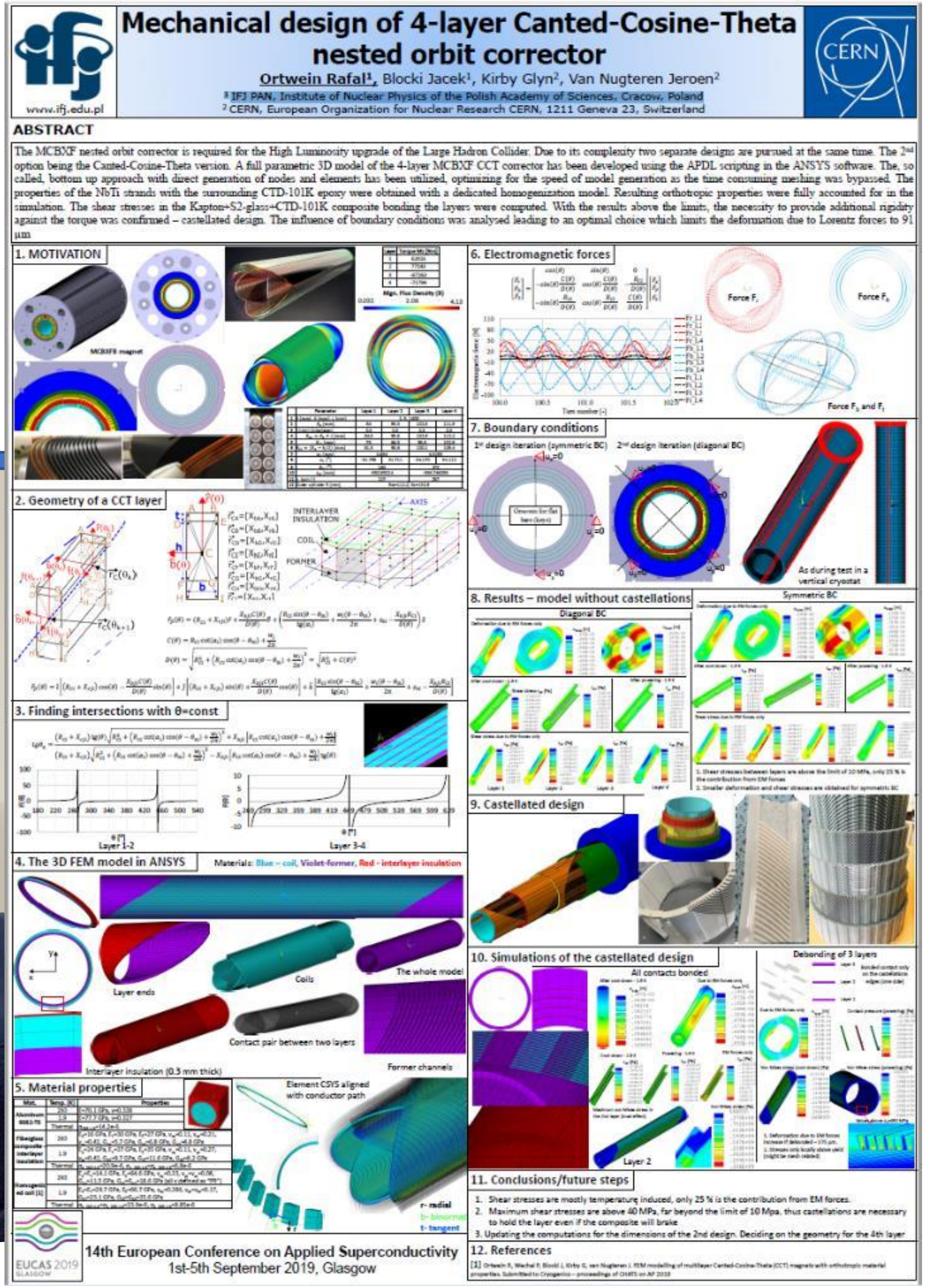


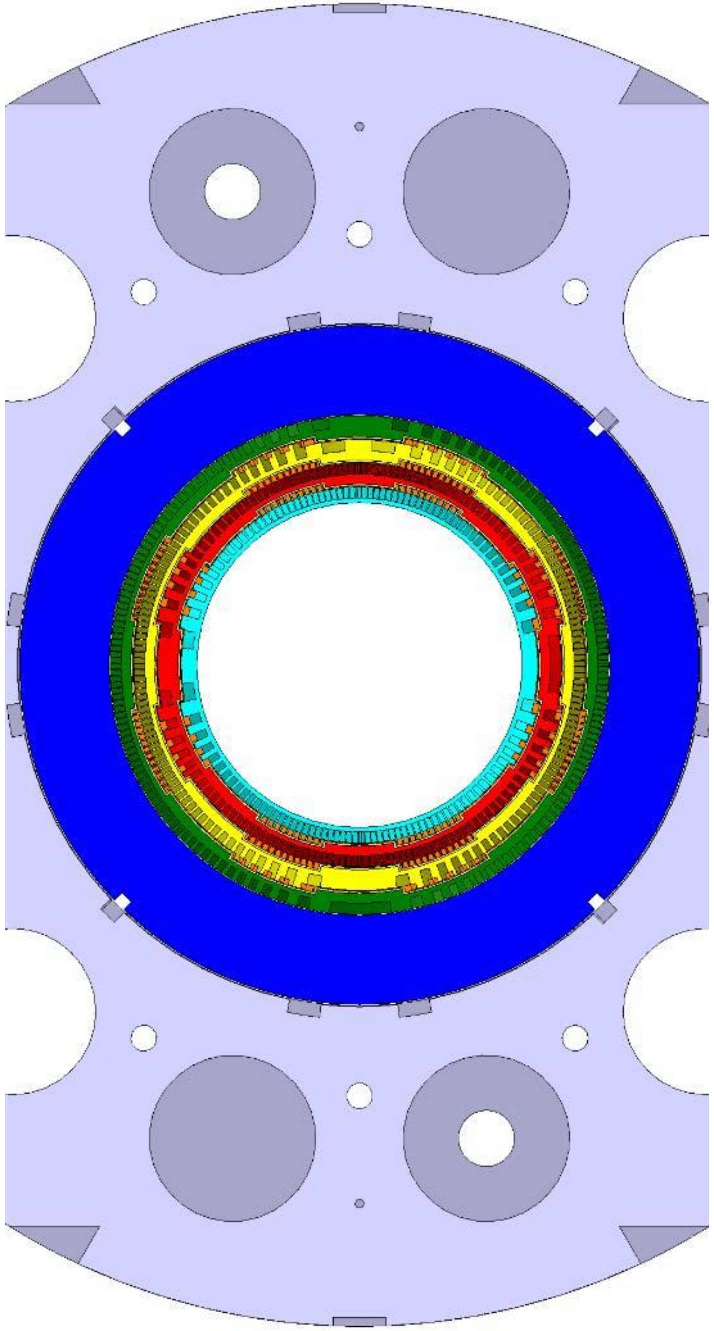
This magnet has the torque of 140 *F1* race cars in 1 m length

CCT fast FEA stress and deflection new approach

by Rafal Ortwein now at IFJ
paper presented at EUCAS 2018

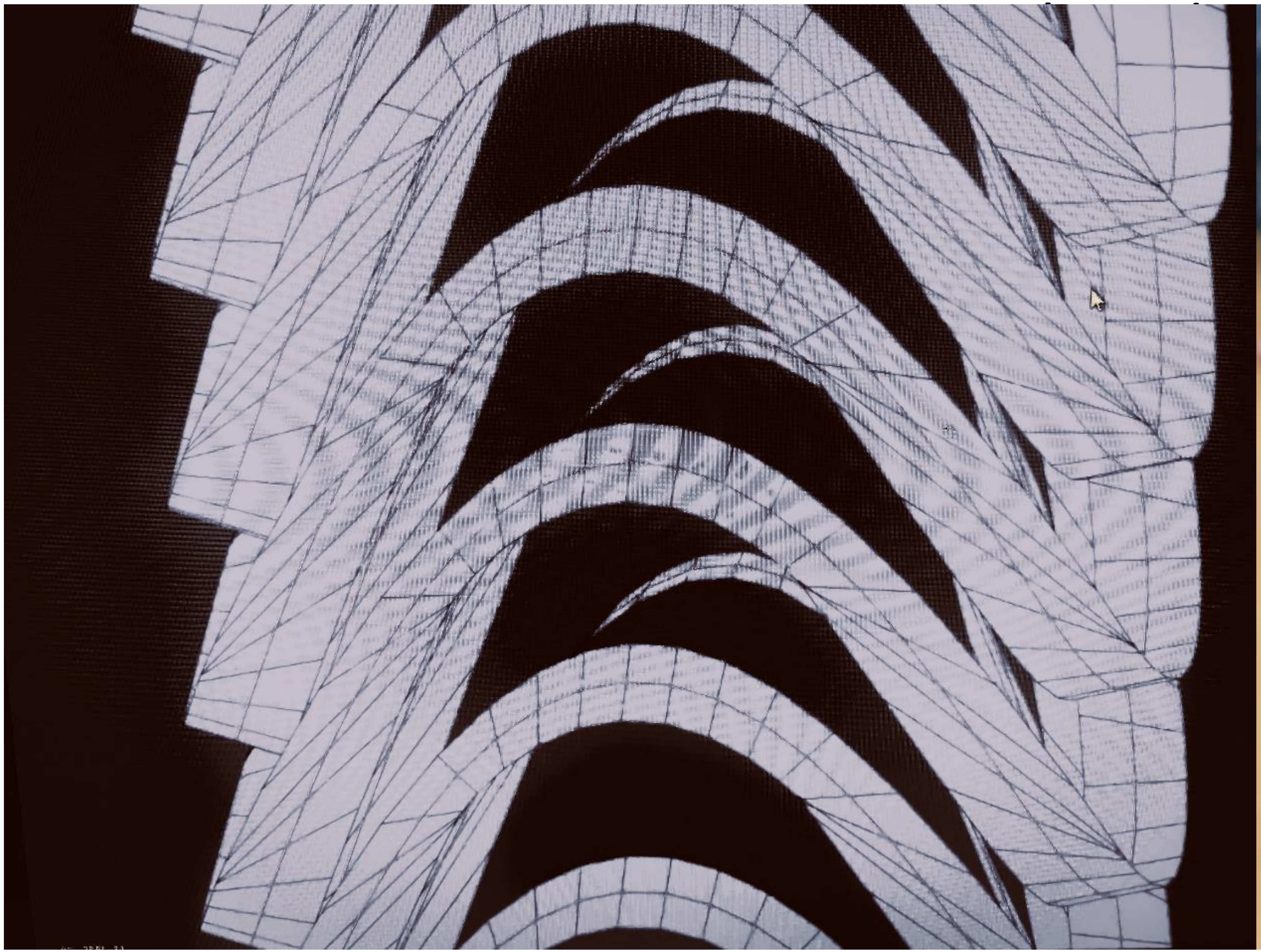




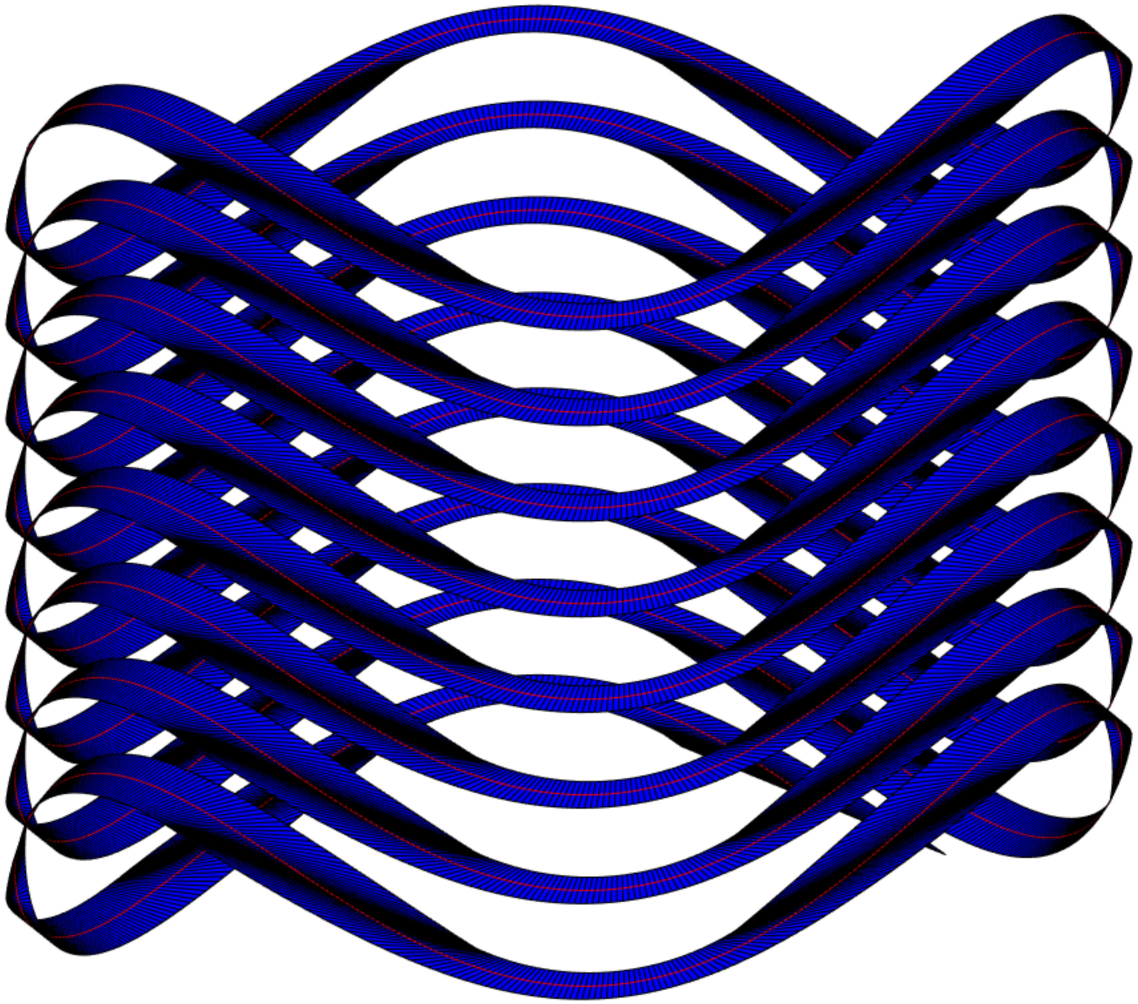


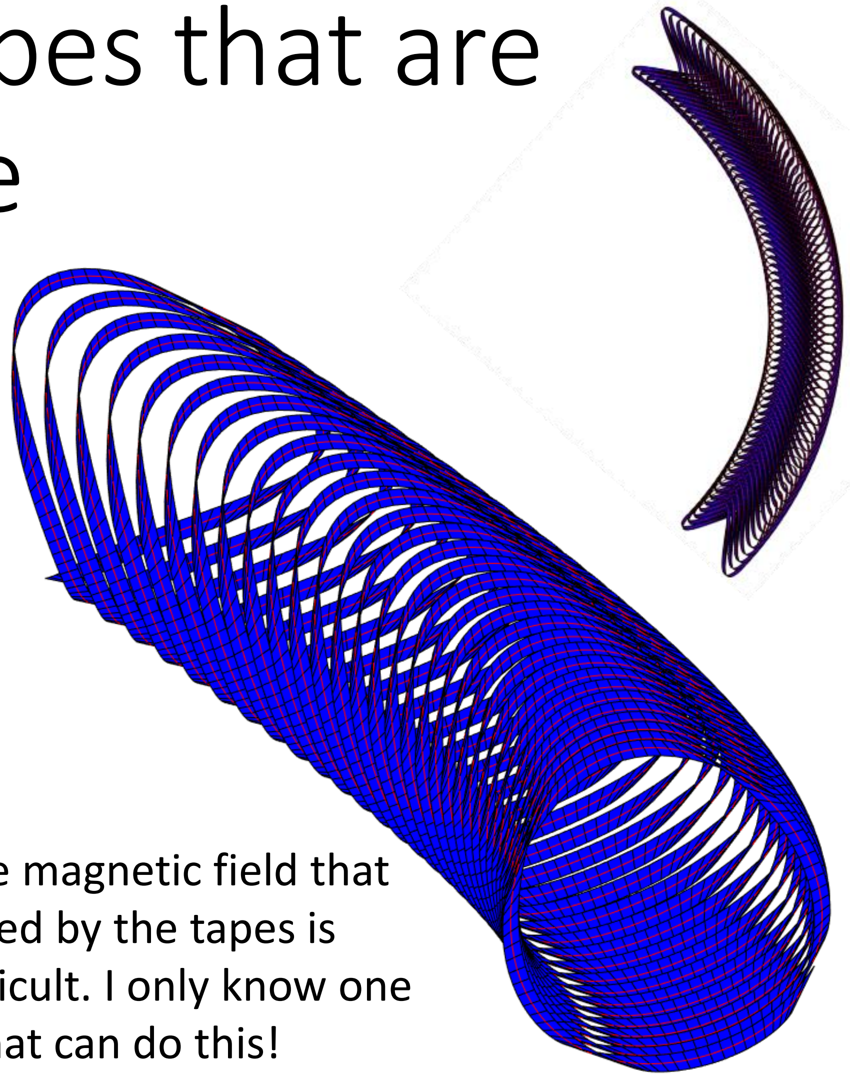
Rafal is from IFJ PAN, Institute of Nuclear Physics of the Polish Academy of Sciences, Cracow, Poland

Thanks to Thomas Nes who has taken his zero-bend calculation for HTS tapes and added CCT



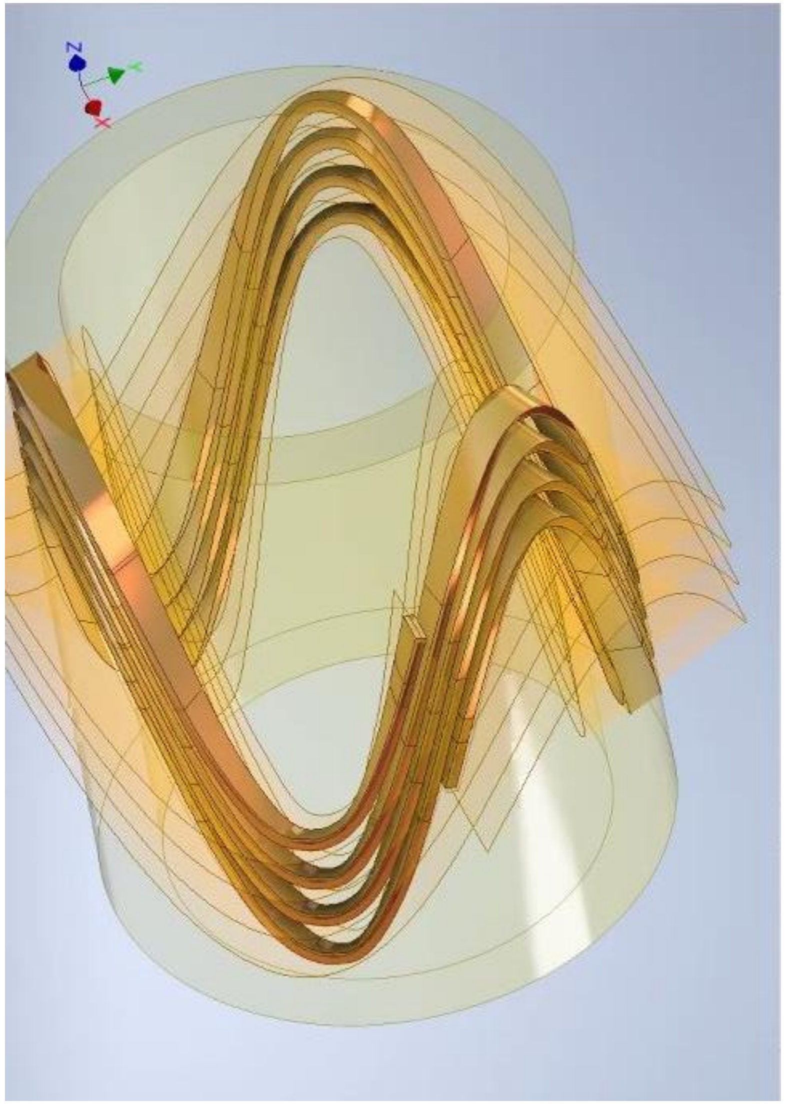
Zero hard way bend in the tapes that are following the CCT guiding line





To get the magnetic field that is produced by the tapes is more difficult. I only know one person that can do this!

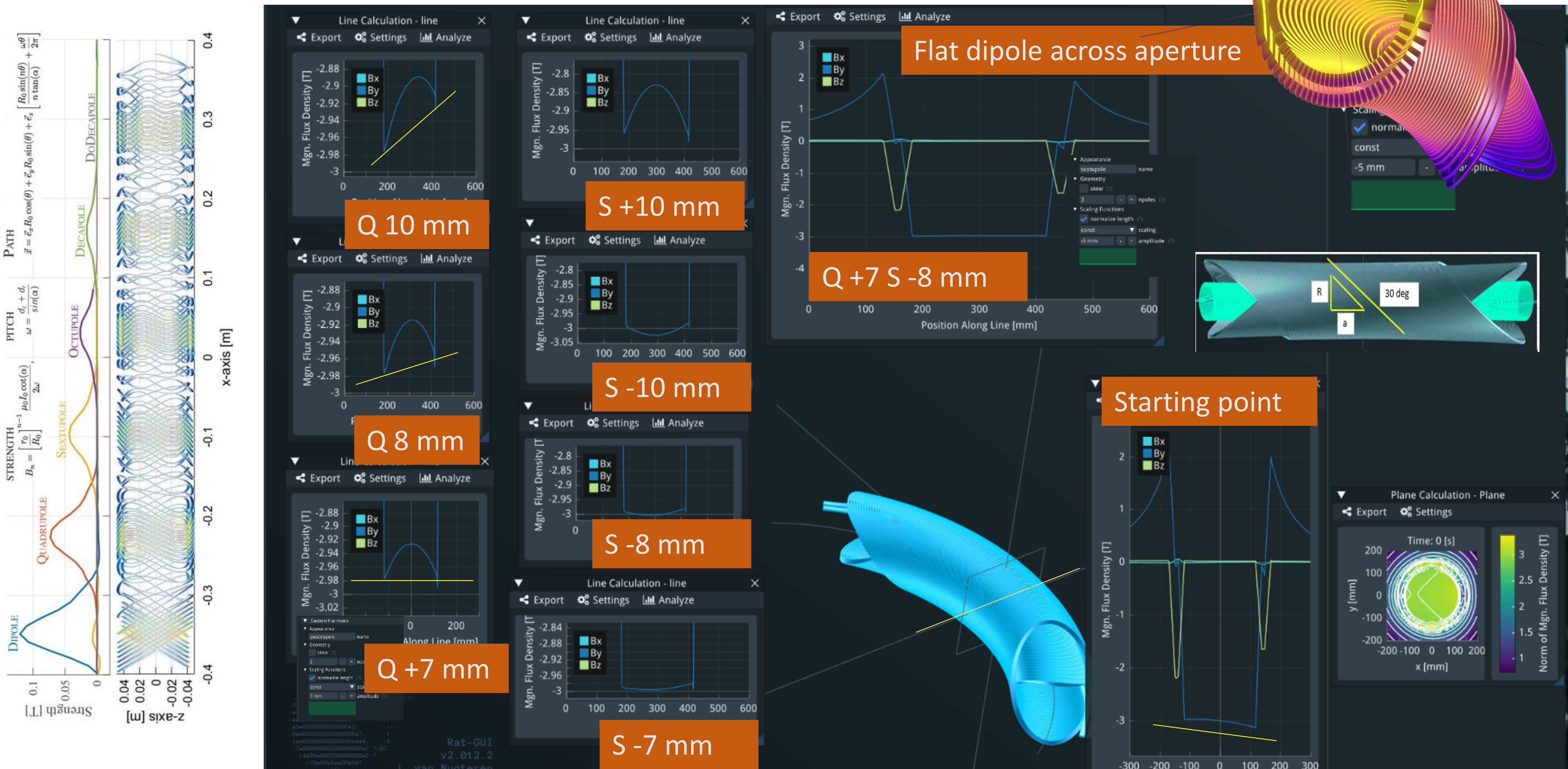
Thank's to thomas Nes for the images.



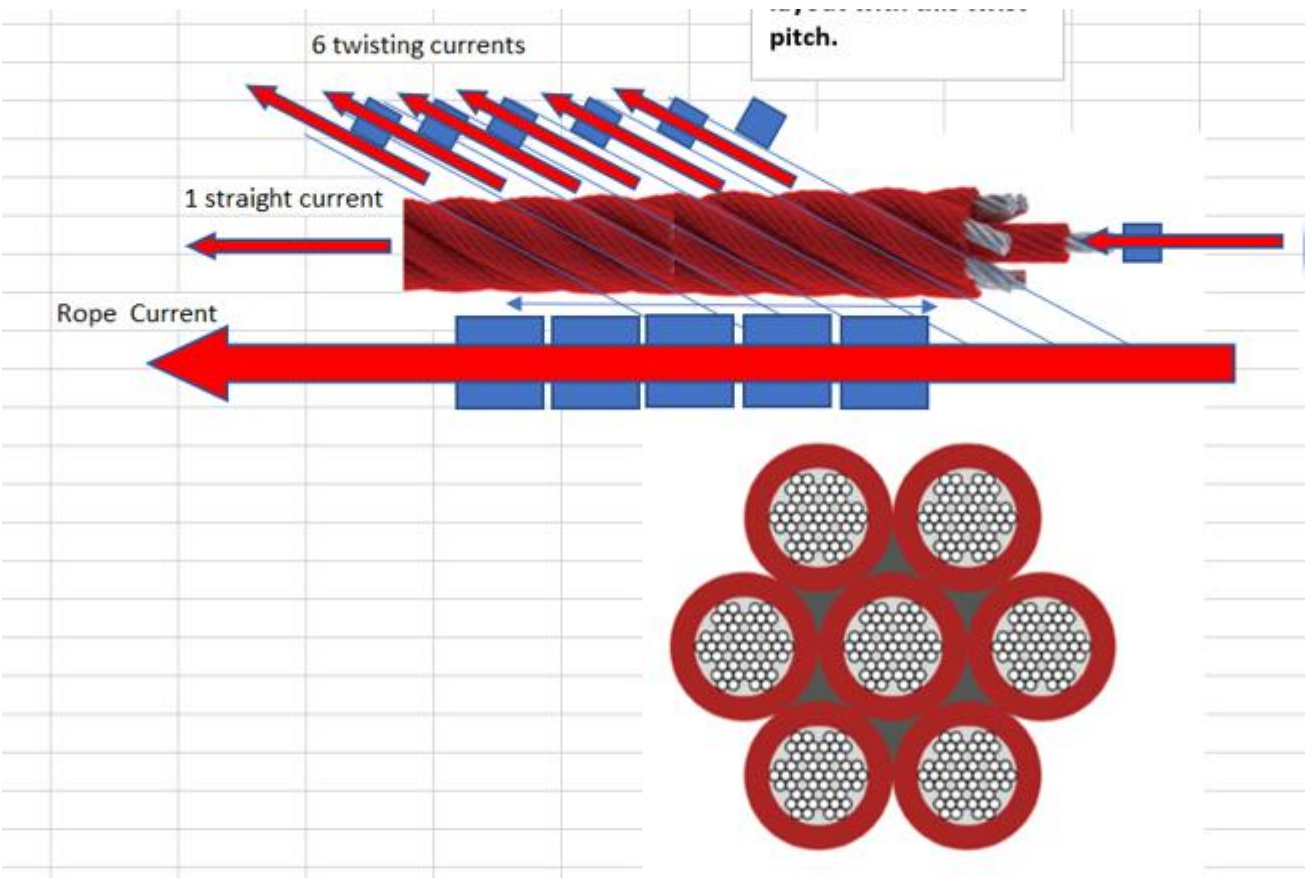
REBCO CCT IDEARS Quad & Sextuple paten pending!

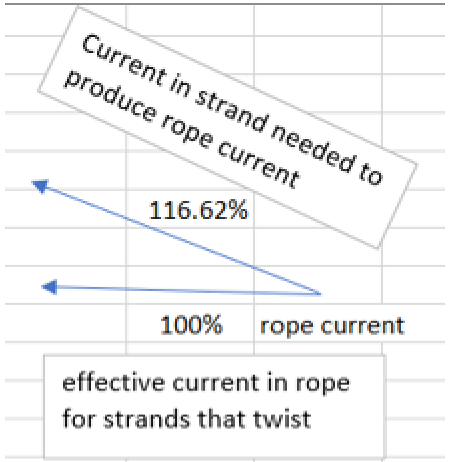
Dipole gradient adjustment with combined functions Quadrupole and Sextupole

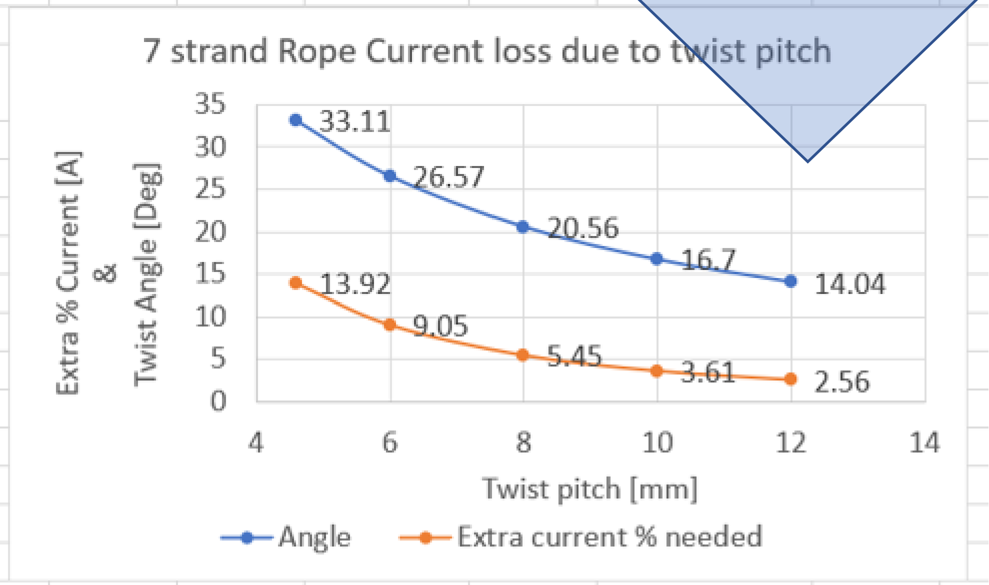
(first pass to correct not fully optimized)



Rope twist pitch angle losses in effective current.

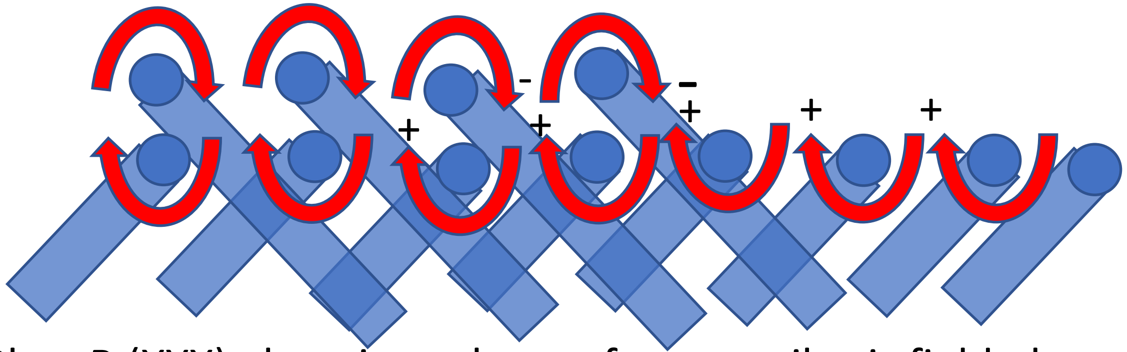




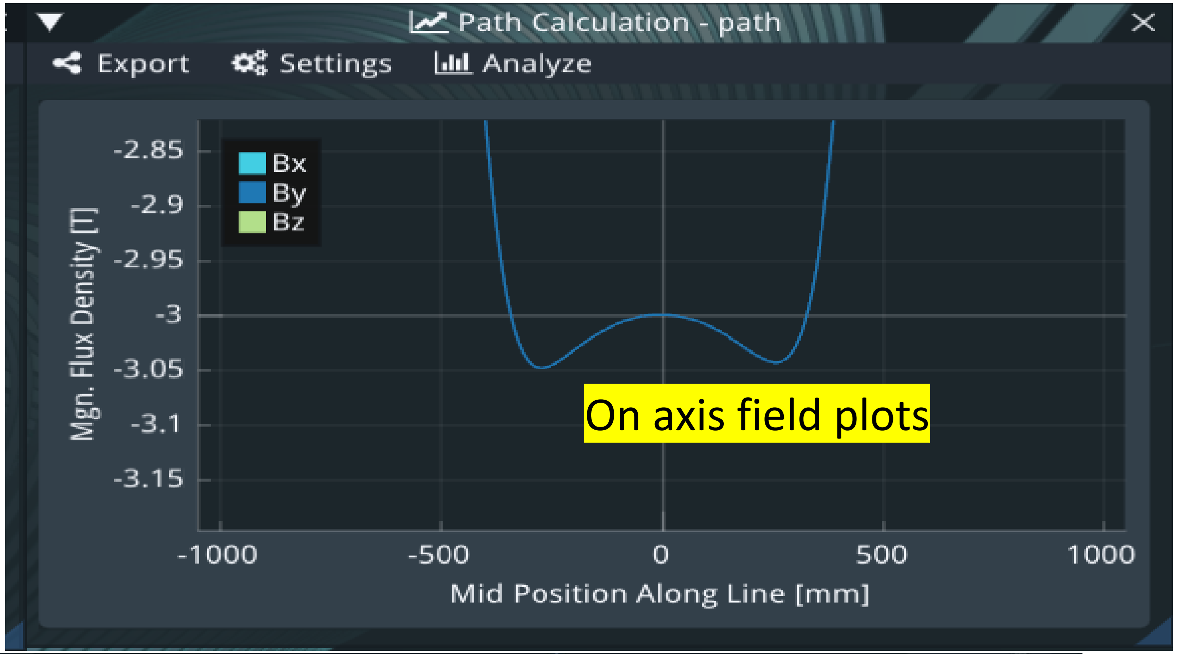


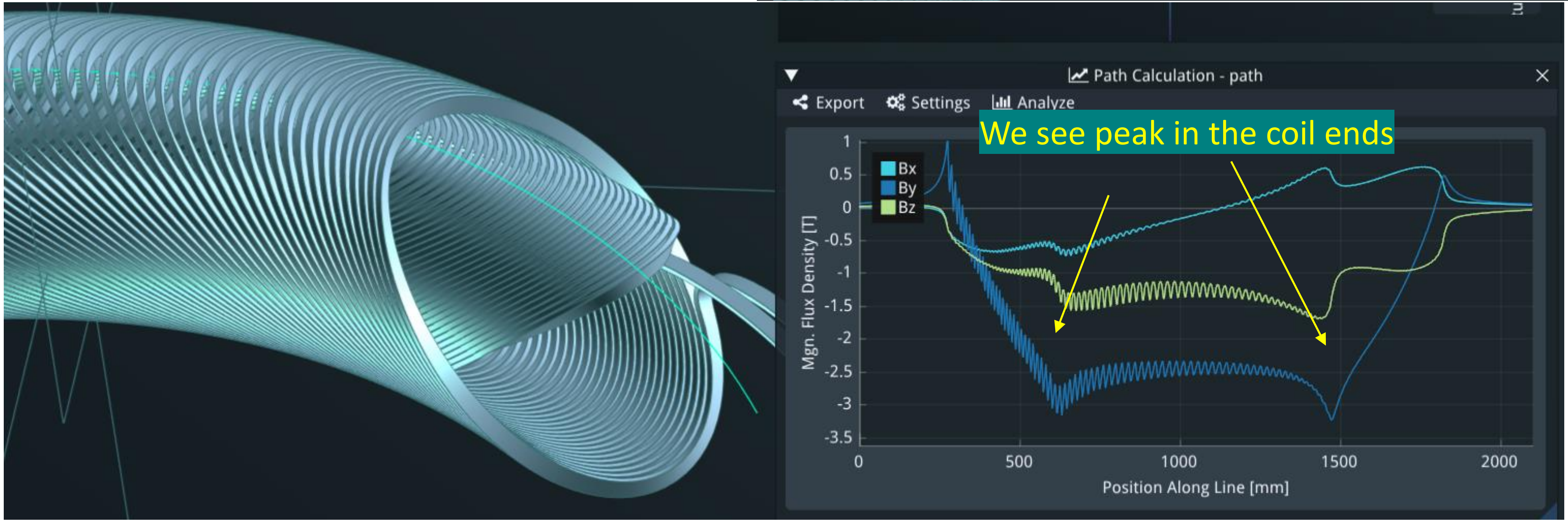
Peak field in ends

The peak field is at in the coil ends and occurs due to the not having an infinitely long coil,

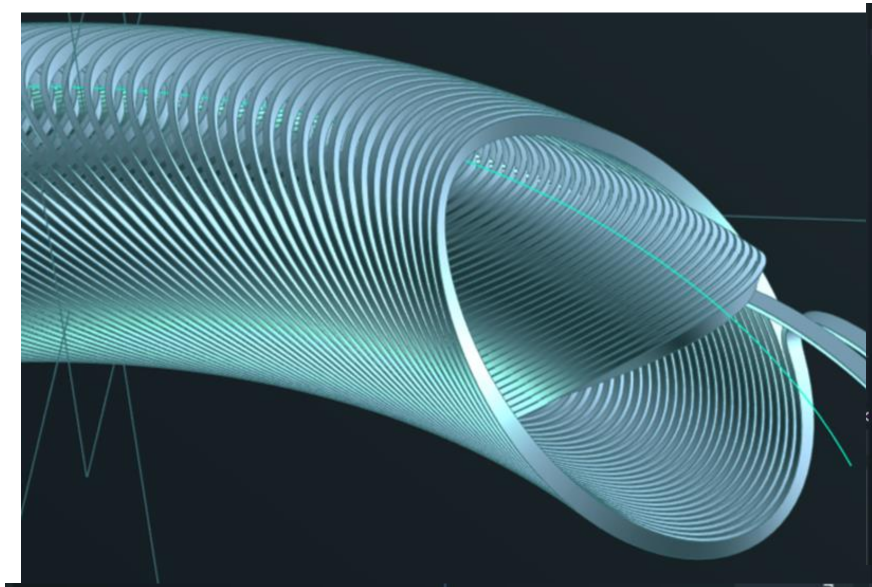


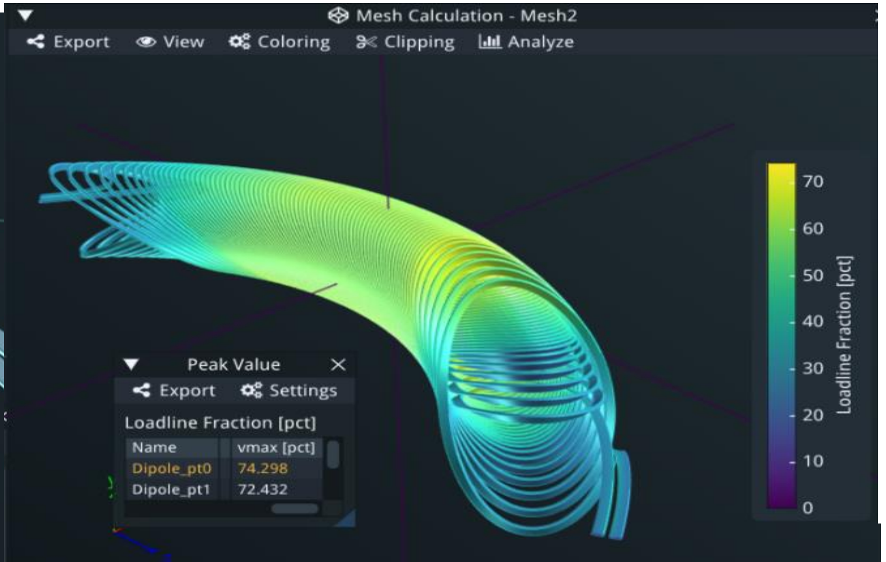
Plots B (XYX) along inner layer of outer coil axis field plots

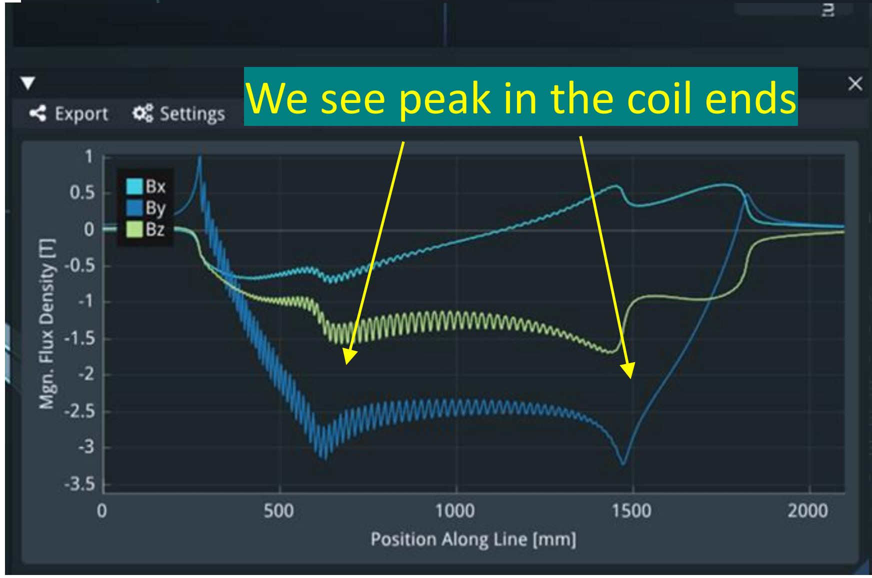


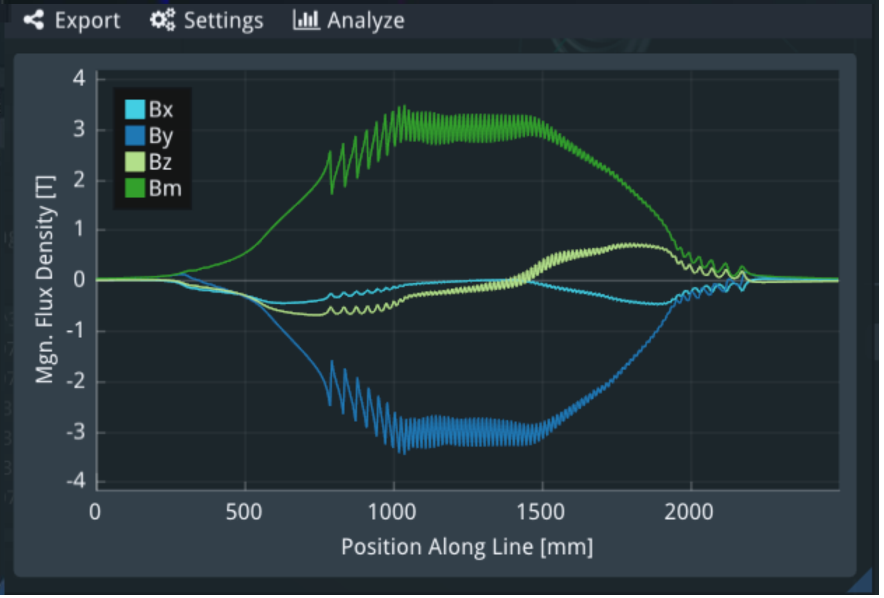


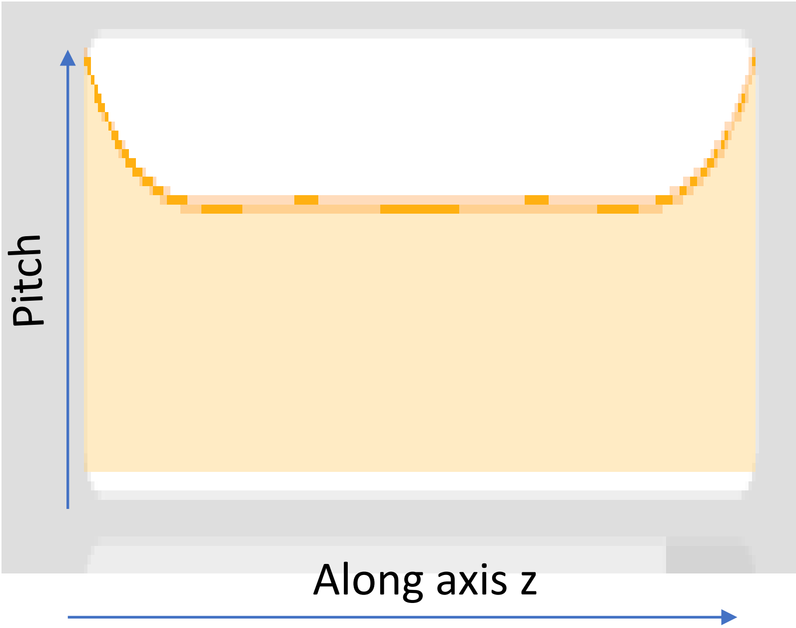
Peak field Smoothing



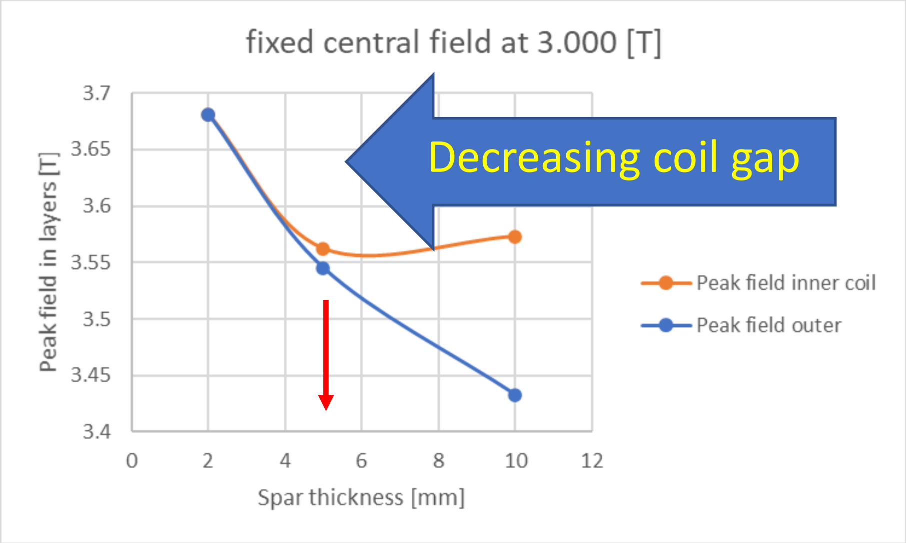




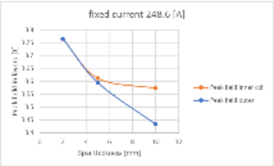


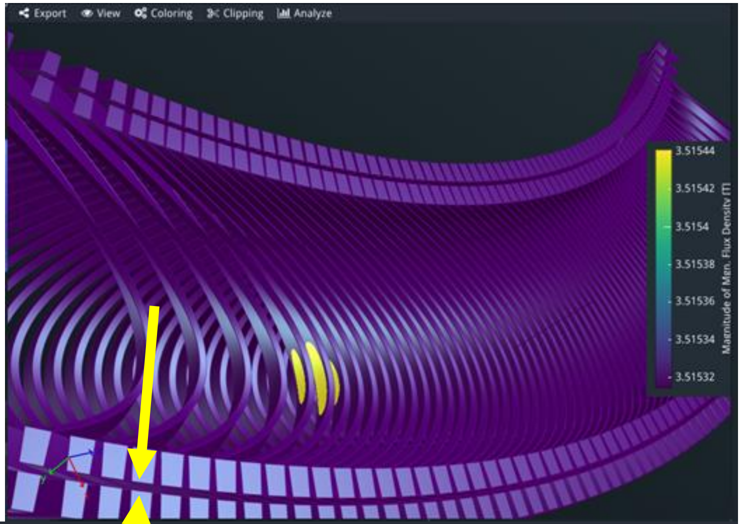


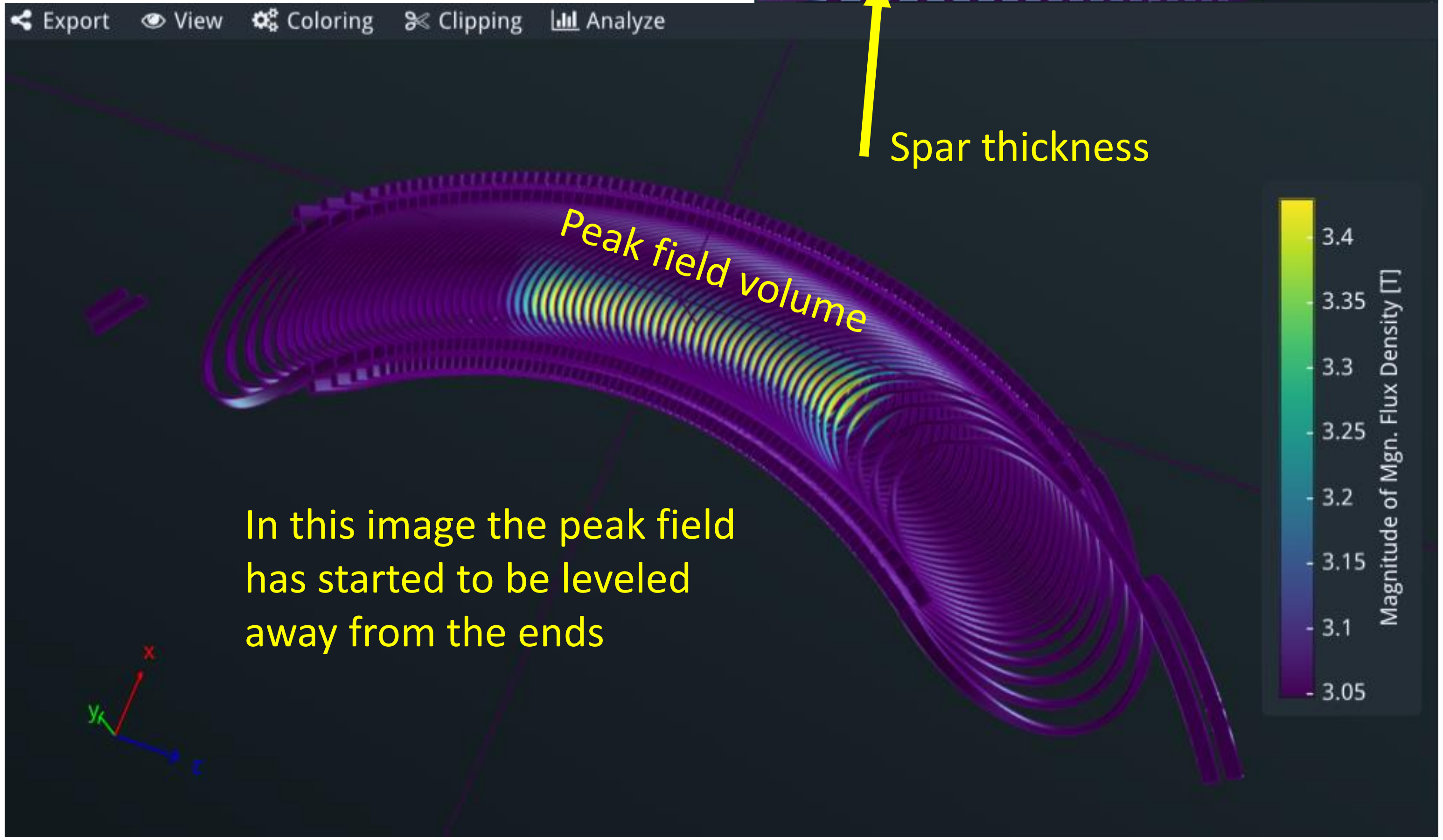
Peak field due to spar thickness or more precisely the gap between coils



As the SPAR reduces in thickness the layers get closer and at 5 mm (for this coil) both inner and outer coil peak field are equal further reduction in the gap increases peak field

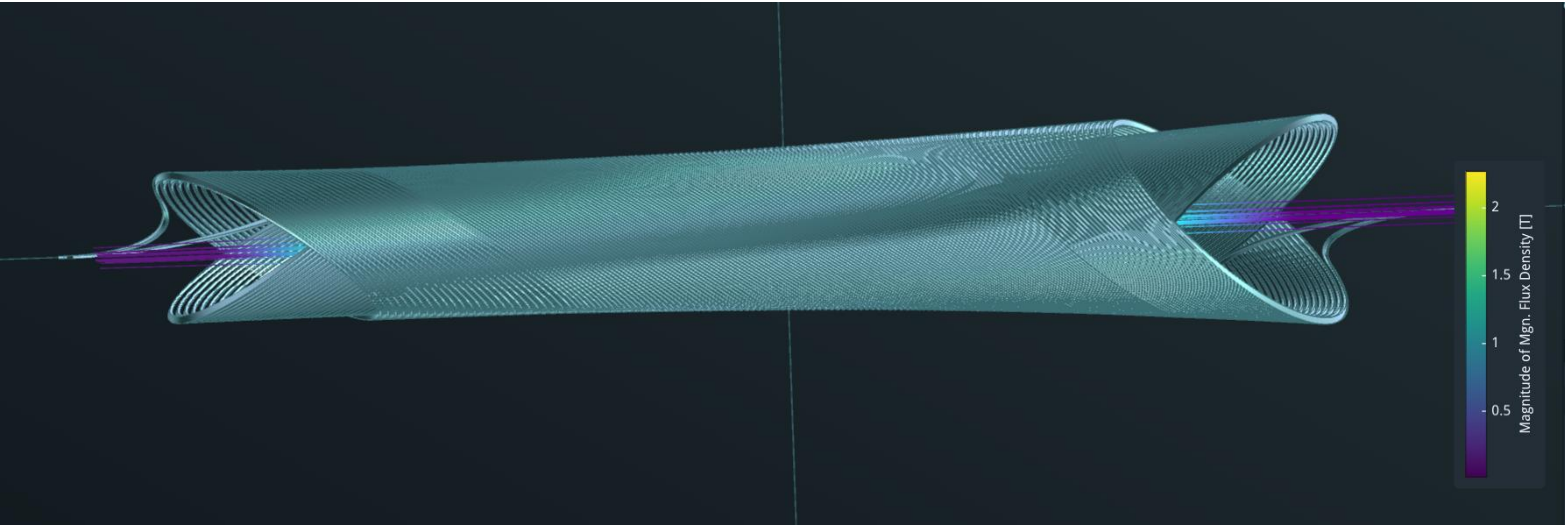






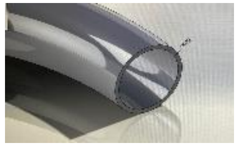
Tapered Coil aperture 230 mm to 235 mm

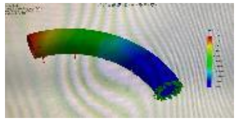
this helps with ***assembly*** and ***radial pressure***,
but the taper produces a skew quadrupole that is then corrected out!

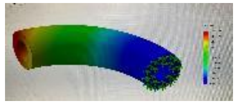


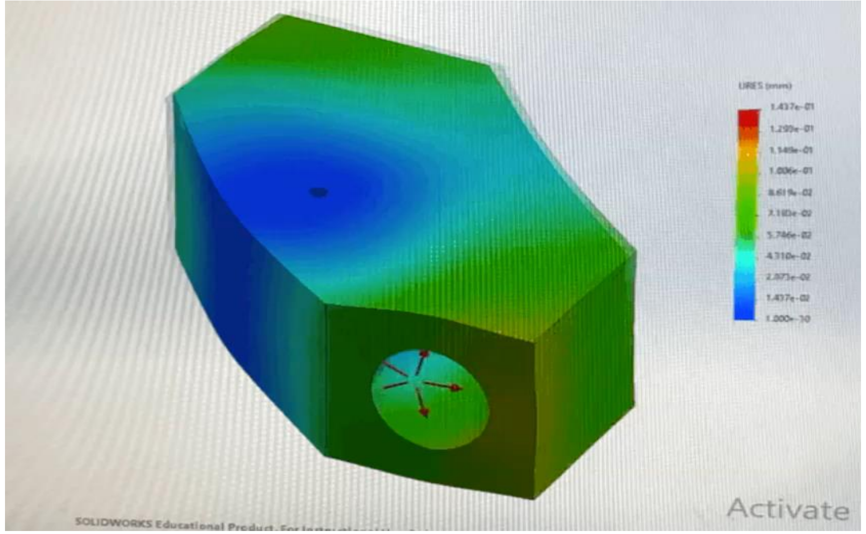
Coil Support Conceptual Design deflection stress

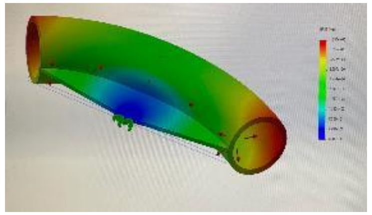
The initial support was just a thin 15 mm thick curved tube as in MCBRD! however, the deflection with a curved coil ~80 mm. Increasing the thickness to 100 mm reduced the deflection to about 4 mm. reducing the tube to 20 mm thick and adding a 10 mm thick wed reduced the support's mass, but the deflection was still 4 mm. increasing the wed to 20 mm took the deflection to 1 mm. The pragmatic massive aluminum block clam-shell design reduced the deflection to ~ 0.15 mm with Von Mises max stress at ~ 30 MPa the support block mass is ~ 370 Kg. This is just an initial look at the deflection and using internal pressure derived from the magnetic forces in the magnet at 3 tesla. Targets are 2.2 T, < 0.3mm deflection , & stress < 200 MPa.

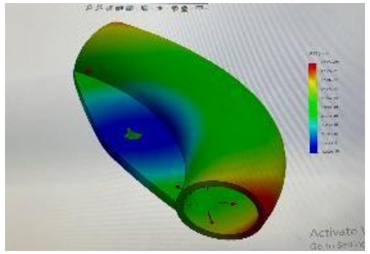


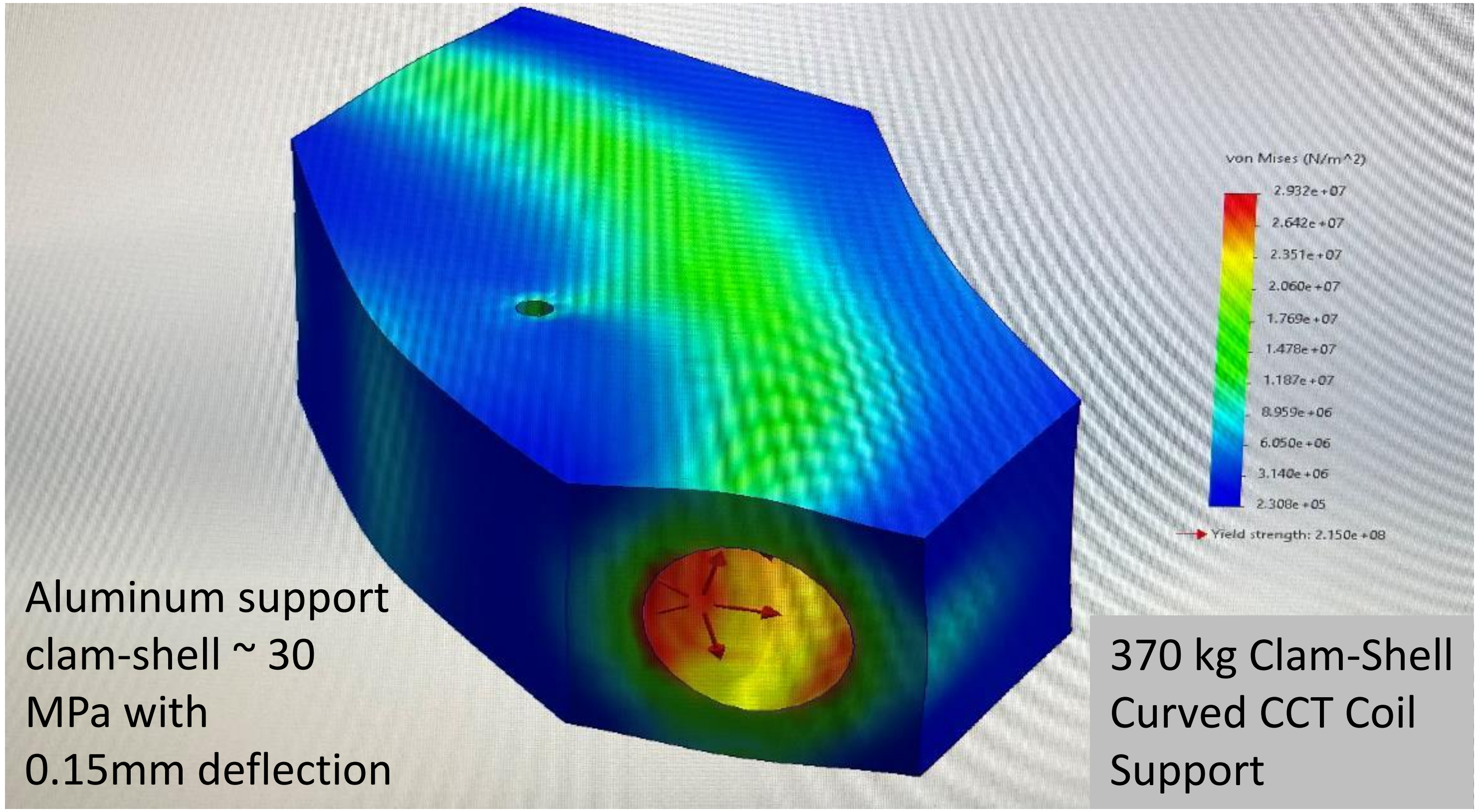








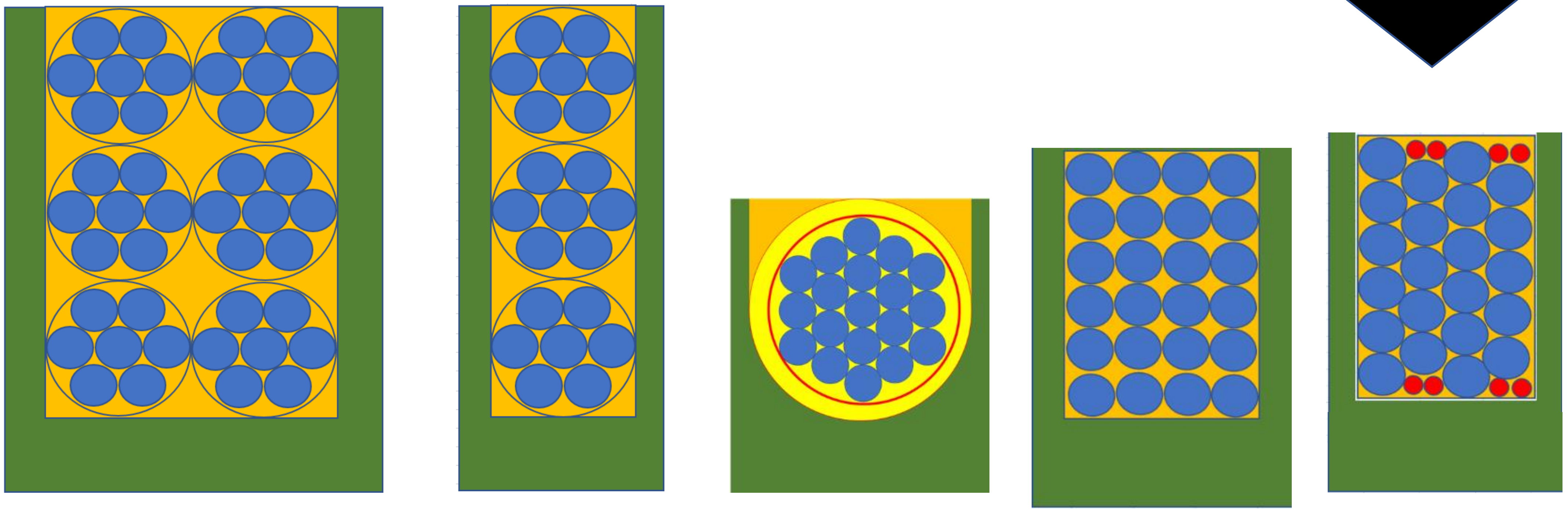




Thanks to Oliver Kirby for the modelling

Channel layouts *some ideas*

Some channels with different packing lay out



6 x 7strand ropes 42 wires
~5 kA
Je 61.09 %

3 x 7 strand ropes 21 wires ~ 5 kA
Je 61.09 %

19 strand rope
13.5 kA
Je < 59.6 %

24 wires
710 A
Je 78.54%

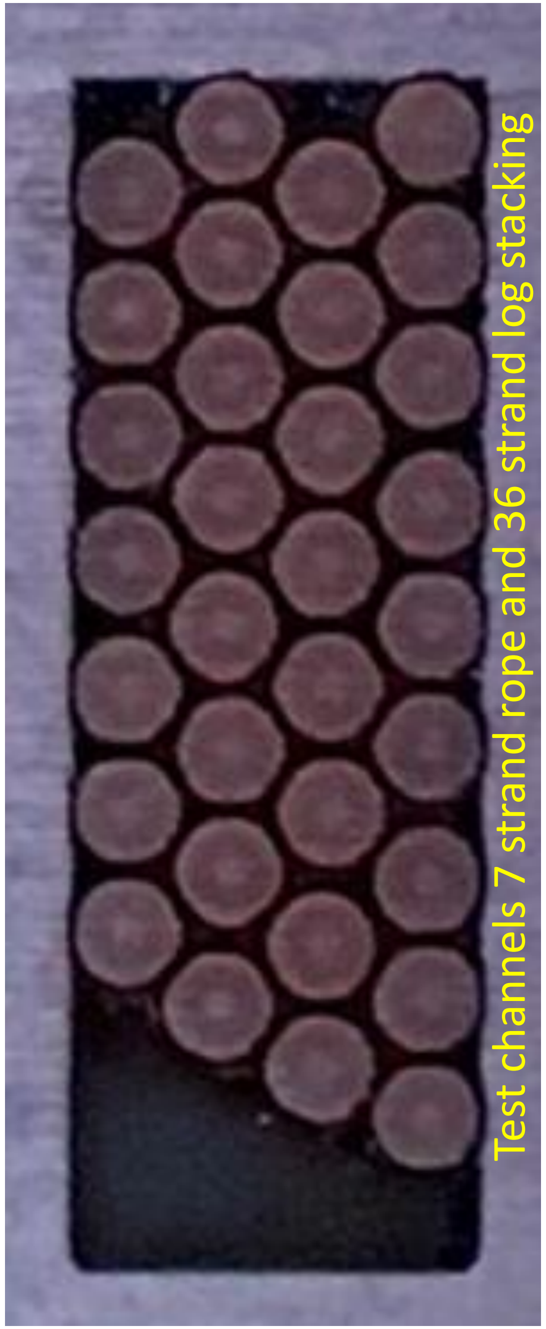
22 wires
710 A
Je 83.8%

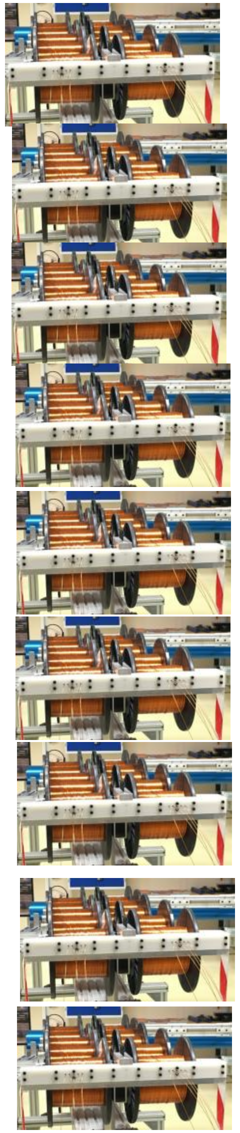
Log Stacking

Layout in channel	Je %
Log stacking	83.8
Rectangular stacking	78.45
7 strand rope	61.09
19 strand rope	59.6

10 spools

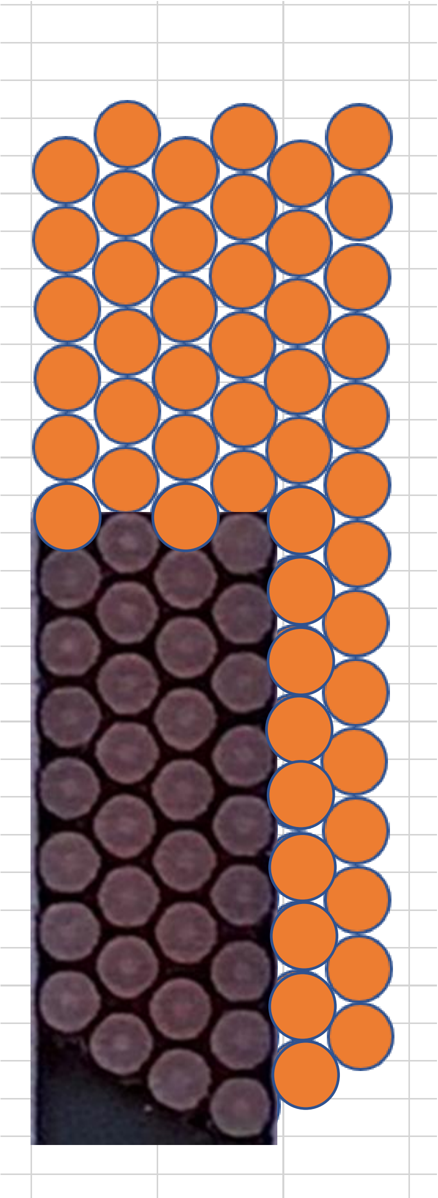
MCBY coil pack in Sweden
7 strand rope
0.3mm strands





90 spools

?



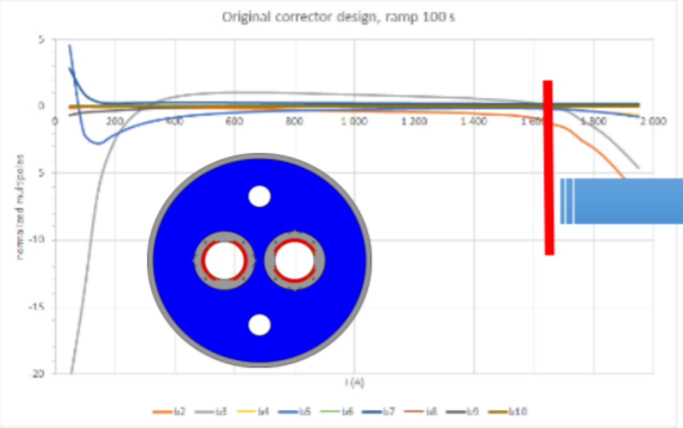
Fusillo 84 strand log stacking with chisel base to add stacking

Yoke steel between apertures?

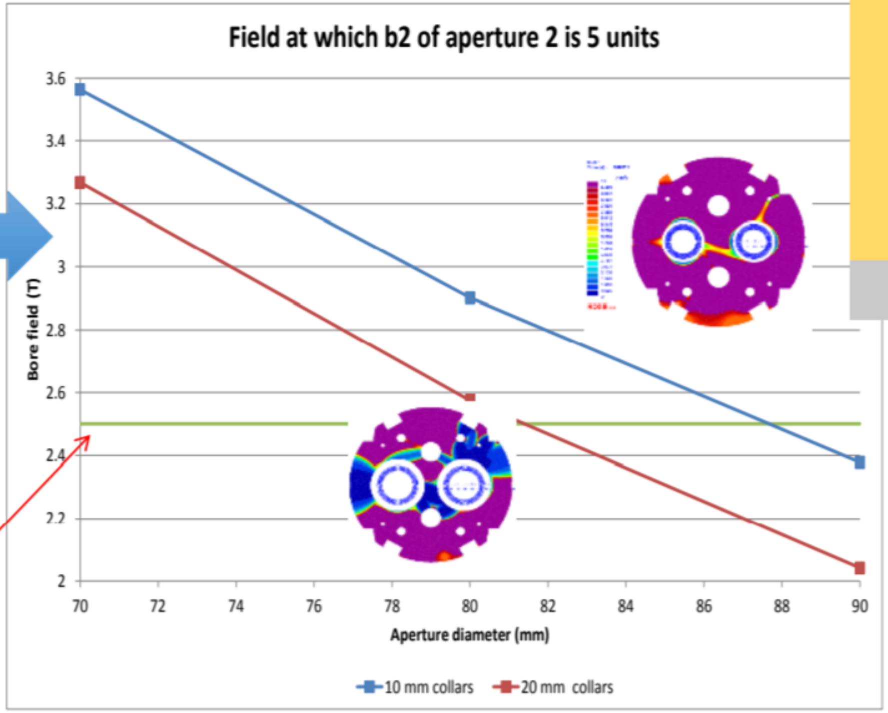
Low current option – cross talk

- MQY yoke diam. (475 mm) & 10/20 mm collars.

Bore field	Magnetic length
2	2.25
2.1	2.14
2.2	2.05
2.3	1.96
2.4	1.88
2.5	1.80
2.6	1.73
2.7	1.67
2.8	1.61
2.9	1.55
3	1.50
3.1	1.45
3.2	1.41
3.3	1.36
3.4	1.32
3.5	1.29
3.6	1.25
3.7	1.22
3.8	1.18



Ref magnet Harmonics
f(current) at 100 sec ramp



Limit of 4.5 Tm & ~1.8 m magnetic length

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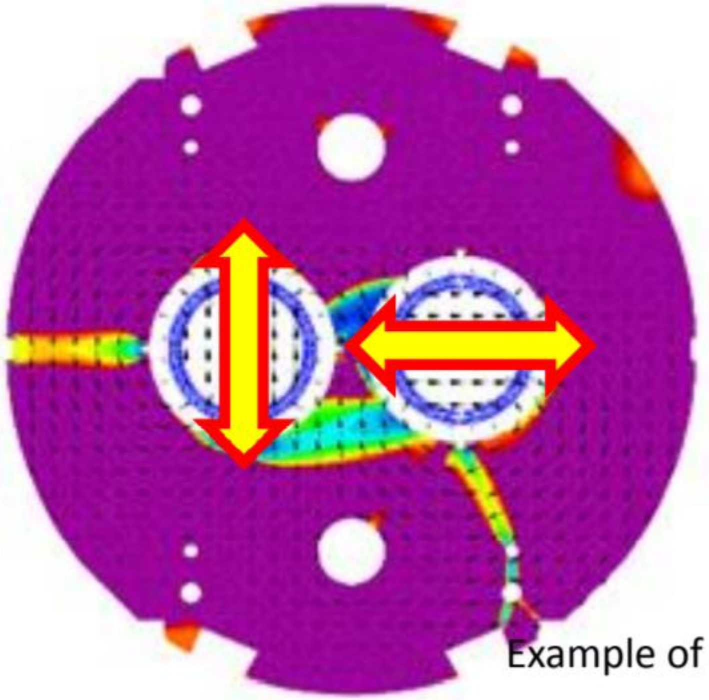
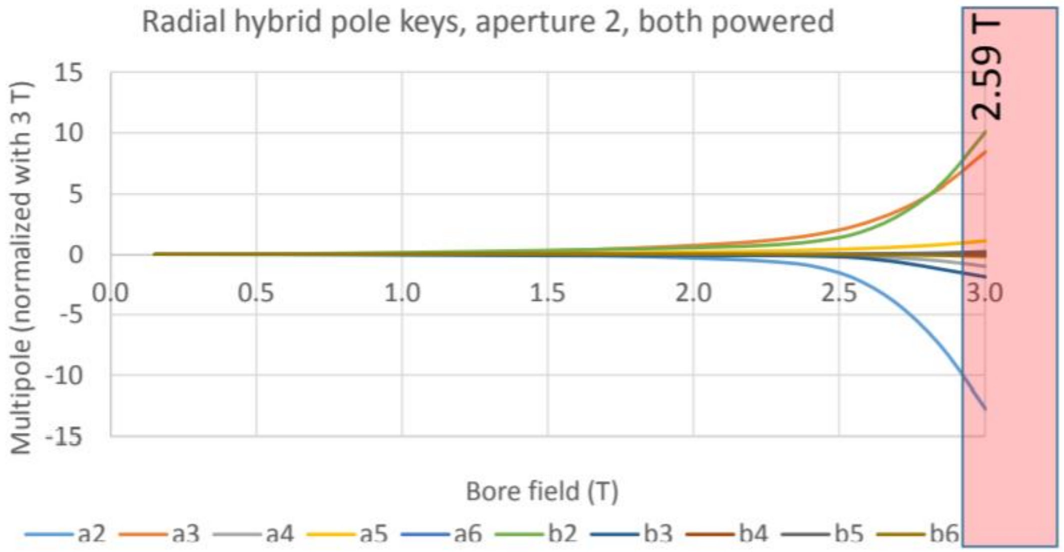
Magnetic Field Optimization, Independently powered apertures

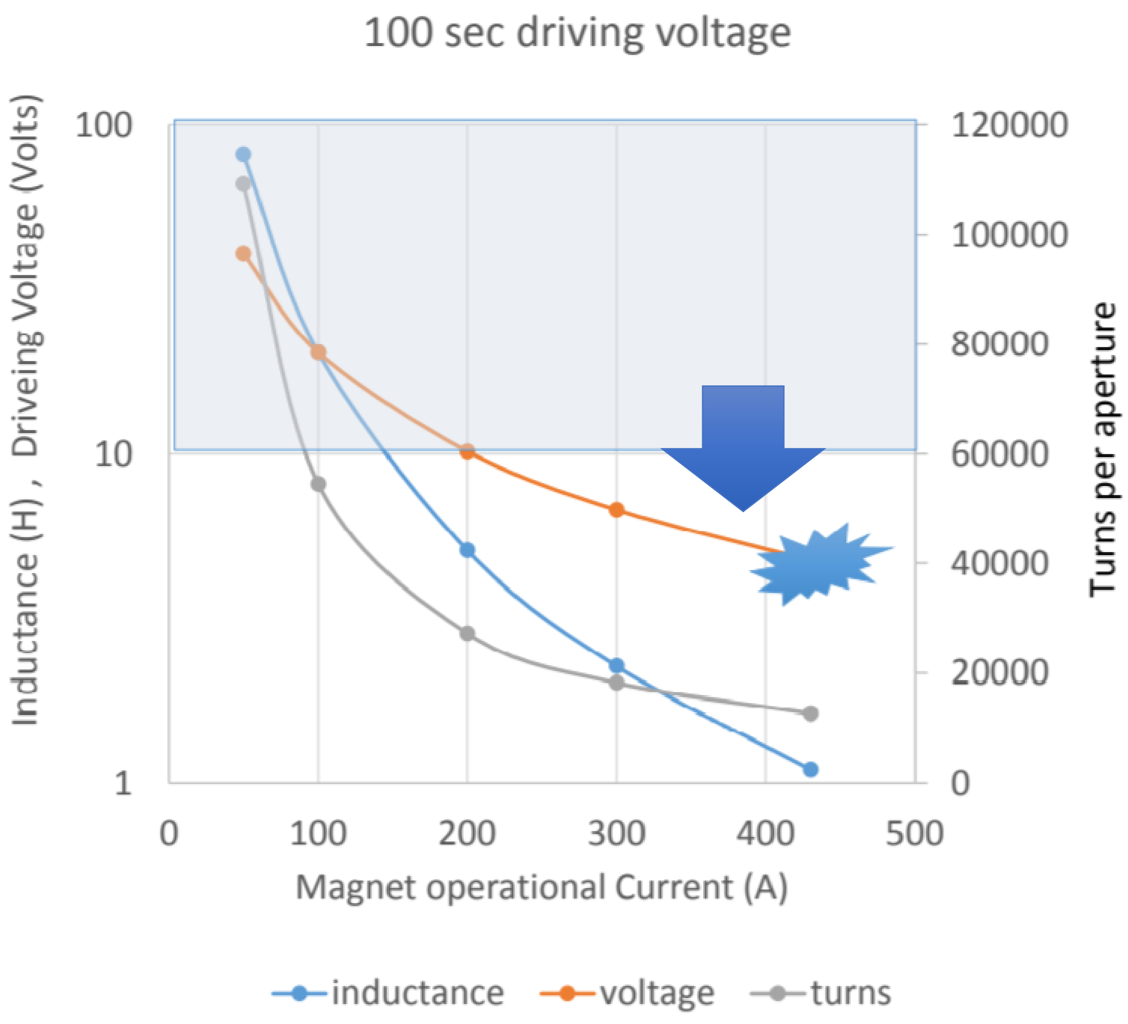
- To achieve 5 Tm field integral with less than 10 units we first determine the maximum field in one aperture that will not pollute the field quality in the adjacent aperture.





More complicated than one plot, Details to follow!

Example of one configuration Presenting harmonic solution due to high field in the adjacent aperture



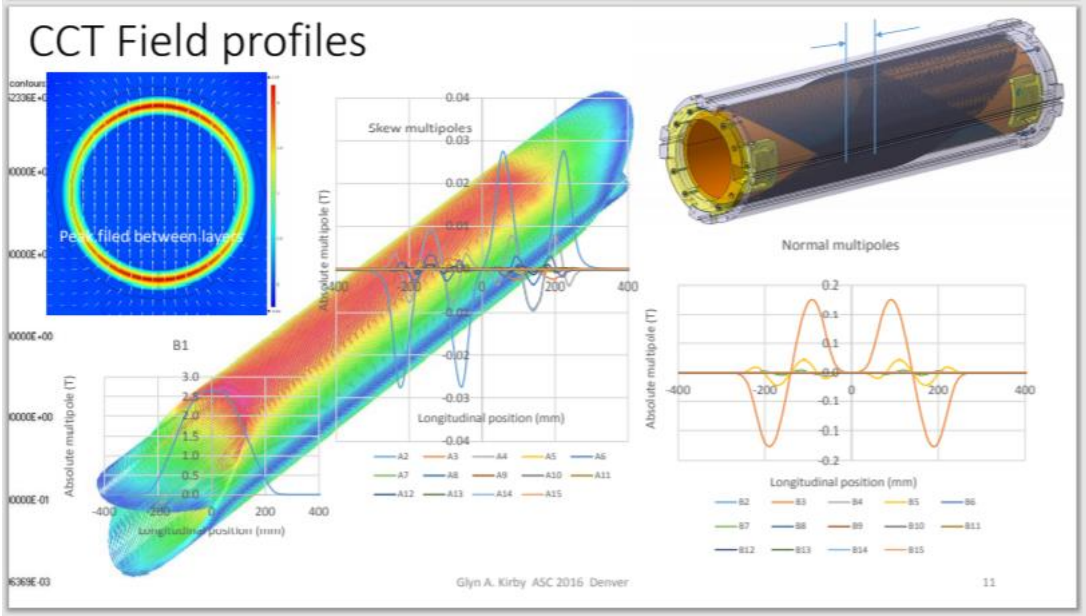
+&- 600A, 4 quadrant, 10 V, with 0.7 to 1.0 ohm Dump.

Approximate Power supply Costs

Power converter	Current	Voltage	Quadrant	Unit price KCHF
Type 1	16.5kA	20V	1	500
Type 2	13kA	18V	1	350
Type 3	6kA	8V	1	200
Type 4	±2kA	±10V	4	150
Type 5	±600A	±10V or ±40V	4	50
Type 6	±200A	±10V	4	10
Type 7	±120A	±10V	4	10

http://te-epc-lpc.web.cern.ch/te-epc-lpc/general.stm

Power In	*3 ~ 230V/16A*
Power Out	*+/- 600A +/-10V (or +/-40V)*
Converter Type	*4 Quadrant*
Control type	*FGC2 / WorldFip*
Current Accuracy	*10 ppm@ 30 mn*
	50 ppm@ 24 h
	200 ppm@ 1 year
	(1 ppm=0.6mA)


CCT Field profiles
Peak filed between layers
Skew multipoles
Normal multipoles
B1
Absolute multipole (T)
Longitudinal position (mm)
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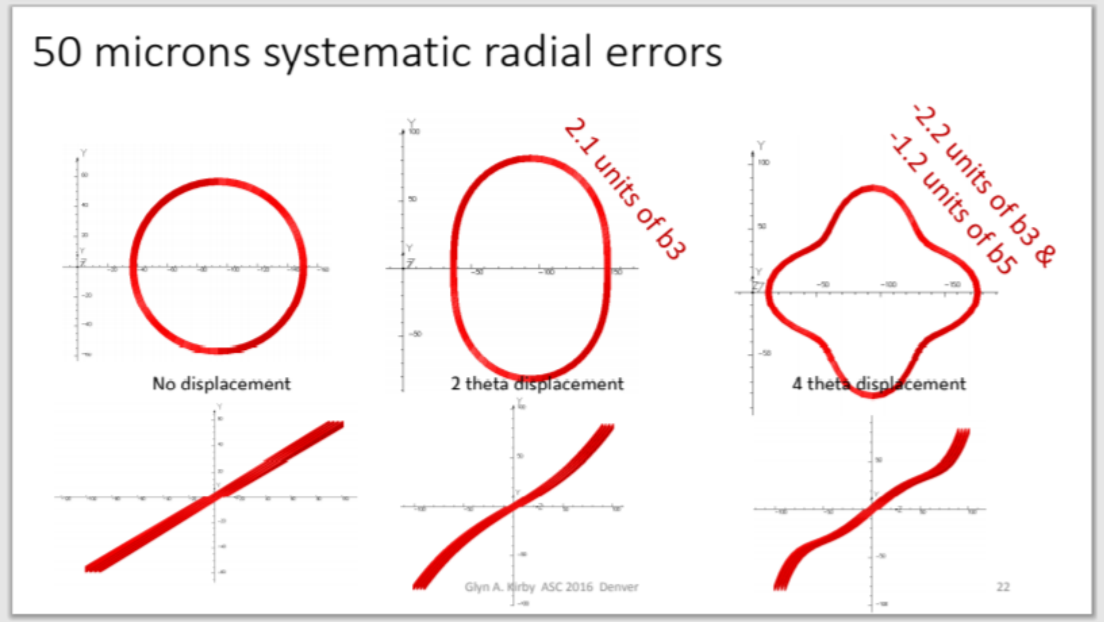
50 microns systematic radial errors
2.1 units of b3
-2.2 units of b3 &
-1.2 units of b5
No displacement
2 theta displacement
4 theta displacement
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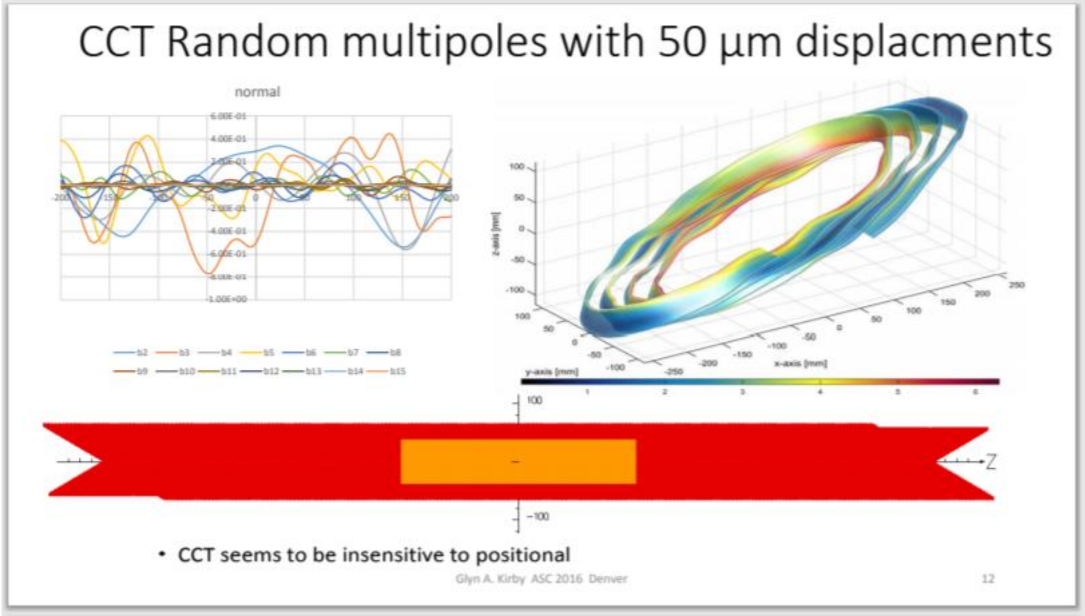
CCT Random multipoles with 50 µm displacments
normal
• CCT seems to be insensitive to positional
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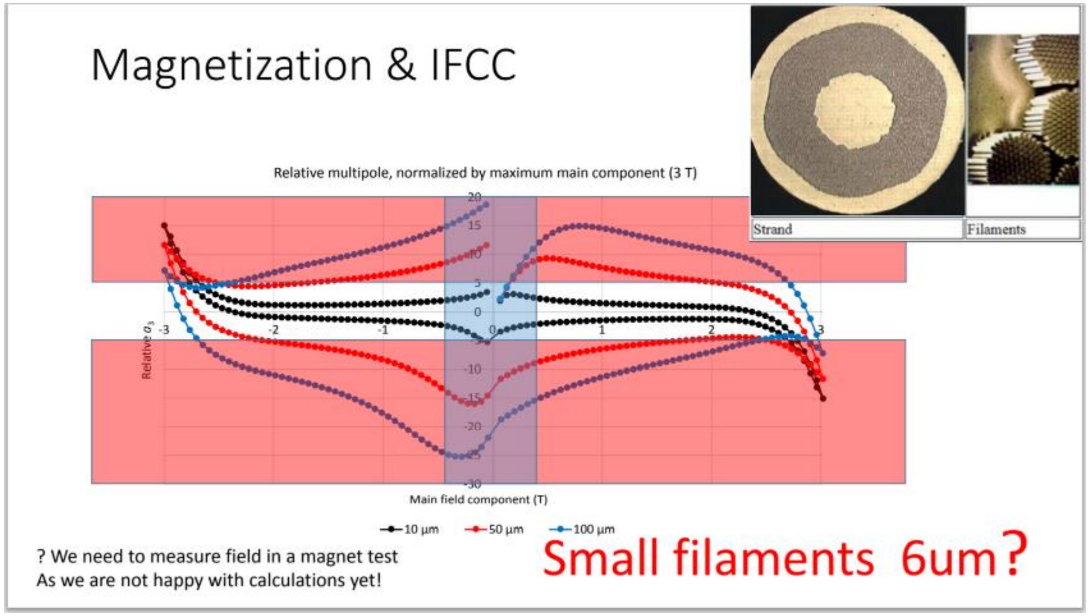
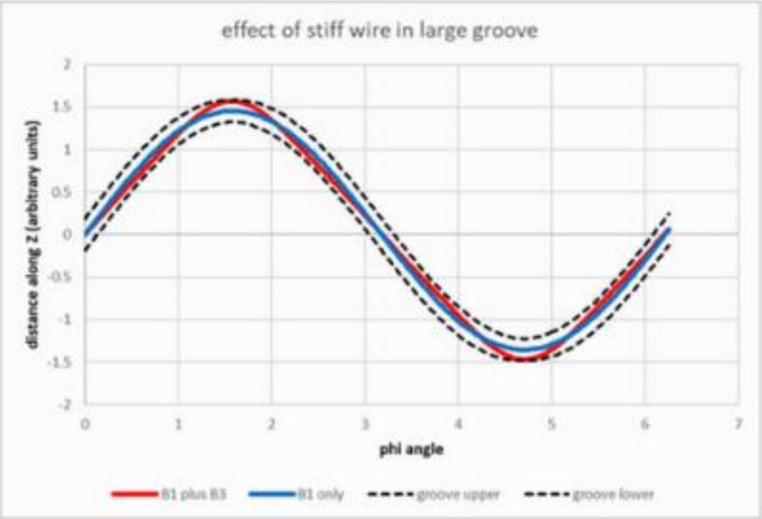
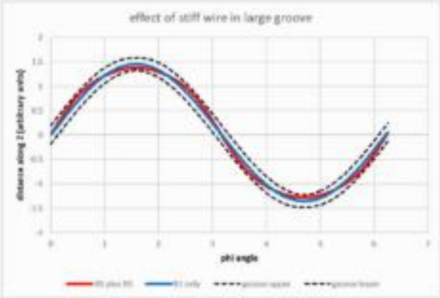

Magnetization & IFCC
Relative multipole, normalized by maximum main component (3 T)
Main field component (T)
10 µm
50 µm
100 µm
Strand
Filaments
? We need to measure field in a magnet test
As we are not happy with calculations yet!
Small filaments 6um?

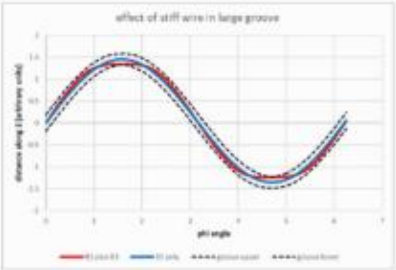
Effect of wire placement in channel



Following is +ve B1, B3, B5

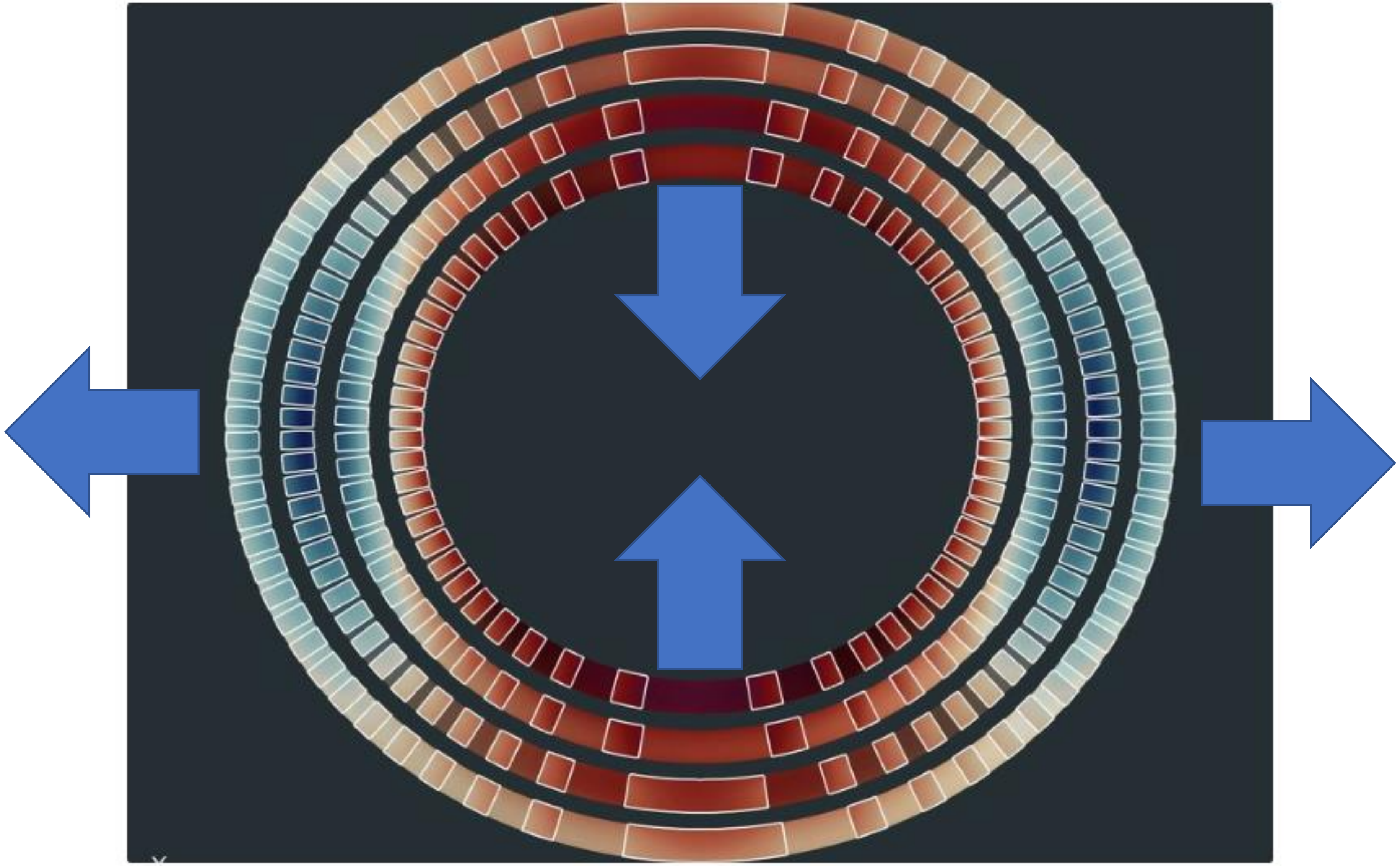


Last is with +ve B1, B3, -ve B5:



This picture reminds me of a much stiffer cable.

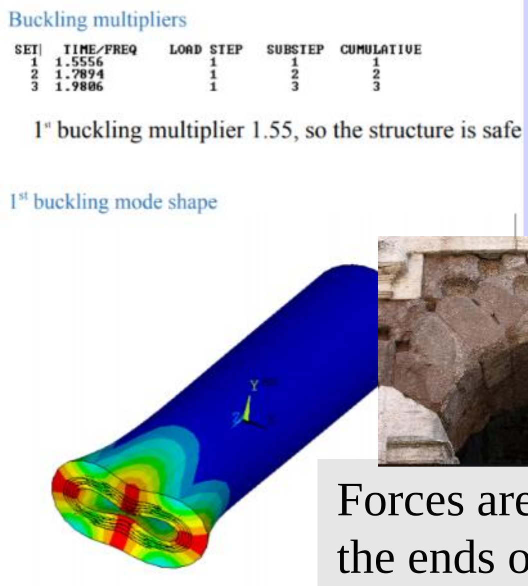
Some Calculations to look at field errors due to wire misplaced in the channel

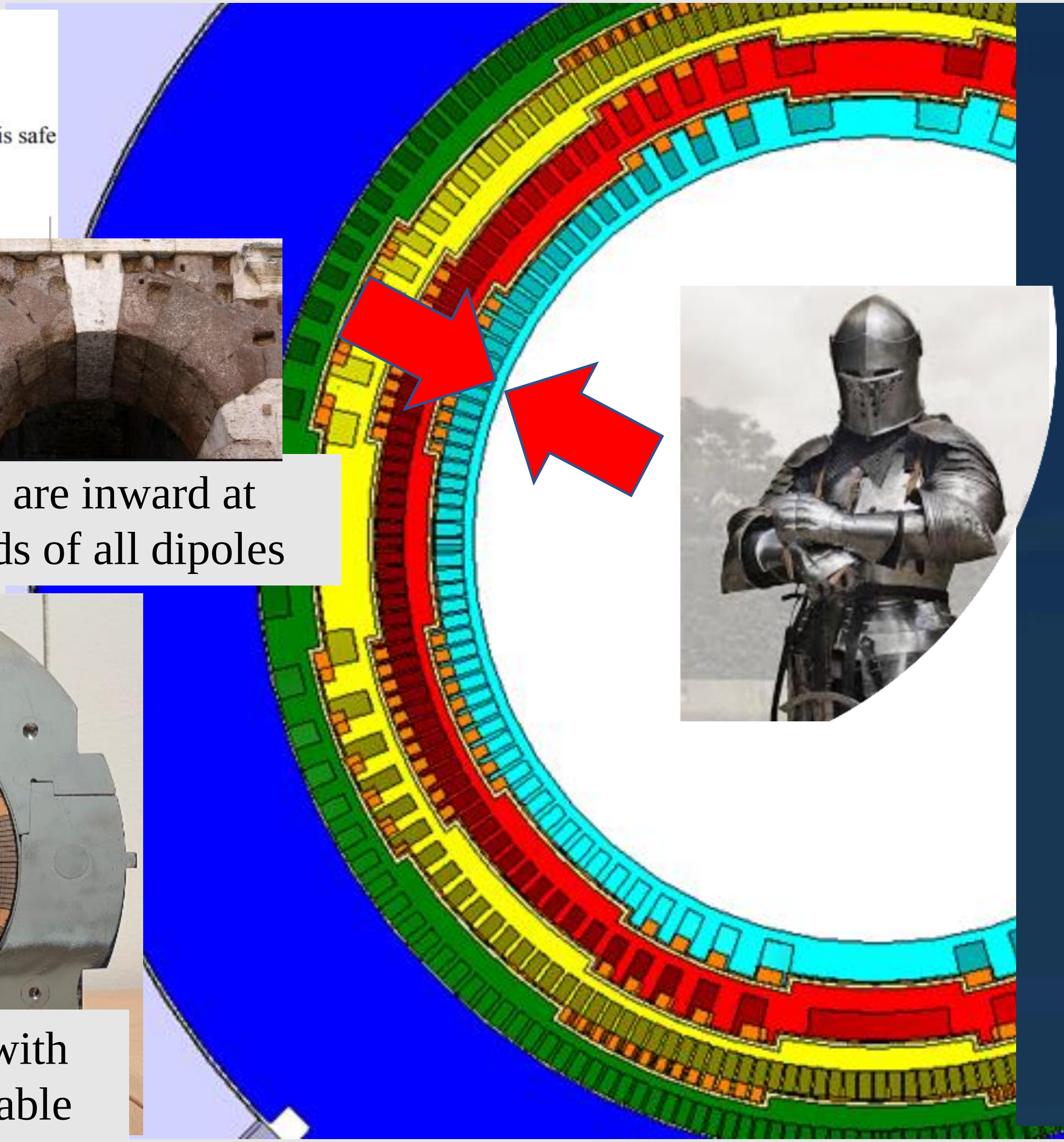


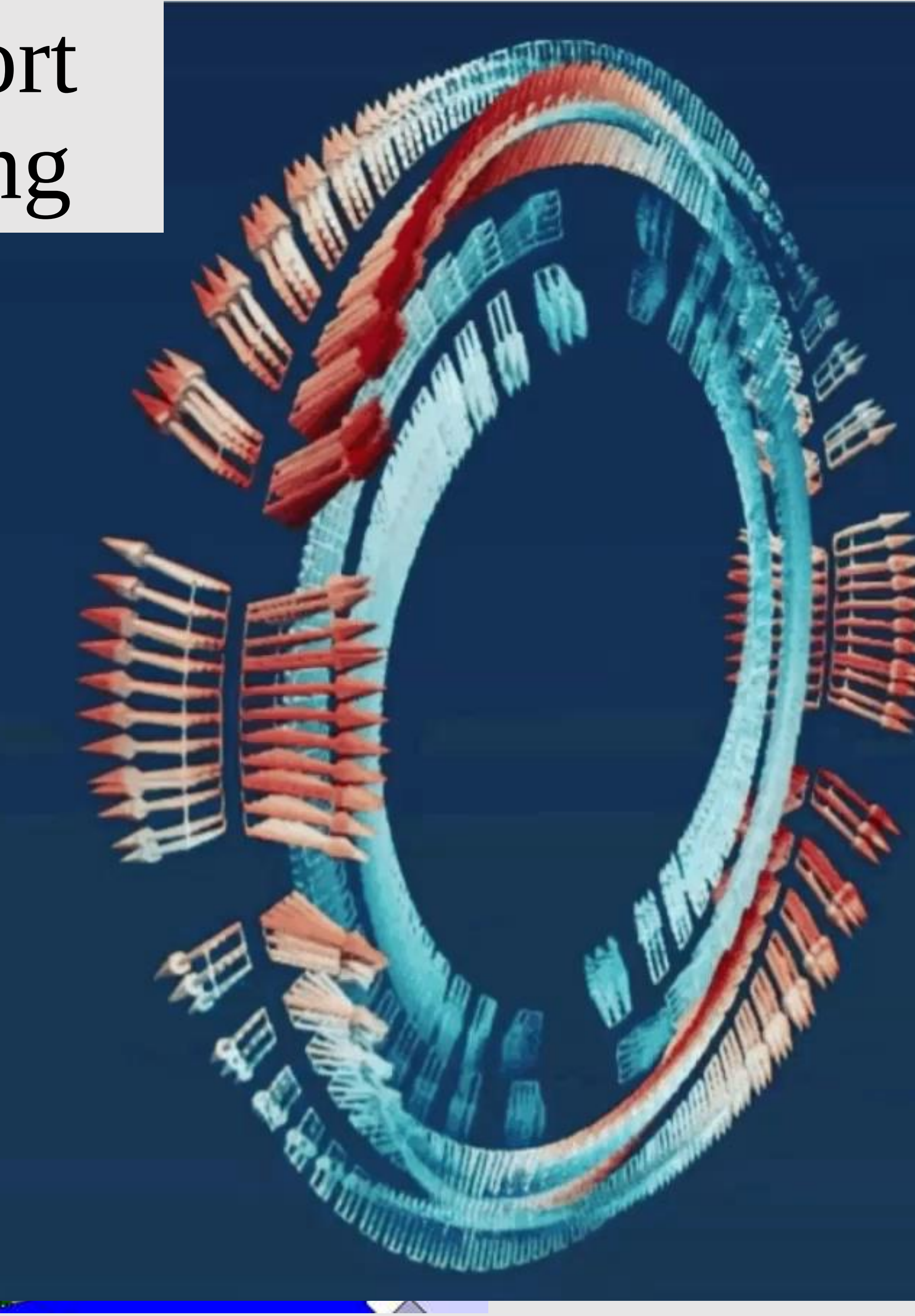
Field errors due to coil deformation.

We calculated the effect on the field quality of a squeezed/oval CCT. If the aperture is stretched by 1% i.e. on 105 mm that is 1.05 mm extra. It only get 2 units of B3 field error. To get to 10 units it would need to stretch by 5%. So 5 mm.

Large apertures need internal support due to reduced resistance to buckling



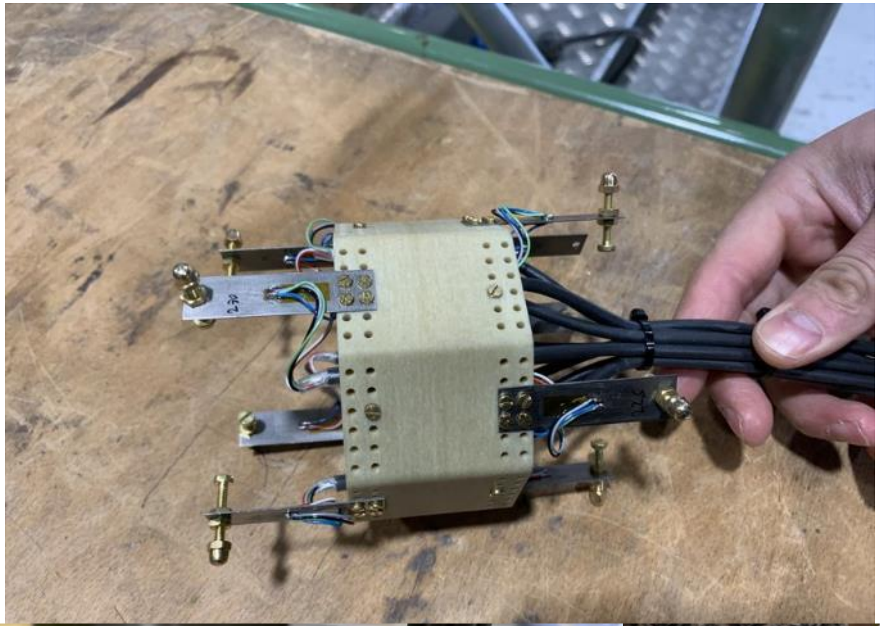


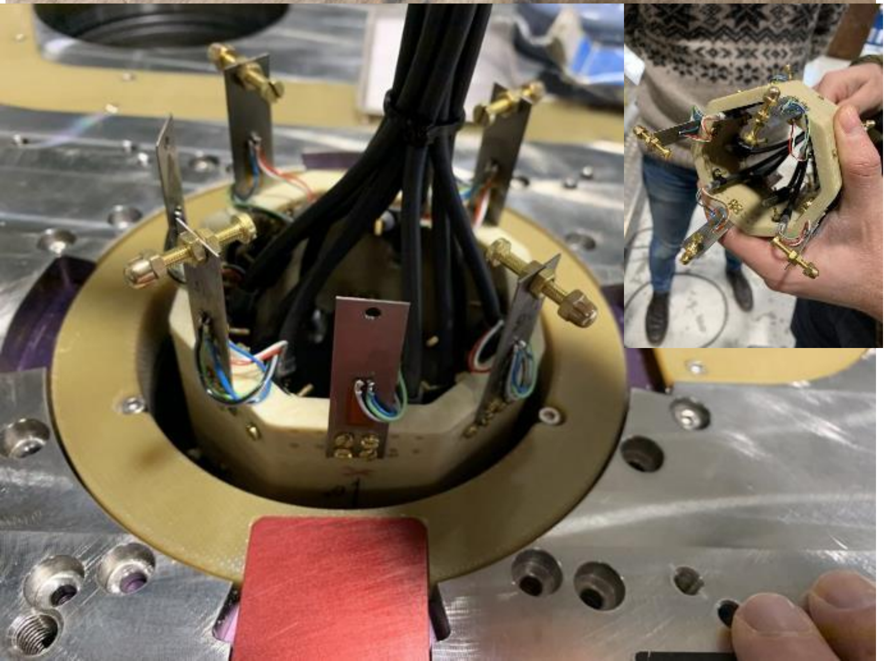


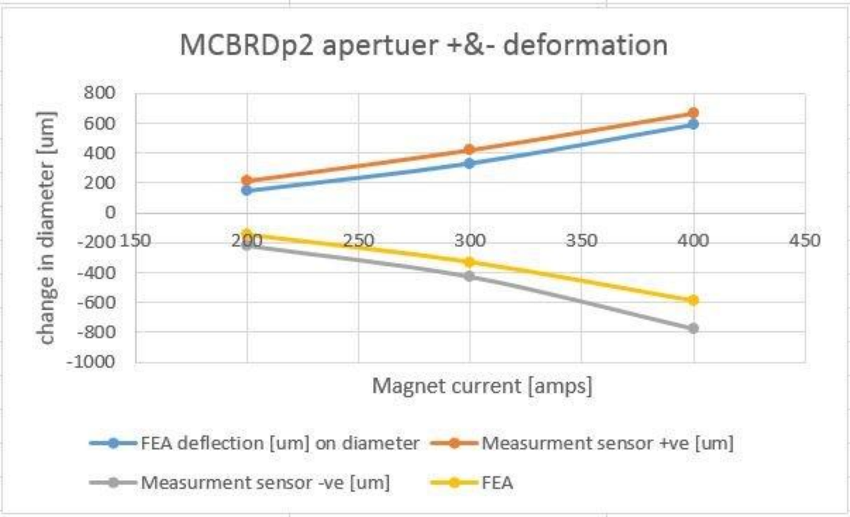
Forces are inward at the ends of all dipoles

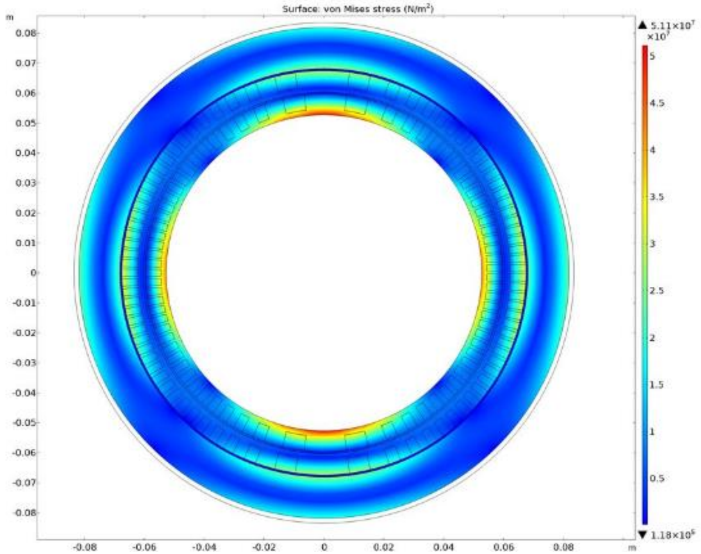
LHC small apertures with wide coils are more stable

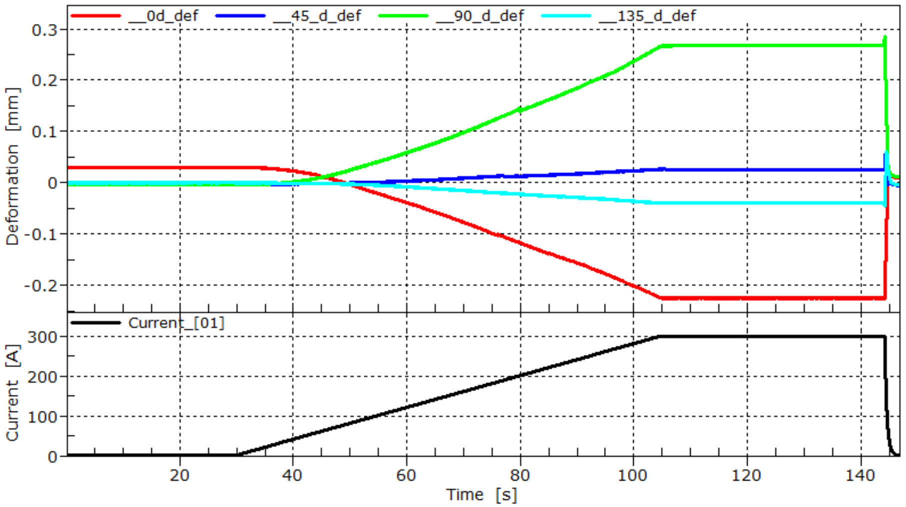
Aperture deflection cold measurement

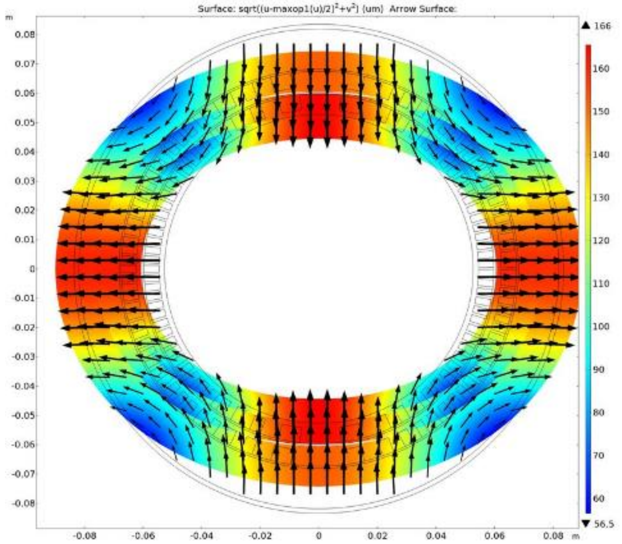






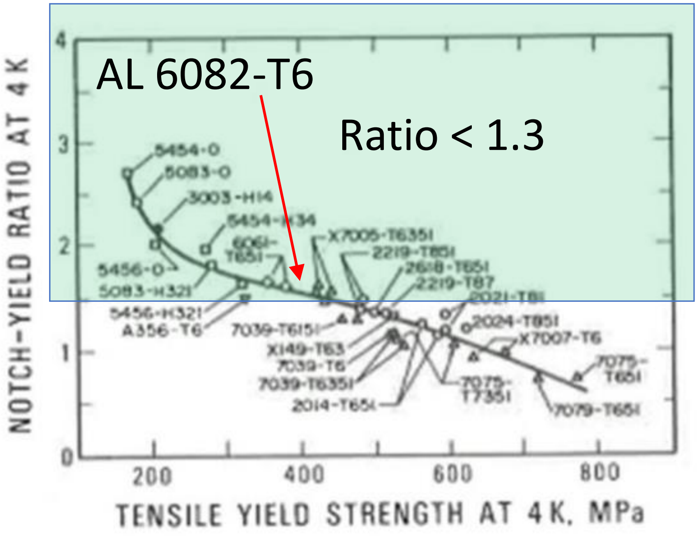


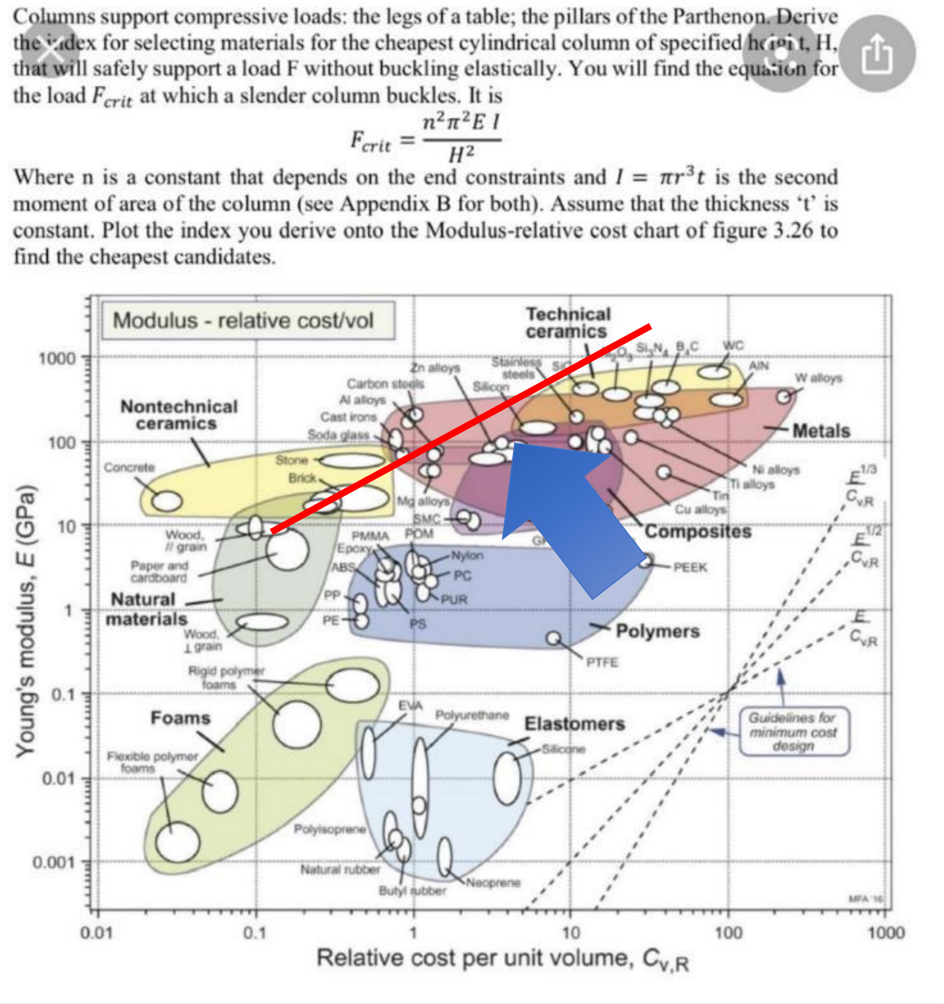




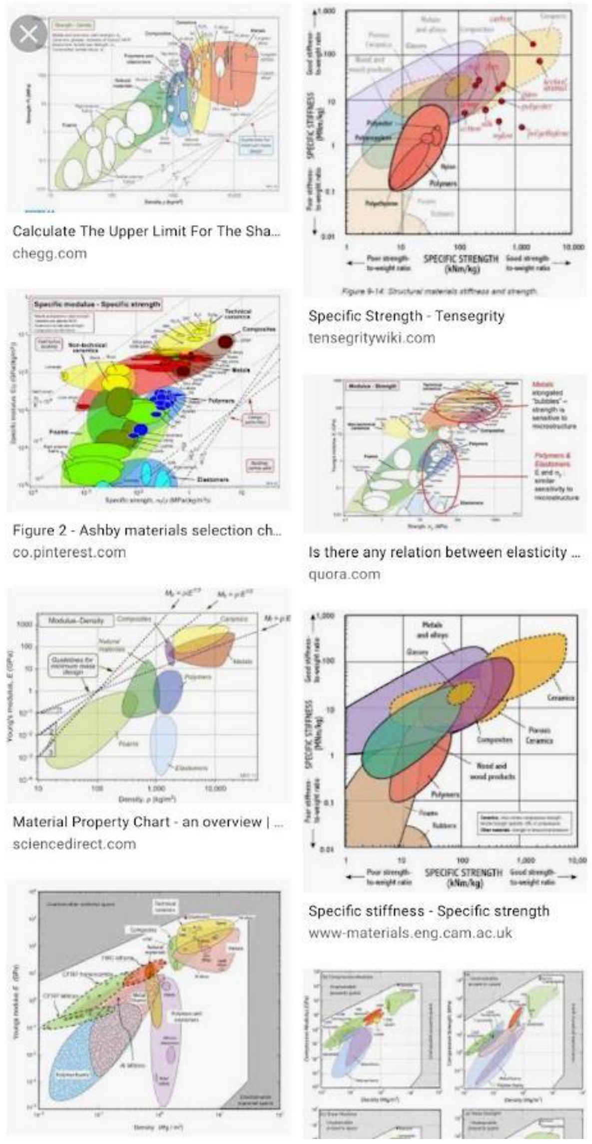
Former material selection Ashby….. plots and toughness

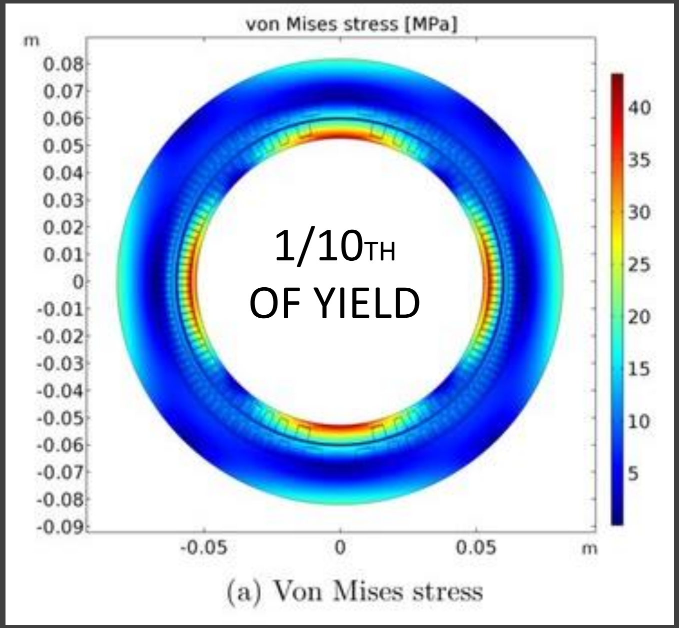
Machinability
Material availability
Insulating coating compatibility
Strength
Fracture Toughness
Notch sensitivity
Crack sensitivity
Electrical resistivity
Cost





Al 6082-T6 with a hard anodized surface





Former material AL6082T6

2.1 Tensile tes at 4K

Tensile tests at 4K were perfomed with the UTS tensile machine on four specimens, mean values and standard deviation are given in table 1, tensile curves were presented in chart 1 and sample before and after the test could be seen on figure 1 and 2.

Sample Nº 2 was not take in account since artefact happen during the mechanical test, values were calculated using samples 1, 3 and 4.

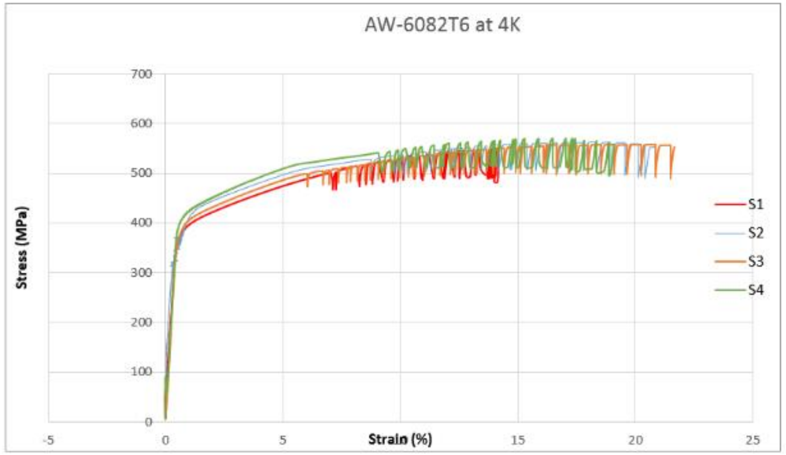
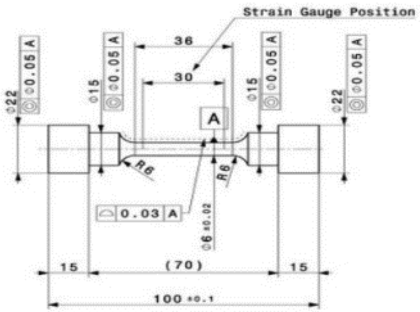


Chart 1 – Tensile curve at 4K

Figure 2 – Samples after the test

YS (MPa)	UTS (MPa)	E (GPa)	A (%)
389 ± 14	560 ± 7	79 ± 3	17.6 ± 4.3

Table 1 – Mechanical properties (Avergae ± St. Dev.)



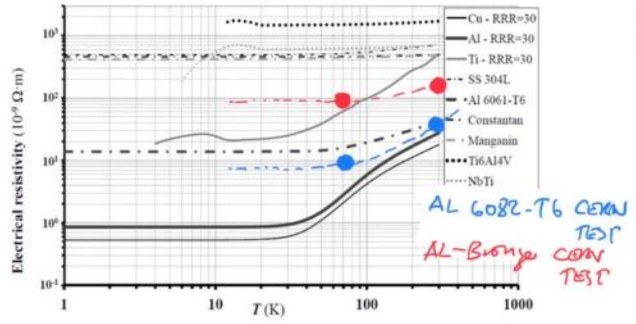
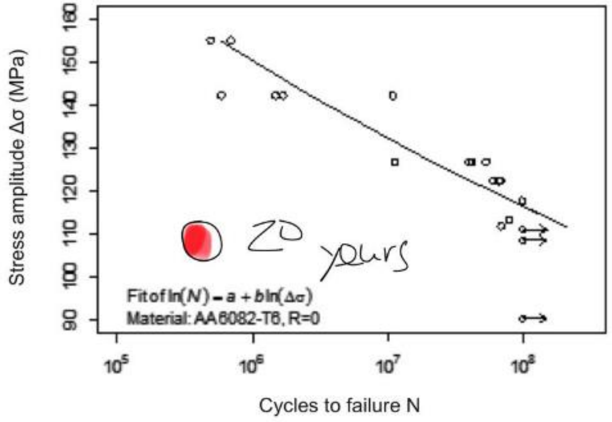


Fig. 10: Electrical resistivity ρ ($\Omega{\cdot}m$) of various materials versus temperature T. Metals are plotted with solid lines, metallic alloys with dot-dashed lines, and two superconducting alloys with dotted lines.

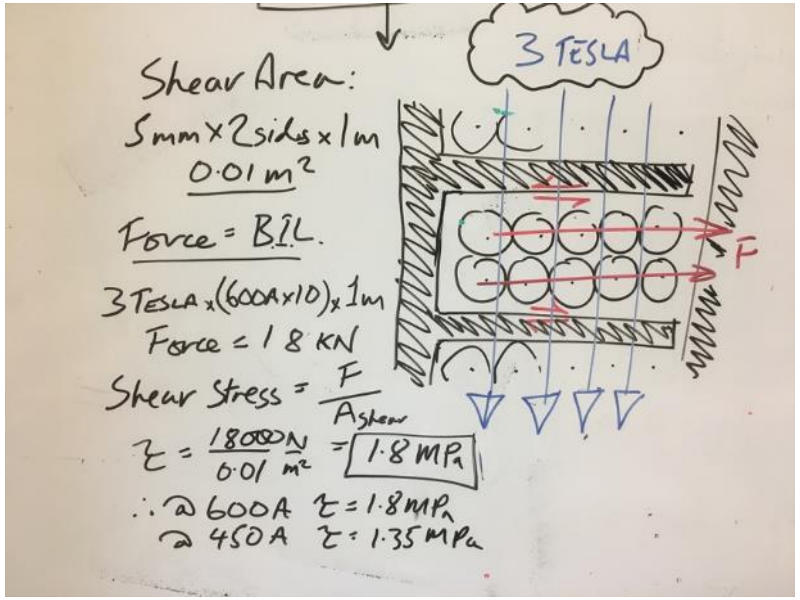


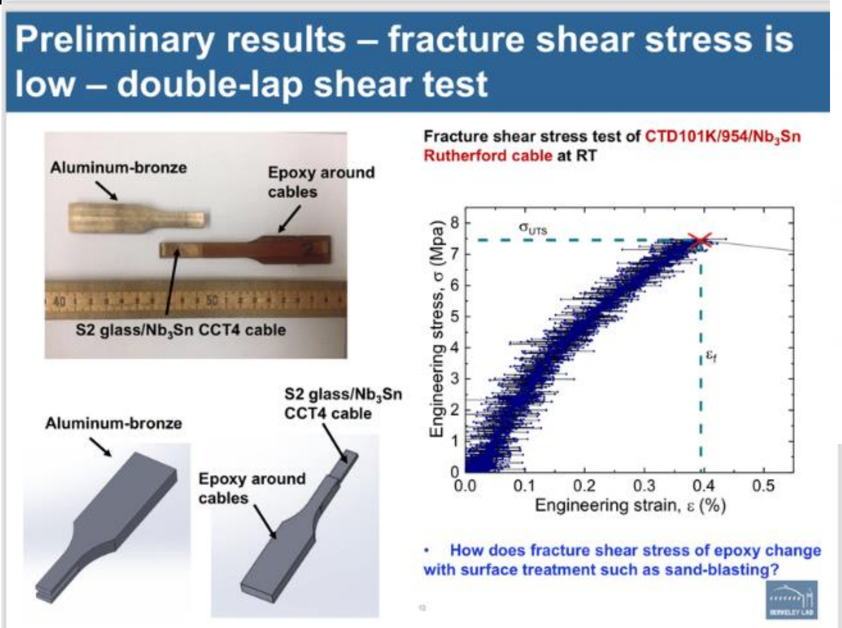
Yield < 400 MPa (40 MPa in former)

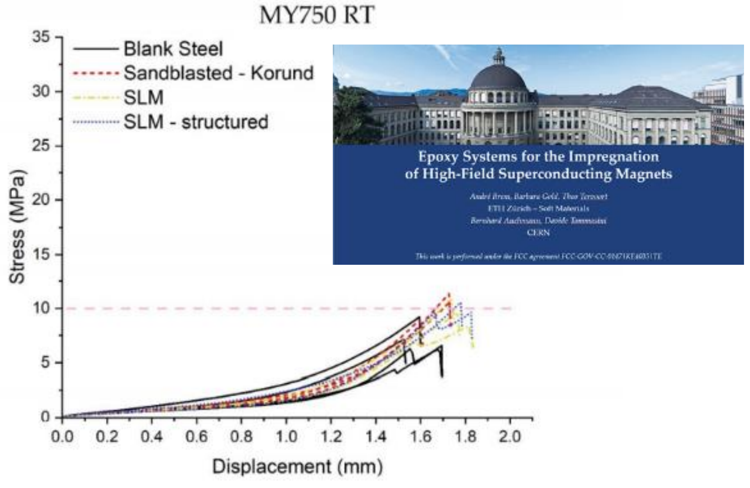
RRR Al >> Al-Bronze

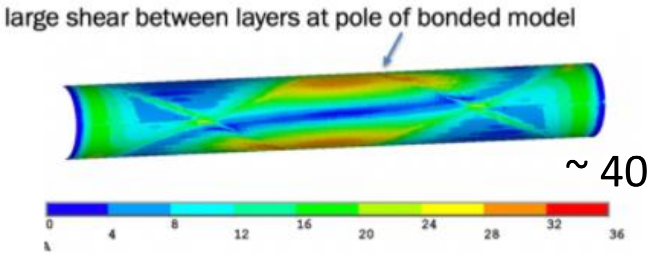
Fatigue lim >> operation point

Bond shear strength is very low



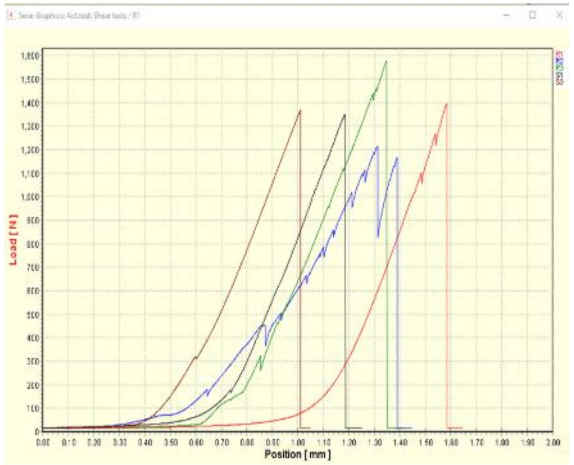






~ 40 MPa

CERN CCT Shear at 3 T ~ 2 MPa but that's not the problem, it's the resin



LBNL test Al-Bronze 7 Mpa
CERN shear tests Al anodized surface ~ 7 to 5 Mpa

Many papers report low values in the same range

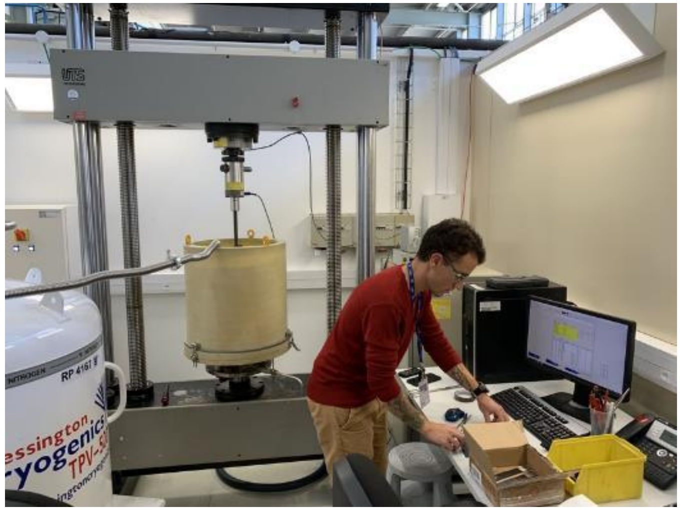
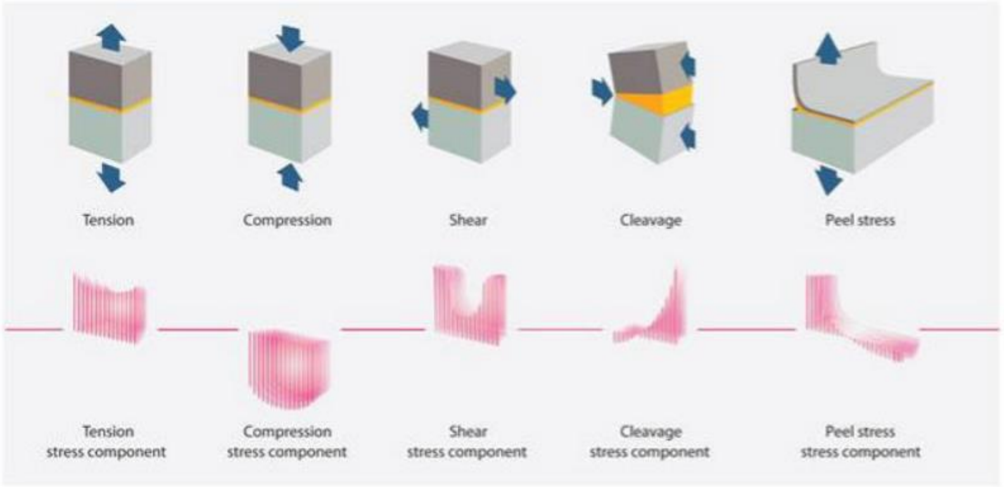
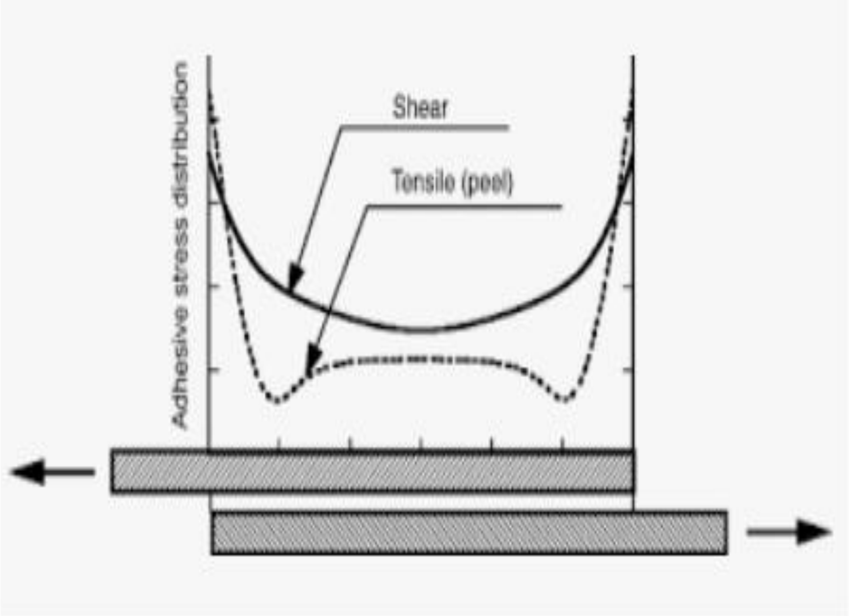


Fig.3 Loading conditions

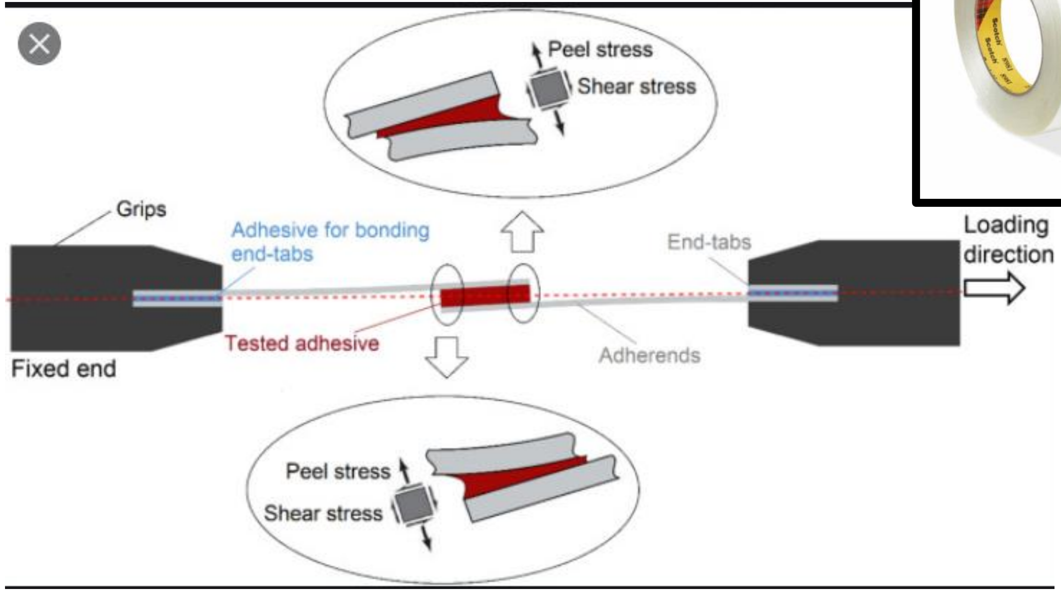


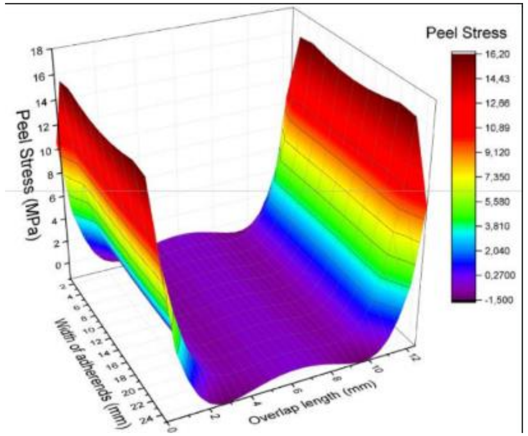
A bonded joint can be loaded in five basic ways (as shown in the diagrams above). Cleavage and peel loading are the most severe as they concentrate the applied force into a single line of high stress. In practice, a bonded structure has to sustain a combination of forces. For optimum strength, the bonded assembly should be designed in such a way as to avoid cleavage and peel stresses.

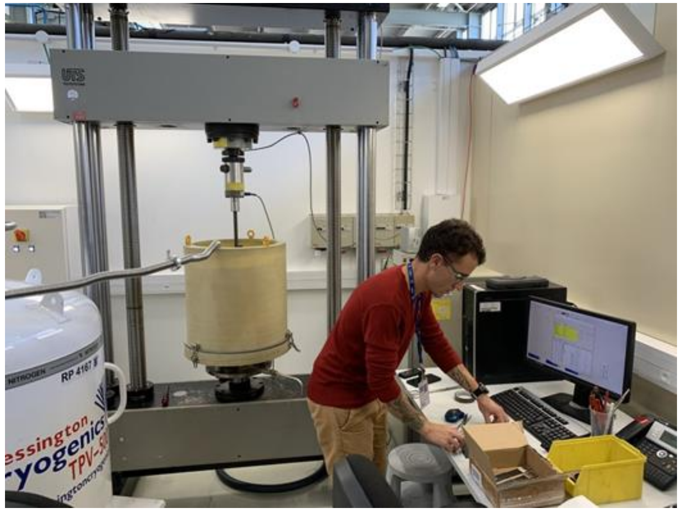
https://www.composites.media/huntsman-to-provide-advice-for-adhesive-bonding-applications/



https://inpressco.com/wp-content/uploads/2017/05/Paper1564-70.pdf







Bond -STRENGTH

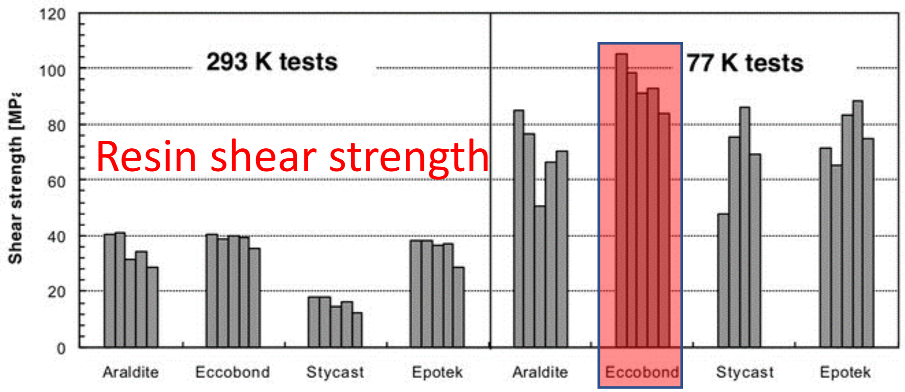


FIGURE 4. Results of the compression/shear tests at 293 K and 77K

strength which is about 15 MPa for these adhesives. Only the Stycast adhesive appears to have a significantly lower strength of 15.3 MPa. Concerning the spread of the measured values, the Eccobond specimens show a significantly smaller relative deviation of 5%, while the other adhesives have all relative deviations between 12 % and 16 %.

At 77 K the average shear strength increases considerably with all values ranging between 70 MPa and 95 MPa. While all adhesives show improved strength at 77 K, the Eccobond adhesive, with an average shear strength of 95 MPa produces joints with significantly higher strength than the other adhesives. The relative standard deviation of the measured shear strength at 77 K is the same as the ones obtained at room temperature. The value of 8 % obtained with the Eccobond adhesive is also significantly lower than the value measured with the other adhesives.

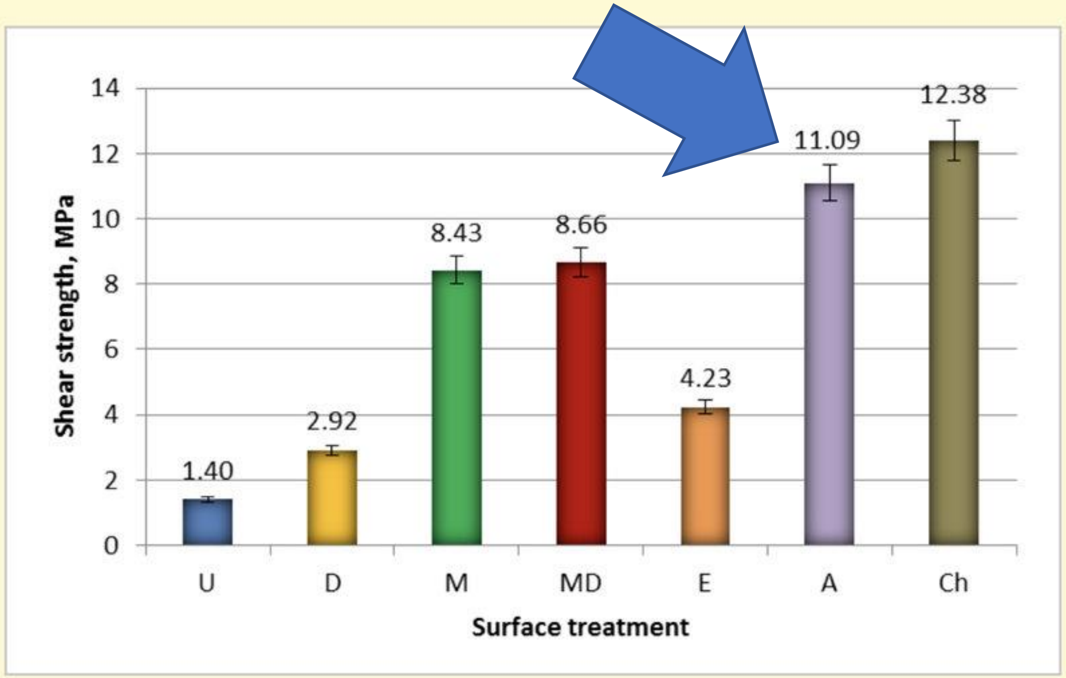


Figure 2.

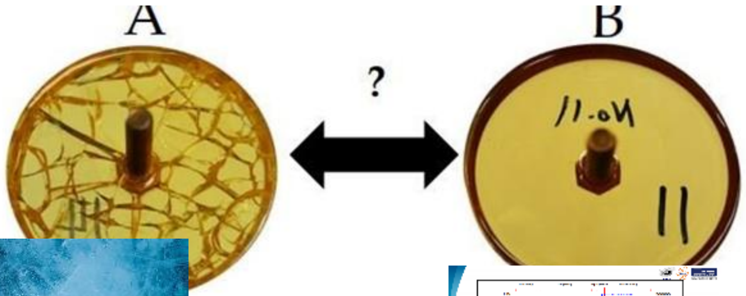
Shear strength tests of EN AW-2024PLT3 aluminium alloy sheet adhesive joints after different surface treatment methods: U - untreated, D - degreasing (chemical cleaning), M - mechanical treatment, MD - mechanical treatment and degreasing, E - etching A – anodizing, Ch - chromate treatment

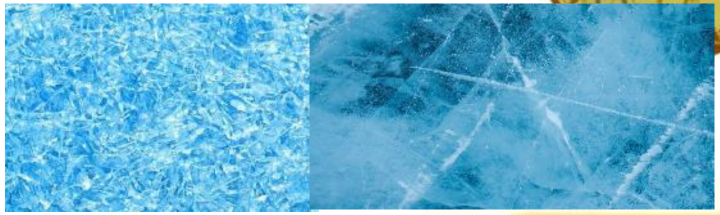
Impregnation ? What should we use?

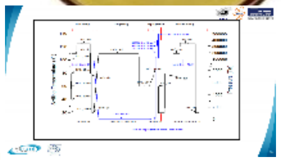
We use CTD101K because we follow the USA development its qualified for radiation.

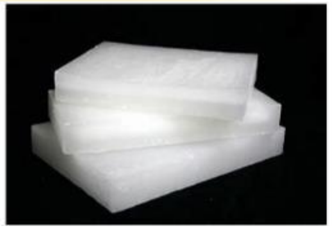
BUT I have other ideas we could try:

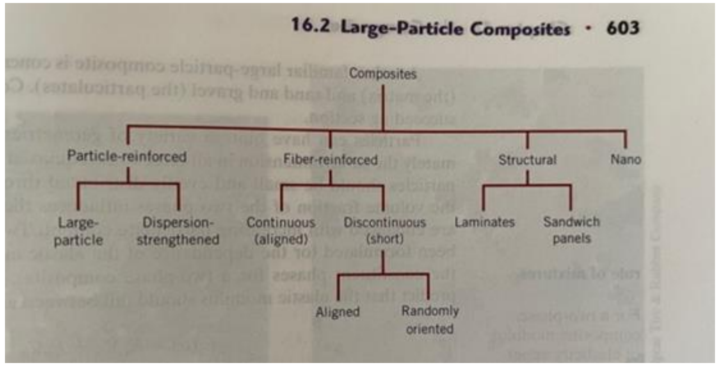
1) MY750 a much tougher resin. 12 mm/m
2) Amorphous-Water expands
3) Bee's wax
4) Paraffin wax
5) Teflon coated former, no impregnation-> Lh4
6) CTD101G thermal contraction 5 mm/m
7) Nano partials in resin need studying ?
8) Invar spacers to prestress?
9) Kevlar –ve thermal expansion………?

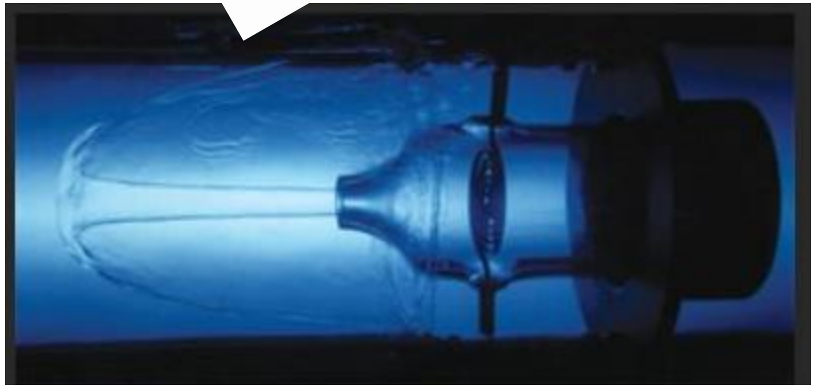




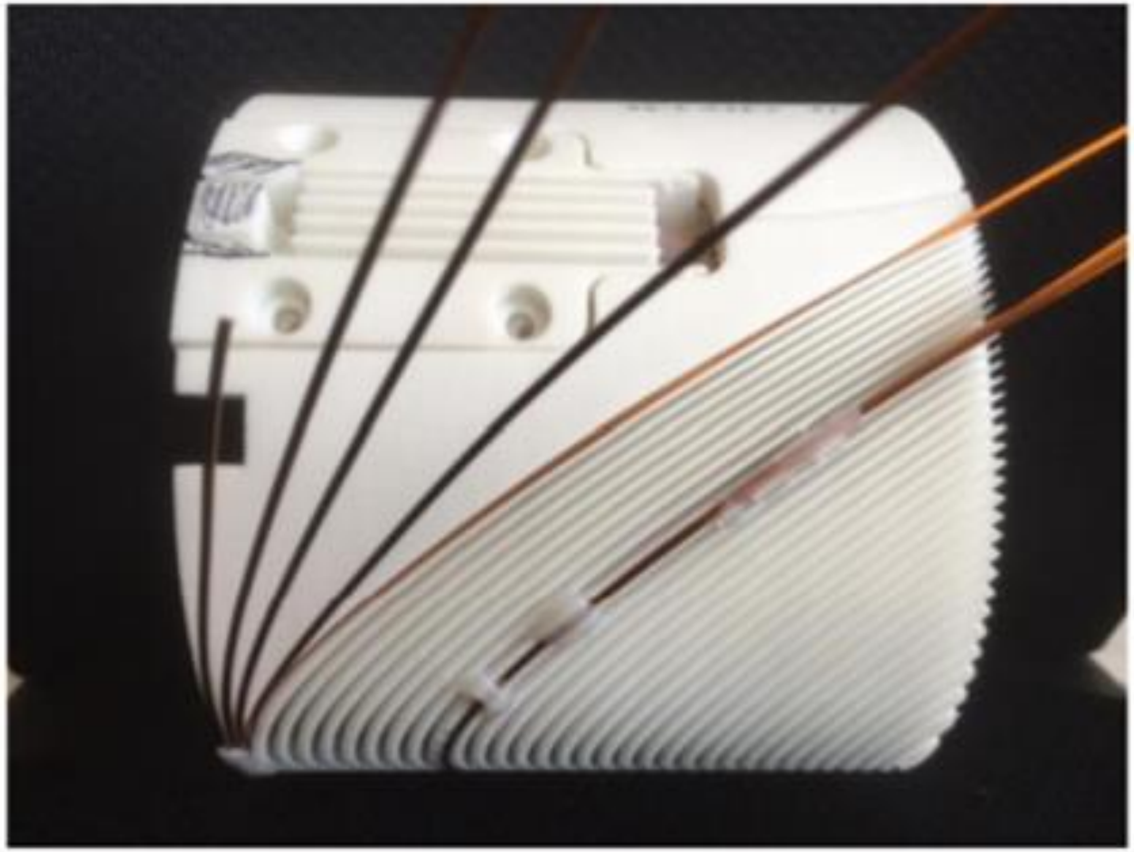






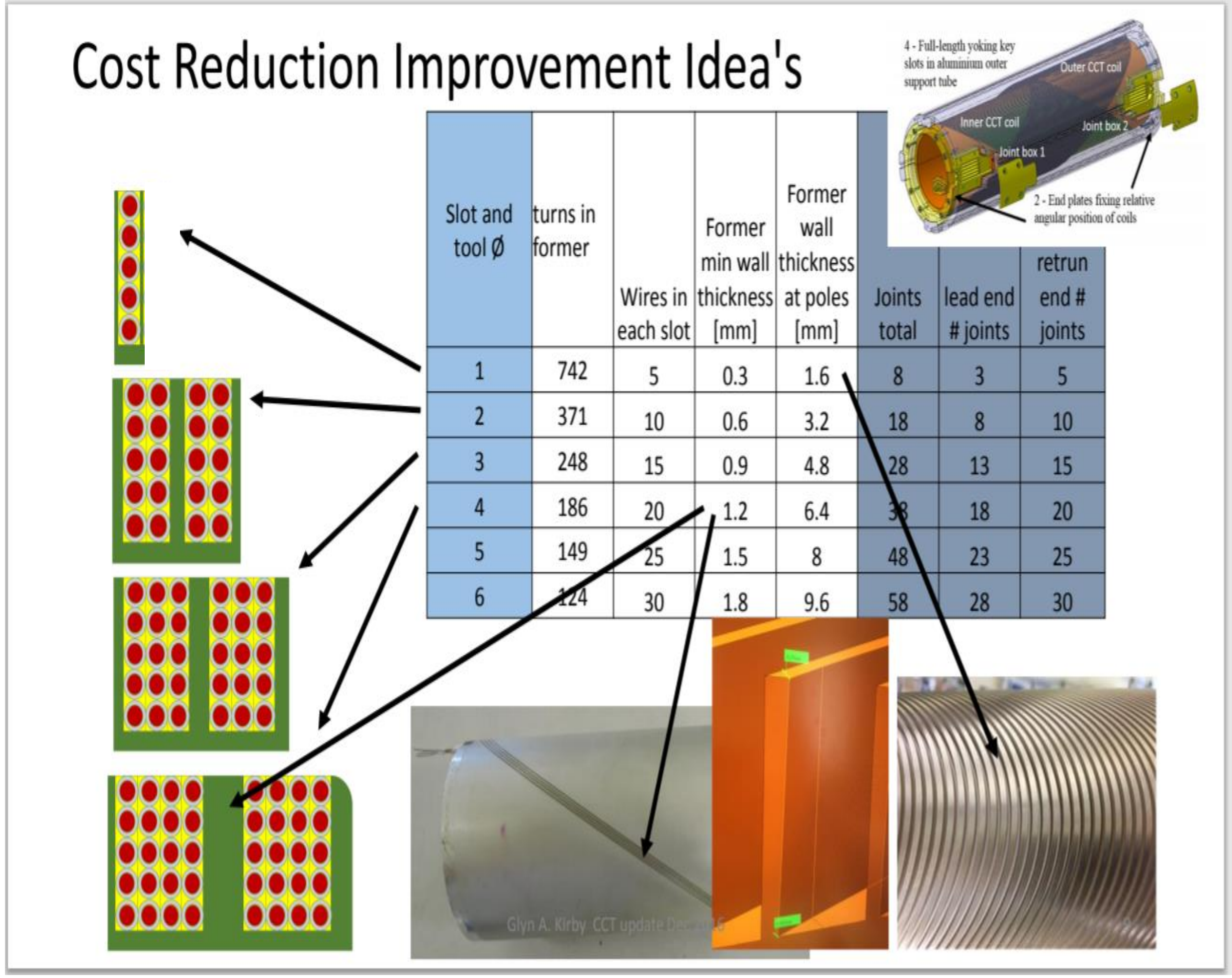


1st winding test with the rectangular wire
!!!!failed!!!

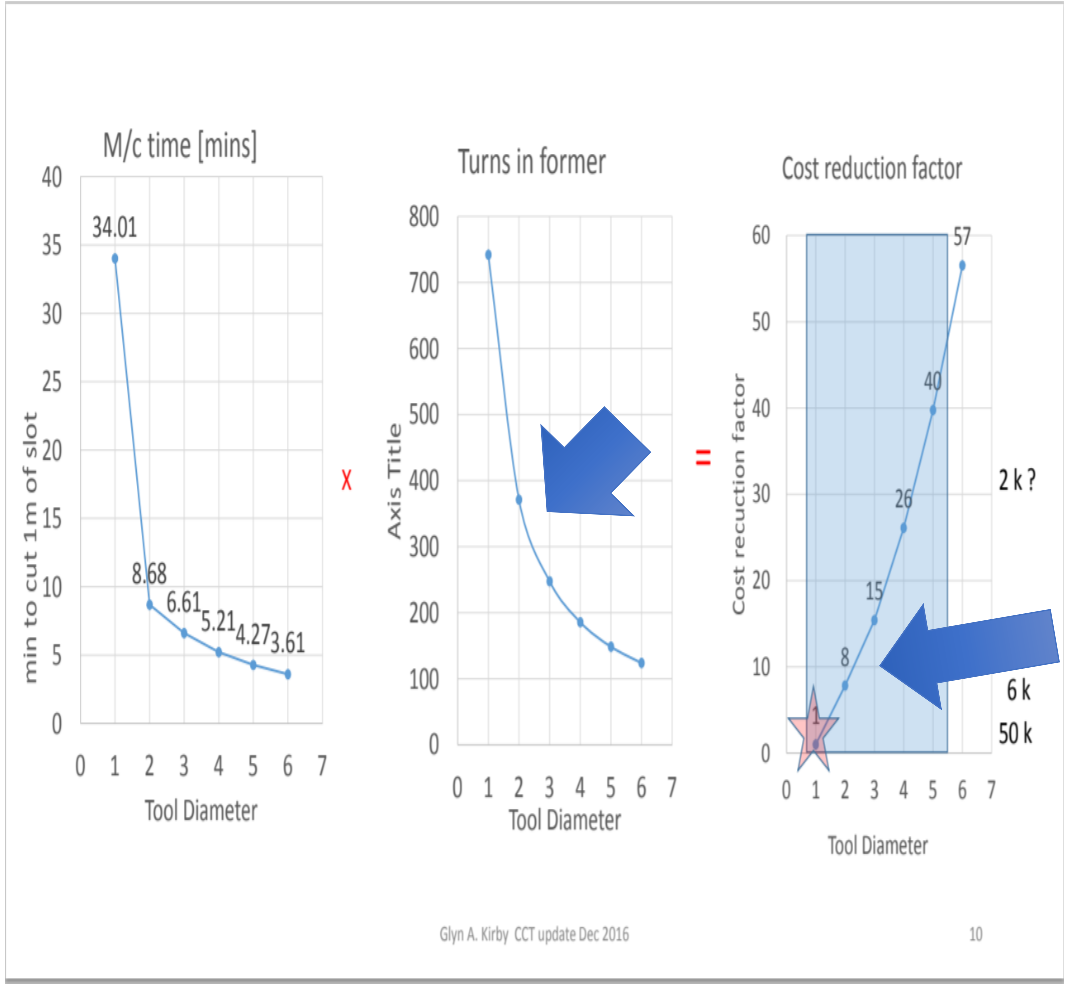


The enamel rectangular wire rotated as we tried to wind and finally was impossible to wind into the slot!

Machining 5 to 1 ratio limit



Slot and tool Ø	turns in former	Wires in each slot	Former min wall thickness [mm]	Former wall thickness at poles [mm]	Joints total	lead end # joints	retrun end # joints
1	742	5	0.3	1.6	8	3	5
2	371	10	0.6	3.2	18	8	10
3	248	15	0.9	4.8	28	13	15
4	186	20	1.2	6.4	38	18	20
5	149	25	1.5	8	48	23	25
6	124	30	1.8	9.6	58	28	30



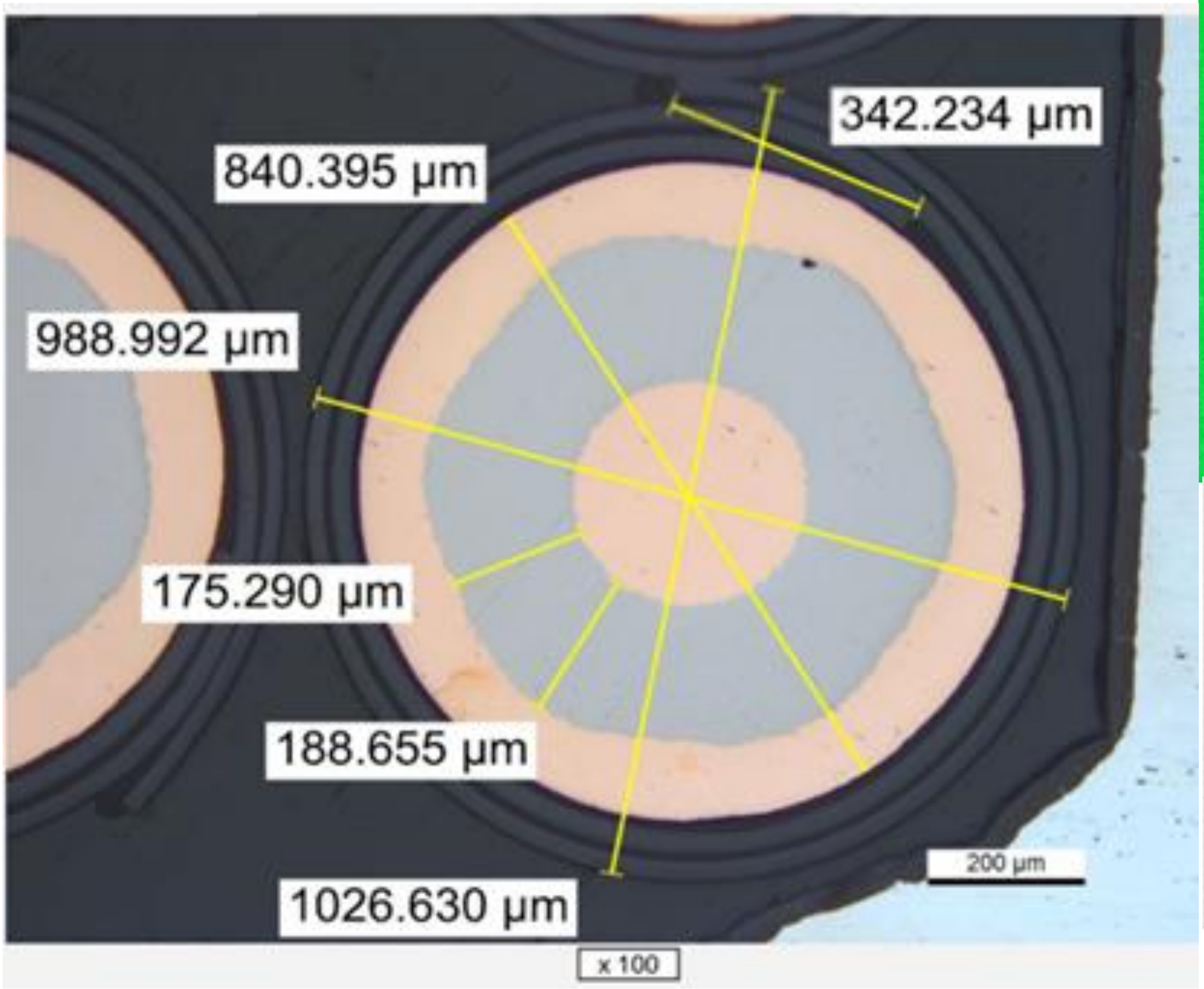
Costing is out of date! Much less now!

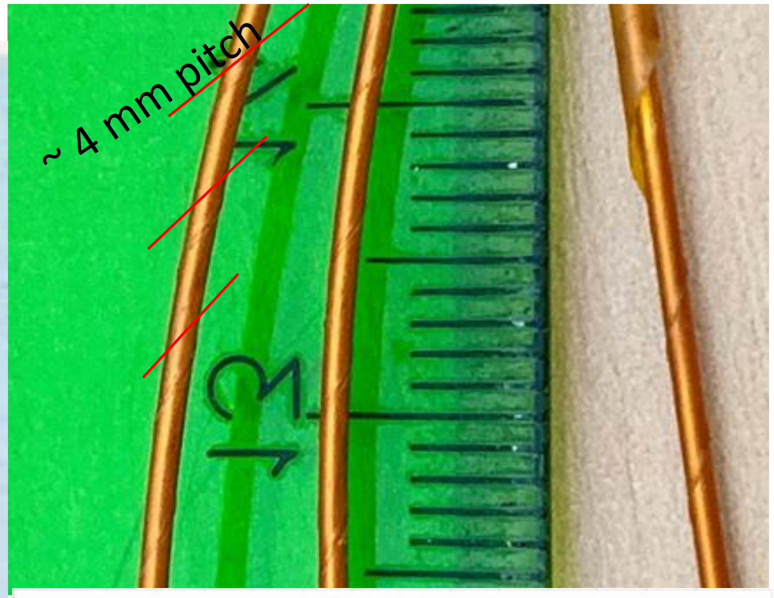
Wire insulation is key!

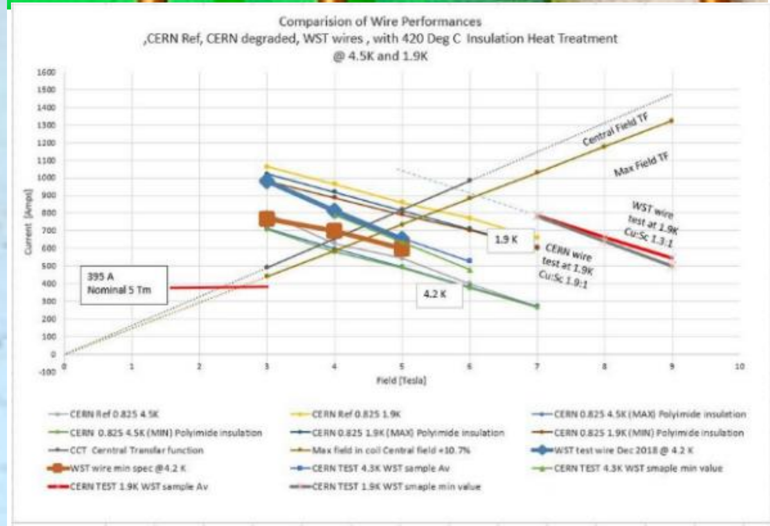
Wire insulation & Performance

55% overlap 2 layers + 3 layer spiraling spacer rib !

CERN 1.9:1
filaments 6 um
Prototype stock
CERN wire
Magnet SS 55%





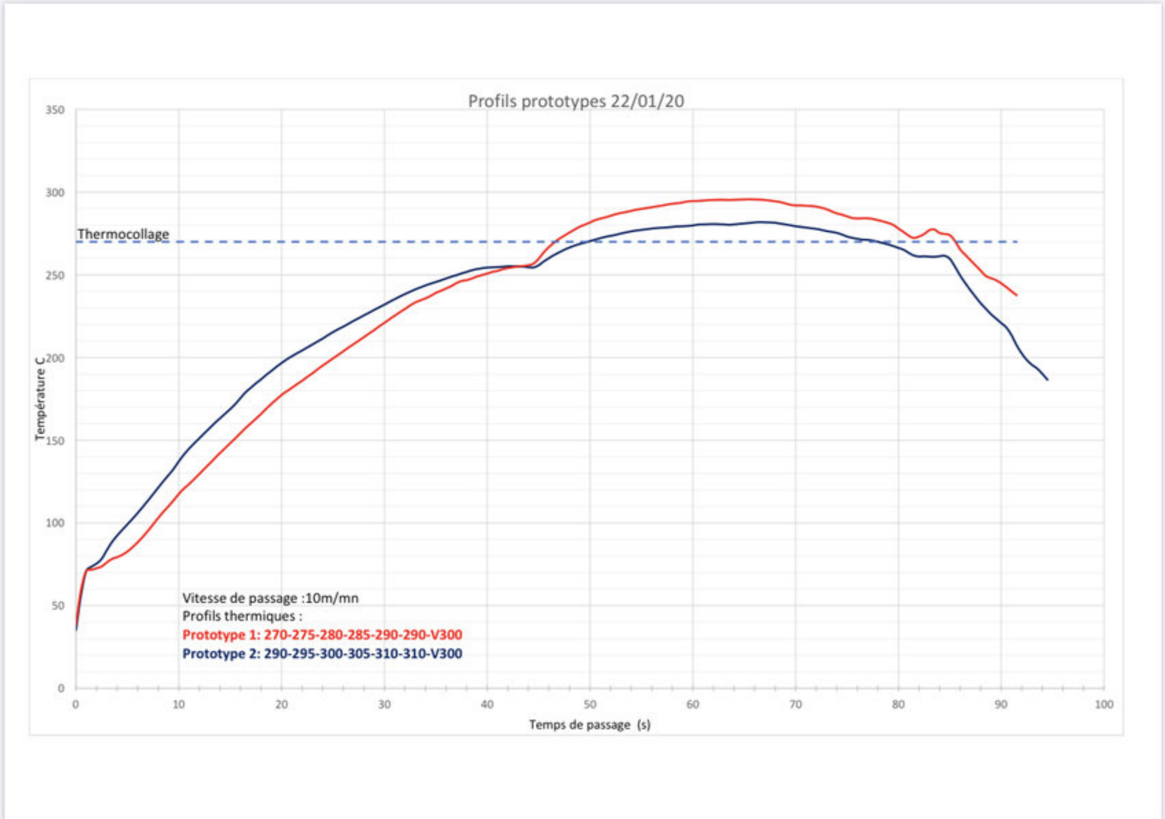


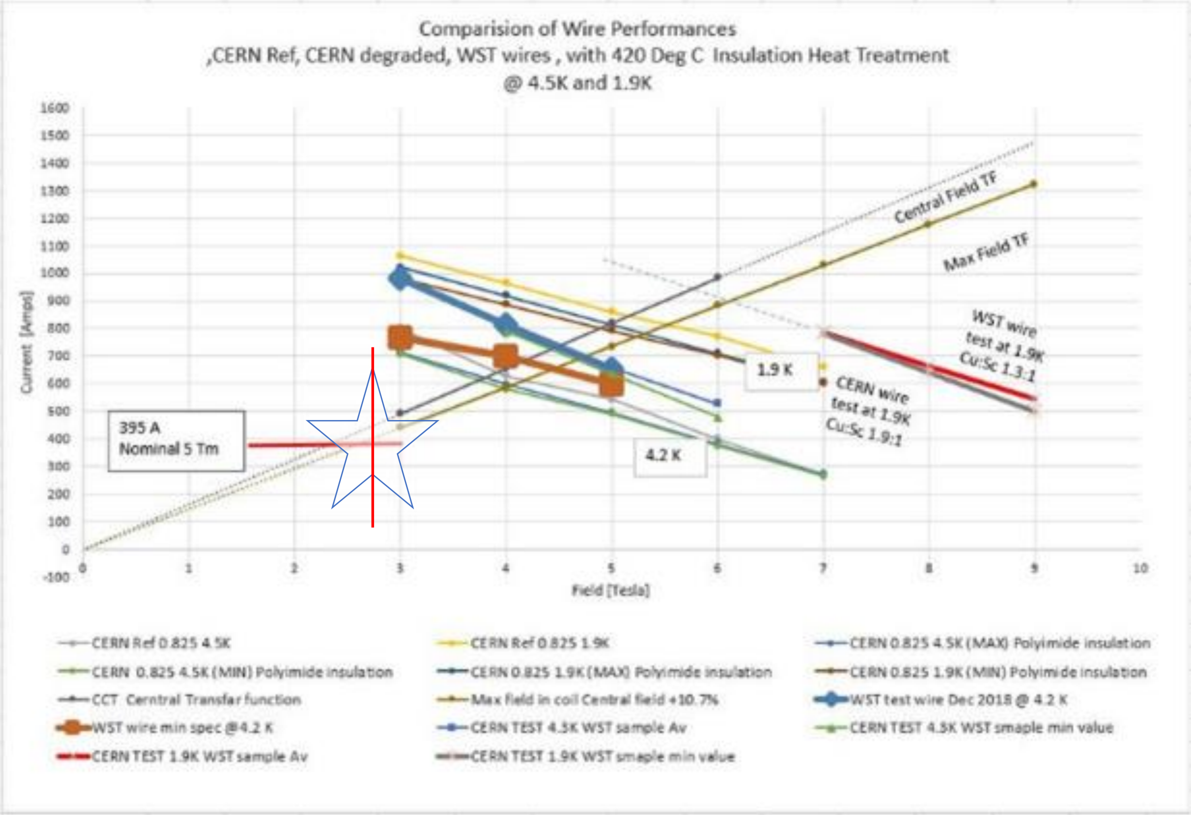
11kV wire insulation

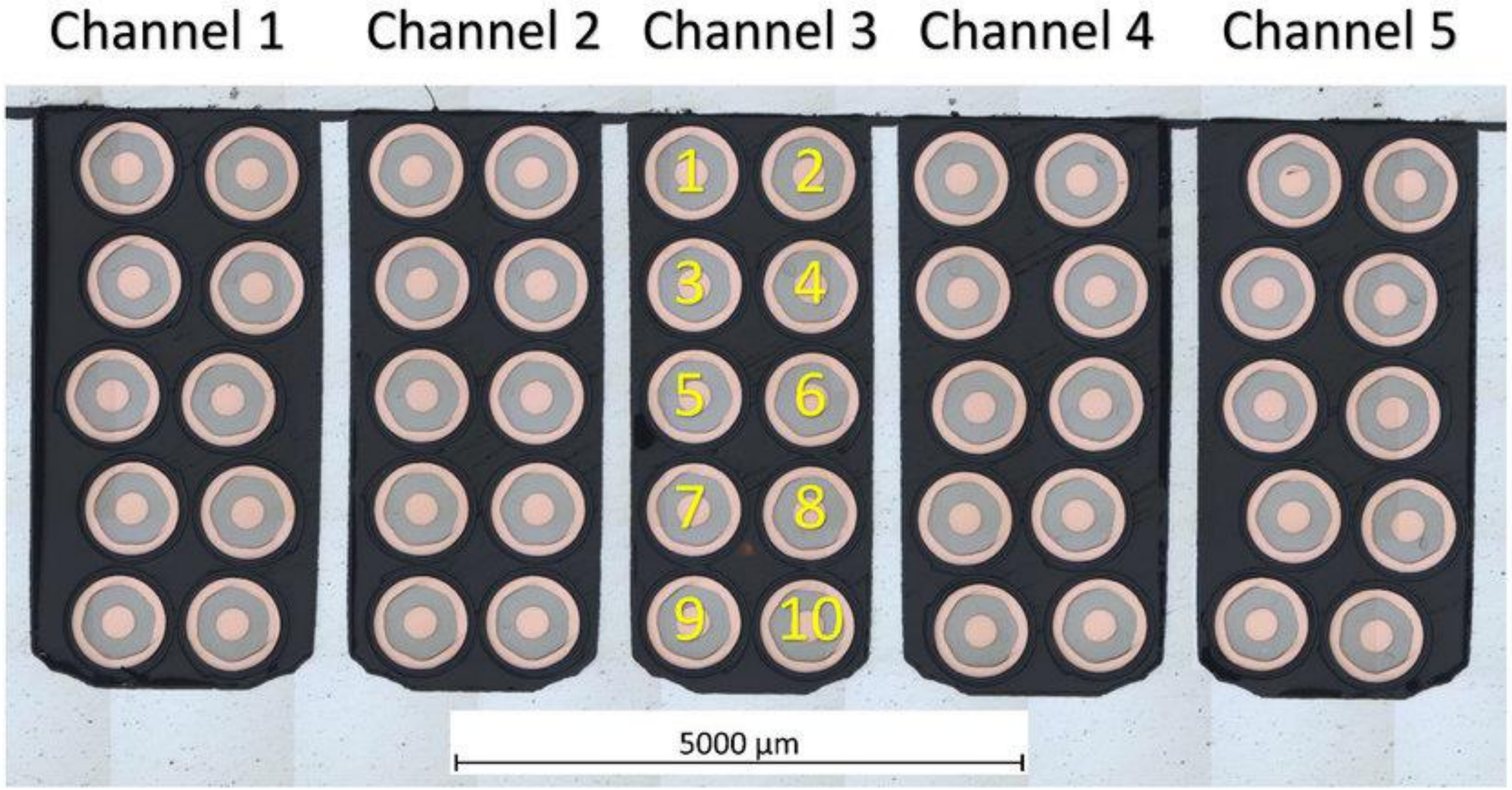
Strong bond to wire!

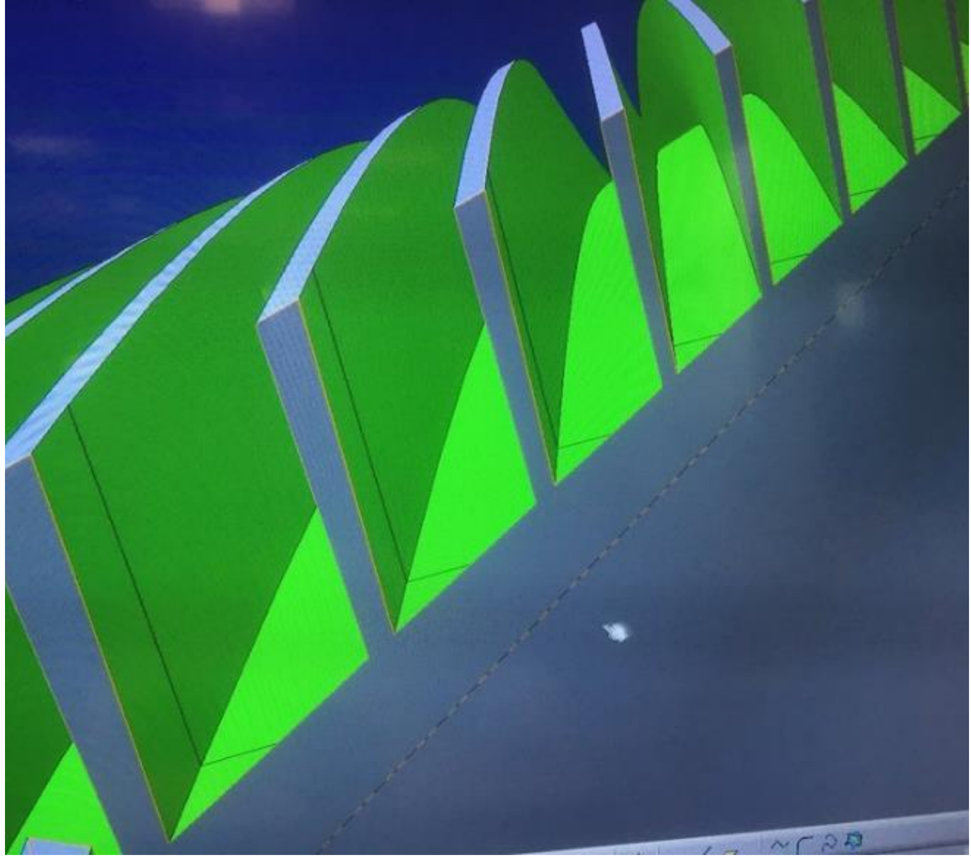
Bonding Polyimide into wire

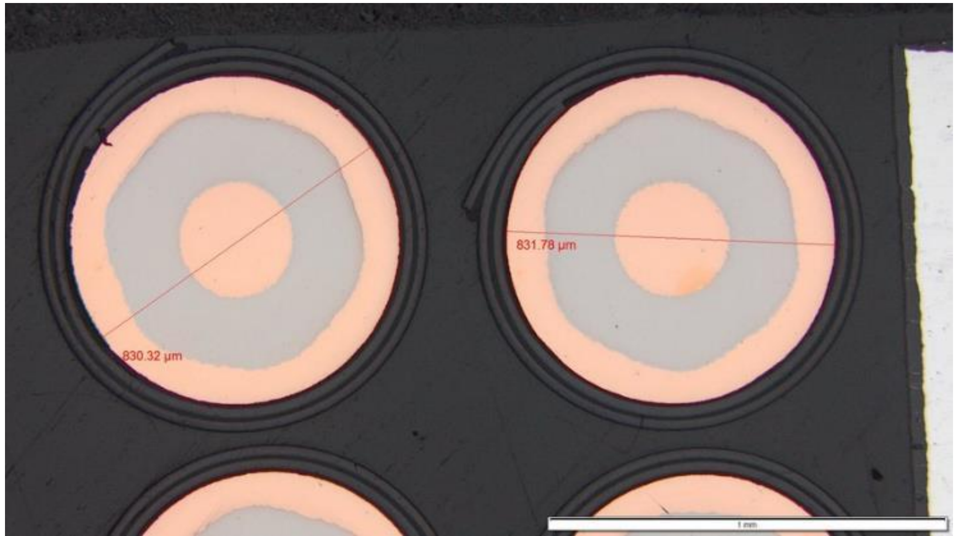
First tests bonded at 420C with 7% degradation but strong bond !
Later we reduce to 250 C no degradation but weak bond and insulation!
Final bonding 300C no degradation and strong bond!











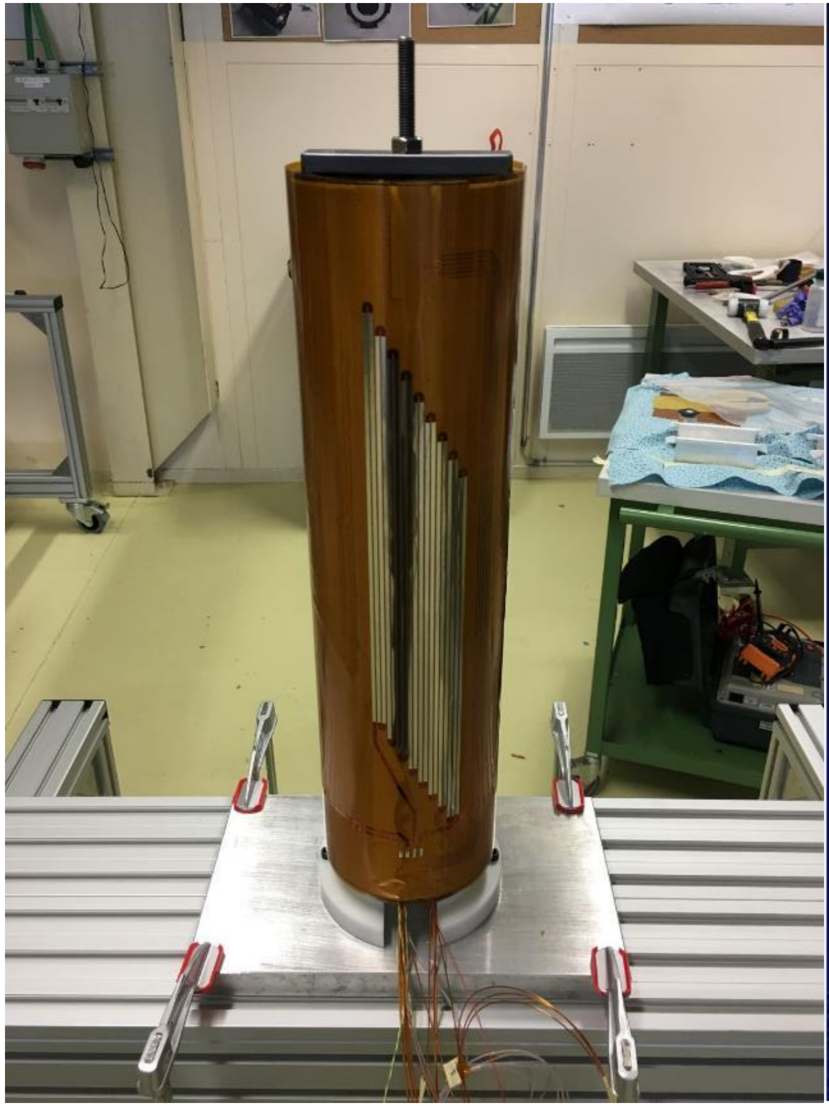
Set of test channels to find the best width.
we tested the min wall thickness, achieves 0.1mm but selected 0.3 mm

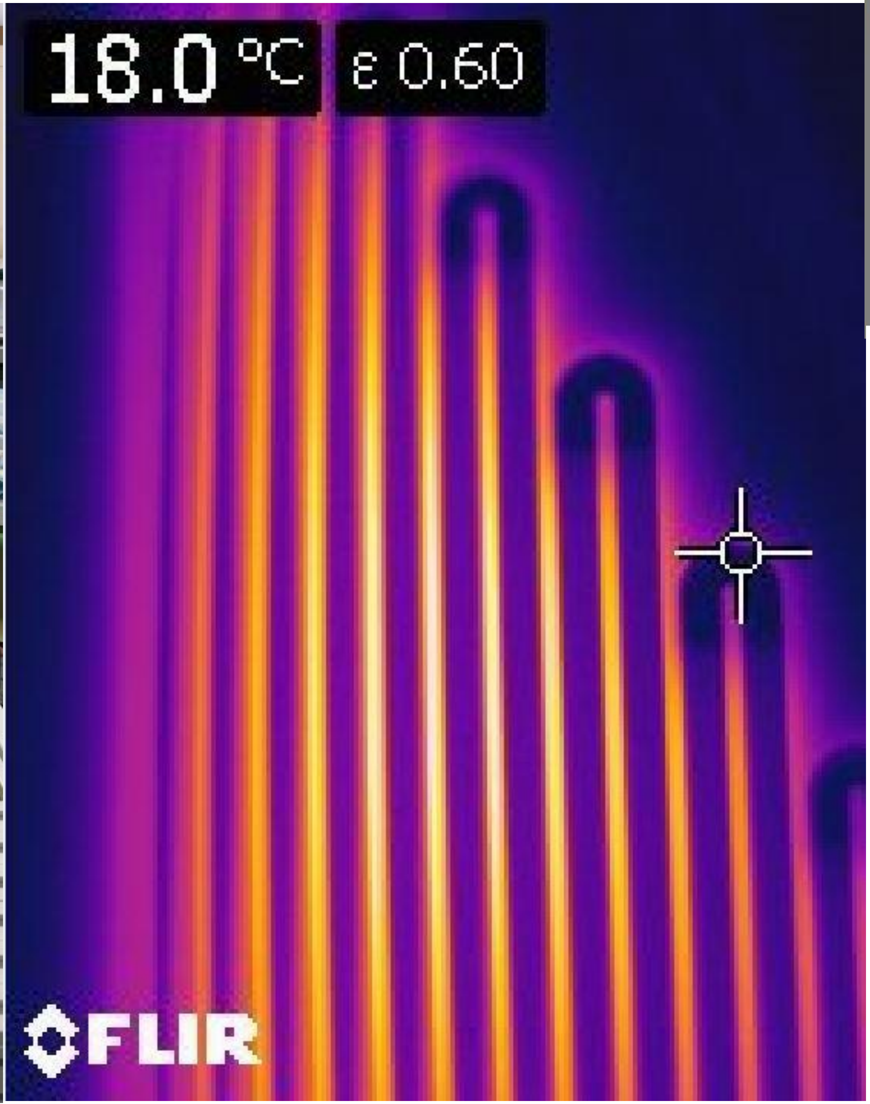
The depth of the channel 5:1 ration with width limit for M/c tools !

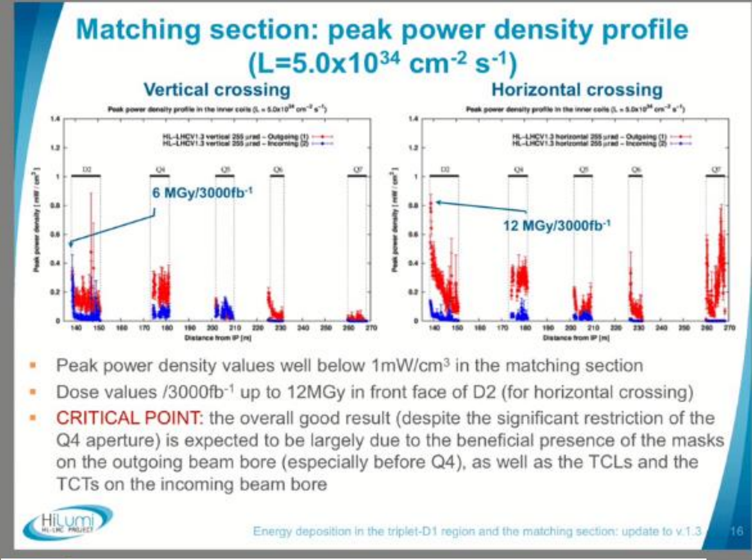
Beam simulation & heating test

Beam heating calc predicted increase the outer former above lambda 2.15K

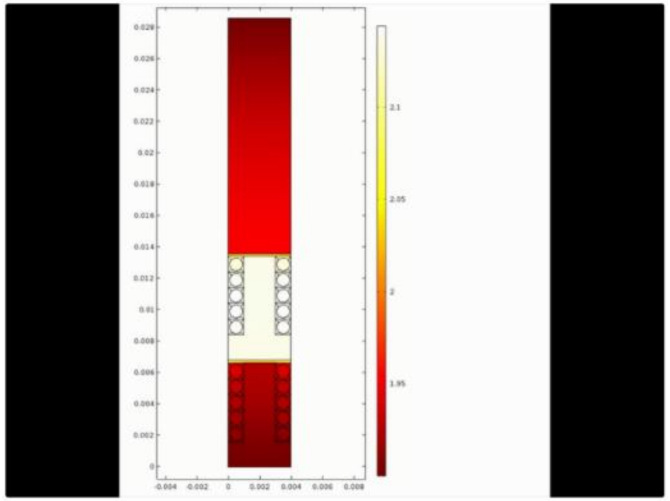
Cold heating injected 3 x the expected heat before quench! ;-) Tc







You May 18, 2017
added an update

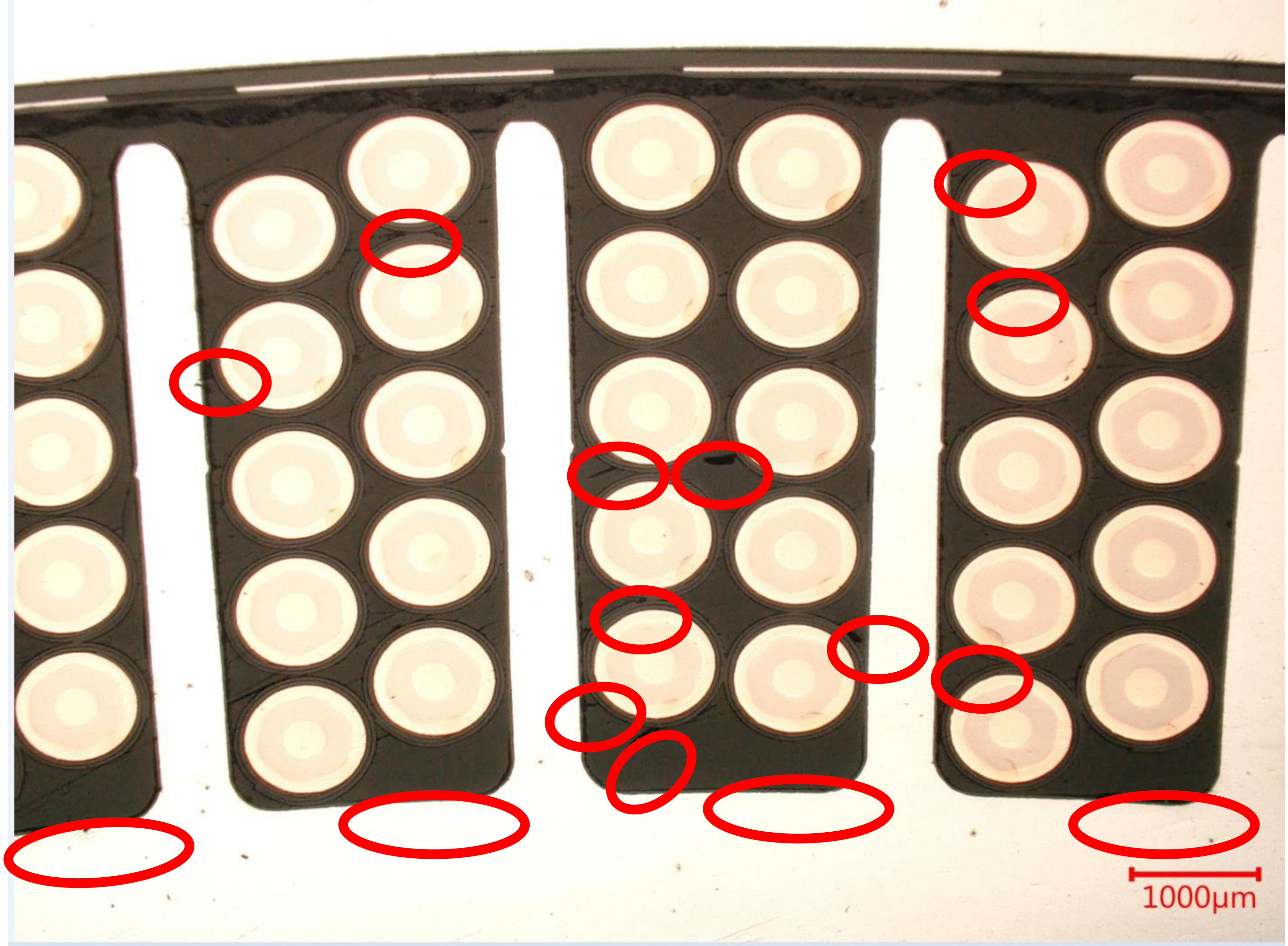


Heat load from radiation. 1 mW/cm^3 (1000 W/m^3) was applied to the full cross section and fixed the former boundaries (i.e. the interface with the helium) at 1.9 K.

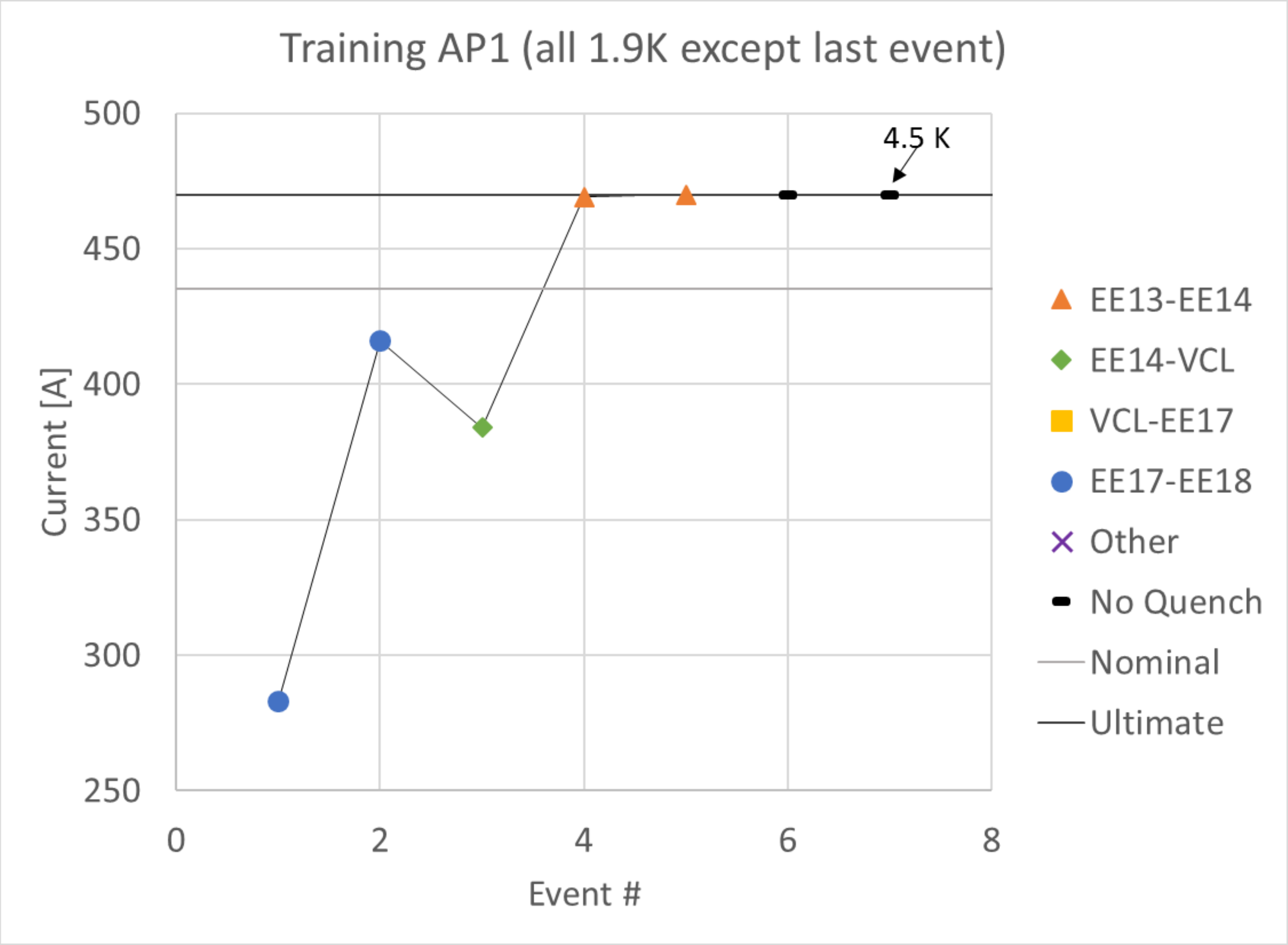
The result of this calculation is that the peak temperature is 2.15 K. This number is mainly determined by the thickness of the polyimide insulation separating the middle former from the innermost and outermost former. Here I assume a polyimide insulation thickness of 0.2 mm and a thermal conductivity of 0.0037 W/(m*K).

The heat load towards the helium is rather low; I find an average load of 14 W/m2, well below the Kapitza limit of 35000 W/m2.

to conclude the temperature in the coil will not increase above the lambda point. However boundaries are in perfect contact this may not be the case in the magnet.


1000µm

1st cold test quench performance



- Three quenches to nominal current
- Two last quenches within 1 A of ultimate current (in the decelerating ramp)
- No precursor in any quench
- Afterwards: held 2 h at ultimate current

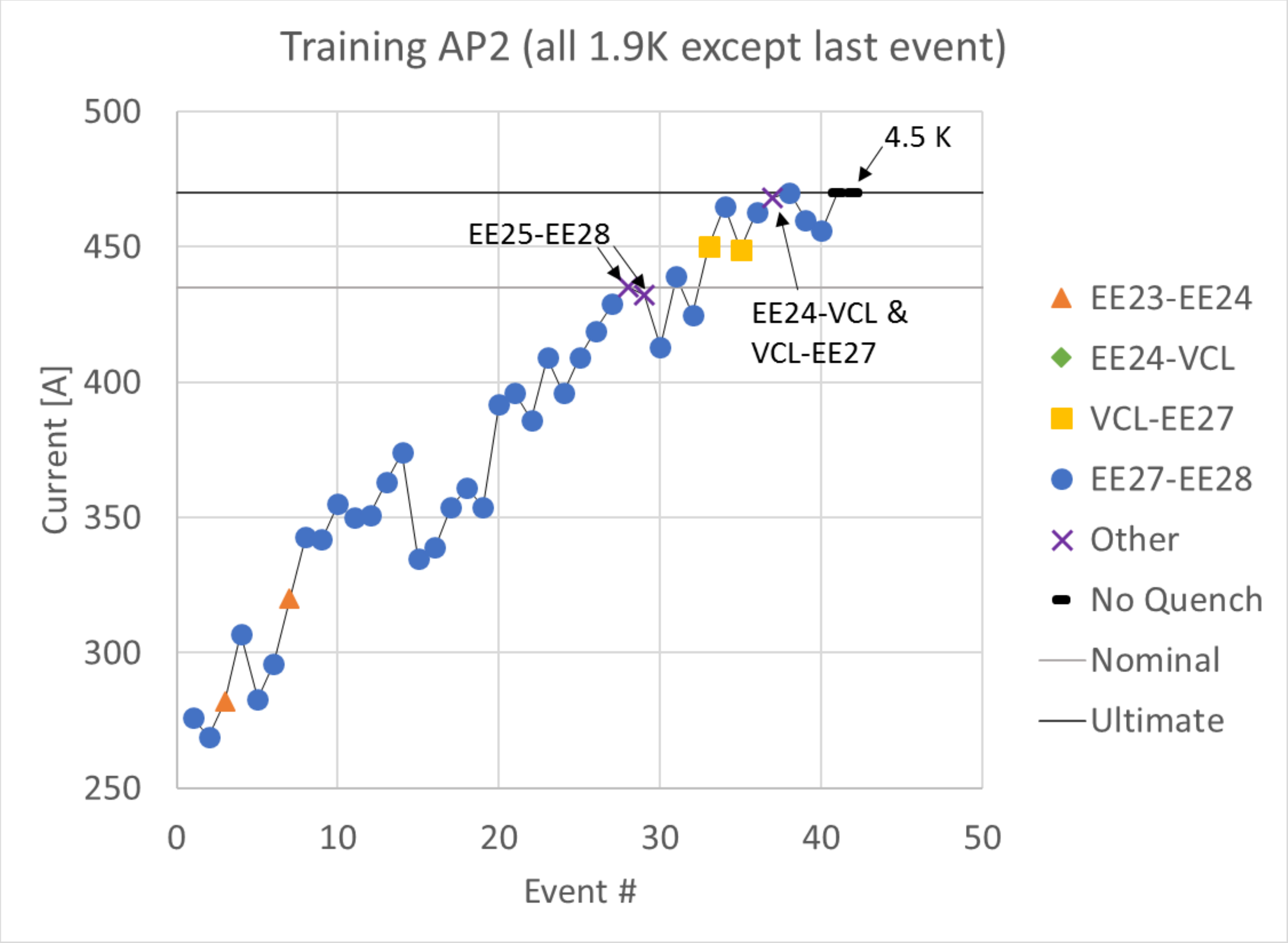
- Protection: first two quenches above maximum allowed QI (hotspot temperature ~350 K)
  - More on this later

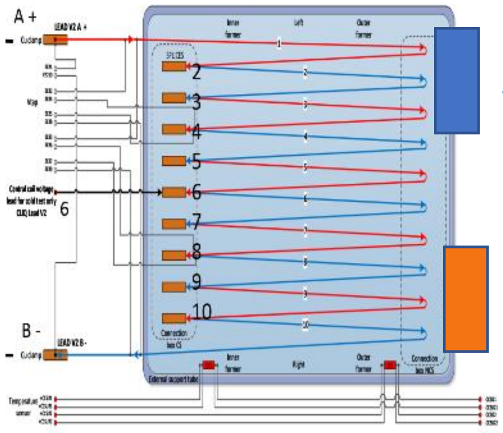
Shallow

Deep

CERN Training AP2 Blue

We can't separate the position inner and outer former quenches





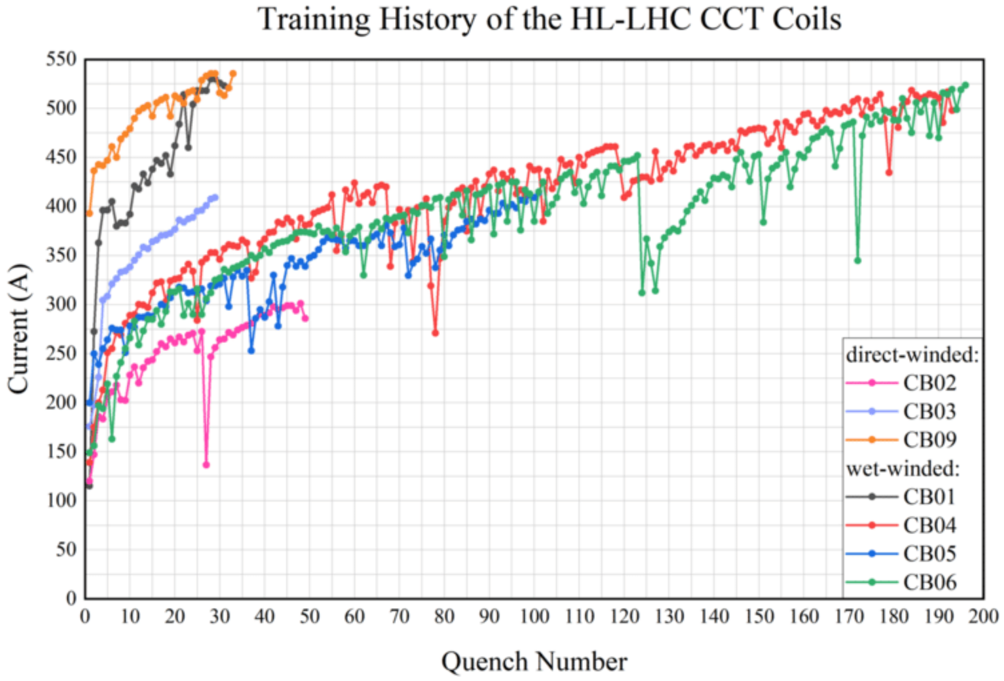
Shallow

Deep

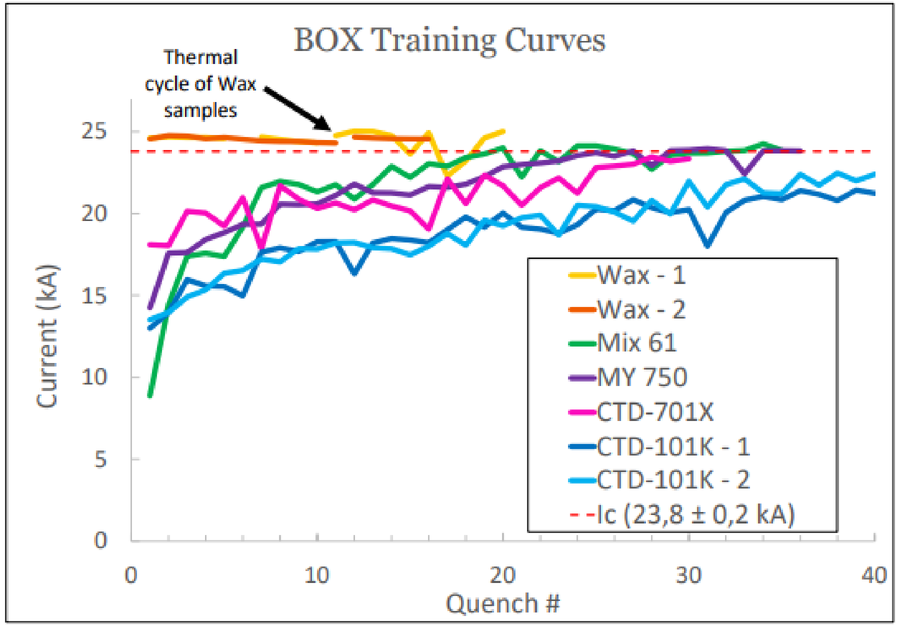
- Very long training, mostly on EE27-EE28
- After 32 quenches: no quench below nominal
- After 40 quenches training finished to ultimate current
- Held 2h at ultimate

- Quench #37 is symmetric

Quench training ! Superconducting magnets



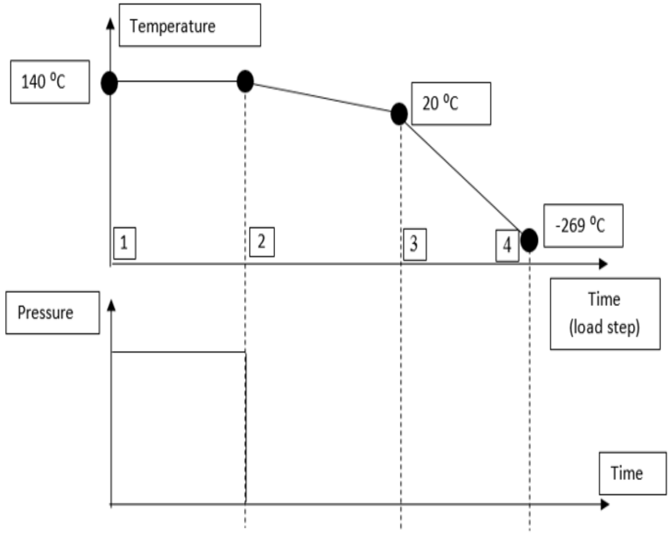
LTS quench with very low energy input



With low temperature superconductors, the magnet can QUENCH with the energy that is in a pin doped 10 mm any So small crack can trigger a quench!

What we need is an elastic support or very low friction! Tests with cold WAX have been very promising. My first every magent was potted in wax, and all ultra high field NMR 20 T + magnets use wax!

Stress in the channel   is it + or – ? principal stress?



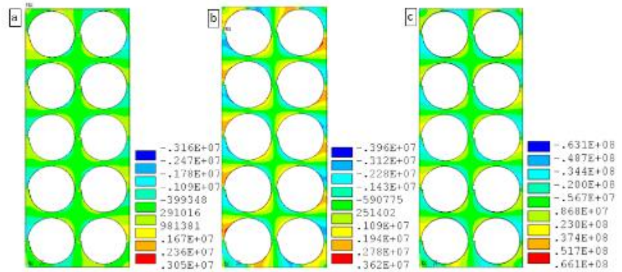


Figure 10. Shear stress in the resin: a) Step 2, b) Step 3, c) Step 4

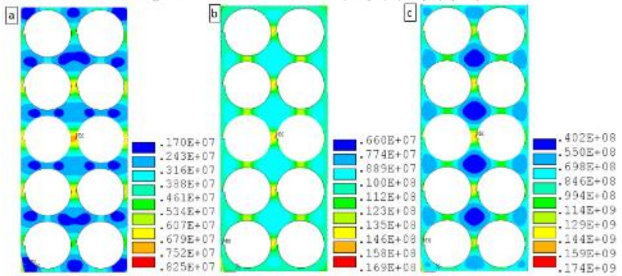
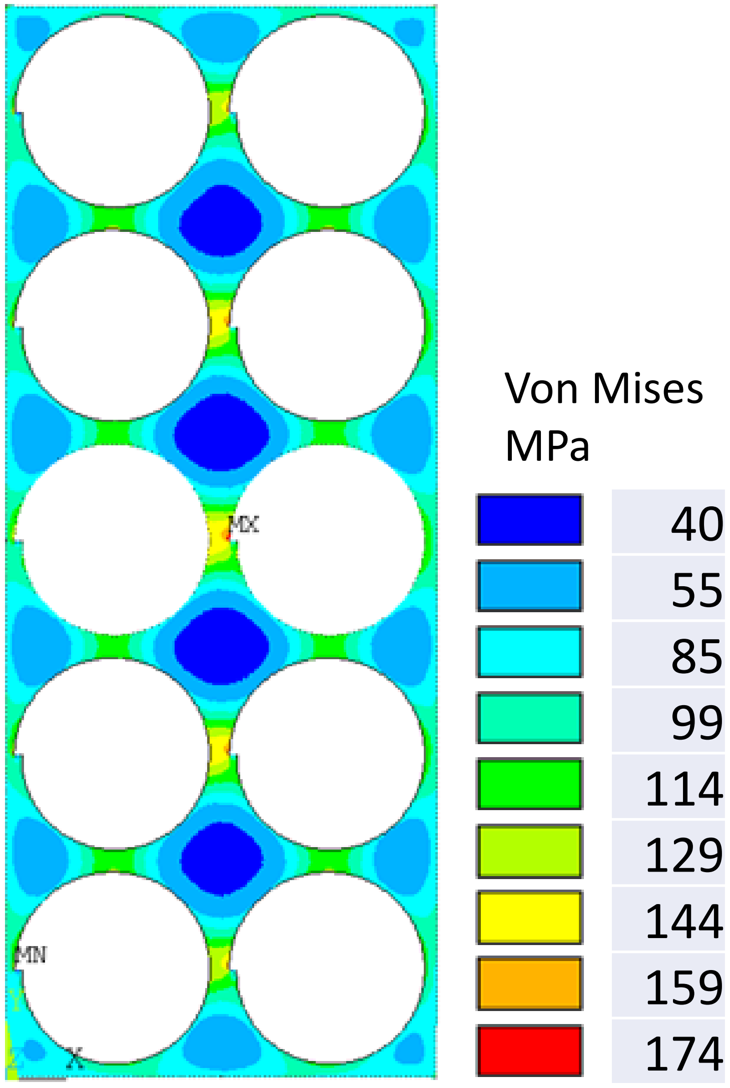
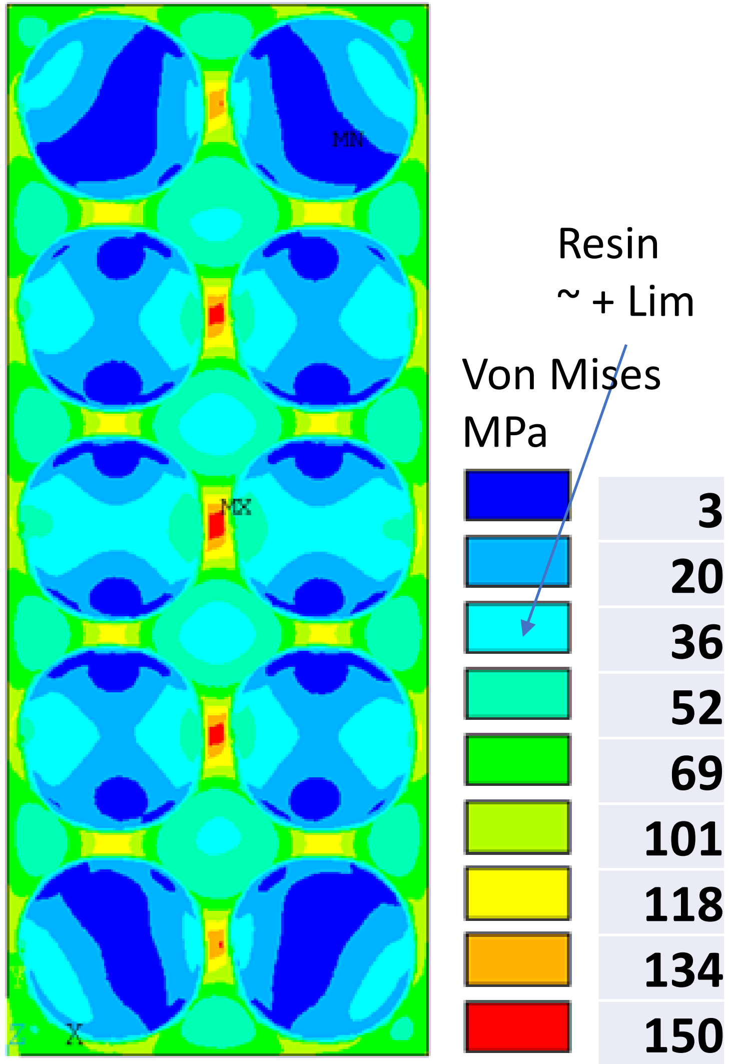


Figure 11. Von Mises stress in the resin: a) Step 2, b) Step 3, c) Step 4



Von Mises stress in the resin Mpa

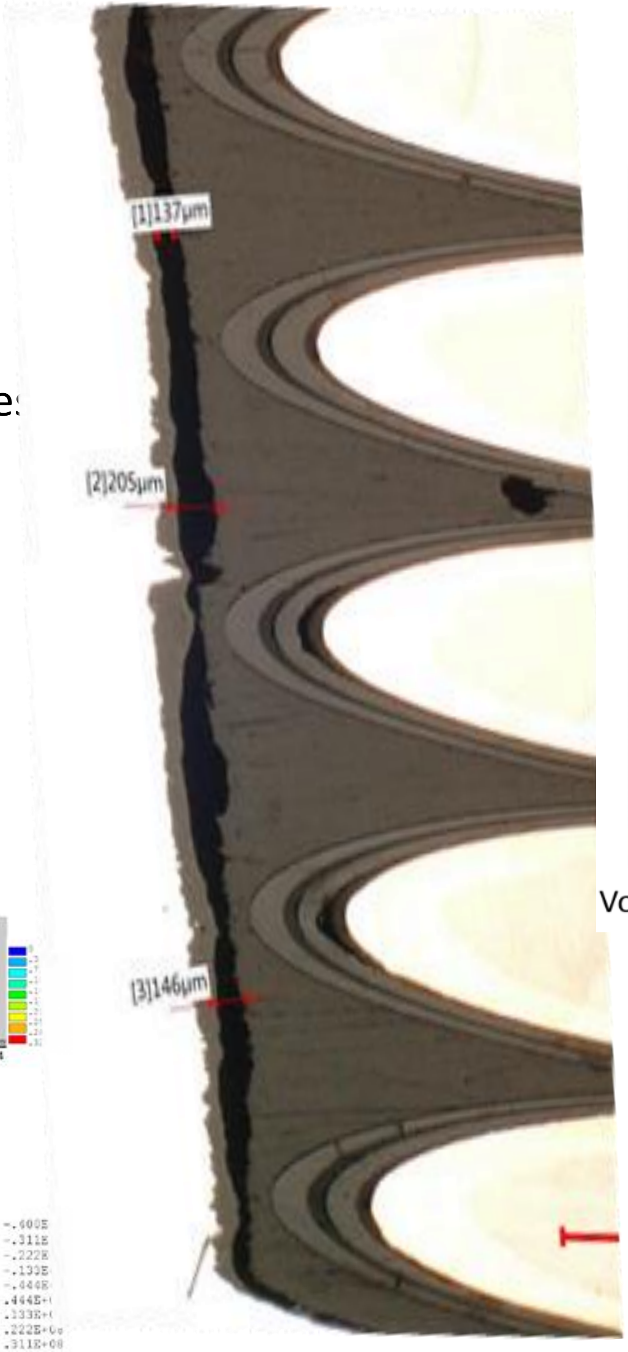


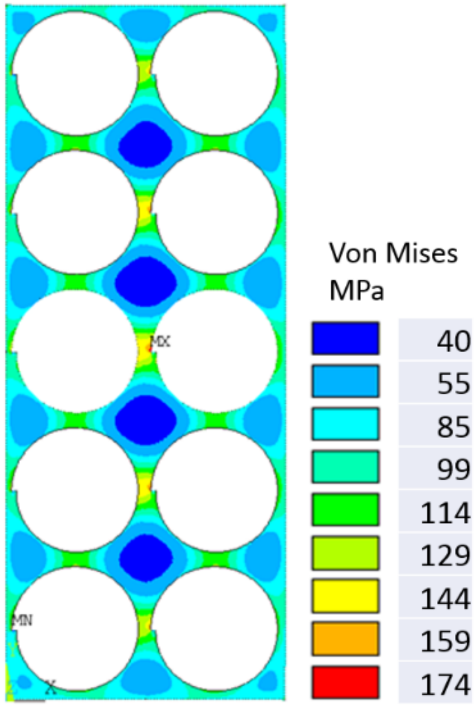
Von Mises stress in cross section

Free at the Wall

The bonds will brake at the surfaces of the insulated wire and at the walls with ~ 5 MPa in shear or 10 MPa tension.

At 4 K one side will has released. When the magnet is powered the other side brakes free, (quench?)





Von Mises stress in the resin Mpa

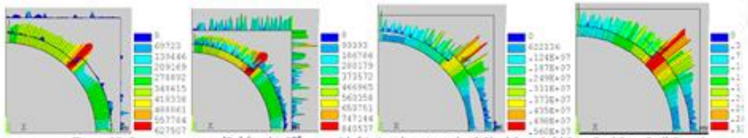


Figure 16. Contact pressure [Pa] for the 2nd case with frictional contacts (μ=0.3): a) Step 1, b) Step 2, c) Step 3, d) Step 4

The shear stress in the resin reached 7 MPa at the interface with Kapton at RT and up to 40 MPa at 4 K (Figure 17).

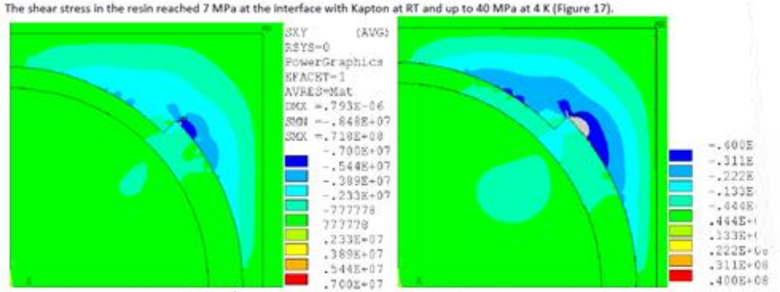


Figure 17. Shear stress ($\tau_{r\theta}$) in Pa for the 2nd case with frictional contacts (μ=0.3): a) after cool-down to RT (step 3), shear stress limited to ±7 MPa, b) after cool-down to 4 K (step 4), shear stress limited to ±40 MPa

Coil stress on channel after cooling down

After one-time thermal cycle

CTD101

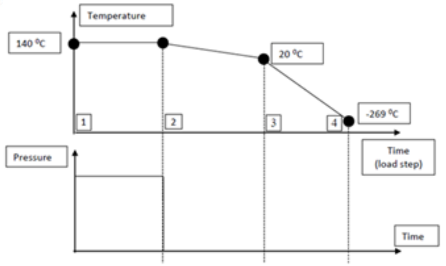
CTD101K 12 mm/m

CTD101K at 4K **150 Mpa to 4 MPa**

After one-time thermal cycle

Afte

CTD101K
With Powders



CTD101G 5 mm/m

CTD101G at 4K **47.5 Mpa to 6 MPa**

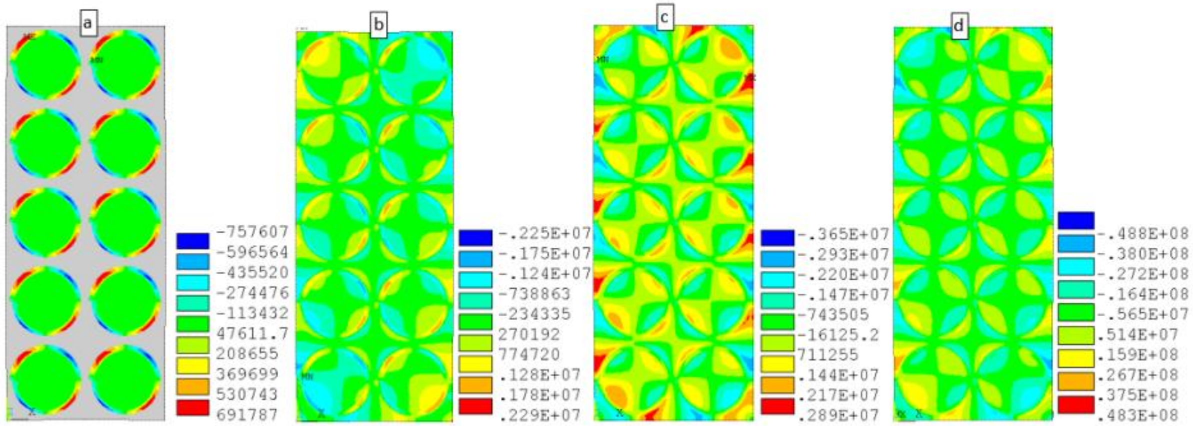


Figure 12. Shear stress in the strand, resin and Kapton: a) Step 1, b) Step 2, c) Step 3, d) Step 4

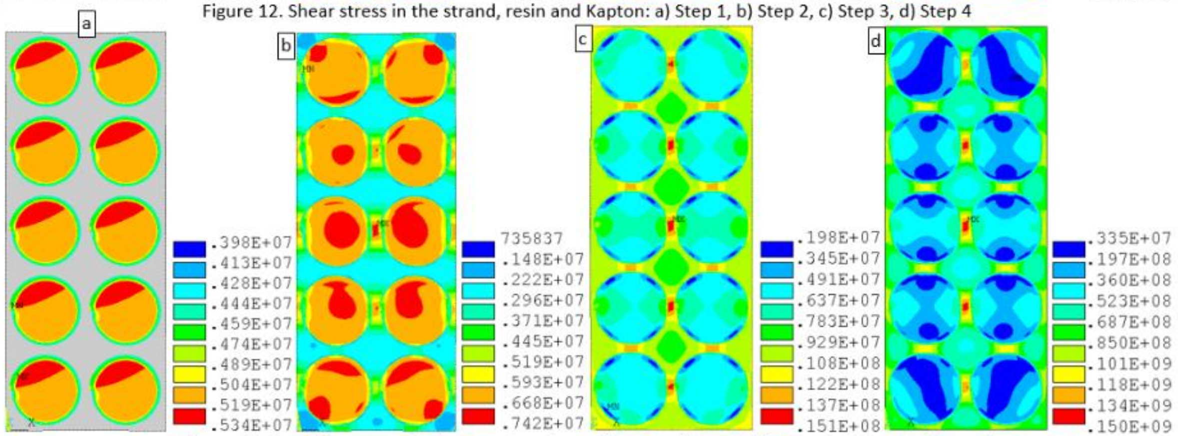


Figure 13. Von Mises stress in the strand, resin and Kapton: a) Step 1, b) Step 2, c) Step 3, d) Step 4

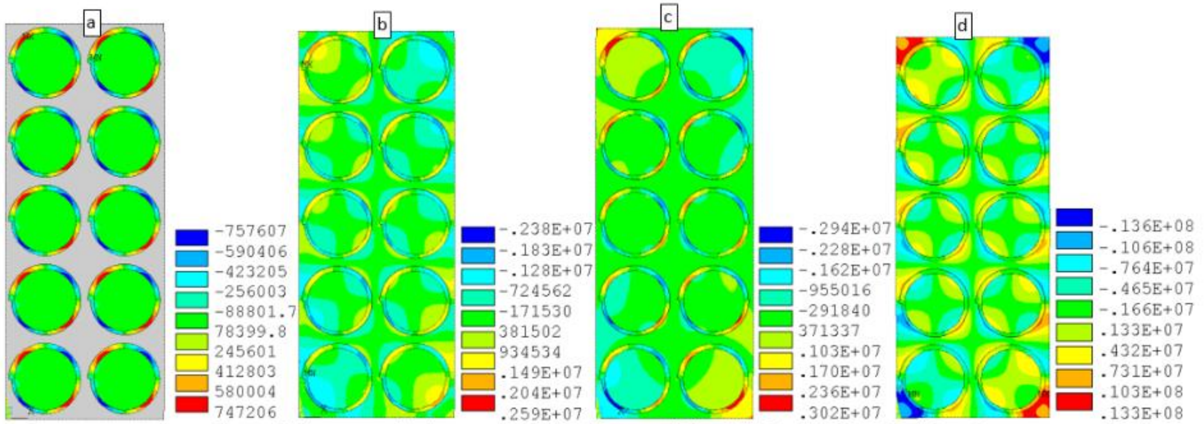


Figure 12. Shear stress in the strand, resin and Kapton: a) Step 1, b) Step 2, c) Step 3, d) Step 4

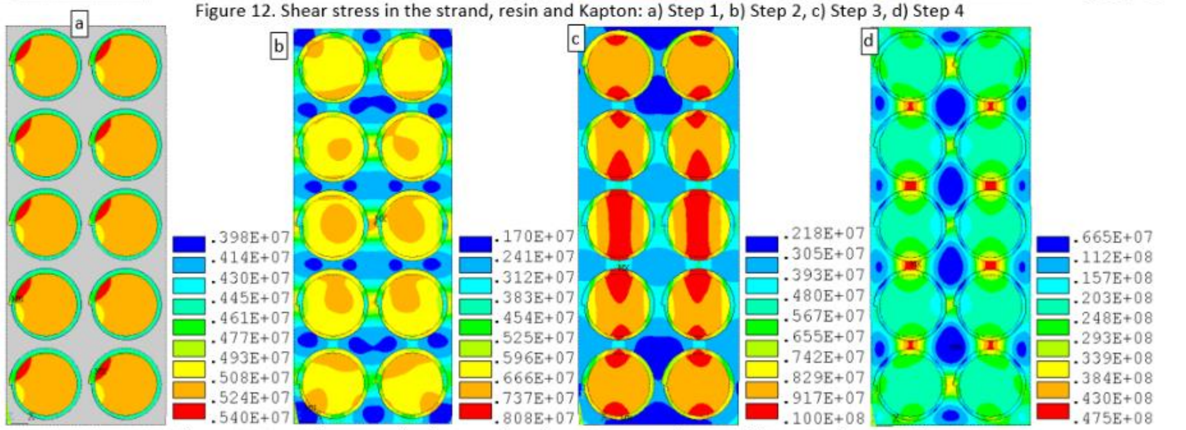
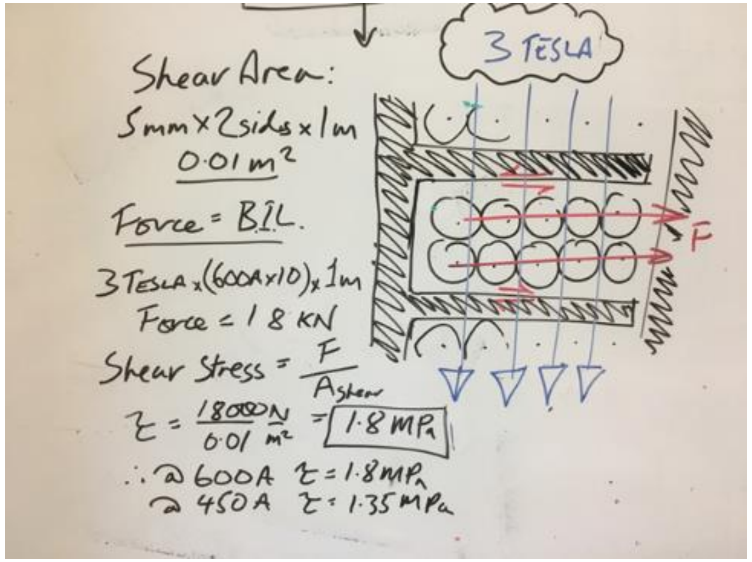


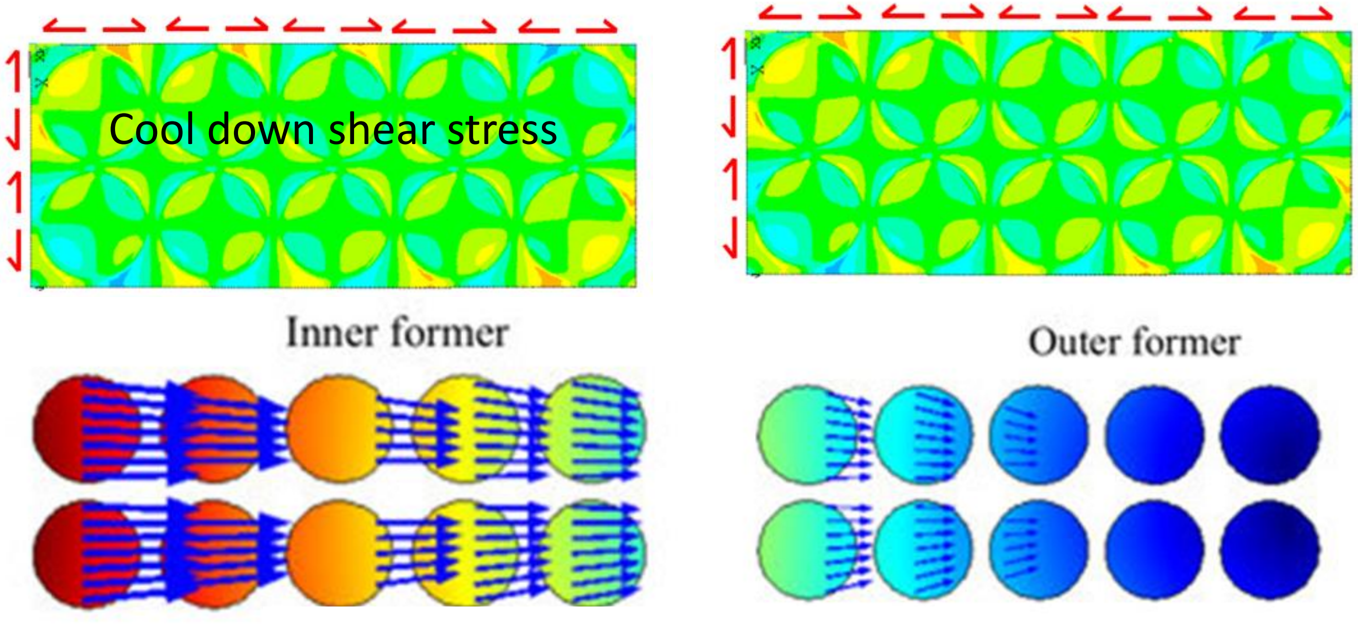
Figure 13. Von Mises stress in the strand, resin and Kapton: a) Step 1, b) Step 2, c) Step 3, d) Step 4

Internal forces

- Adding magnetic forces, give a small increase in stress, but its not uniformly distributed in the channel

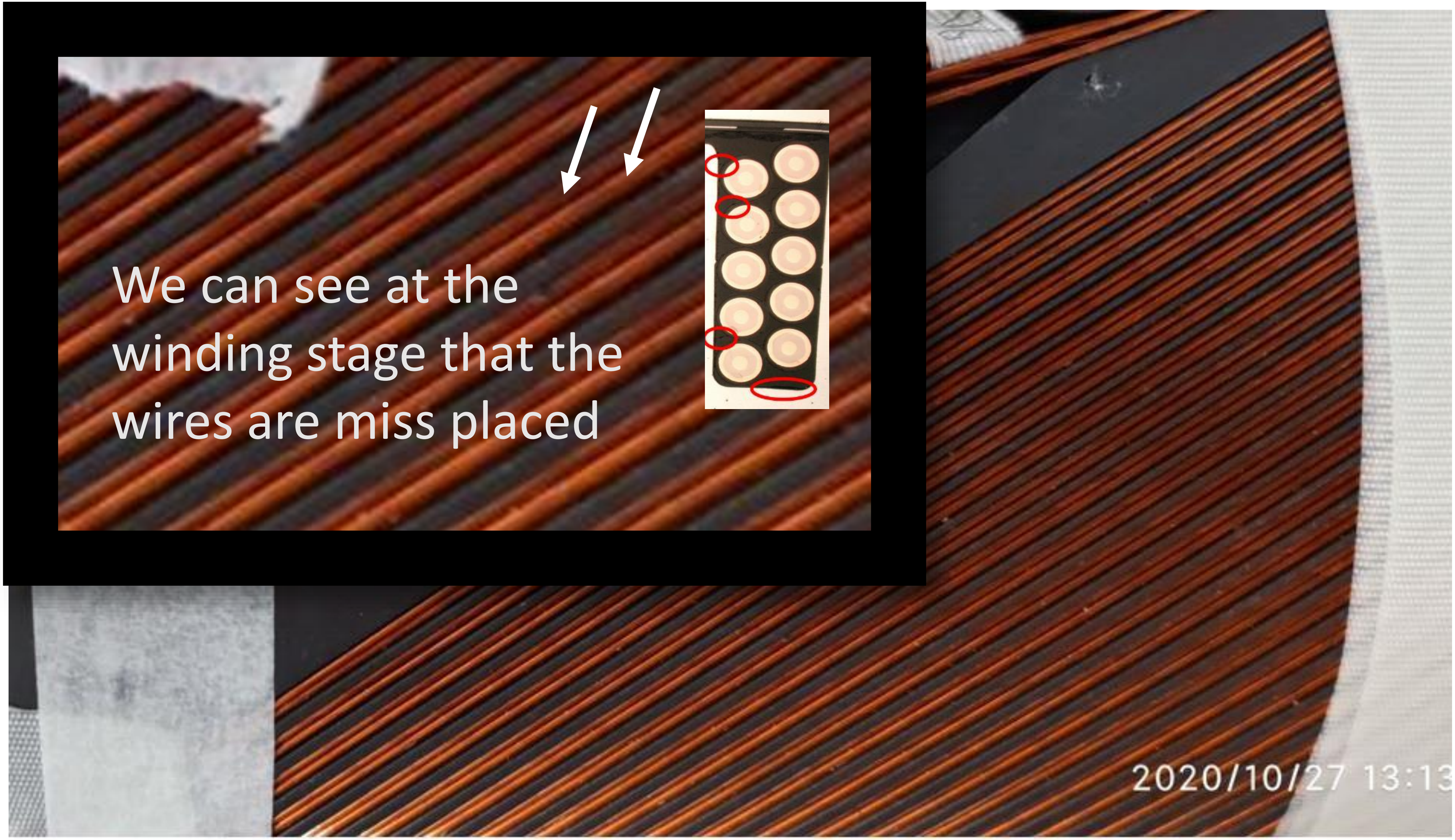


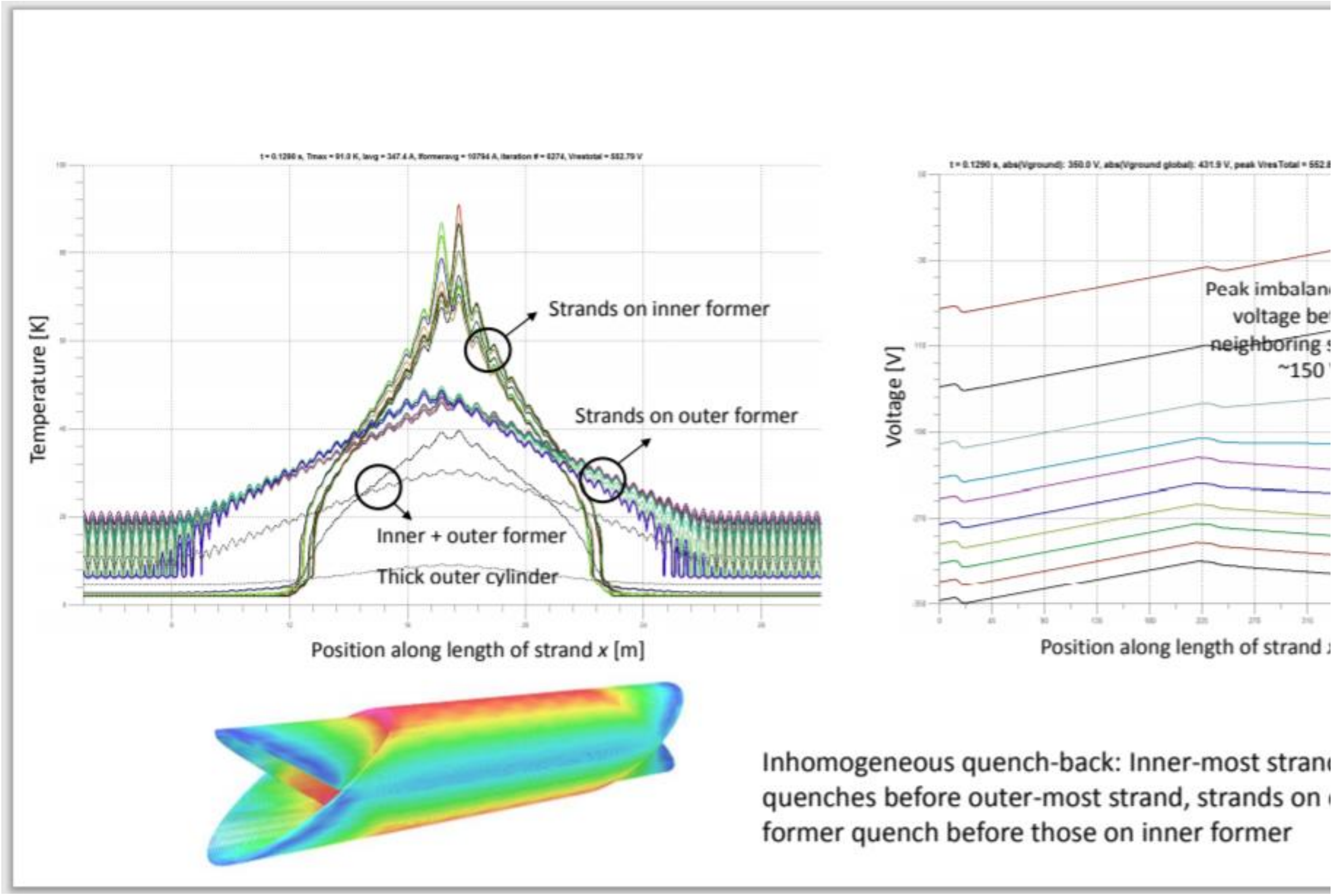
- “log stacking” strand positioning may help reduce resign volumes and transfer forces



t=0 (i.e. regular operation), max Lorentz force per strand: 1070 N/m

Stable Stacking

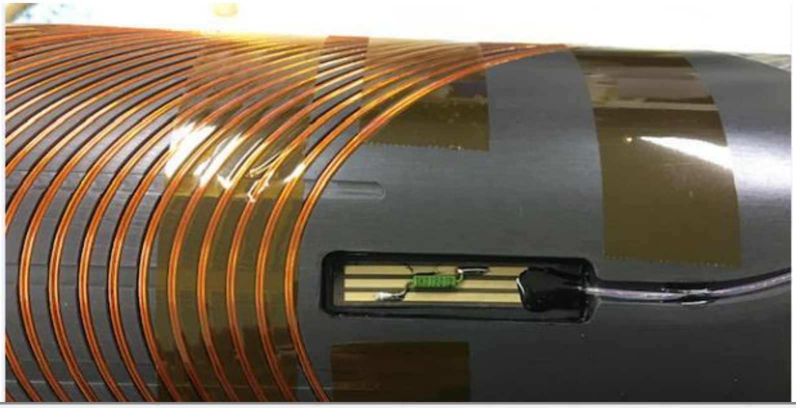

We can see at the winding stage that the wires are miss placed
2020/10/27 13:13



Quench patterns in CCT's thanks to:

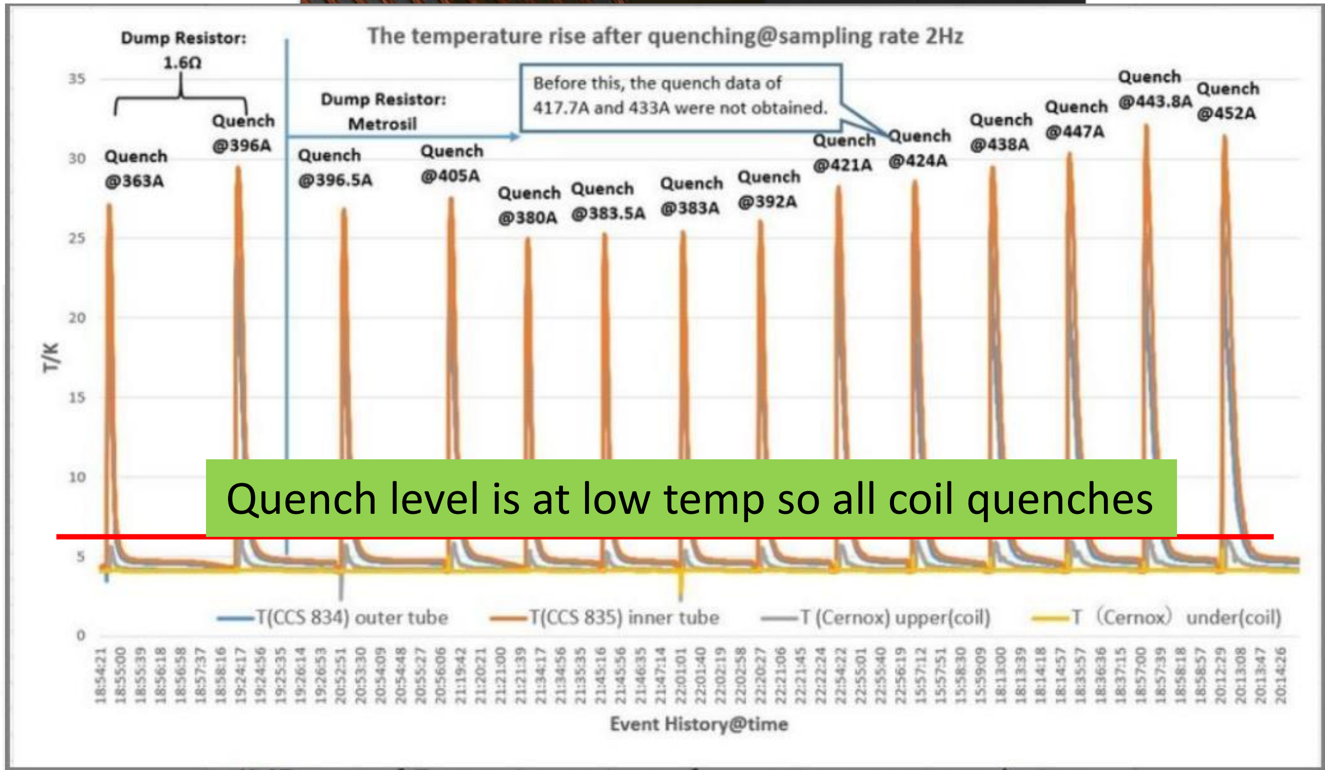
Dr. Matthias Mentink.

Temp of formers quench-back



Temperature sensors in formers.

- Monitor and control cool down
- Measure eddy current temp rise quench dT 20 K
- Measure beam heating in LHC



IMP test of Bama 1 aperture , former temperature during quench events

The CCS temperature sensors that are embedded in the former's inner and outer ! gave some consistent data points. On the plot we also see the CERNOX that are mounted on the yoke in the liquid as expected much less sensitive. the CCS will be an interesting sensor to see beam heating inside LHC

Temperature change after quenching.xlsx · 513.67 KB

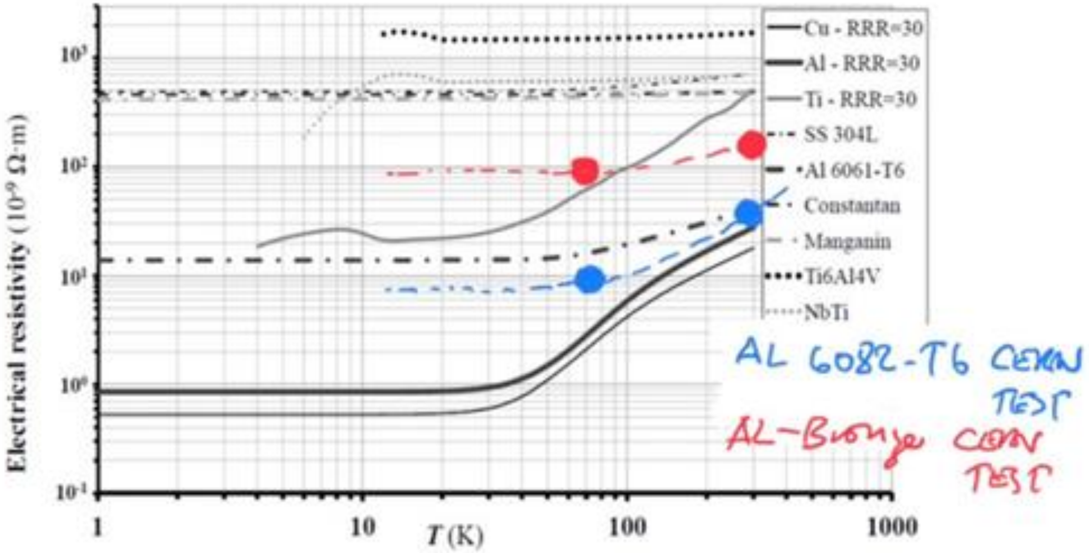
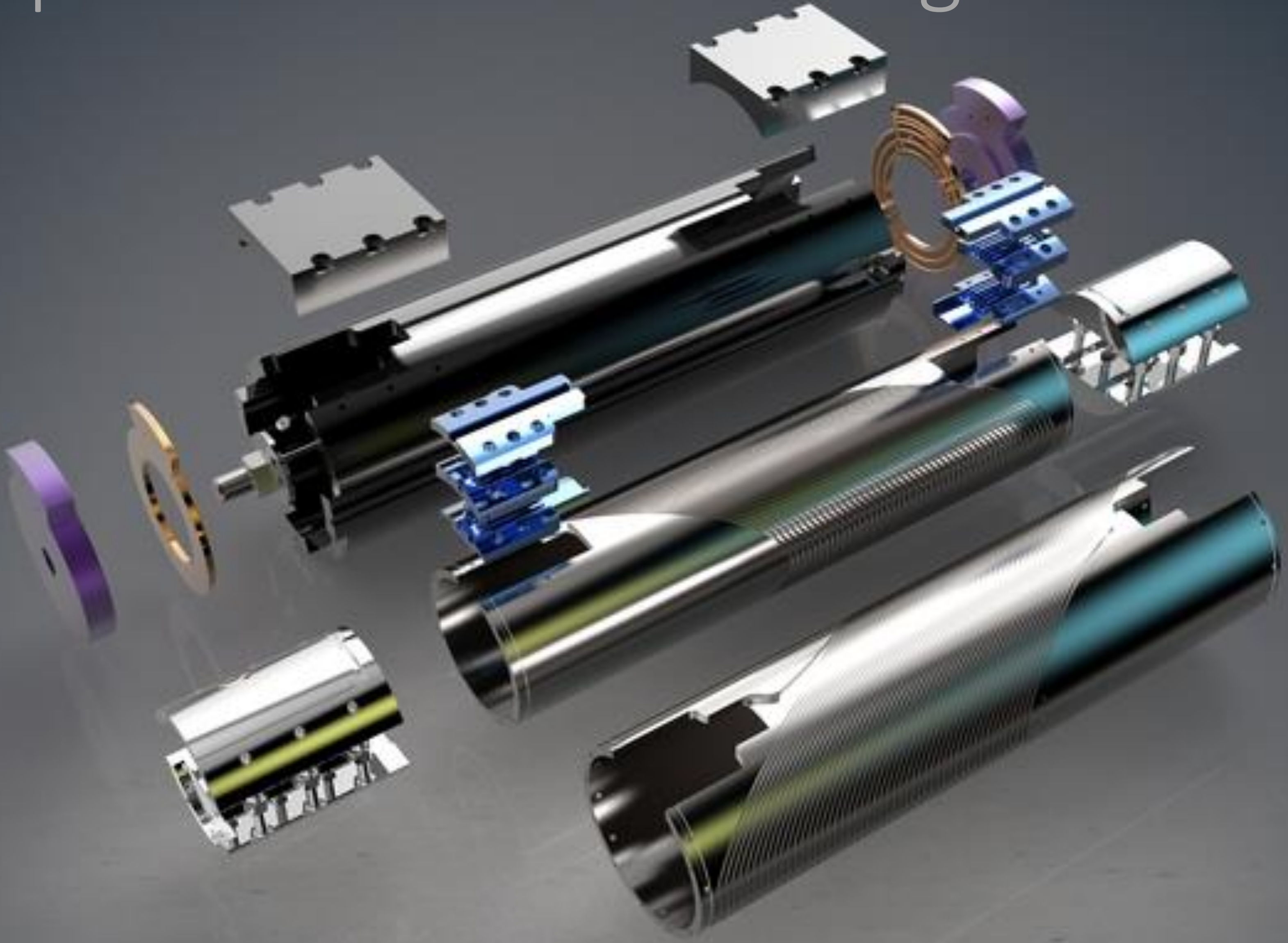


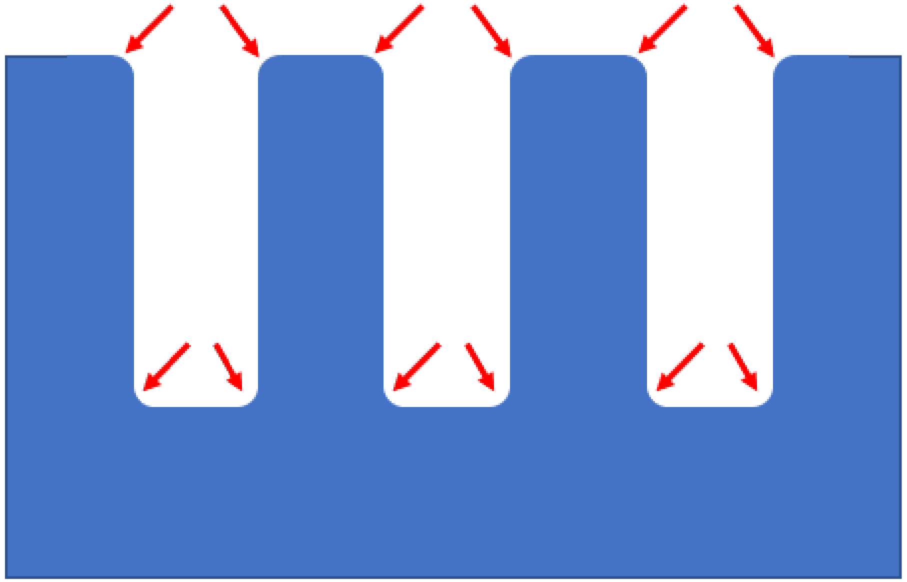
Fig. 10: Electrical resistivity ρ ($\Omega{\cdot}$m) of various materials versus temperature T. Metals are plotted with solid lines, metallic alloys with dot-dashed lines, and two superconducting alloys with dotted lines.

All the parts for the model magnet and tooling

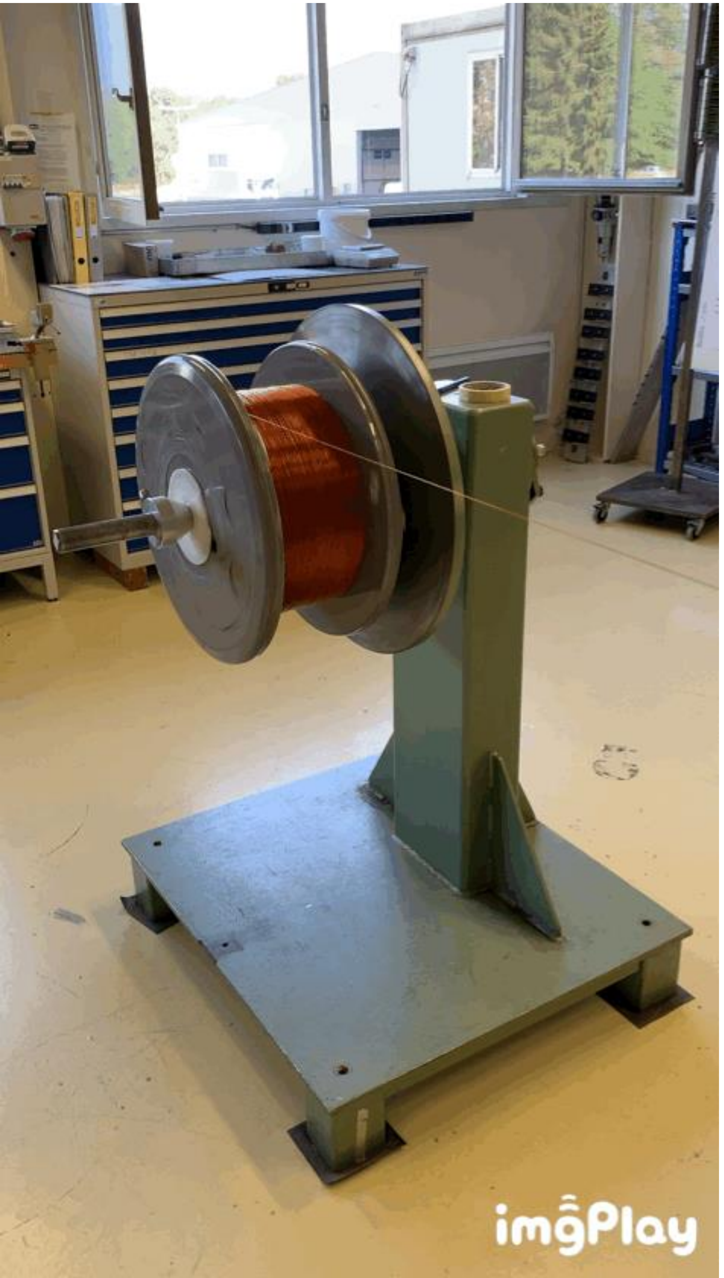


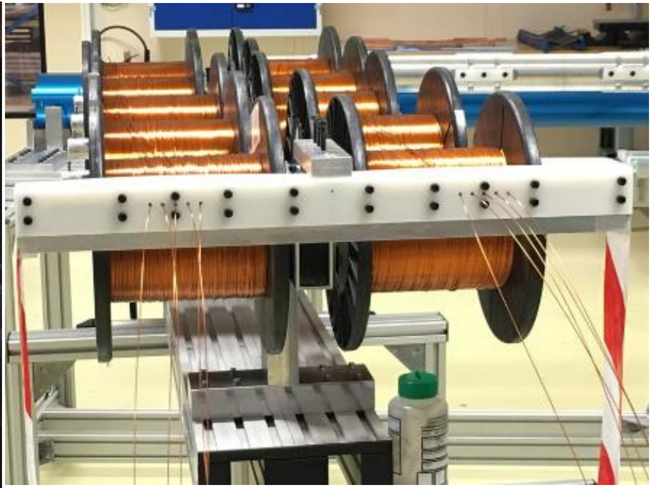
Remove sharp edges before anodization

Radii are *very* important

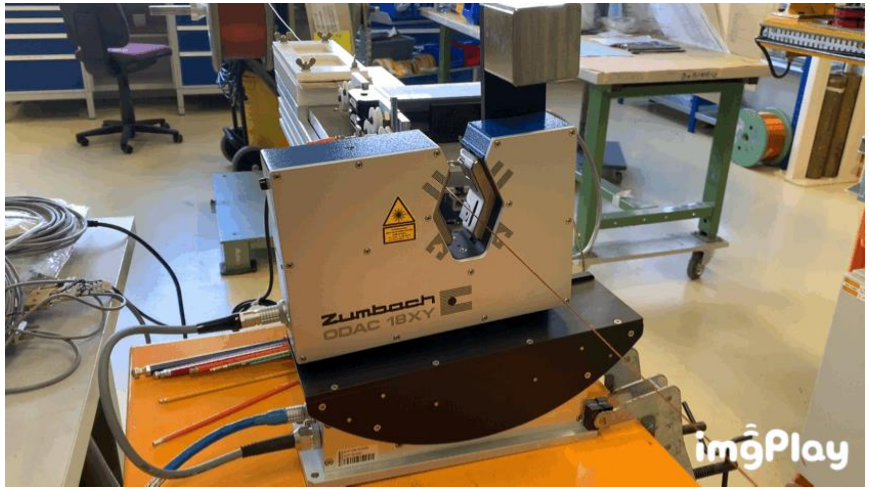


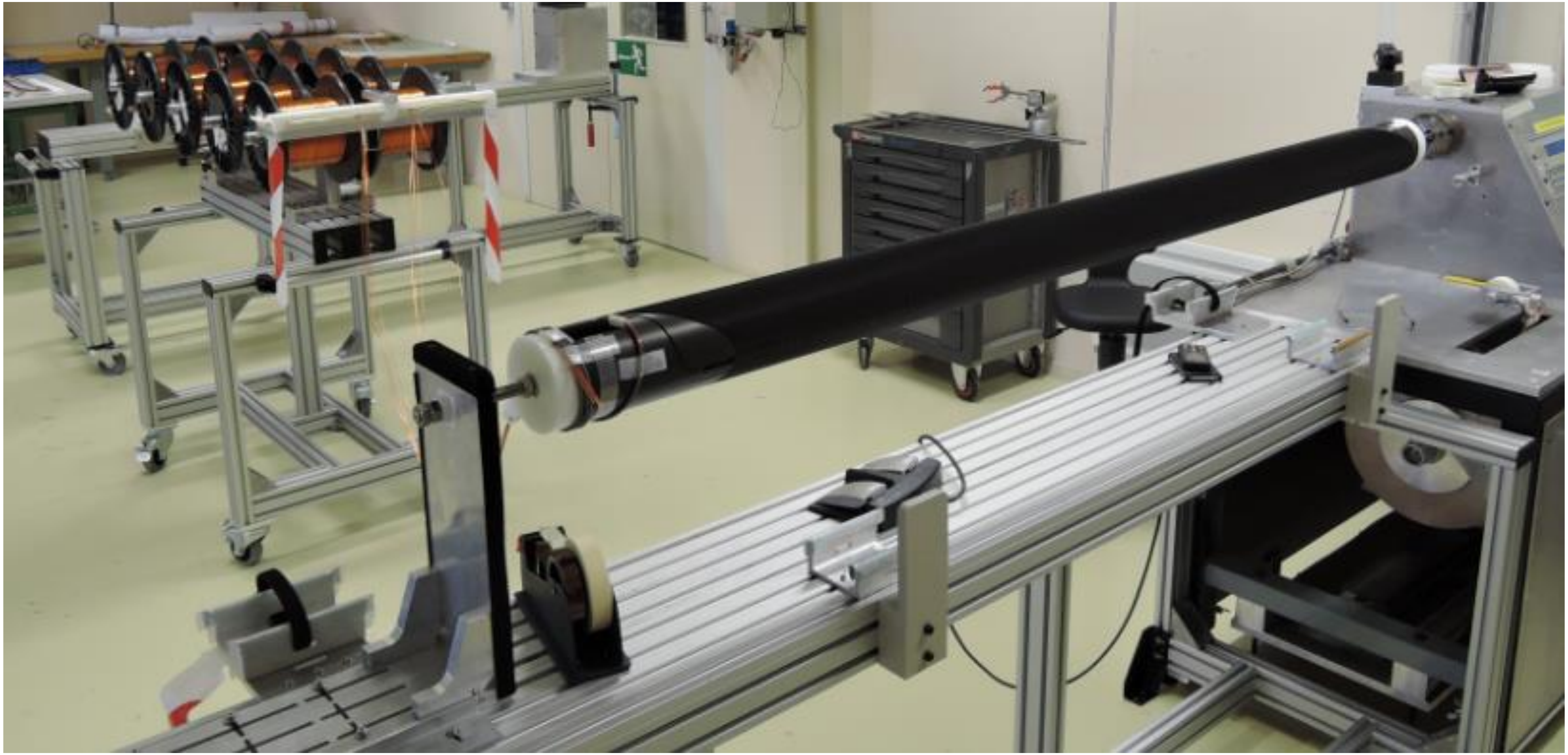
Cleaning the Insulated Wire



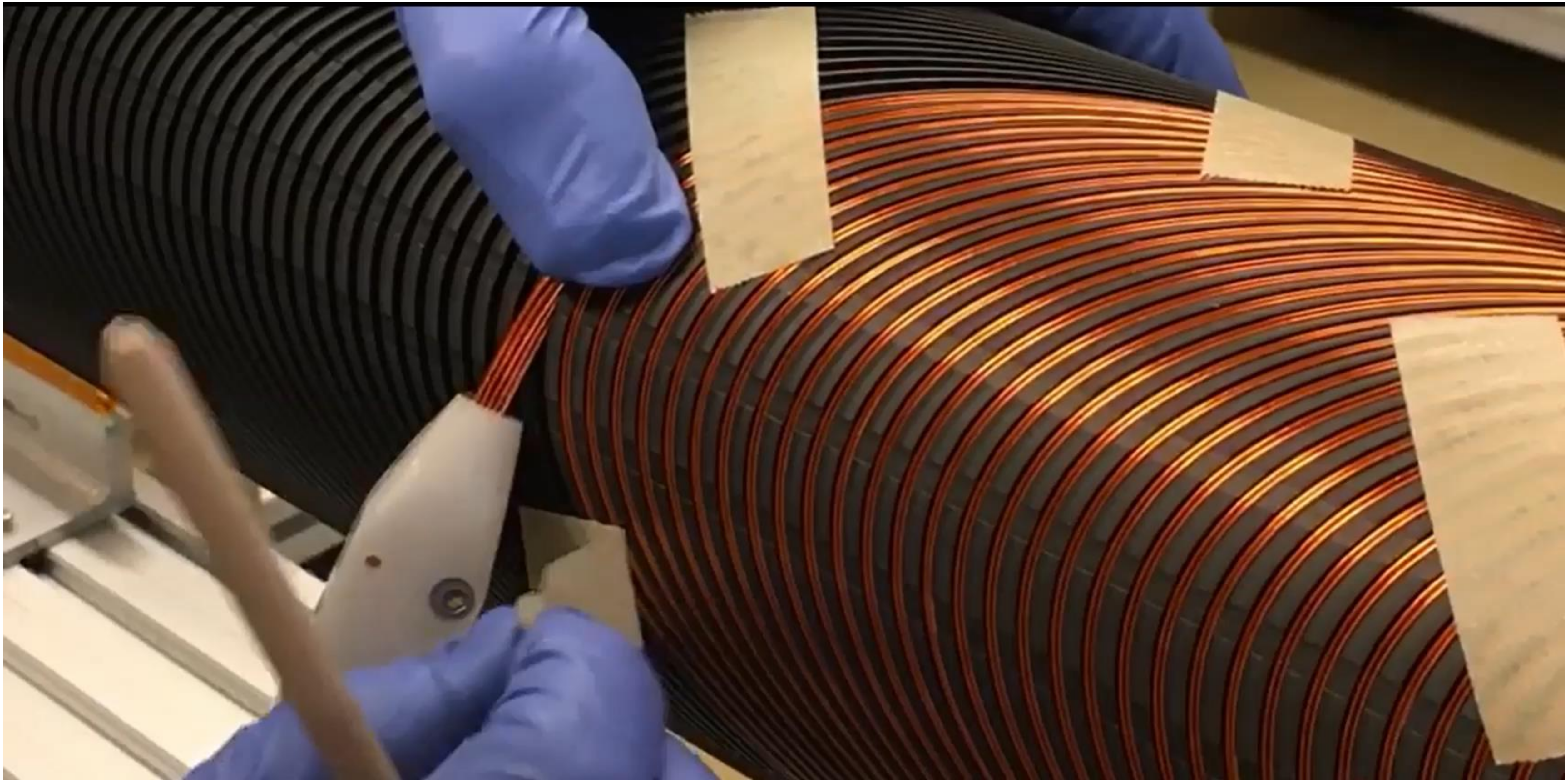


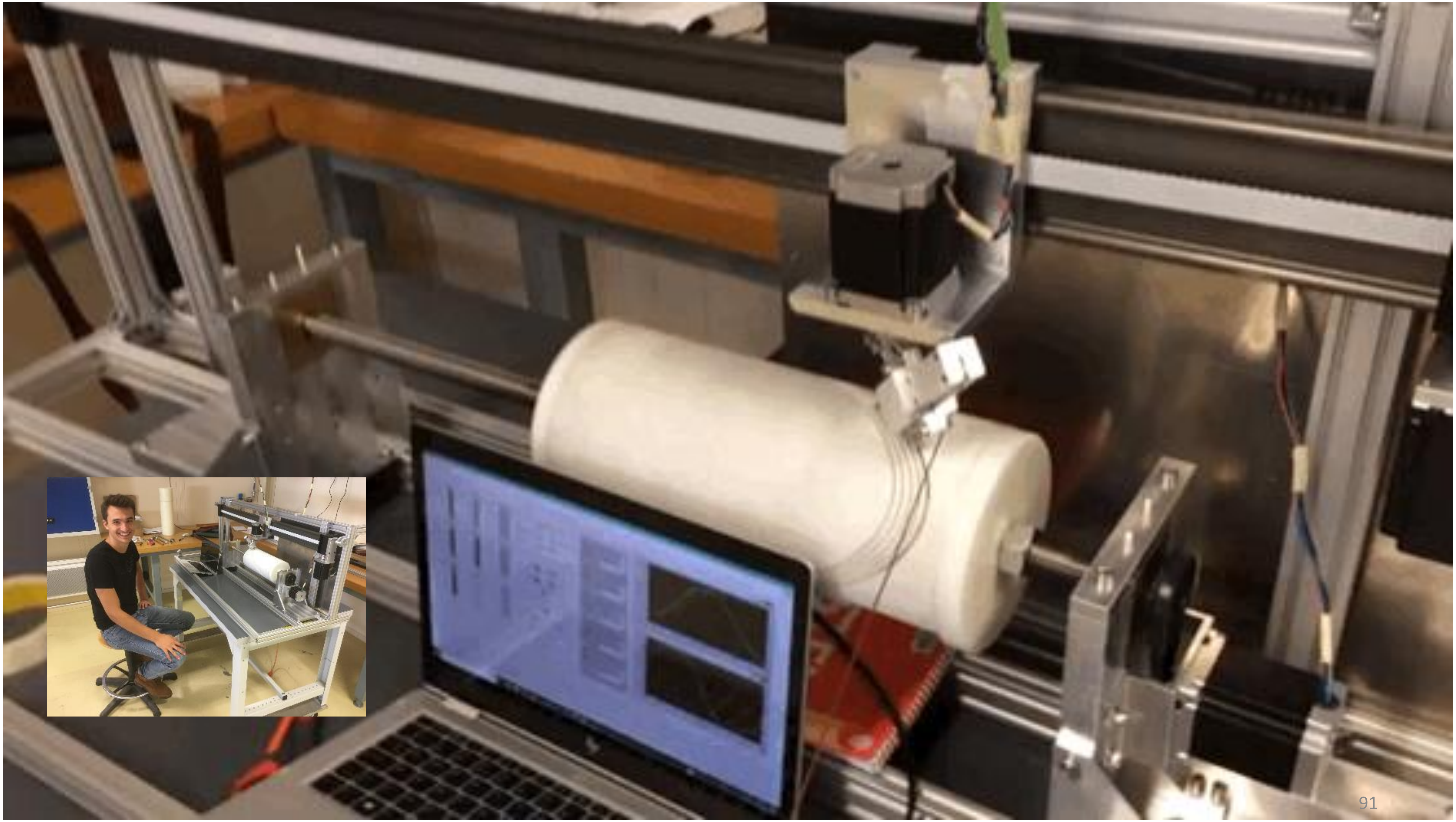
Wire Cleaning ,
Voltage test ,
Size measures.





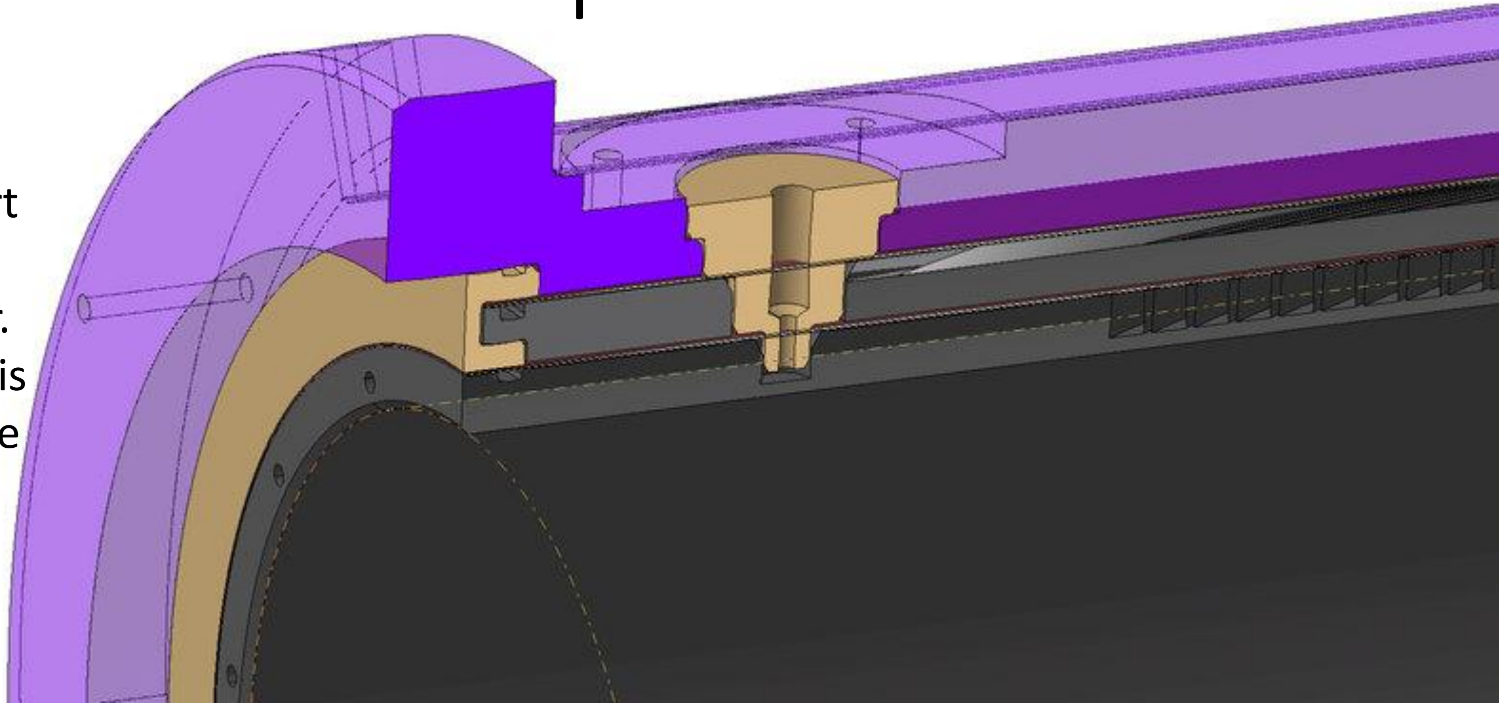
10 spools with insulated wire, Wire cleaning, Hard anodized aluminium 6082-T6 CCT former

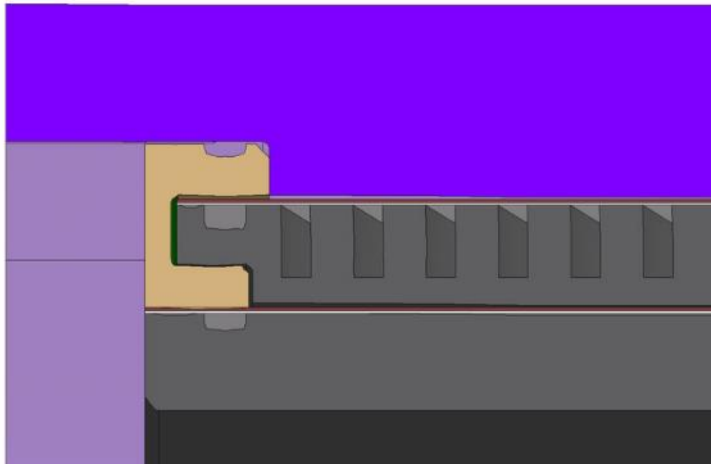




Ground insulation & location pins

The voltage path between the two formers and between the outer former and the outer support ring is at least 4 to 5 mm. The two layers of Kapton sheet provide a general electrical barrier. At the ends we need the 4 to 5 mm distance. This also applies at the alignment pin, the pin is made of a glass resin, the ends are also protected be a labyrinth insulating ring.

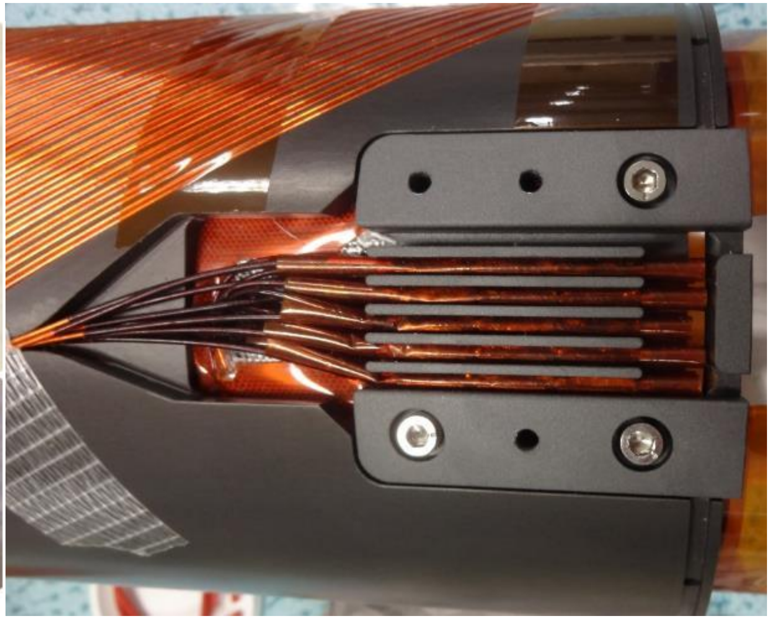


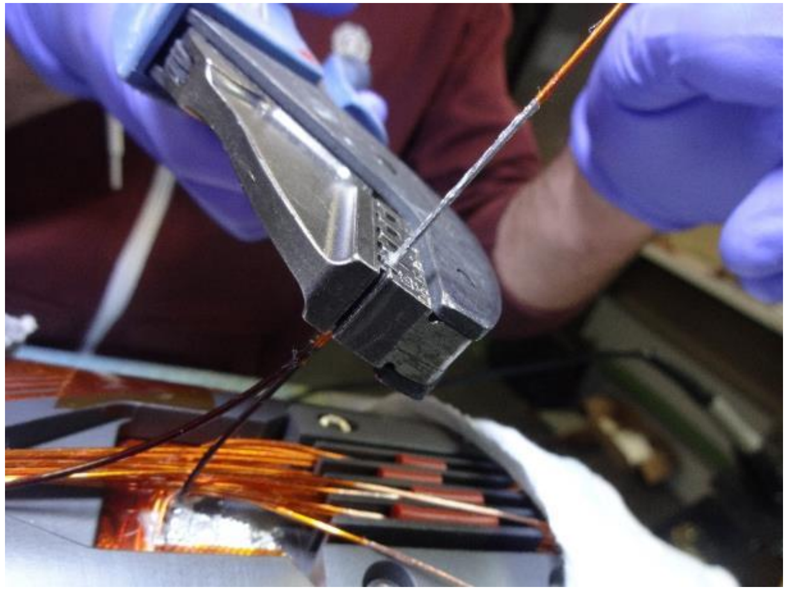


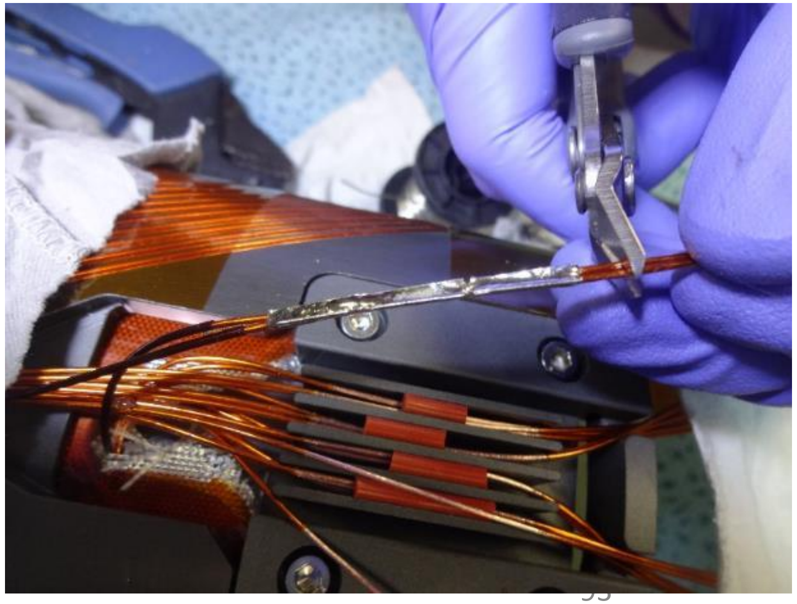
III.Splicing / Jointing

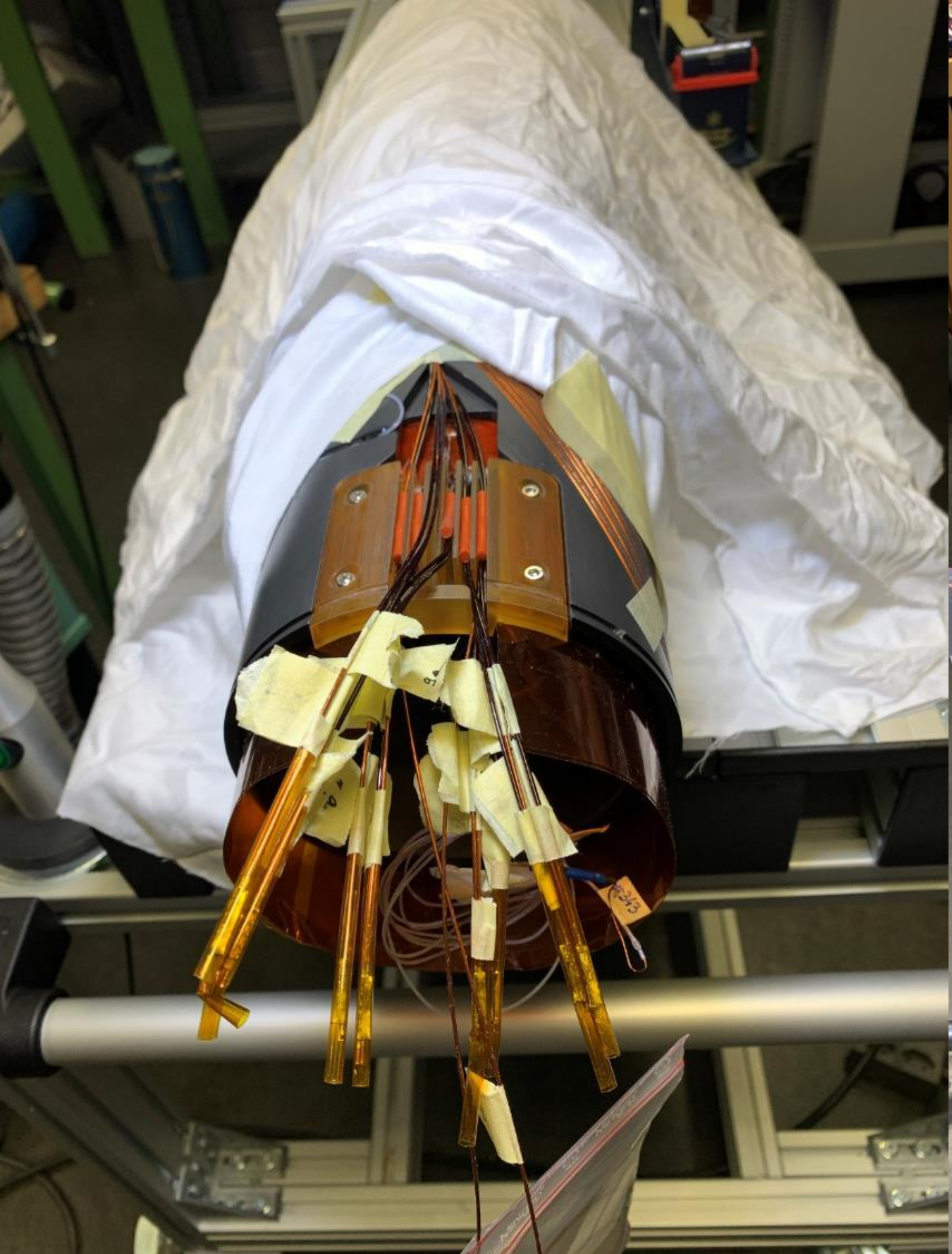
- Short MCBRDS : 21 splices per aperture
- Prototype MCBRDP : 9 splices
- 45 mm long
- Crimping with “non insulated end-sleeve “ (= tube)
- Sn96Ag4 welding alloy
- Flux MOB39
- Poly-imide sleeve for protection
- Connexion box

600A joint Copper tube tined with solder , crimped , and soldered,



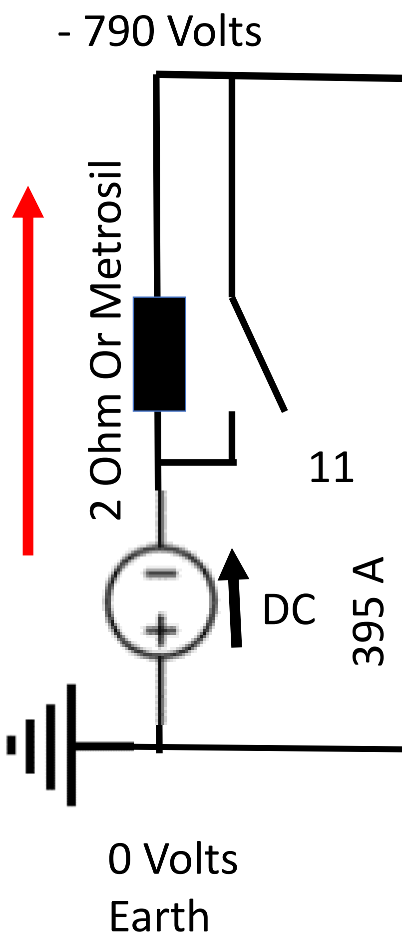


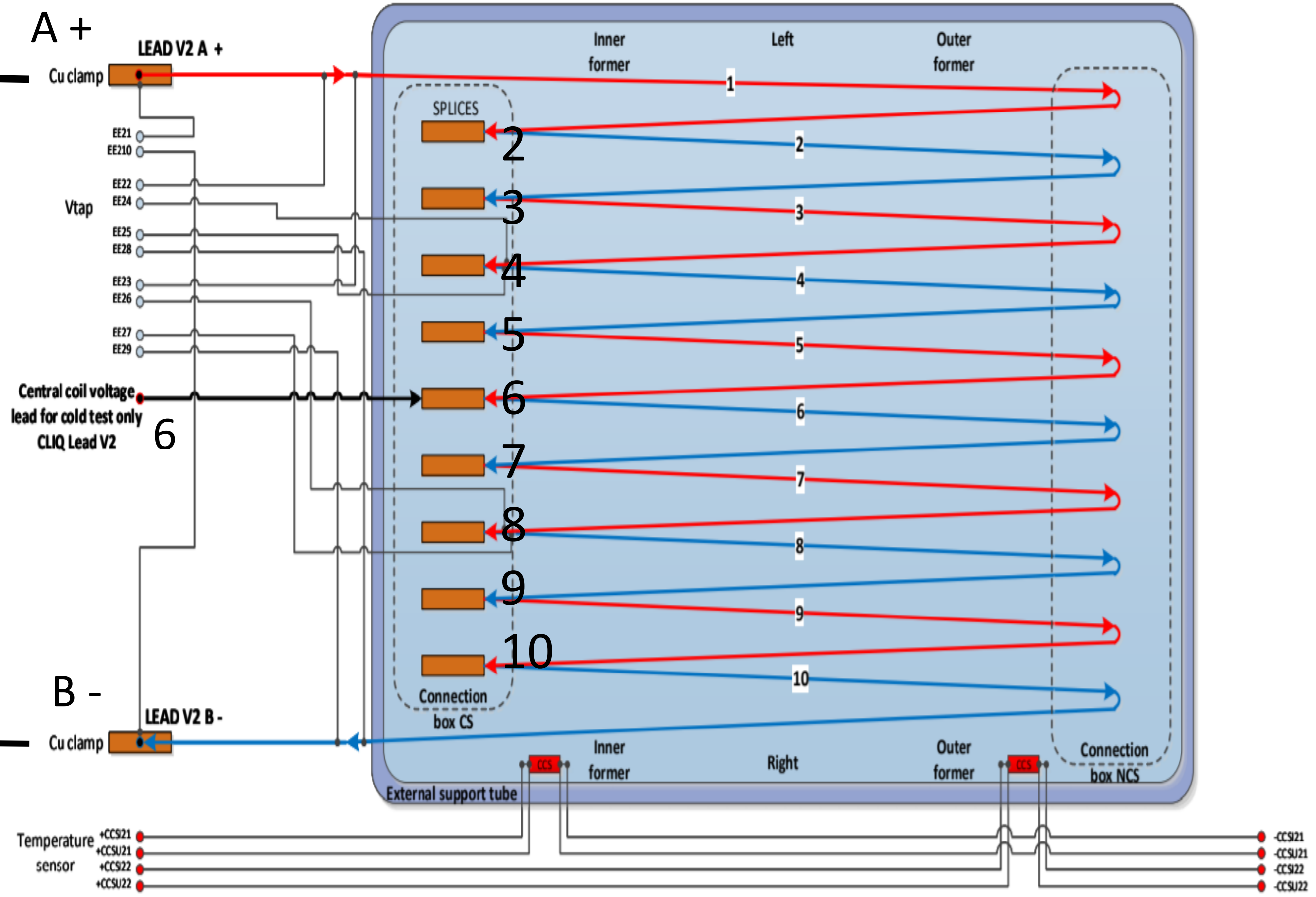




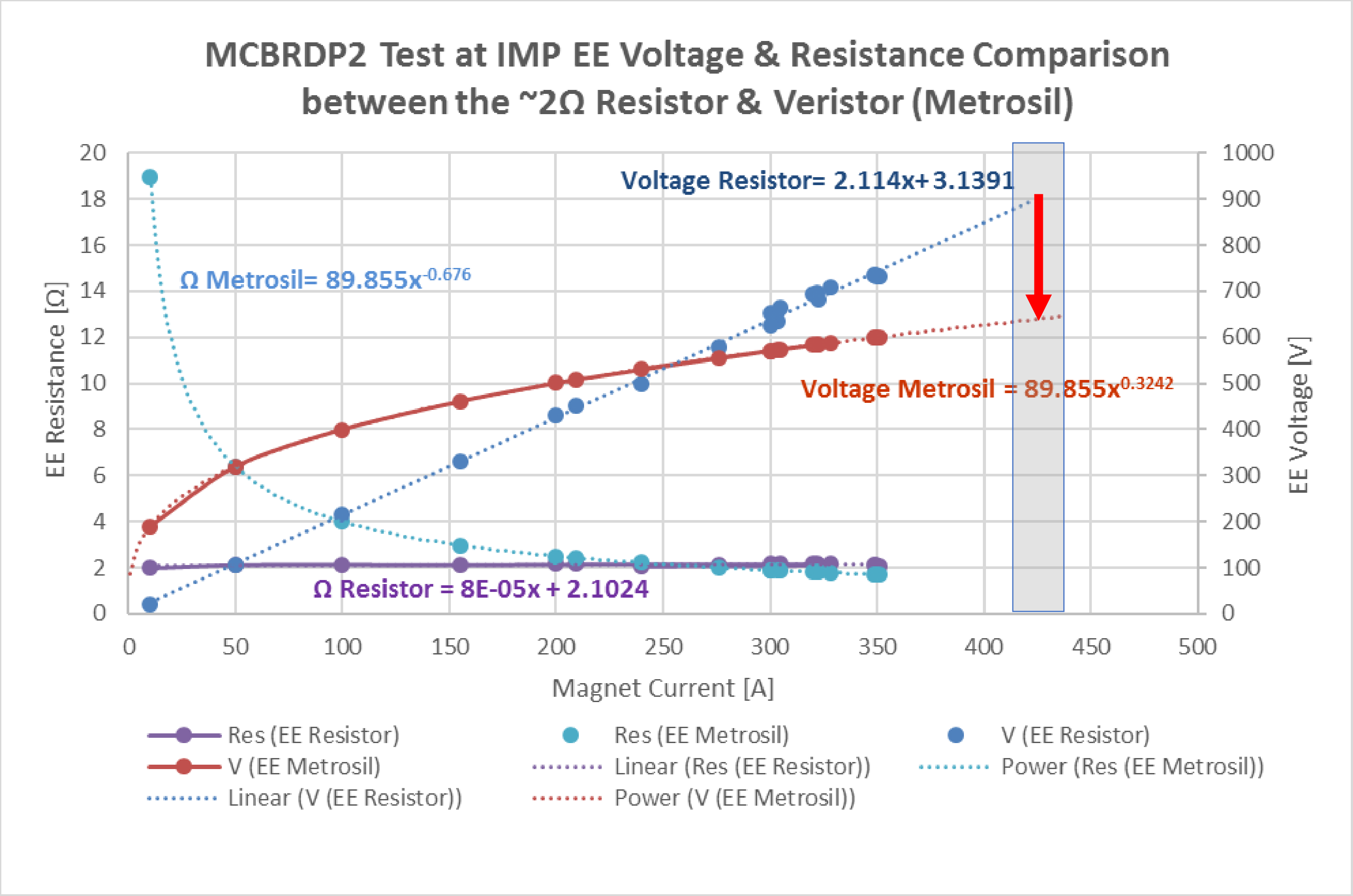
Voltage in the circuit with 2 ohm EE at 395 A

dV =	79	71.1
Voltage position	2 ohm Dump Res.	Metrosil 2 ohm equivalent
#	[V]	[V]
1	-790	-711
2	-711	-639.9
3	-632	-568.8
4	-553	-497.7
5	-474	-426.6
6	-395	-355.5
7	-316	-284.4
8	-237	-213.3
9	-158	-142.2
10	-79	-71.1
11	0	0



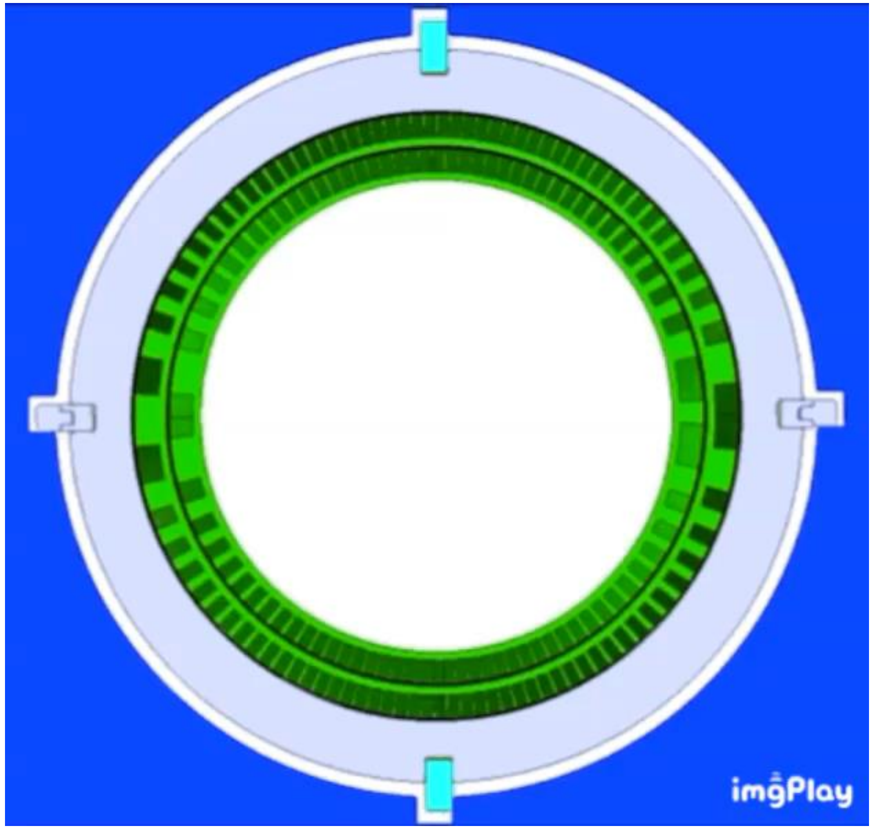


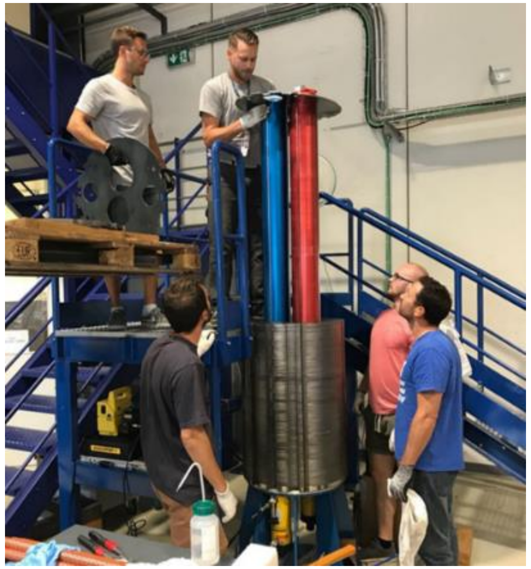
Energy Extraction optimization for low hot-spot & low Vmax



The first Varistor was used at CERN in 1980's if we replace the std Dump resistor with a varistor we can reduce both quench hot spots, and importantly voltages. In this test at IMP for a fixed hot spot of ~ 150K the voltage drops by ~ 30%

Magnet yoke assembly





Vertical yoke assembly

364 yoke laminations, 5.8mm nominal thickness gave the design length

Axial Yoke packing factor 98.64%

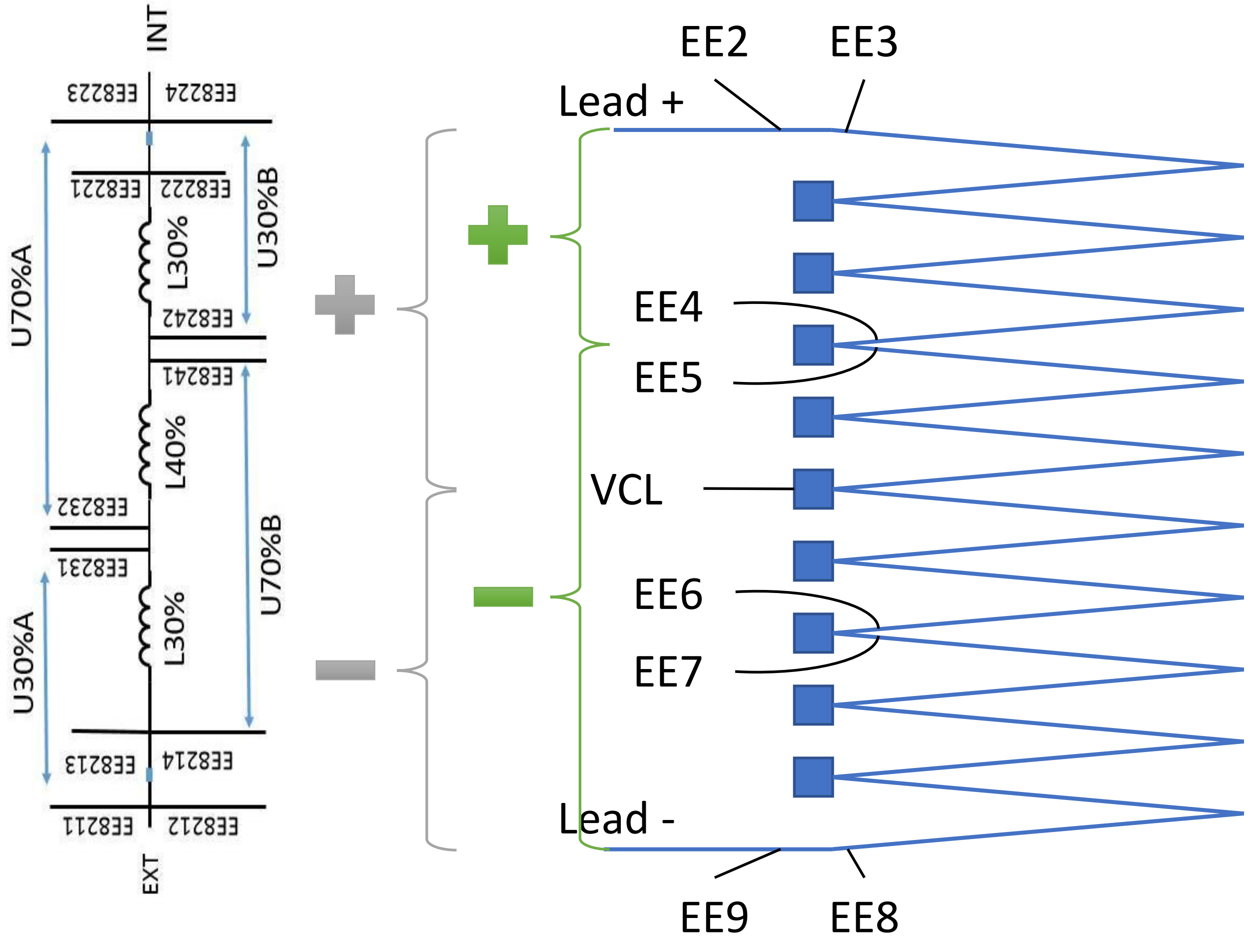
Compressed with hydraulic jacks and held with tie rods.

The first cold test of a full size CCT for LHC hi-Lumi

- MCBRDP1 with two individually powered apertures, 1.9K
- One standard LHC 2 x 600 A power converters
- One standard LHC 600 A energy extraction rack with two switches and two energy extraction dumps (Resistor or Metrosil)

Symmetric Quench detection card

- QDS setup (baseline):
  - 2.3(EE3-EE5) – (EE5-EE8)
  - Trigger after 4 ms @ 100 mV
- Potaim setup:
  - (EE3-VCL) – (VCL-EE8)
  - Trigger after 10 ms @ 50 mV



New protection card against symmetric quenches!

mid- MARCH ready to place orders
Main work shop project.

Type	ST number	Definition	Nomenclature	total qty	Mass	Material	Last Modification	SCEM	CAD Ref
ITEM	ST0826735	2m D2 CORRECTOR ASSEMBLY	LHCMCBRB0001				03.02.2017 16:49		
ITEM	ST0826738	2m MAGNET COIL ASSEMBLY	LHCMCBRB0003	2					
ITEM	ST0826740	D2 FIX EXTREMITY PLATE	LHCMCBRB0004	1		EN 1.4306 (St. Steel 304L)			
ITEM	ST0826741	D2 FREE EXTREMITY PLAQUE	LHCMCBRB0005	1		EN 1.4306 (St. Steel 304L)			
ITEM	ST0826742	D2 CORRECTOR YOKE v4	LHCMCBRB0006	368		ARMCO® (Fe 99,99%)			
ITEM	ST0826745	2m KEY	LHCMCBRB0007	4		EN 1.4307 (St. Steel 304L)			
ITEM	ST0826748	D2 INSULATING WIRE LINE 1	LHCMCBRB0008	1		Epoxy GF EP GC 308 (G-11)			
ITEM	ST0826749	D2 INSULATING WIRE LINE 2	LHCMCBRB0009	1		Epoxy GF EP GC 308 (G-11)			
ITEM	ST0826751	D2 INSULATING WIRE COVER	LHCMCBRB0010	1		Epoxy GF EP GC 308 (G-11)			
ITEM	ST0826746	2m HYBRID YOKING KEY ASSEMBLY	LHCMCBRB0011	12					
ITEM	ST0826757	2m INNER COIL	LHCMCBRB0012	2		Alu EN AW-6082 (T4)			
ITEM	ST0826758	2m OUTER COIL	LHCMCBRB0013	2		Alu EN AW-6082 (T4)			
ITEM	ST0826759	2m EXTERNAL PIPE	LHCMCBRB0014	2		Alu EN AW-5083 (H116)			
ITEM	ST0826761	INSULATING FIXEND PLATE	LHCMCBRB0015	4		Epoxy GF EP GC 308 (G-11)			
ITEM	ST0826762	WIRE EXIT BOX	LHCMCBRB0016	2		Epoxy GF EP GC 308 (G-11)			
ITEM	ST0826763	CONN. BOX WIRES CAGE	LHCMCBRB0017	42		Cu OF C10200 (H02)			
ITEM	ST0826764	CONNECTION BOX COVER	LHCMCBRB0018	4		Alu EN AW-6082 (T4)			
ITEM	ST0826765	CONNECTION BOX INNER PLATE	LHCMCBRB0019	4		Alu EN AW-6082 (T4)			
ITEM	ST0826766	CONNECTION BOX MIDDLE PLATE	LHCMCBRB0020	4		Alu EN AW-6082 (T4)			
ITEM	ST0826870	2m HYBRID YOKING KEY - INNER PART	LHCMCBRB0021	12		EN 1.4306 (St. Steel 304L)			
ITEM	ST0826871	2m HYBRID YOKING KEY - OUTER PART	LHCMCBRB0022	12		ARMCO® (Fe 99,99%)			
ITEM	ST0826753	YOKE ROD 2m	LHCMCBRB0023	4		EN 1.4307 (St. Steel 304L)			
ITEM	ISO 4032_M20-A4	HEX NUT STYLE 1 GRADE A M20		4		Stainless Steel A4 Acier Inox A4		47.43.77.200.3	
ITEM	ISO 4762 M3x8-A4	HEX SKT HD CAP SCREW_M3X8		17		St. Steel A4			
ITEM	ISO 4762 M4x12-A4	HEX SKT HD CAP SCREW_M4X12		16		St. Steel A4		47.62.71.155.7	
ITEM	ISO 7089_20x37-A4	NORMAL PL WASHER_20X37		4		Stainless Steel A4 Acier Inox A4		47.78.15.020.2	
ITEM	ISO 8752_12x80-A2	Slot heavy duty spring pin_12x80		112		Stainless Steel A2 Acier Inox A2			
ITEM	ST0345798	SPRING LOCK WASHER M04 (GROWER)		16		St. Steel A4		47.78.15.202.8	
ITEM	ISO 4762 M3x25-A4	HEX SKT HD CAP SCREW_M3X25		32		St. Steel A4		47.62.71.110.0	
ITEM	ST0263158	SPRING LOCK WASHER M03 (GROWER)		32		St. Steel A4		47.78.15.200.0	
ITEM	ST0529395	HEX SKT LOW HD SCREW M4x25		16		St. Steel A2			
ITEM	ISO 4762_M2x8-12.9-A0U	HEX SKT HD CAP SCREW_M2X8		180		Steel 12.9			

Glyn A. Kirby CCT update Dec 2016 48

COST of CCT magnets

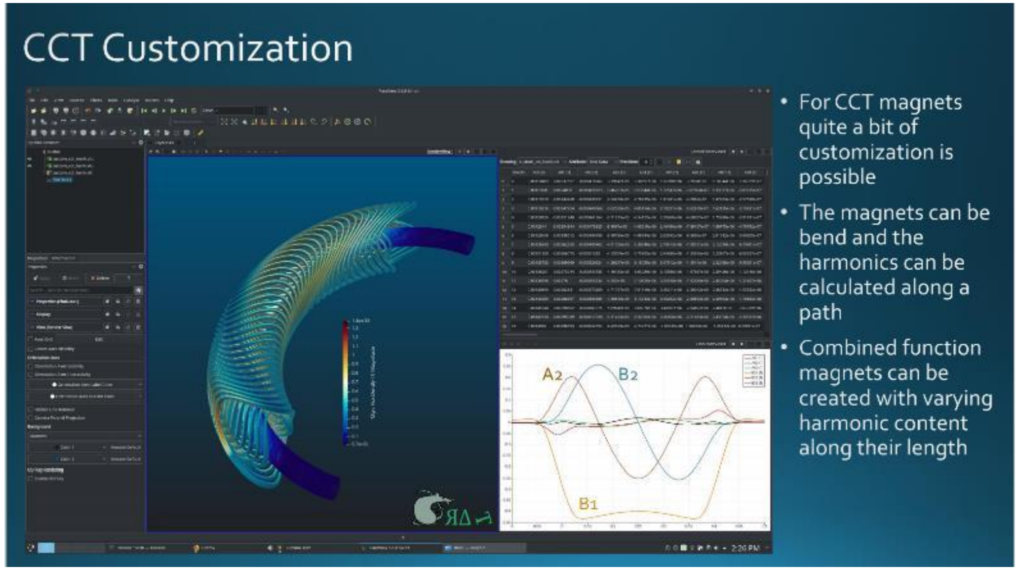
Only 21 Drawings. !!! For the full magnet production including tooling!

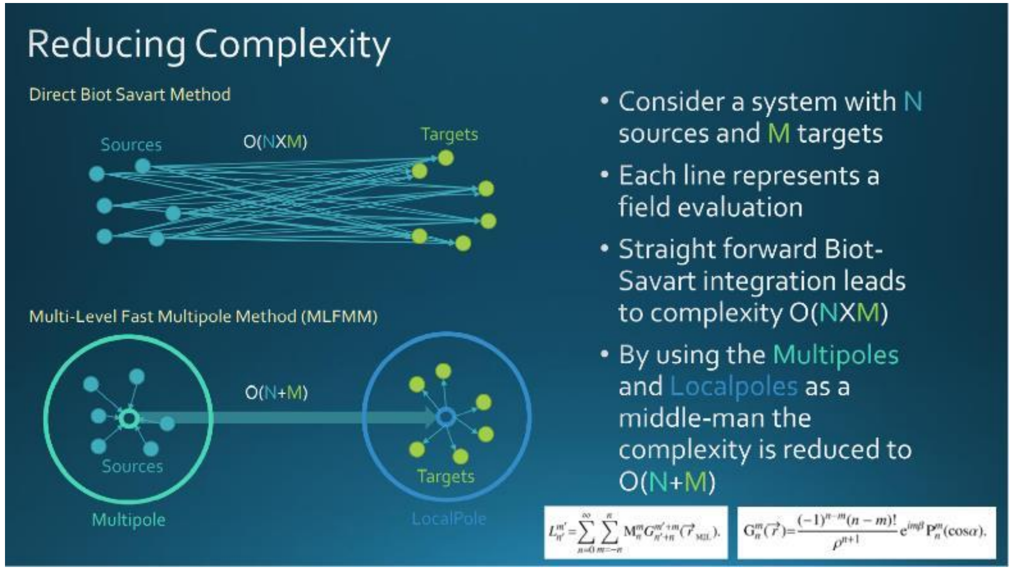
LHC MCBY had 500+ drawings

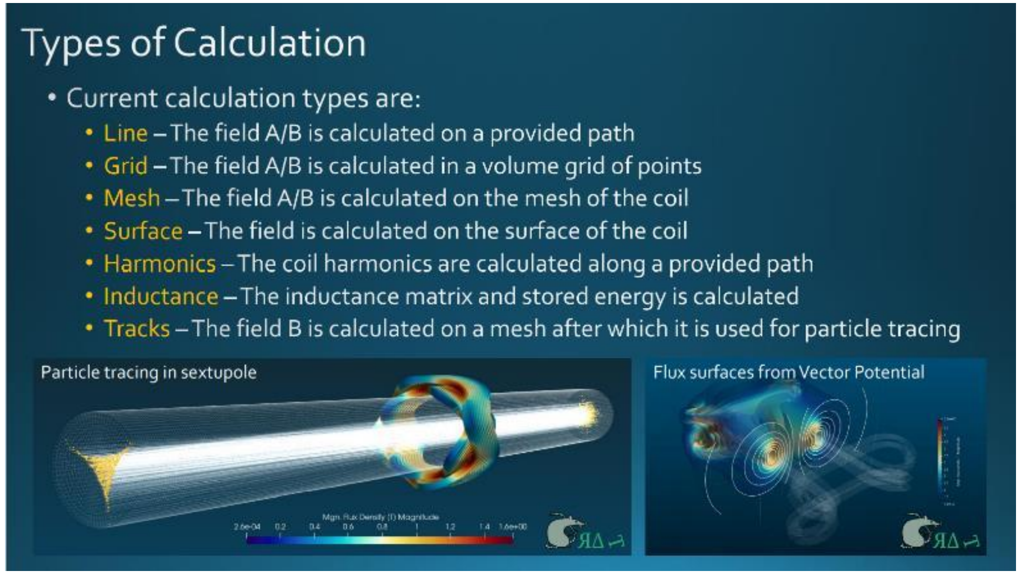
Cost for low production quantities

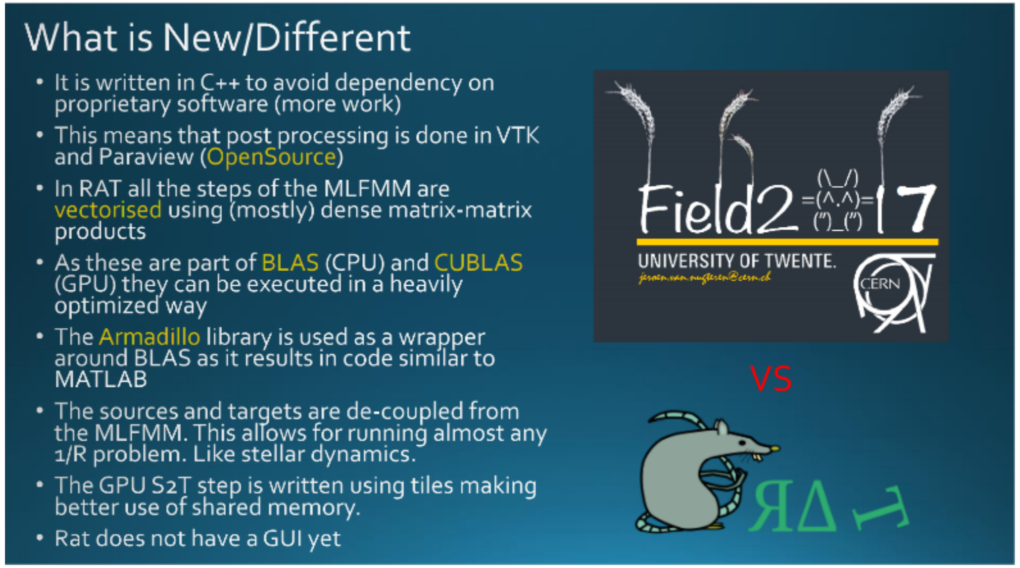
can be **¼** that needed for the classical design

Big Thanks to Jerone for his Field and now Rat programs Used for Designing CCT's and much more!





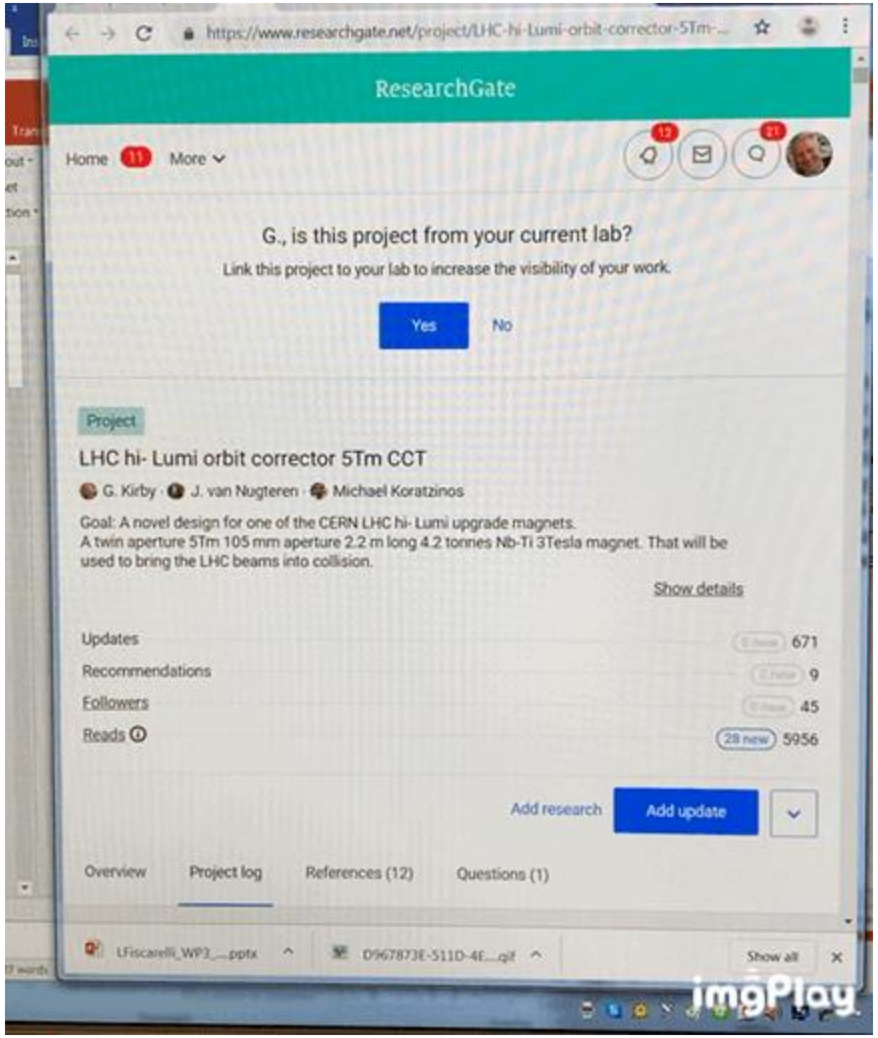




Conclusions

CCT's

- *Low cost!*
- *Good field quality*
- *Simple to design, you can do it with paper and pen.*
- *lots of opportunity to invent new magnets.*



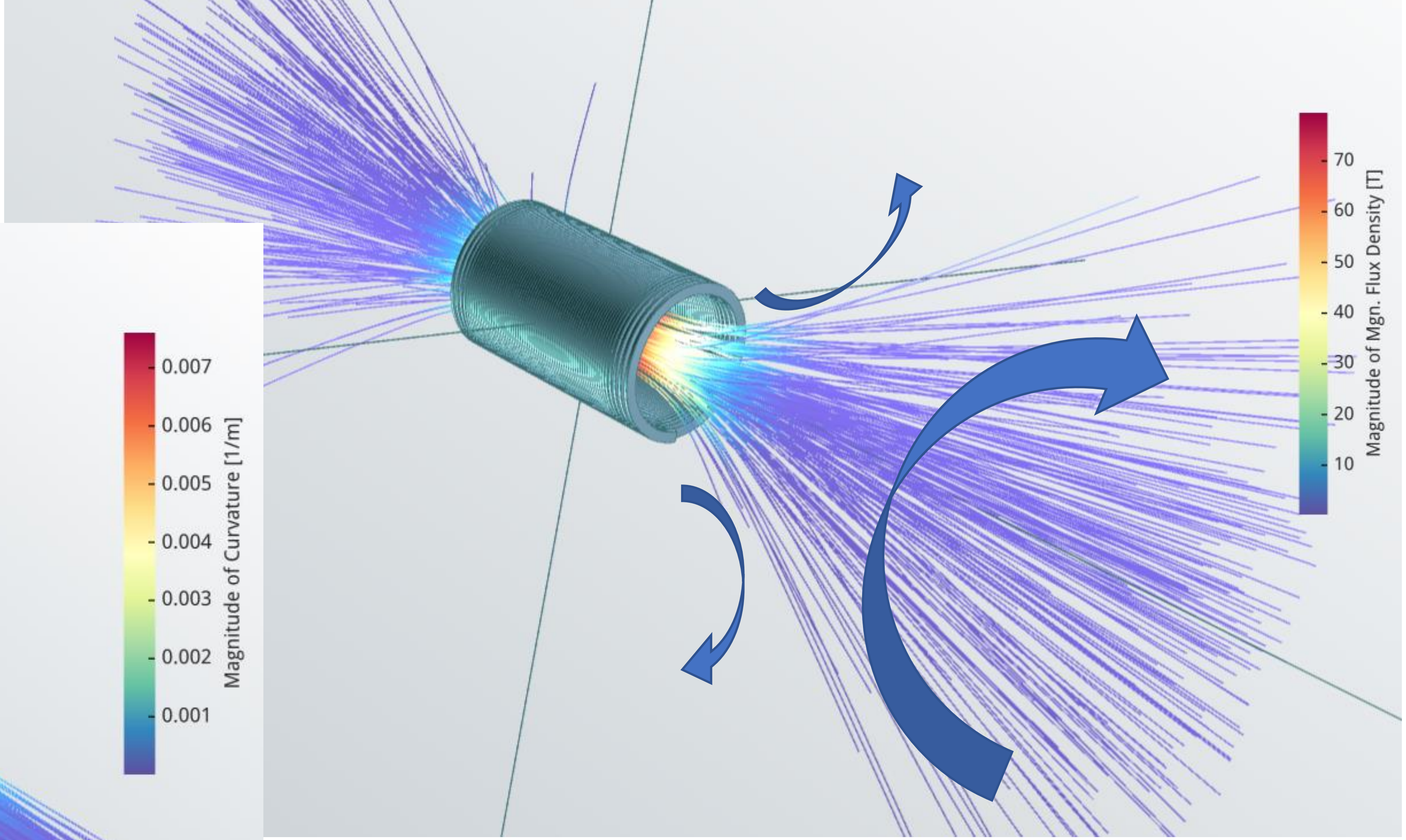
Follow day by day, and look back over 5 years the progress on my ResearchGate G Kirby project log with every idea, paper, success and failure !
https://www.researchgate.net/project/LHC-hi-Lumi-orbit-corrector-5Tm-CCT

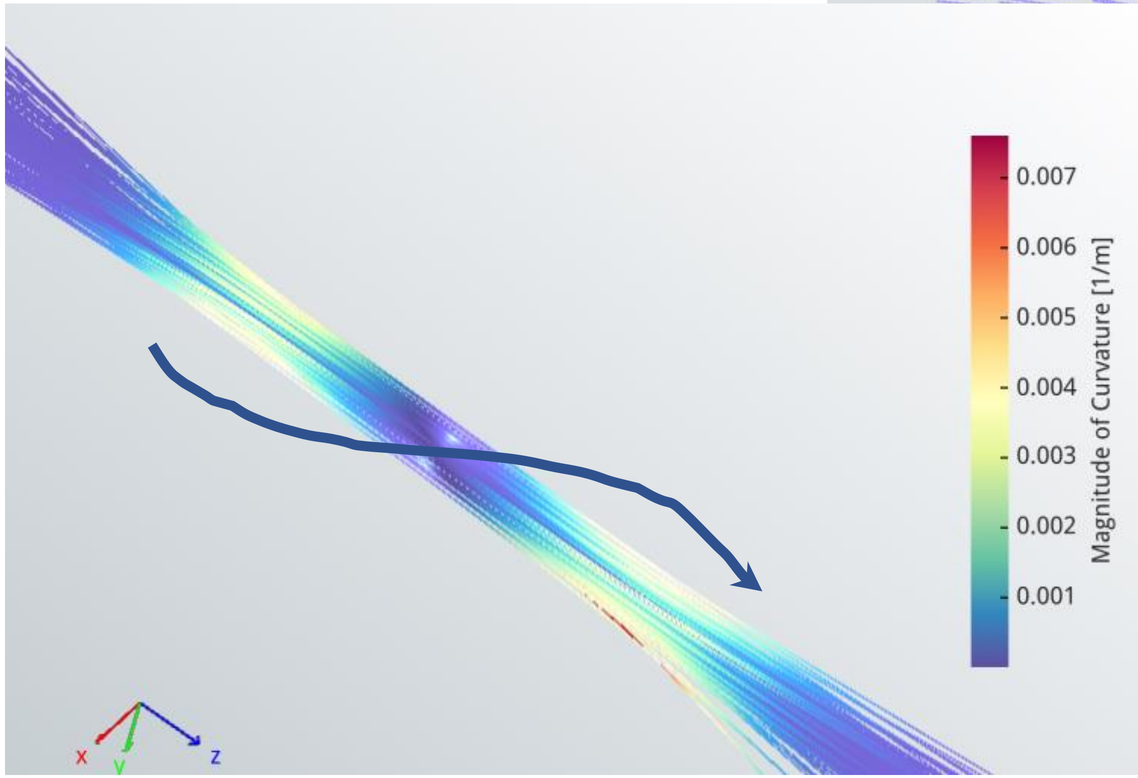
Thanks to all who have contributed to the CCT development over the last 10 years

- *Jeroen Van Nugteren,*
- *The design office team Matt and Luca.*
- *All the 927 team, Jacky, Francois-Olivier, Carols, Nicolas, Sebatian, Juan, & all the rest!*
- *Gijs, Ezio, Andrea and the many students form inside and outside of CERN .*
- *Matthias Mentink , Emmanuele Ravaioli & and the protection team, Mike.*
- *Rafal Ortwein,& Daniel and his Sushi team, Arnaud Foussat.*
- *Karol and the CERN main machine shop.*
- *all SM18 test teams.*
- *Magnetic measurement team: Lucio, Carlo, …*
- *The materials testing team, Stefano , Mickael Denis Crouvizier, The IHEP, IMP test team all in china.*
- *Oscar Sacristan De Frutos.*
- *Shlomo, Bernhard, Mike, Stefania, Thomas, Chris.*
- *Lucio Rossi, Luca Bottura.*
- *Kevin and the team in Sweden*
- *And many more that have helped start this new era in accelerator magnet design!*

The End

Solenoid puts a twist on the beam and divergence at exit!

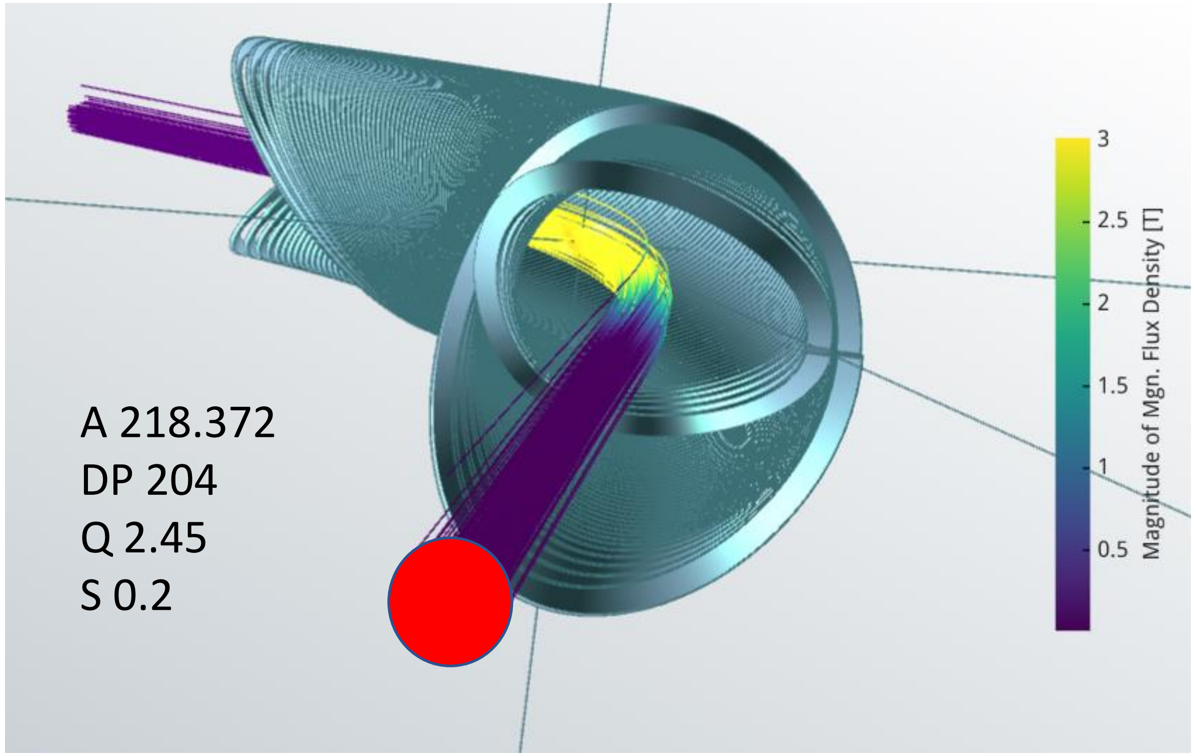


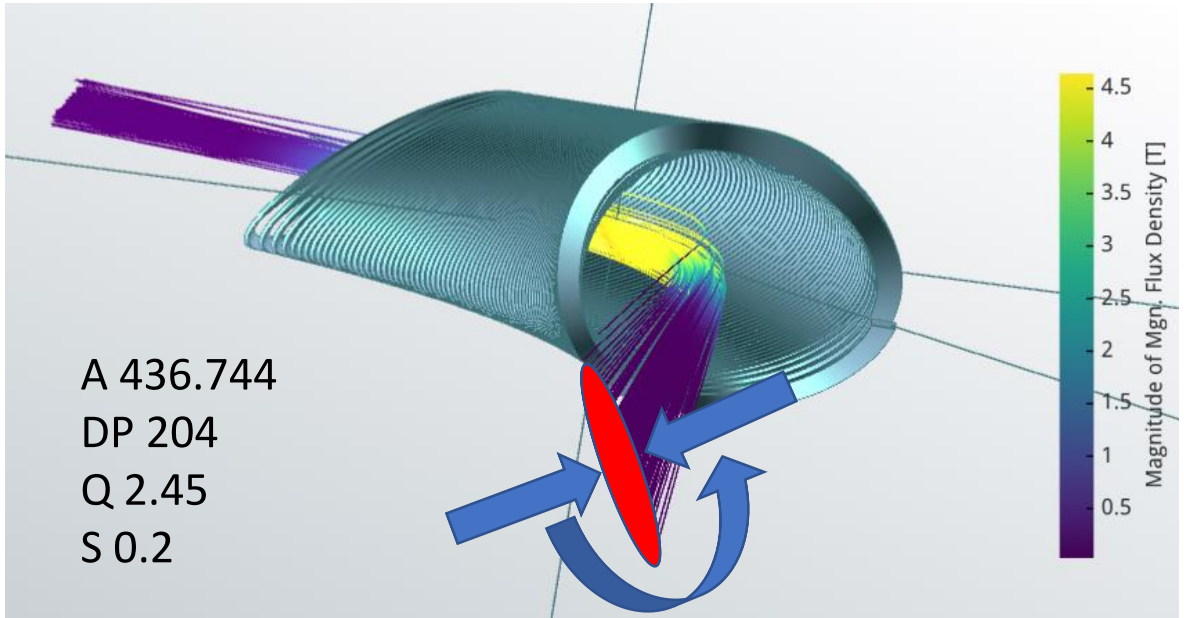


Dipole pushes beam round the corner.

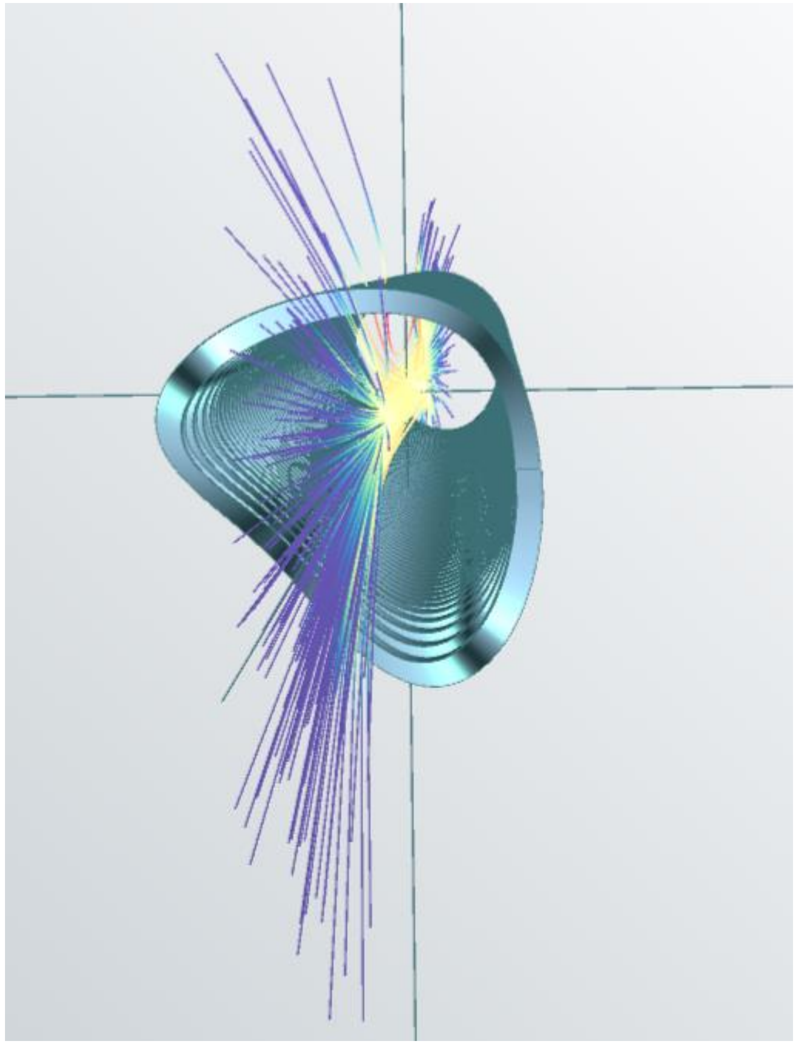
Two layers cancels the solenoid field

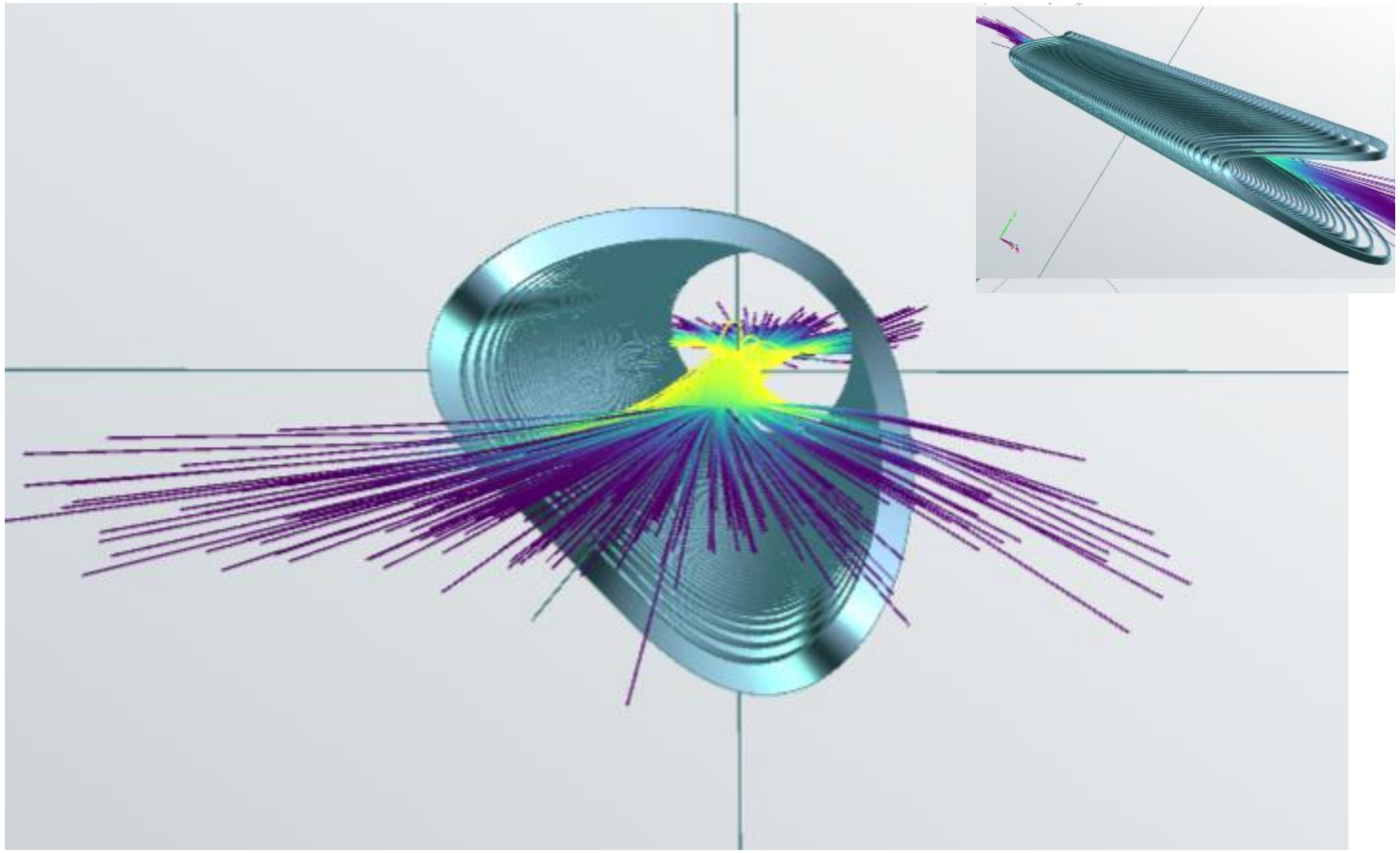
curvature adds other high order harmonics quadrupole + ...



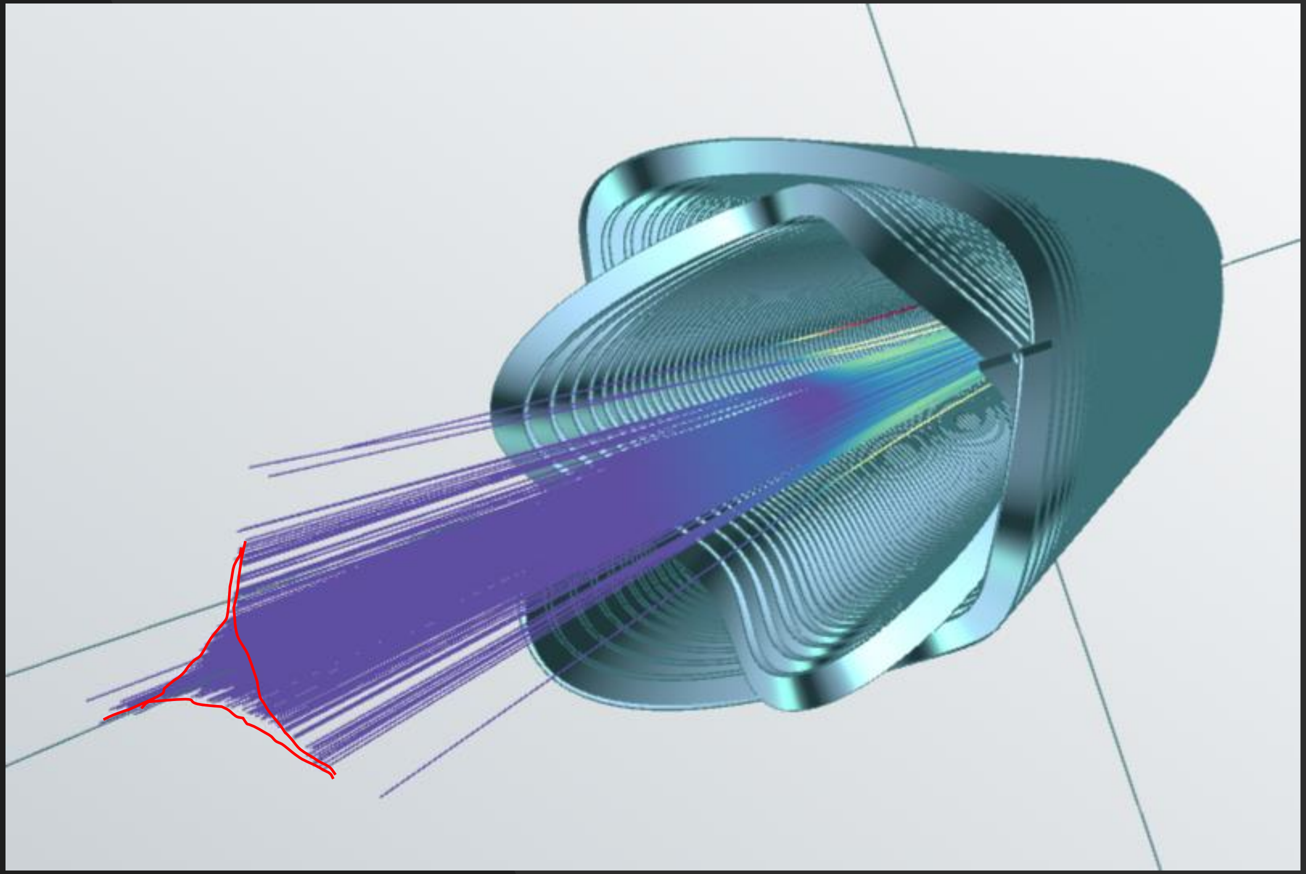


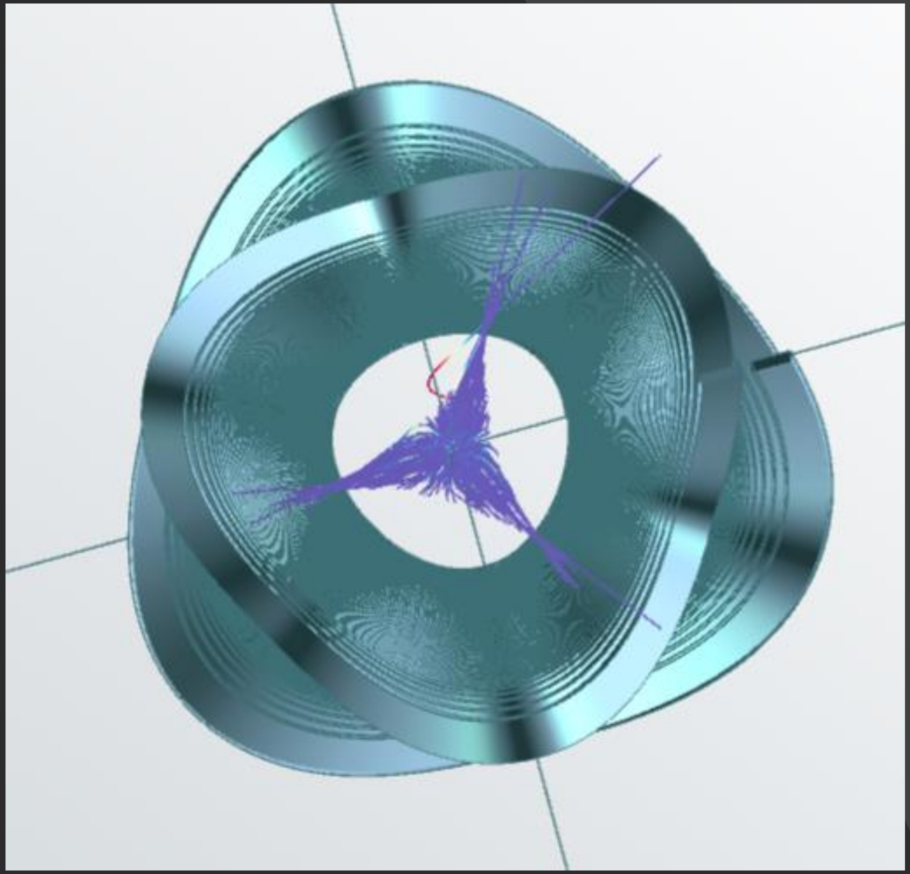
Quadrupole focuses in one plane
+ & - Current effect on beam rotates 90 deg.

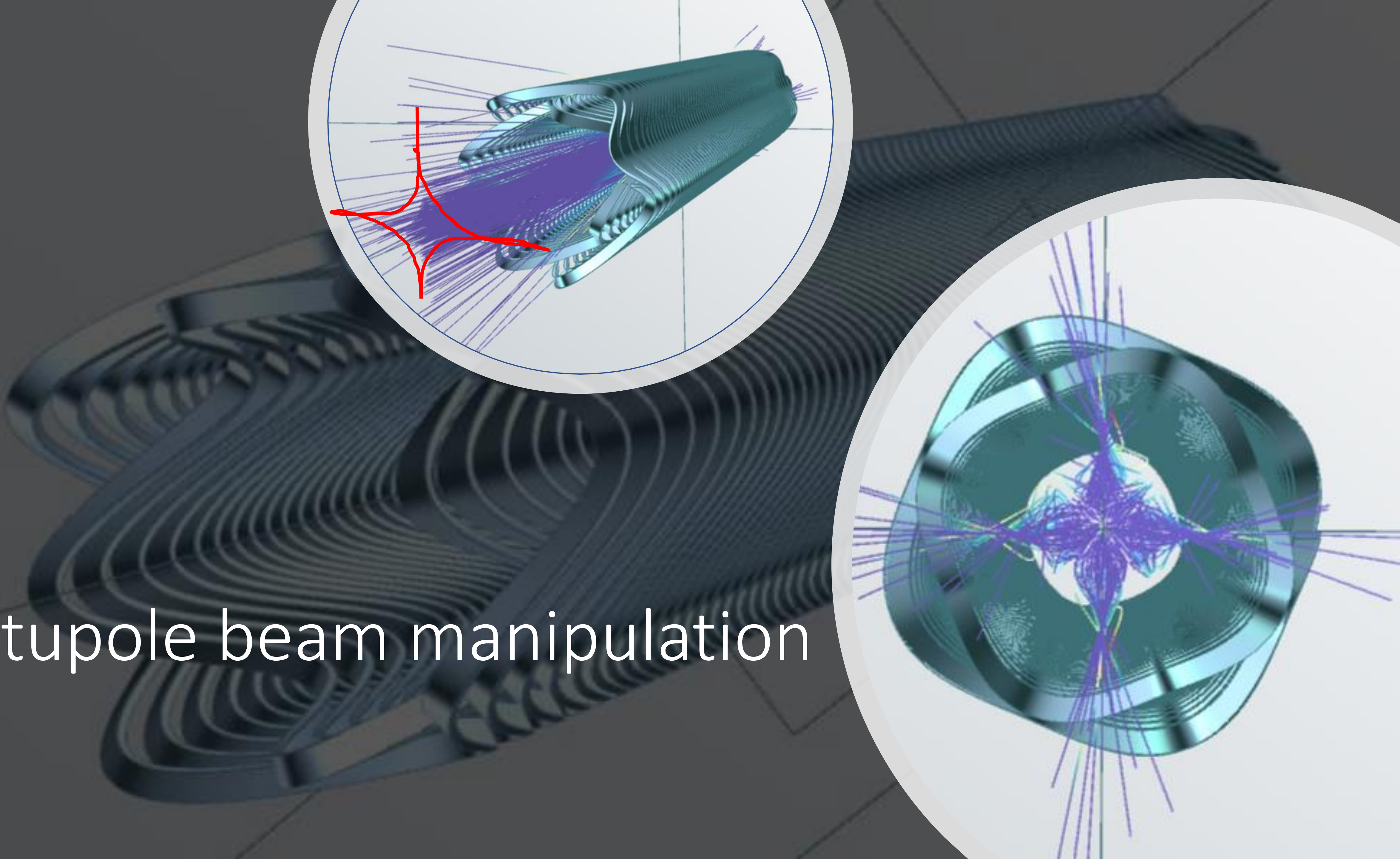




Sextupole beam manipulation

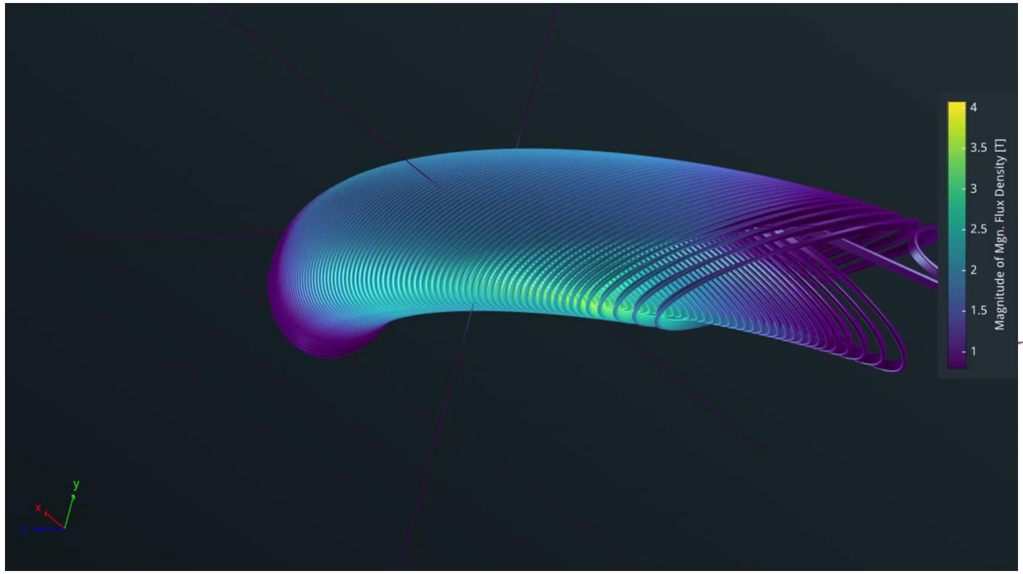


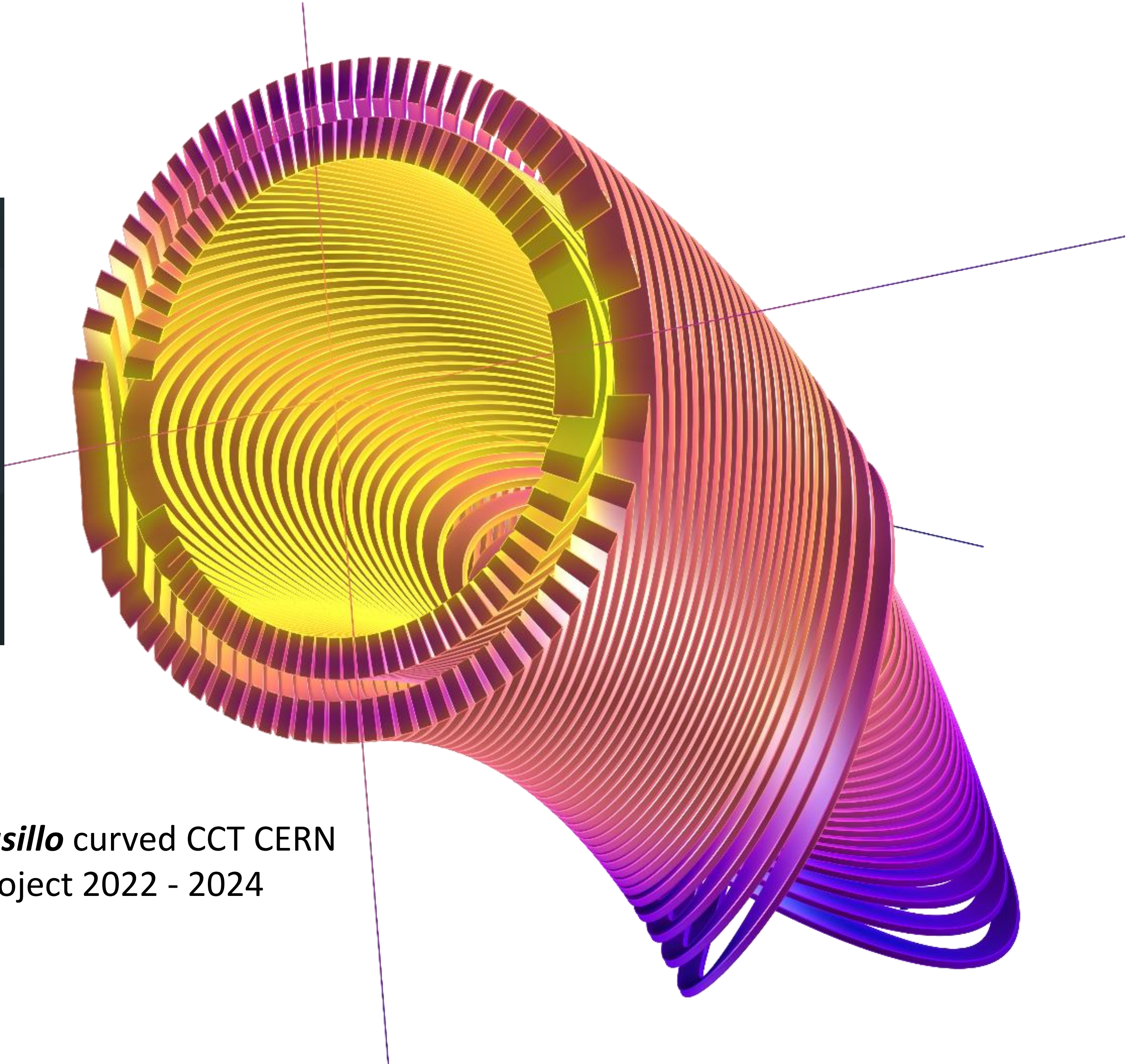




Octupole beam manipulation

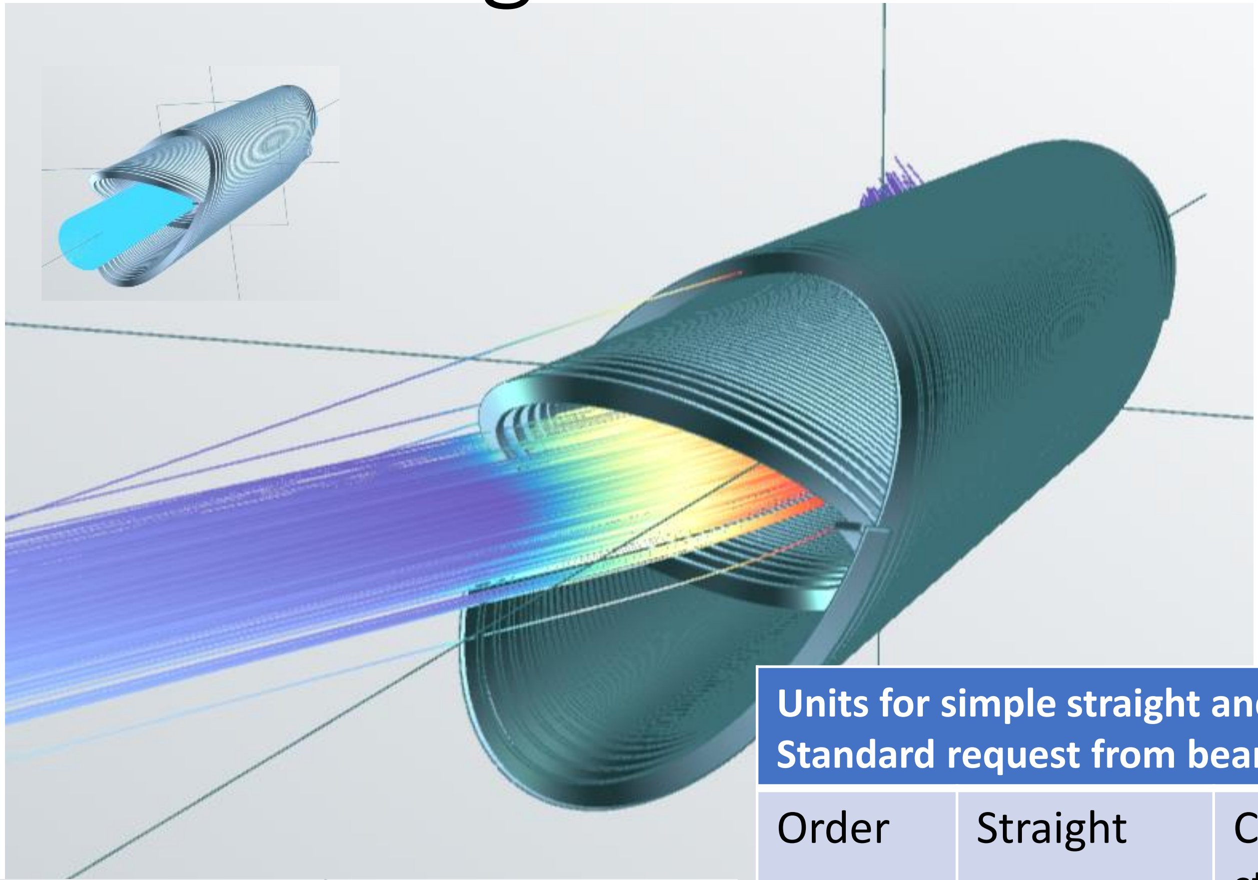
Design features

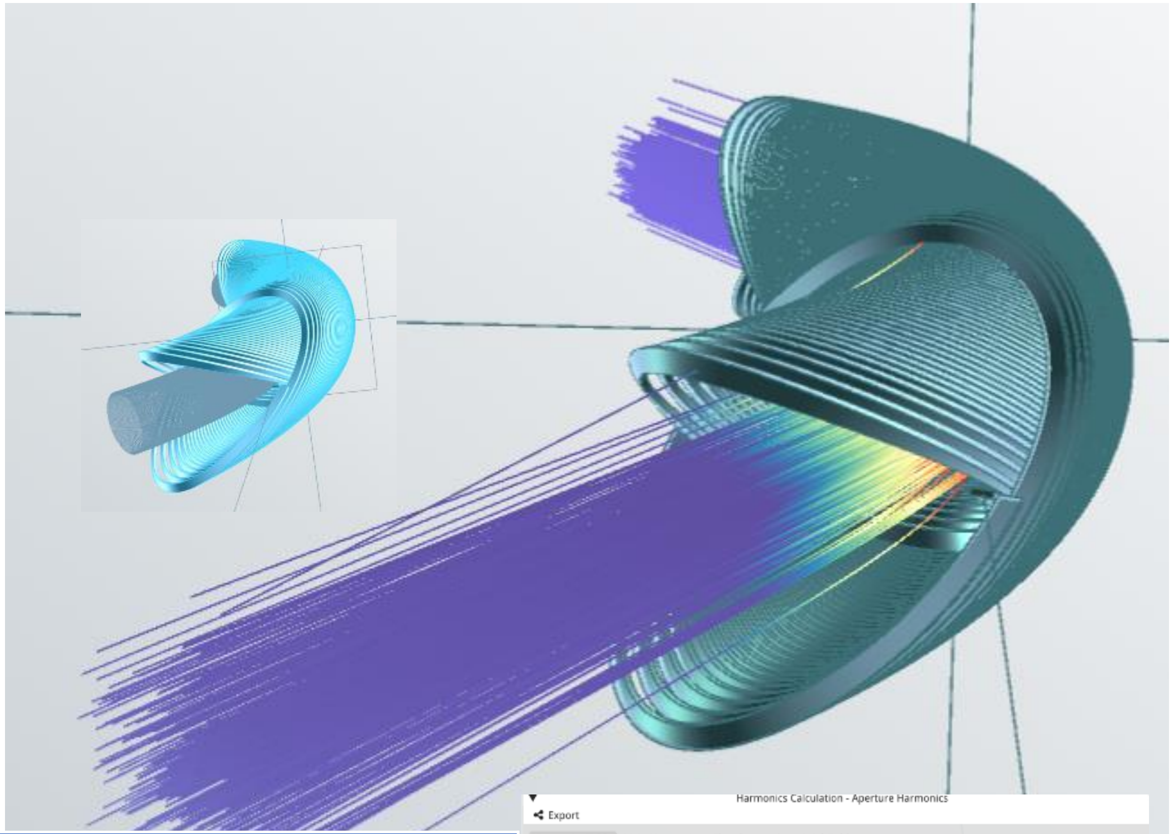




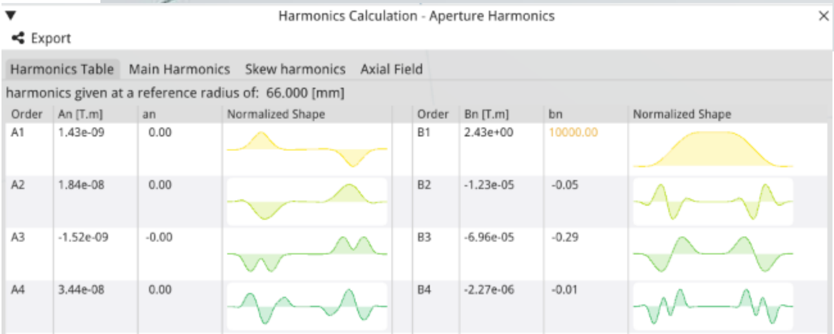
Fusillo curved CCT CERN project 2022 - 2024

Effect of tight curvature





Units for simple straight and curves coils 1571 mm Standard request from beam dynamics is < 10 units			
Order	Straight	Curved std calc	Curved compensated
B2	- 0.23	- 333	-1250
B3	-0.696	-3.36	7.66
B4	-0.0227	- 0.406	-0.294
B5		-0.0411	-0.029



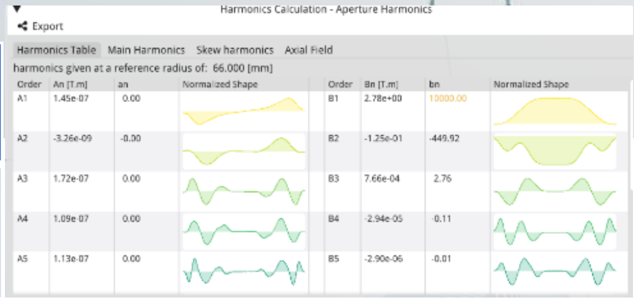
Harmonics Calculation - Aperture Harmonics

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	1.43e-09	0.00		B1	2.43e+00	10000.00	
A2	1.84e-08	0.00		B2	-1.23e-05	-0.05	
A3	-1.52e-09	-0.00		B3	-6.96e-05	-0.29	
A4	3.44e-08	0.00		B4	-2.27e-06	-0.01	



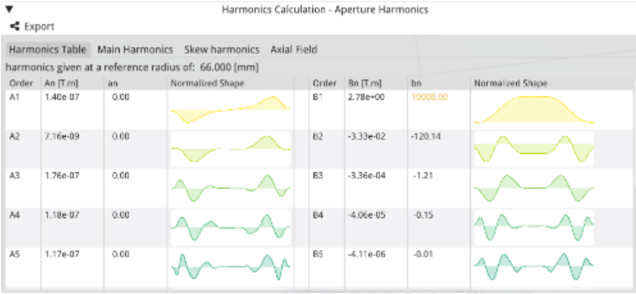
Harmonics Calculation - Aperture Harmonics

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	1.45e-07	0.00		B1	2.78e+00	10000.00	
A2	-3.26e-09	-0.00		B2	-1.25e-01	-449.92	
A3	1.72e-07	0.00		B3	7.66e-04	2.76	
A4	1.09e-07	0.00		B4	-2.94e-05	-0.11	
A5	1.13e-07	0.00		B5	-2.90e-06	-0.01	



Harmonics Calculation - Aperture Harmonics

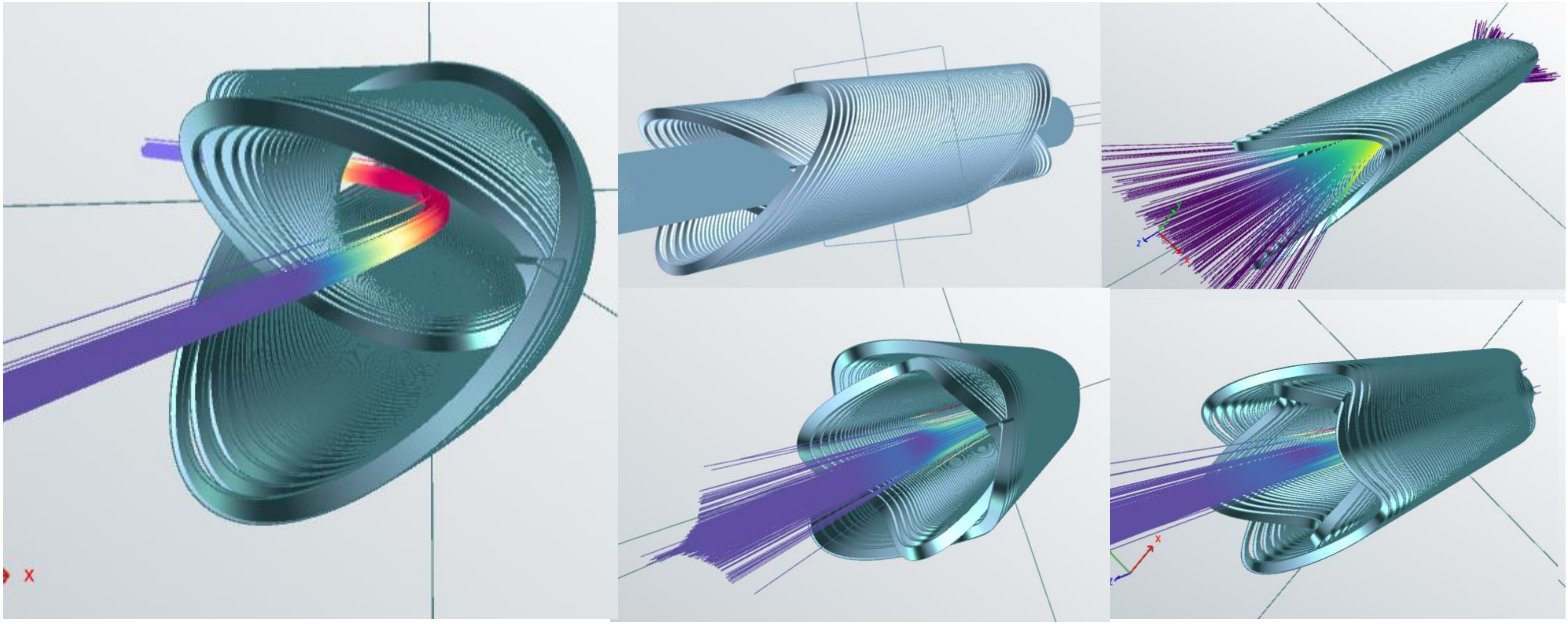
Export

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	1.40e-07	0.00		B1	2.78e+00	10000.00	
A2	7.16e-09	0.00		B2	-3.33e-02	-120.14	
A3	1.76e-07	0.00		B3	-3.36e-04	-1.21	
A4	1.18e-07	0.00		B4	-4.06e-05	-0.15	
A5	1.17e-07	0.00		B5	-4.11e-06	-0.01	

Adding all the coils shapes and more together into one optimized coil.



230 mm aperture , 1 m radii Curved CCT former weld and machining at CERN

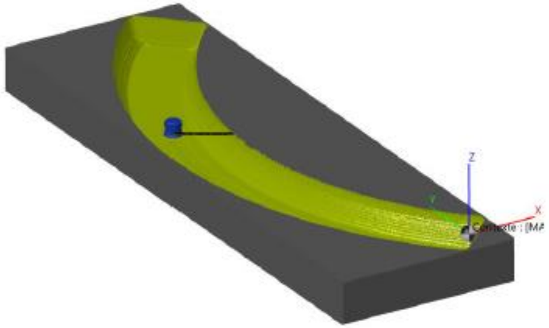


Figure 1 Half-shell interior roughing in bulk material

Figure 2 Half-shell exterior roughing

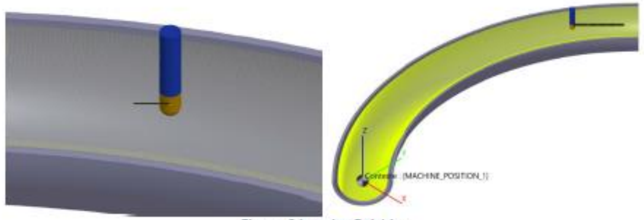


Figure 3 Interior finishing

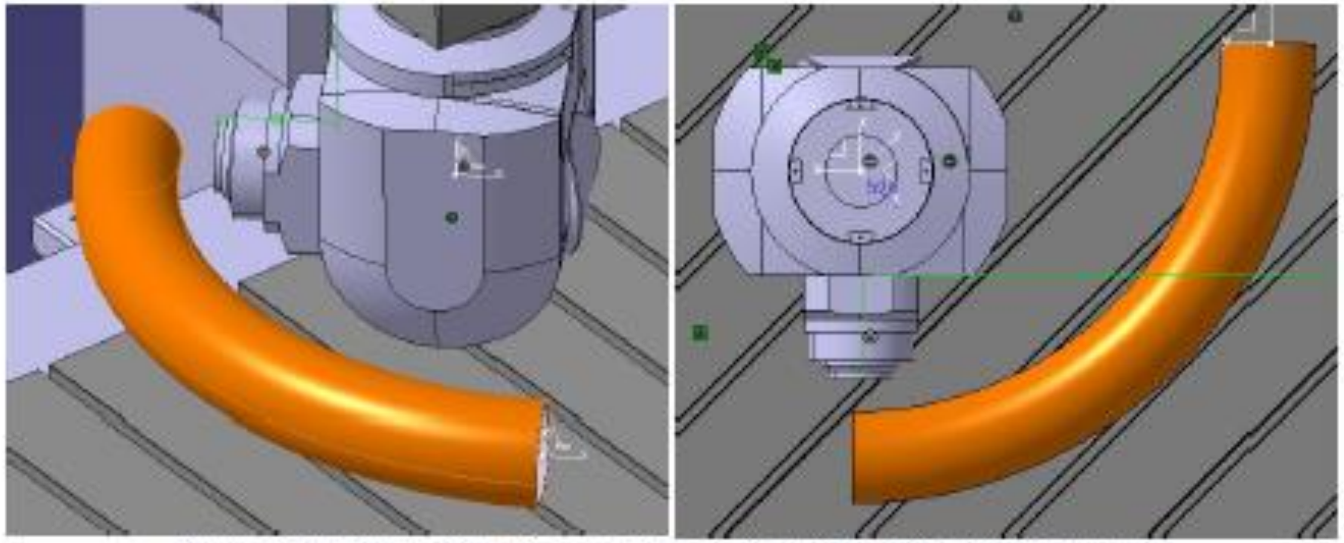
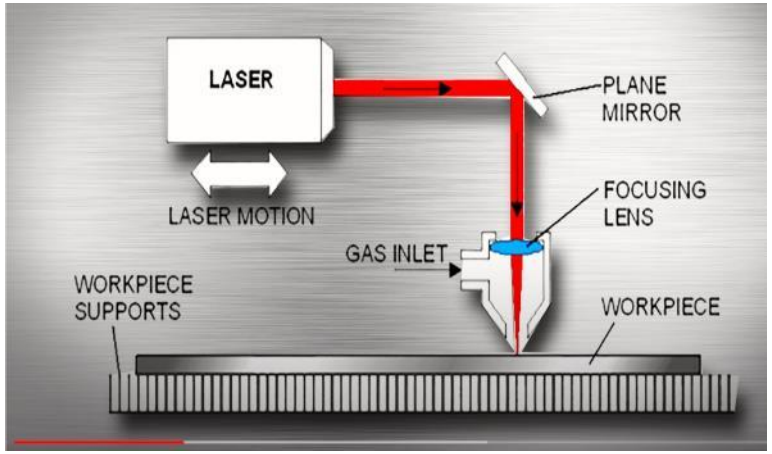
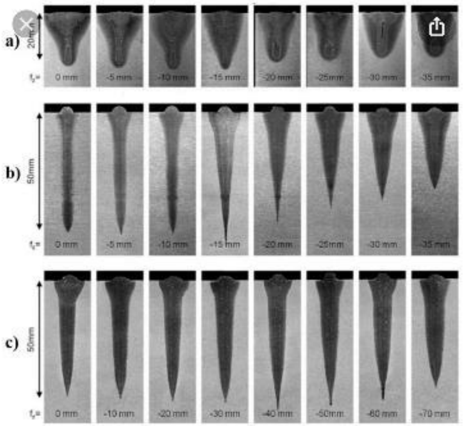
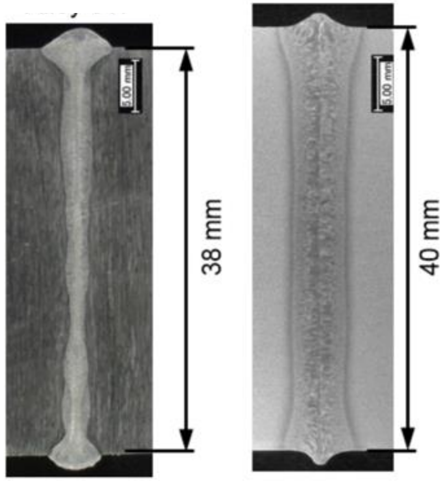


Figure 4 Configuration piece-machine spindle (Waldrich HF30 example)



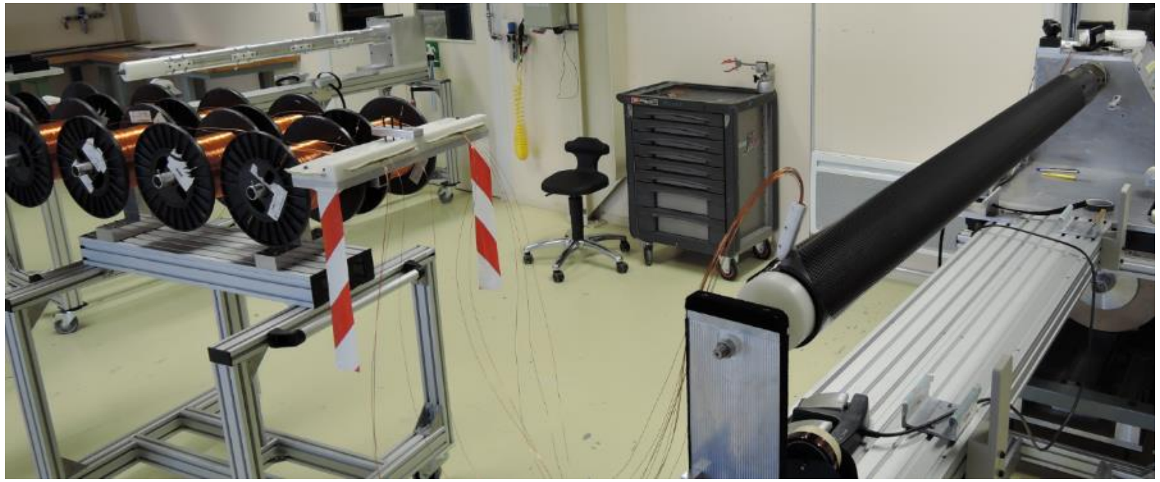


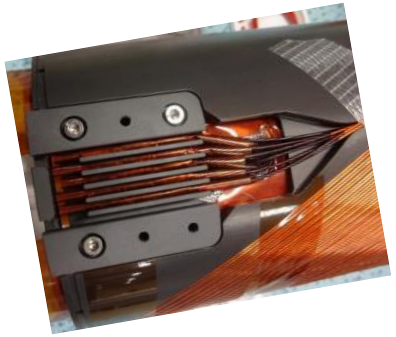


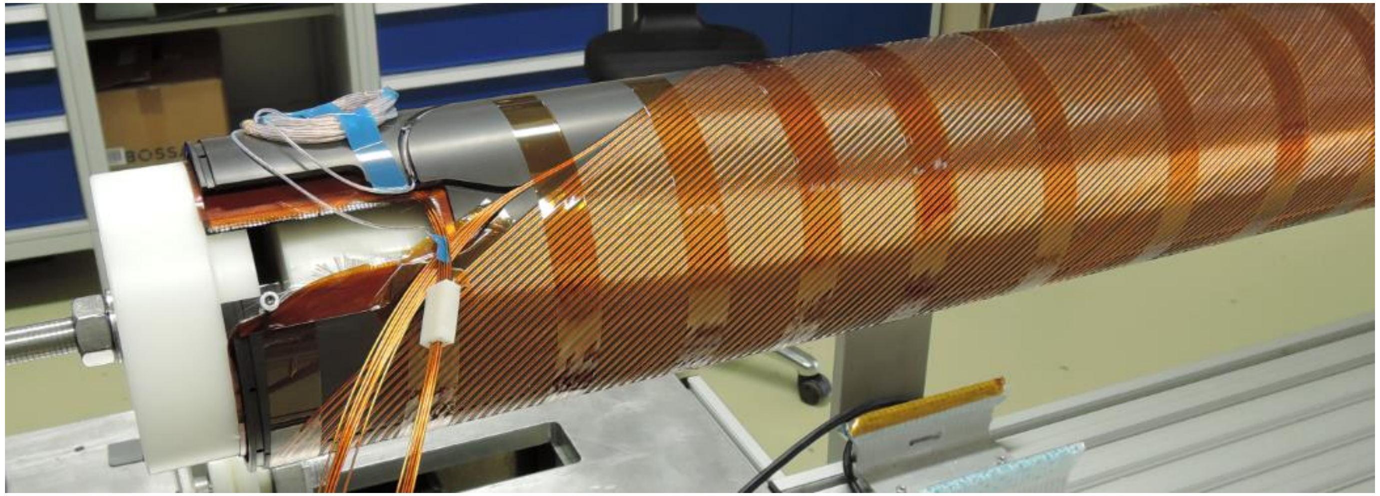
I. Winding

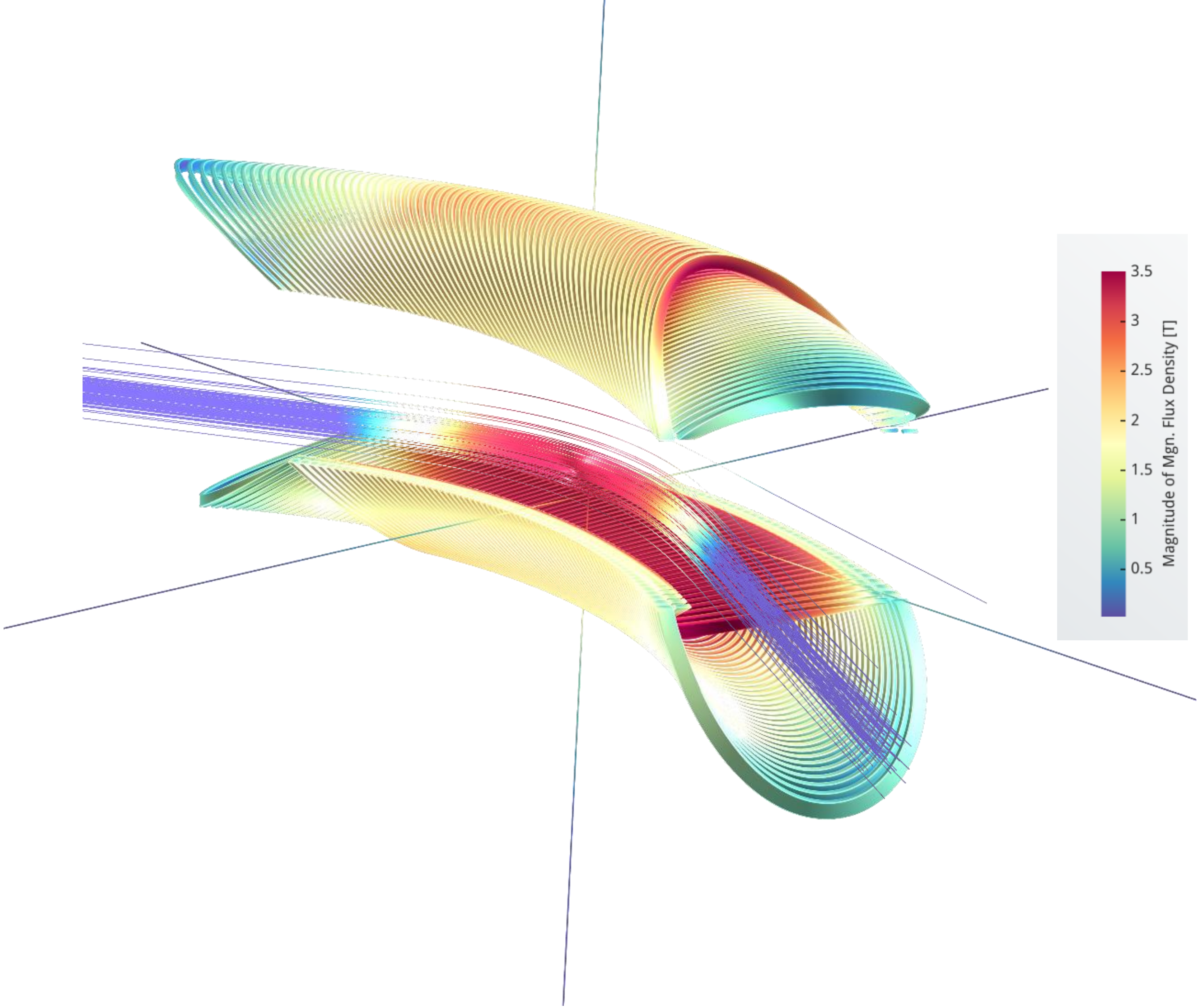
Winding- :

- Winding OUTER layer

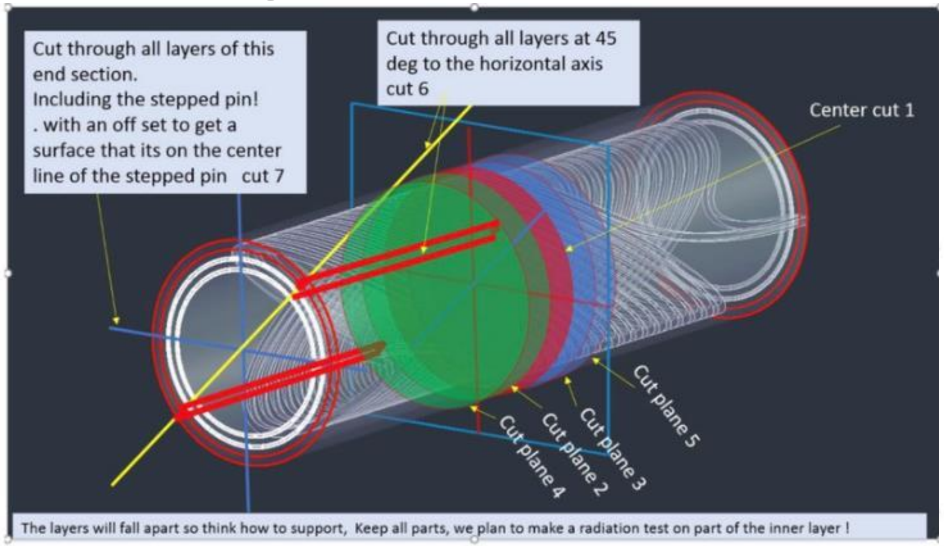


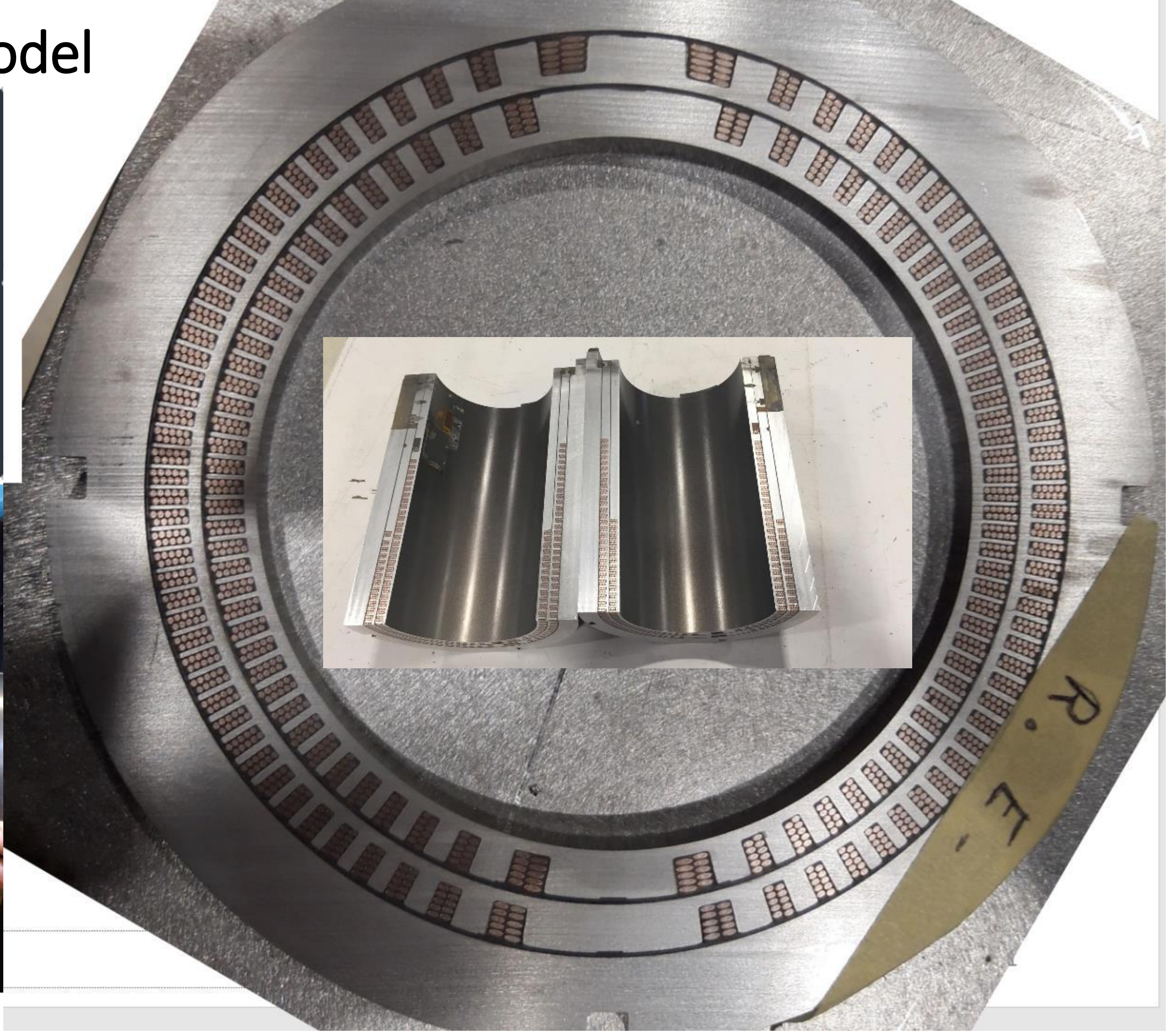





Magnitude of Mgn. Flux Density [T]
3.5
3
2.5
2
1.5
1
0.5

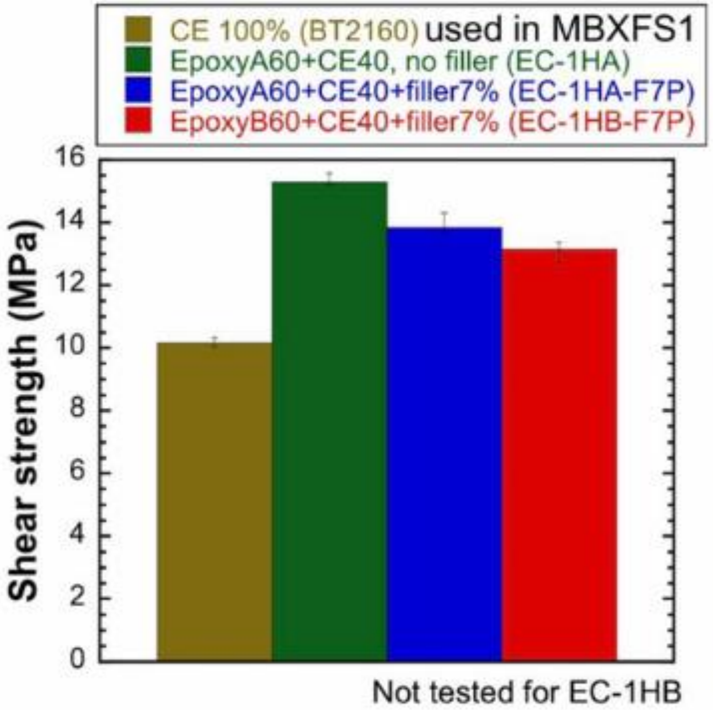
Looking inside the 0.5m model



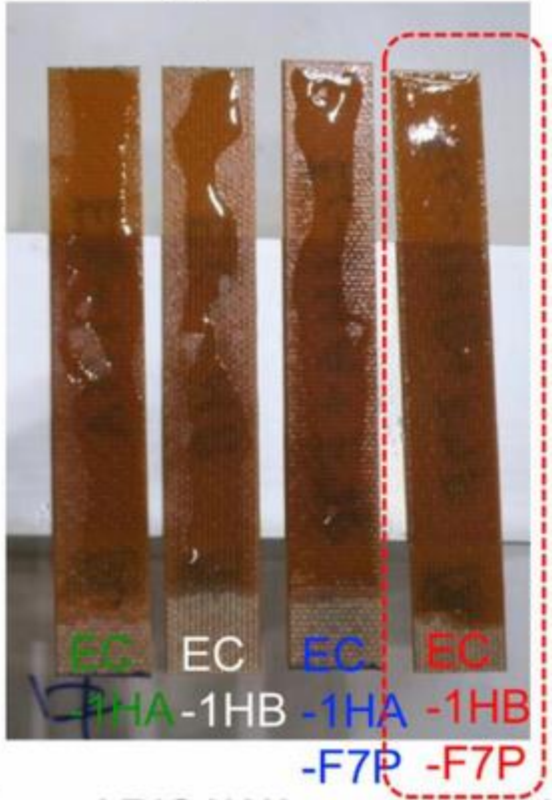


Wet-winding with epoxy-blended CE resin (A countermeasure against coil end deformation)

Shear strength



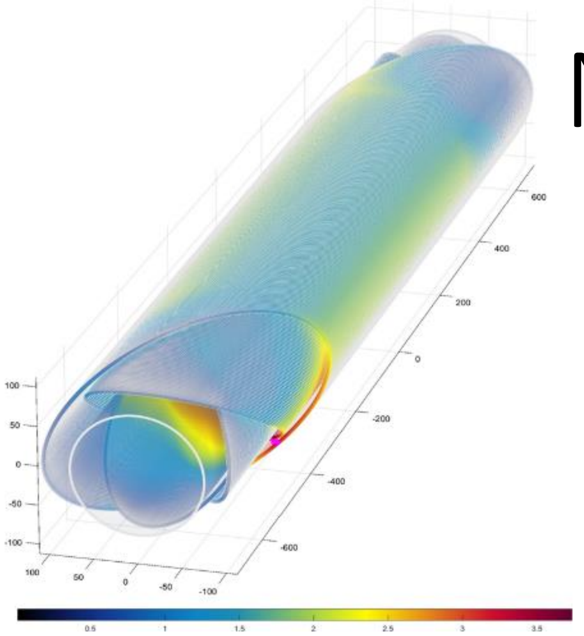
Painting test

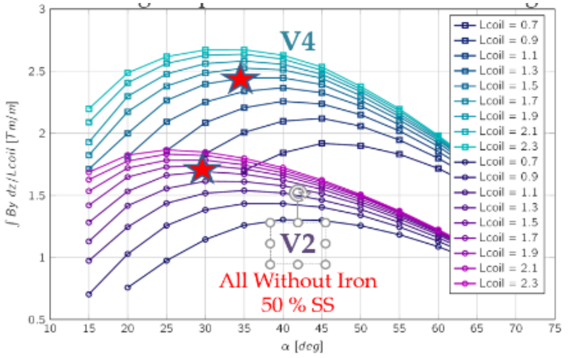


- Four kinds of epoxy-blended CE resins provided from ARISAWA were tested
  - Epoxy : CE = 60 : 40 for all resins
  - Viscosity: lower in epoxy A, higher in epoxy B
  - W or W/O filler (to control viscosity)

→ EC-1HB-F7P (Epoxy B + CE + 7wt% Silica filler) was selected from acceptable bonding strength with highest viscosity

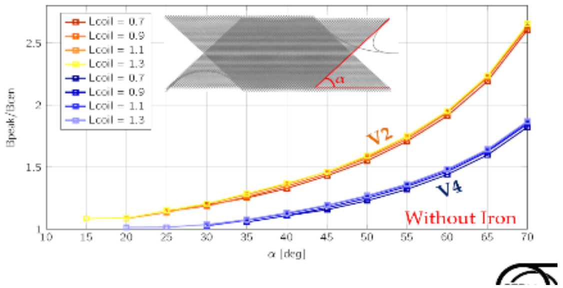
Nested CCT and Rad hard spacers ,

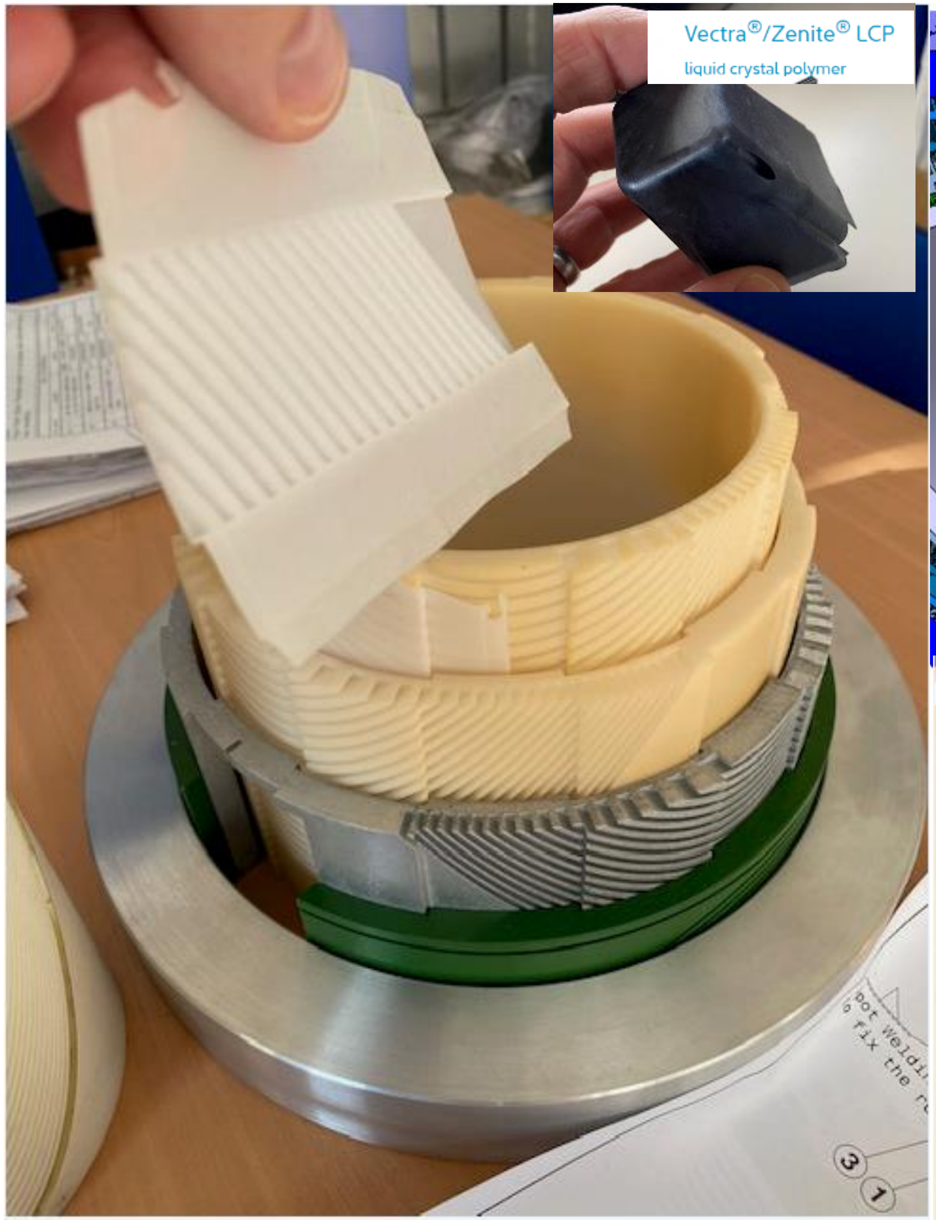


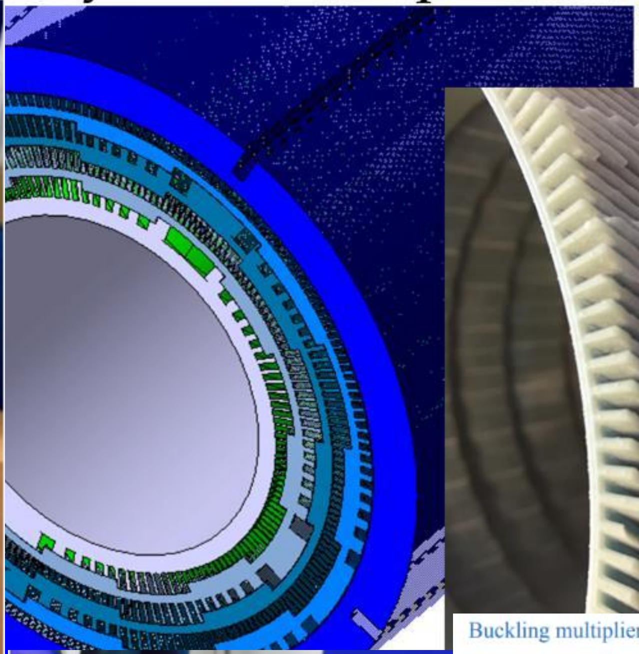


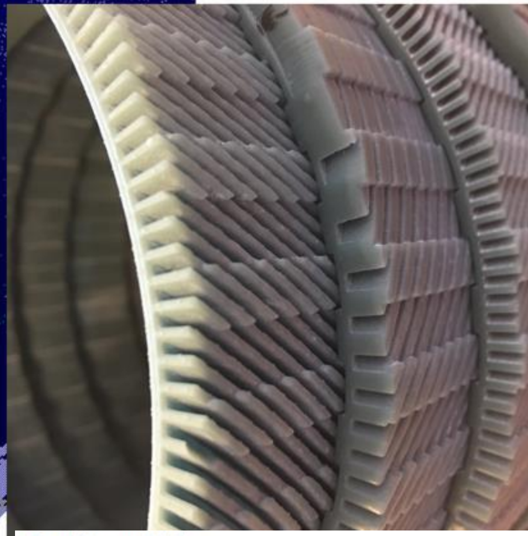
Skew Angle Influence

- Ratio Bpeak/Bcen depends on skew angle and # of layers







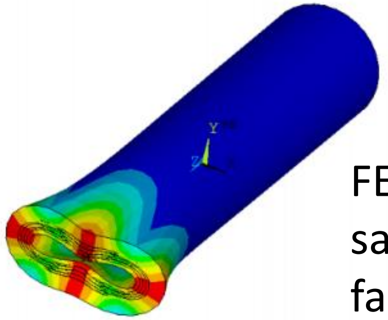


Buckling multipliers

SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	1.5556	1	1	1
2	1.7894	1	2	2
3	1.9806	1	3	3

1st buckling multiplier 1.55, so the structure is s

1st buckling mode shape



FEA safety factor 1.55

You
added an **update**

Mar 22, 2018

Damaged Former : (. and it’s repair ! : j

One of the inner 2.2 m cct formers was damaged during mounting into the hard Anodization tank. A second problem was encountered when too high current melted the connection point.

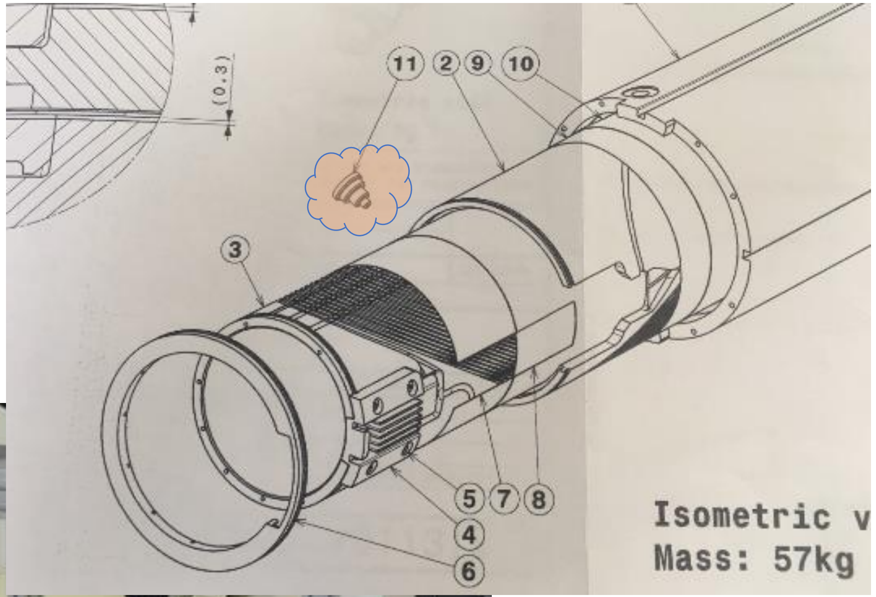
We repaired the damaged channel section, thanks to the main cern machine shop team.

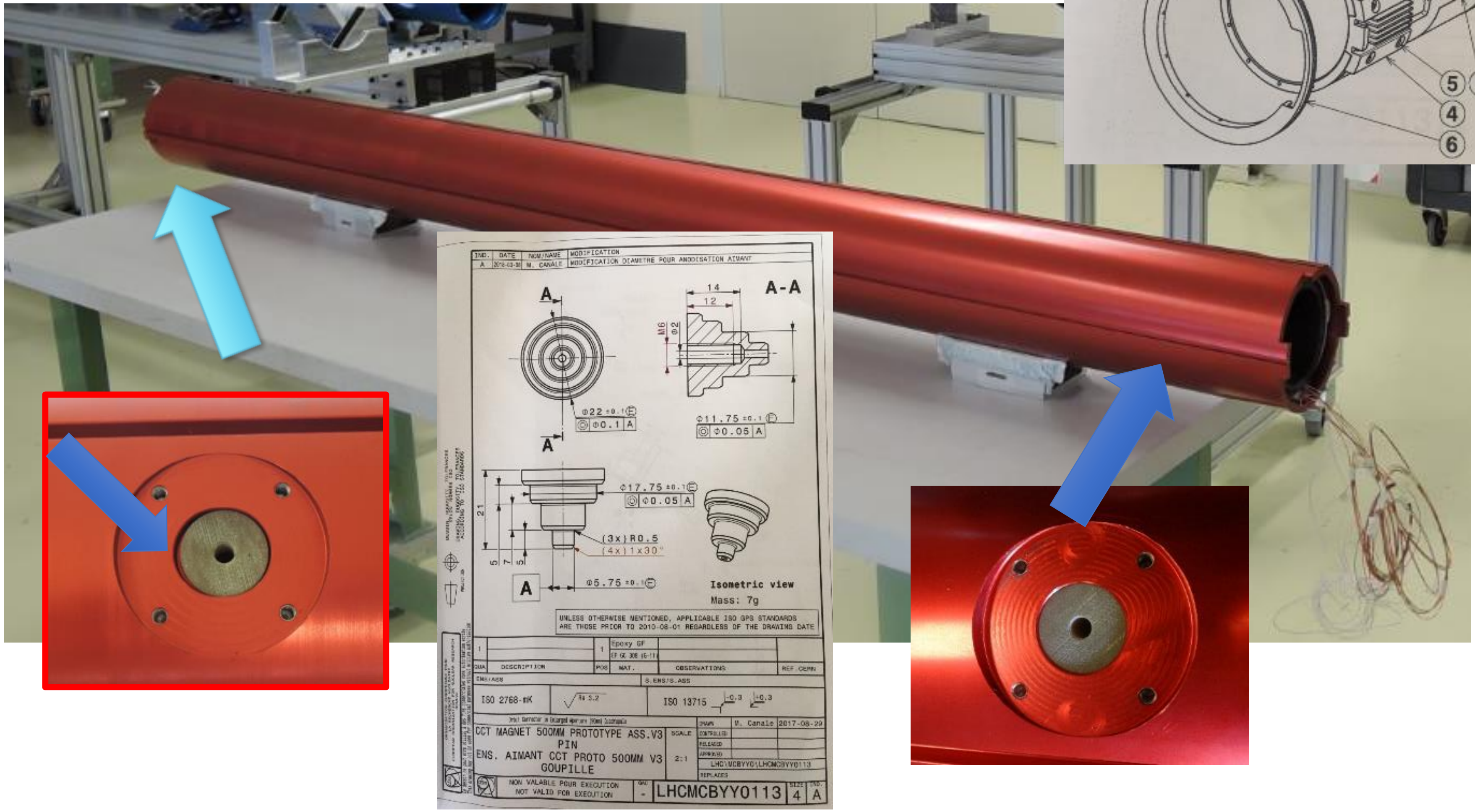
Look for the picture on the initial repair.

Winding

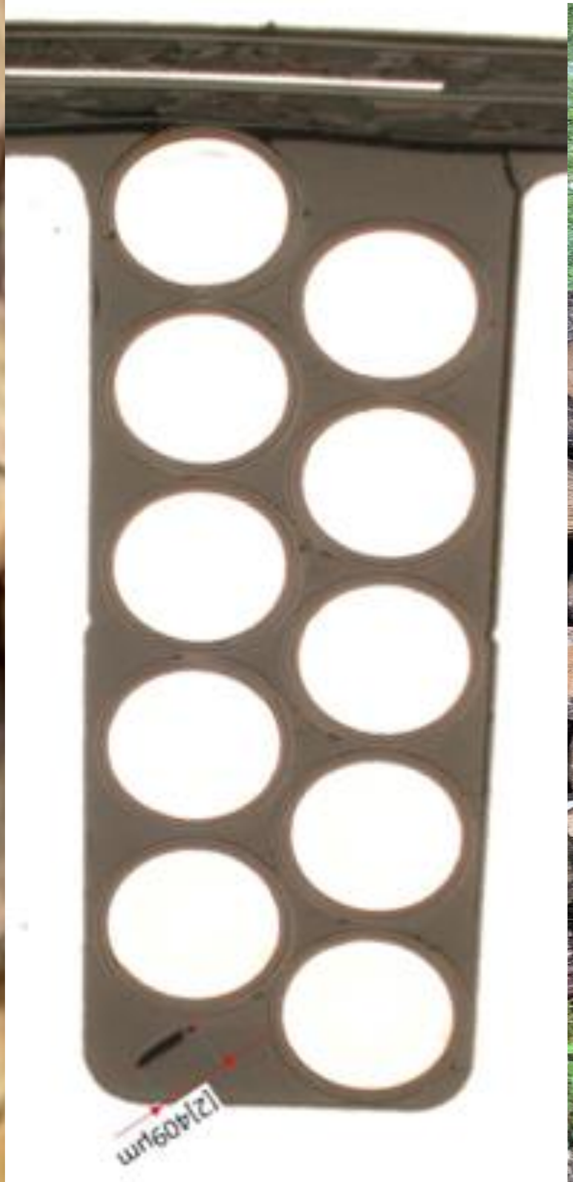
Winding- Assembly EXTERNAL tube :

- Pin for initial alignment



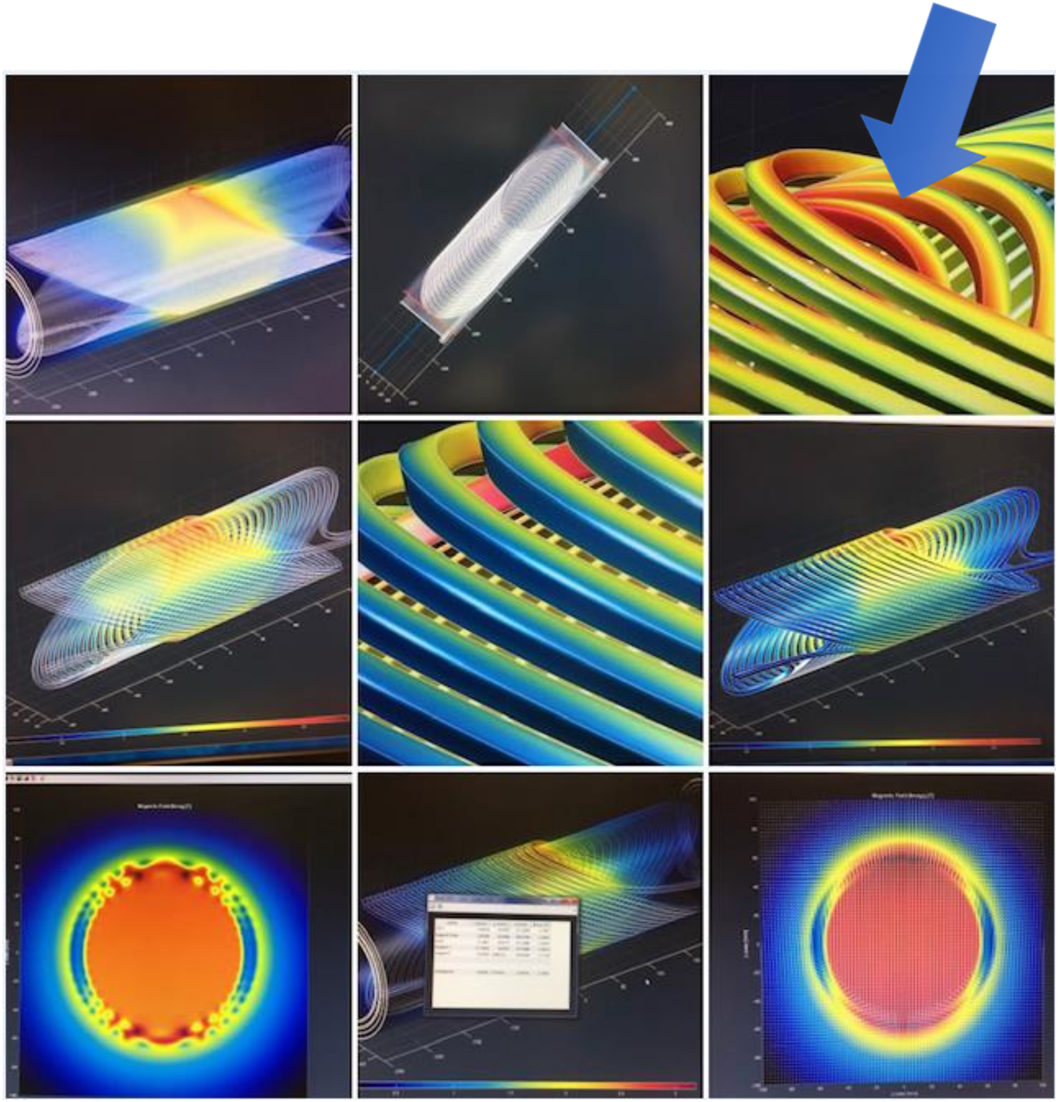


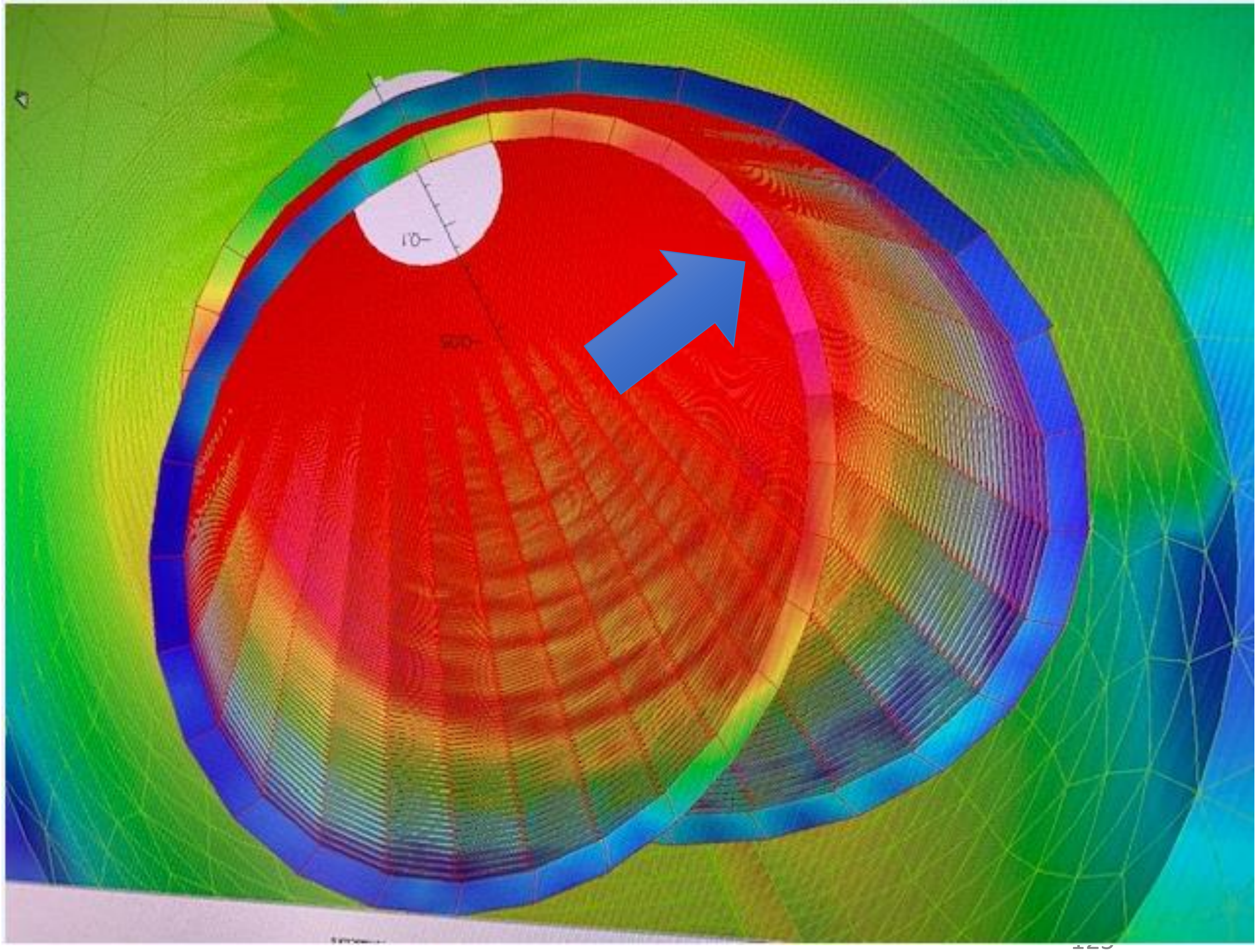
Stable Stacking



We should consider designing the coil to have an inherently stable stacks!

MCBRD CCT 2-layer Max Field is between layers at the ends





	d strand =	1	mm
	# strands in ropes =	7	
4.6 start	twist pitch factor f =	5	
	D rope dia	3	
	twist pitch d x f=	5	mm
	r	1.5	
	a	2.5	
	r/a	0.6	
	angle twist=	**30.96**	**deg**

for 7 strand ropes with insulated strands, powered in serise

6 strans producing	85.75%	effective rope current
1 strand producing	100.00%	effective rope current
total effective rope current =	87.79%	
	12.21%	

Extra current to produce requiared field in magnet using rope with 6 round 1 layout with this twist pitch.

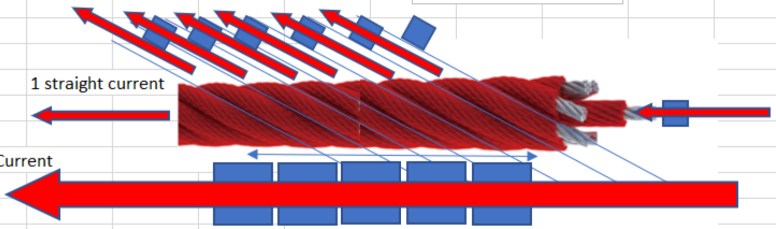
Current in strand needed to produce rope current

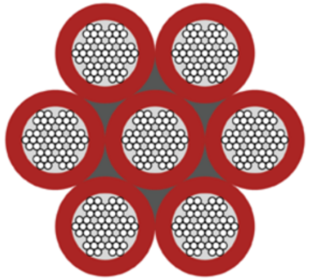
116.62%

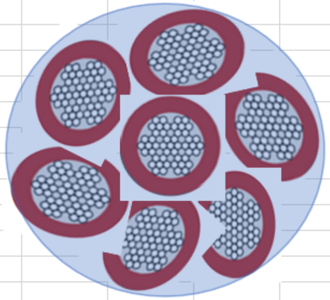
100% rope current

effective current in rope for strands that twist

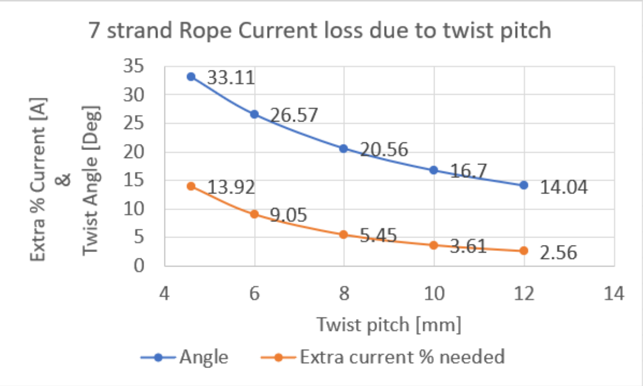
Twist Pitch	Angle	Extra current % needed
4.6	33.11	13.92
6	26.57	9.05
8	20.56	5.45
10	16.7	3.61
12	14.04	2.56



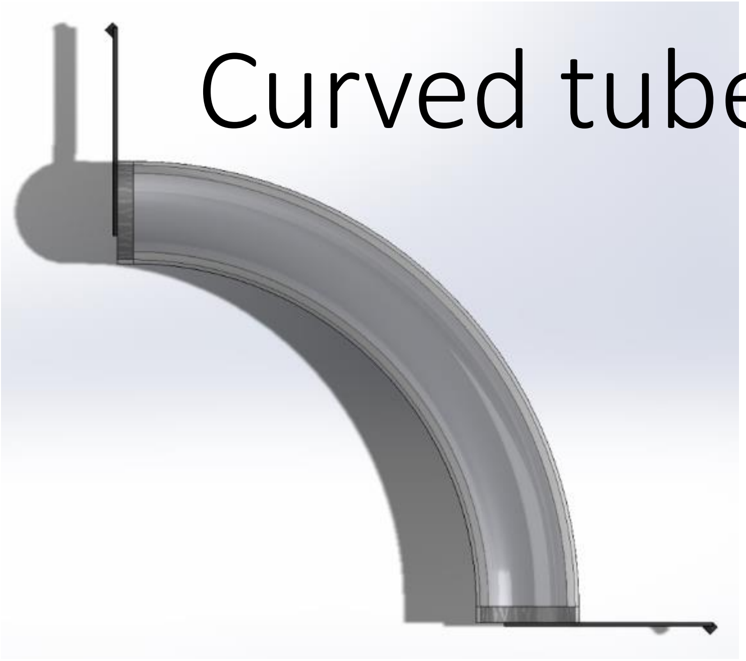


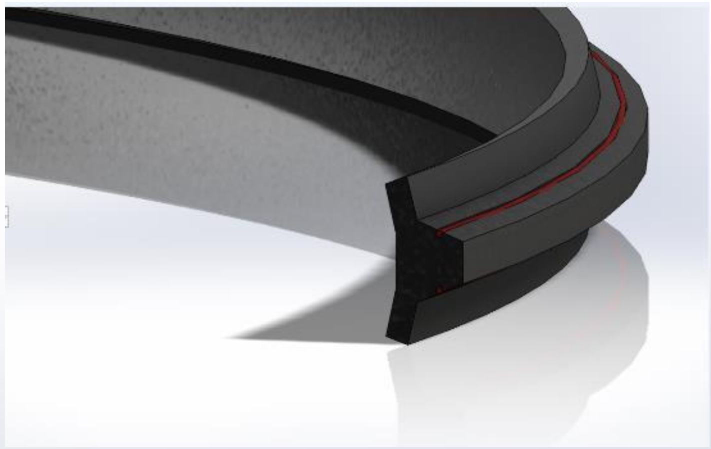


Rope cross section is not a set of circules !



Curved tube manufacture in GRP





We can make curved GRP tubes on a reusable mandrel!

This produces an accurate inner tube surface!!

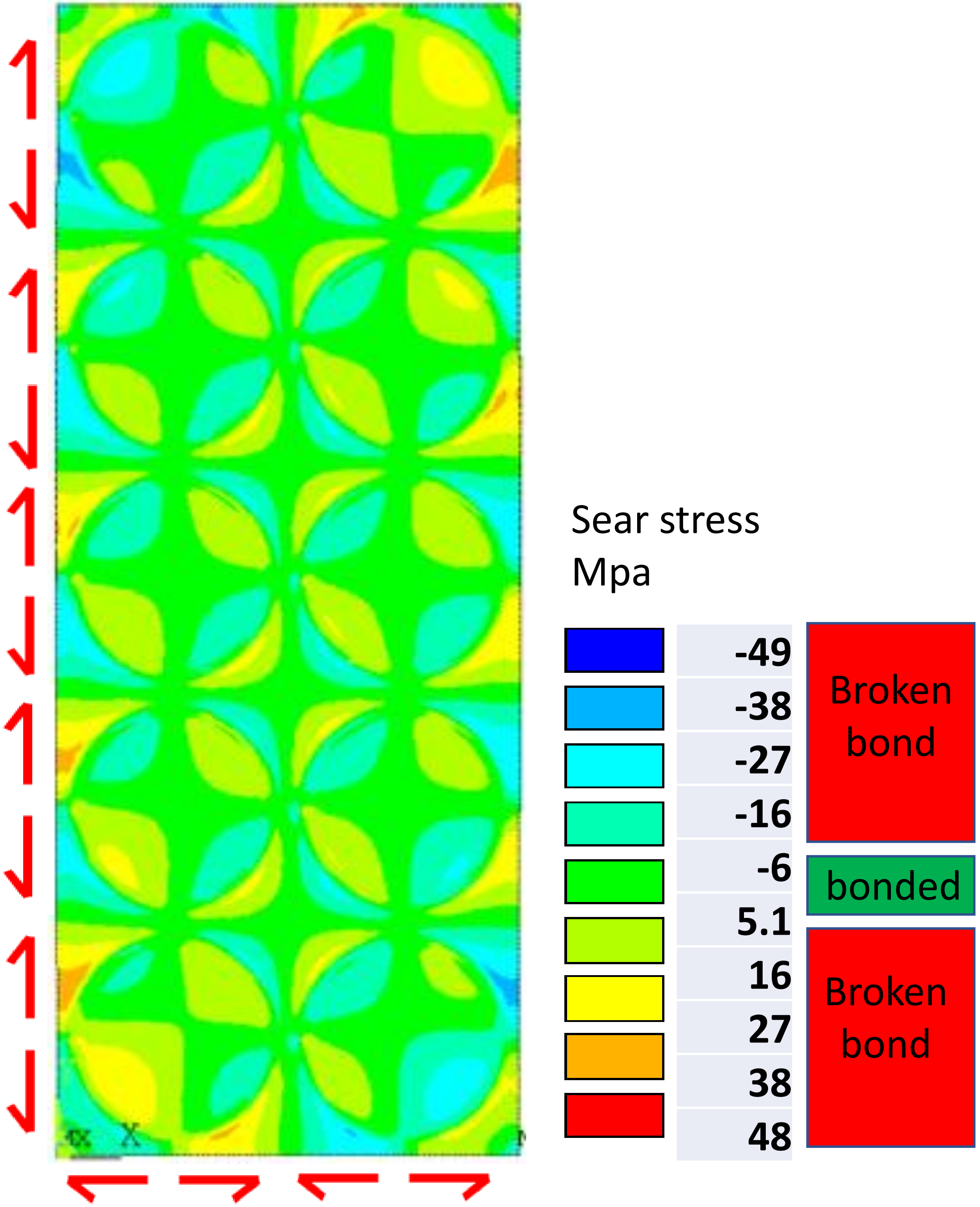
The magnet cost can be reduced significantly < $$$
For subsequent magnets!

Shear Stress at 4 K
No magnetic stress yet

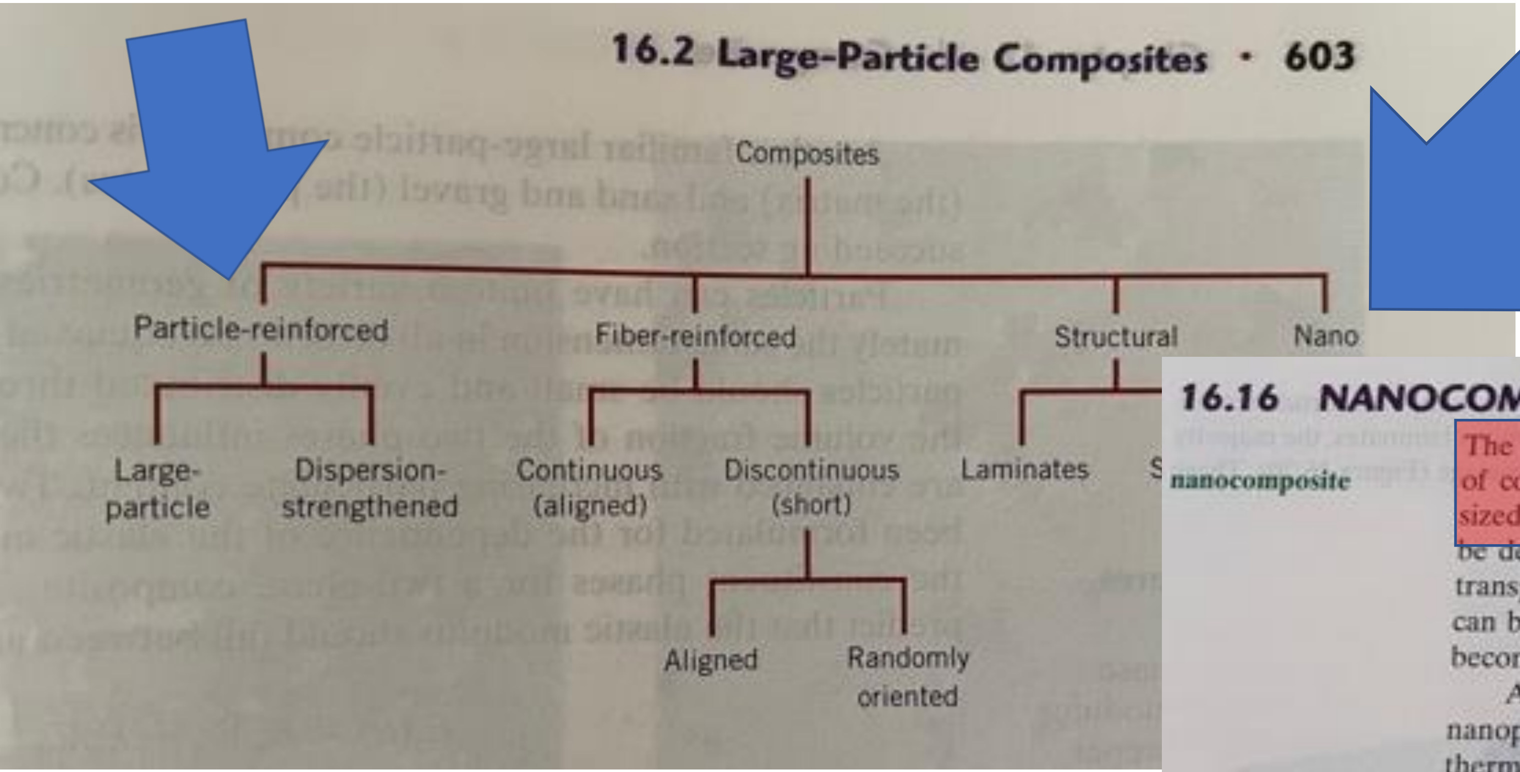
The bonds brake, at the surfaces of the insulated wire and at the channel walls with ~ 5 MPa in shear

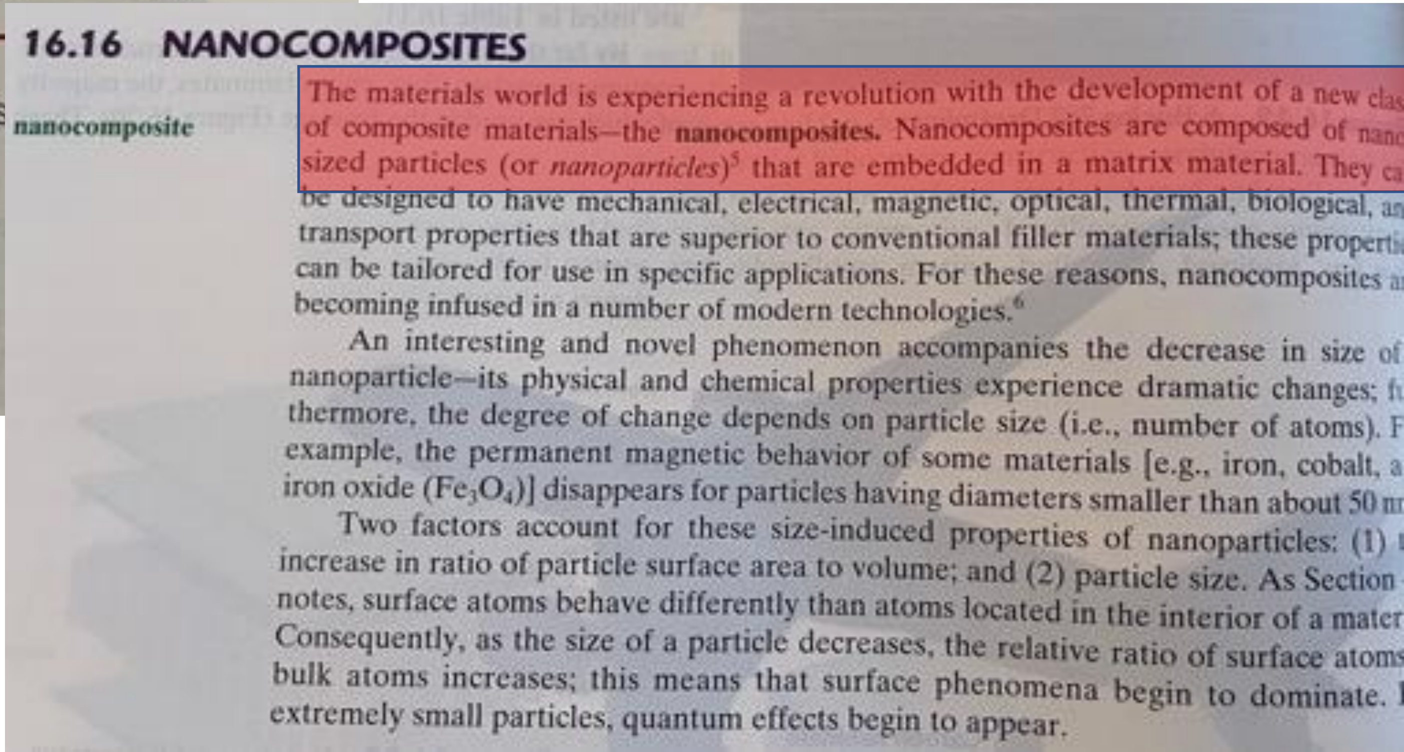
At 4 K with the CTD101K we see 20 to 30 MPa

The we expect the bonds to start to be broken. In some places and not in others.



Composites family





16.16 NANOCOMPOSITES

nanocomposite

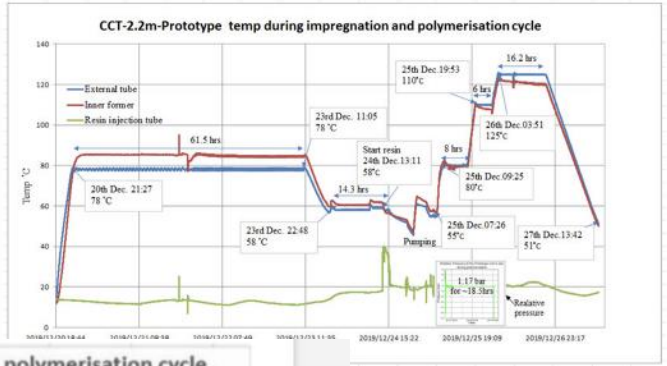
The materials world is experiencing a revolution with the development of a new clas of composite materials—the **nanocomposites.** Nanocomposites are composed of nano sized particles (or *nanoparticles*)[5] that are embedded in a matrix material. They ca be designed to have mechanical, electrical, magnetic, optical, thermal, biological, an transport properties that are superior to conventional filler materials; these properti can be tailored for use in specific applications. For these reasons, nanocomposites a becoming infused in a number of modern technologies.[6]

An interesting and novel phenomenon accompanies the decrease in size of nanoparticle—its physical and chemical properties experience dramatic changes; fu thermore, the degree of change depends on particle size (i.e., number of atoms). F example, the permanent magnetic behavior of some materials [e.g., iron, cobalt, a iron oxide (Fe_3O_4)] disappears for particles having diameters smaller than about 50 n

Two factors account for these size-induced properties of nanoparticles: (1) increase in ratio of particle surface area to volume; and (2) particle size. As Section notes, surface atoms behave differently than atoms located in the interior of a mater Consequently, as the size of a particle decreases, the relative ratio of surface atoms bulk atoms increases; this means that surface phenomena begin to dominate. extremely small particles, quantum effects begin to appear.

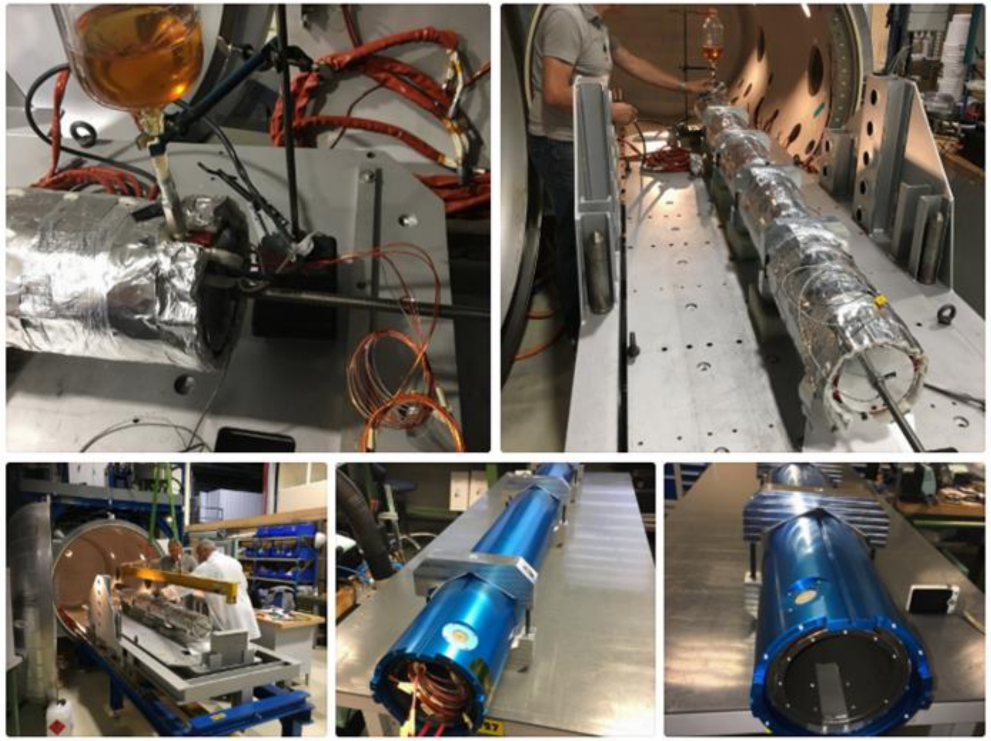
Development ideas

Impregnation 2 to 5 bar over pressure



You
added an **update**

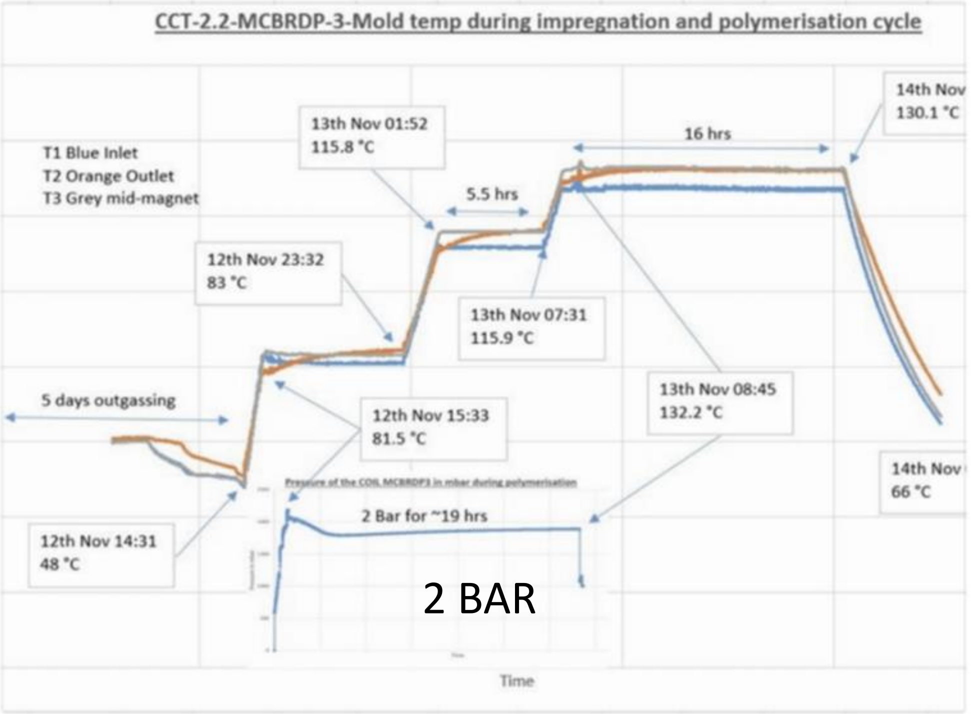
Jun 18, 2018



Impregnation of first long aperture & 2nd waiting

The resin filed the coil in 1hr 5 mins. A press of 2 bar was applied without any leak. 4 kg in total of resin was in the system. With about 3.5 kg in the magnet. We will increase the volume for the next apertuer.

The 0.5 m model filled in 55mins.



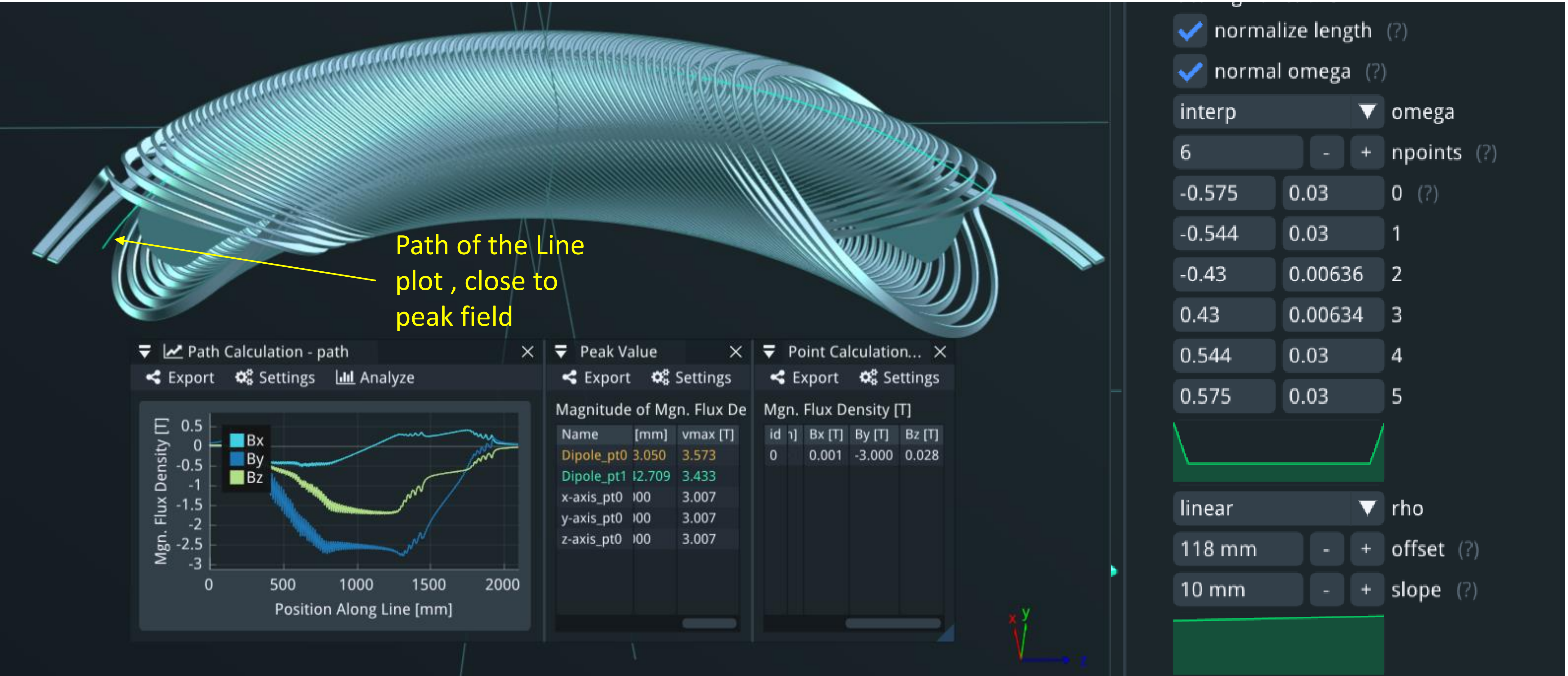
CCT 3 Impregnation: Temperature and Pressure Plot.

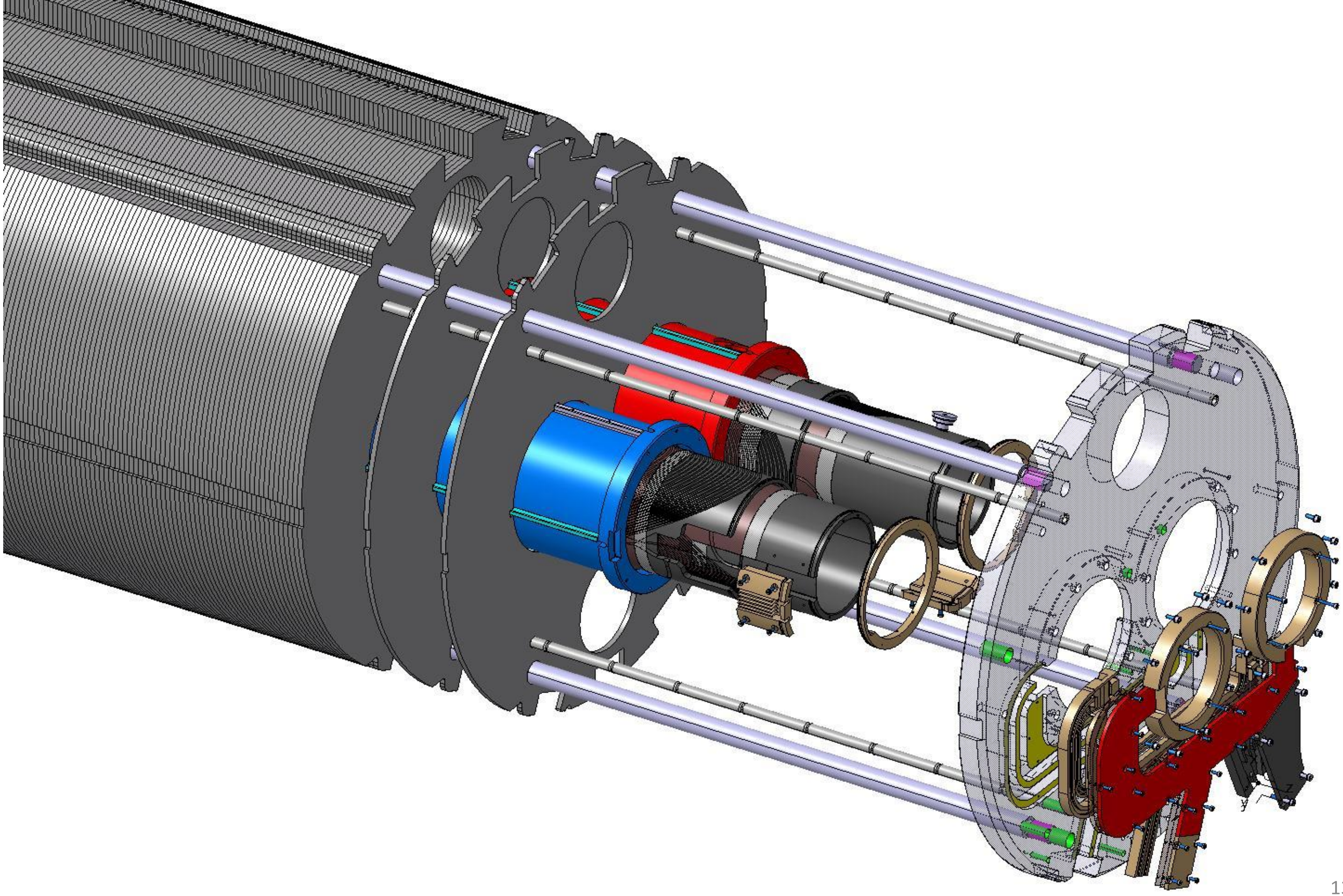
The attached plot gives the overview of the temperature and pressure profile during impregnation.

Cutting tool 5 deep to 1 wide ratio of channel

Min wall 0.3mm with 2mm wide channel

Peak field reduction at end in coil!!! *The important one !*
By pitch increase in last few end turns ,



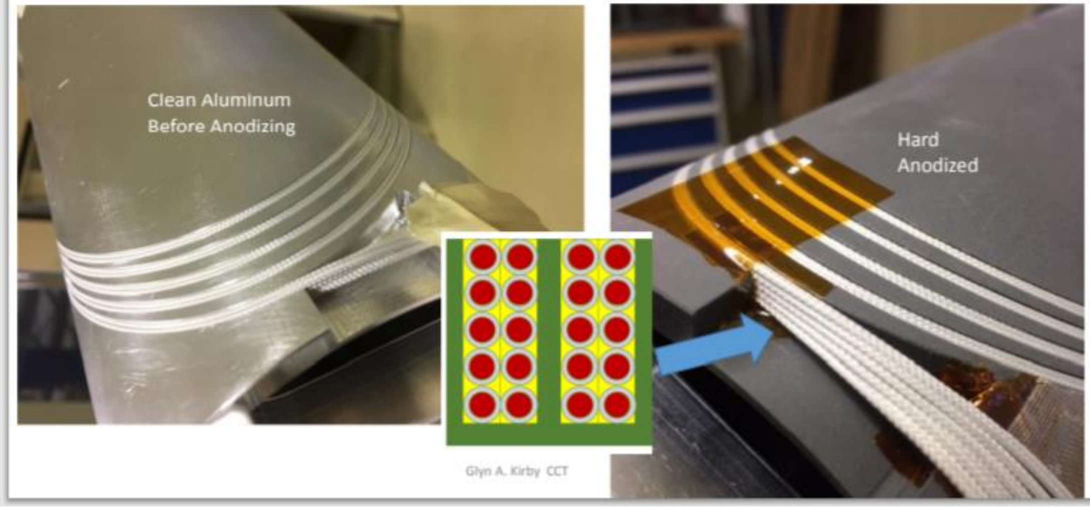


Insulation system

LHC dipole Nb-Ti wire 0.825 dia   1.95:1 Cu:Sc with PVA or PEI. Enamel coating, then S2 Class 0.05mm thick sleeve, Resin Impregnated. Former Hard anodized.

10 joints ,in 2 layer joint boxes at both ends

2 x 5 wire coil, Hard Anodized former
this is part of the ground insulation design



Vacuum bag impregnation of 2x5mm model

Some interesting resin data

CTD101G
But would need to be wet wound as Bama did !

TABLE II

PITTING COEFFICIENTS FOR EPOXIES

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

Substance	a	b	c	d	e	f
Accura 25	-12.70	4.43e-03	1.55e-04	-4.31e-07	2.35e-09	-3.89e-12
[illegible] 48	-11.30	7.07e-04	2.18e-04	-7.82e-07	2.63e-09	-3.41e-12
Araldite [illegible]	-12.00	4.05e-04	2.37e-04	-8.51e-07	2.86e-09	-3.76e-12
Bluestone	-5.97	1.98e-03	1.11e-04	-5.42e-07	2.13e-09	-2.90e-12
CTD101G	-5.35	1.84e-03	7.26e-05	-7.17e-08	1.84e-10	-4.53e-13
CTD101K	-12.10	4.27e-03	1.90e-04	-2.90e-07	3.69e-10	-4.27e-13
CTD101 with Fibre	-1.94	1.49e-03	4.34e-05	-2.57e-07	9.26e-10	-1.19e-12
CTD101G with Fibre	-2.10	1.14e-03	4.21e-05	-2.11e-07	7.11e-10	-8.21e-13
CTD521	-11.60	2.25e-03	2.23e-04	-8.55e-07	2.91e-09	-3.76e-12
CTD521 (mixing)	-2.06	9.71e-04	4.12e-05	-7.20e-08	-7.52e-11	2.79e-13
CTD521-S40	-8.51	3.82e-03	1.48e-04	-6.33e-07	2.41e-09	-3.33e-12
CTD521-S40 with Fibre	-2.11	8.07e-04	4.34e-05	-1.40e-07	3.39e-10	-3.84e-13
CTD528 SuperTnFF-cryoresin	-2.42	1.09e-03	5.46e-05	-1.50e-07	1.65e-10	-7.53e-15
CTD528 SuperTnFF-cryo-applic	-11.90	1.03e-03	2.18e-04	-7.43e-07	2.58e-09	-3.44e-12
CTD-DP 5.1	-15.30	4.66e-03	2.55e-04	-1.67e-06	7.87e-09	-1.11e-11
CTD-DP 5.1 with Fibre	-1.78	4.61e-04	4.06e-05	3.56e-08	-6.99e-10	1.12e-12

CTD101K, 12.0 mmm

CTD101G 5.3 mm/m

CTD528 Super 2.4 mm/m

3.8 CTD101K

description: *Anhydride cured epoxy. Radiation resistant. Made by Composite Technology Development.*

weblink: www.ctd-materials.com

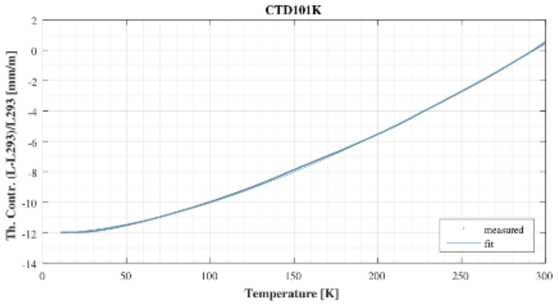
Thermal Contraction at 10K (mm/m)
-12.04

Start Temp (K)	End Temp (K)
10.9	299.5

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

Coeff	Value
a	-1.21e+01
b	4.27e-03
c	1.90e-04
d	-2.90e-07
e	3.69e-10
f	-4.27e-13

R Squared	0.999976



3.7 CTD101G

description: *Alumina filled, anhydride cured epoxy. Radiation resistant. Made by Composite Tenchology Development.*

weblink: www.ctd-materials.com

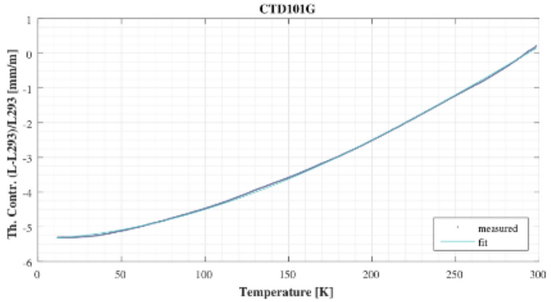
Thermal Contraction at 10K (mm/m)
-5.32

Start Temp (K)	End Temp (K)
11.7	298.2

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

Coeff	Value
a	-5.35e+00
b	1.84e-03
c	7.26e-05
d	-7.17e-08
e	1.84e-10
f	-4.53e-13

R Squared	0.999970



3.15 CTD528 SuperTnFF-cryoresin

description: *Epoxy made by Composite Technology Development for cryogenic uses.*

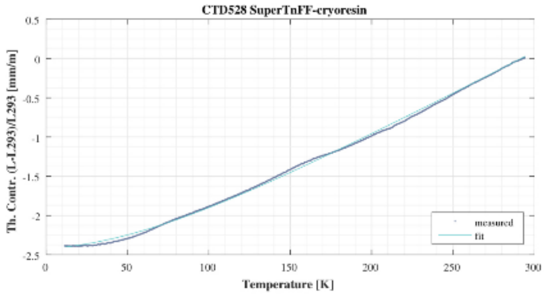
Thermal Contraction at 10K (mm/m)
-2.40

Start Temp (K)	End Temp (K)
11.5	294.1

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

Coeff	Value
a	-2.42e+00
b	1.09e-03
c	5.46e-05
d	-1.50e-07
e	1.65e-10
f	-7.53e-15

R Squared	0.999933

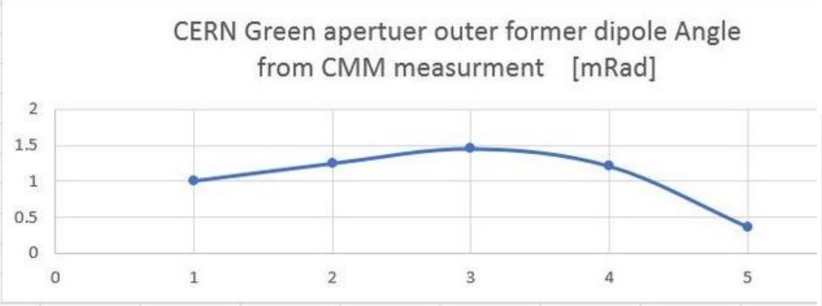


CERN 3m long ~ 0.5 m dia turning CNC milling m/c

m/c spec **7 um** over 3 m and achieves **~ 10 um** for our flexible tube! Very nice.

Target value under 50 um

lateral shift [mm] S	0.0686	0.085	0.0988	0.0824	0.0252
r [mm]	68.15	68.15	68.15	68.15	68.15
Angle in [mRad]	1.006603	1.247249	1.449743	1.209098	0.369773



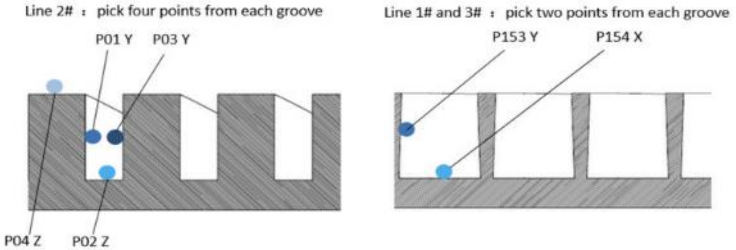
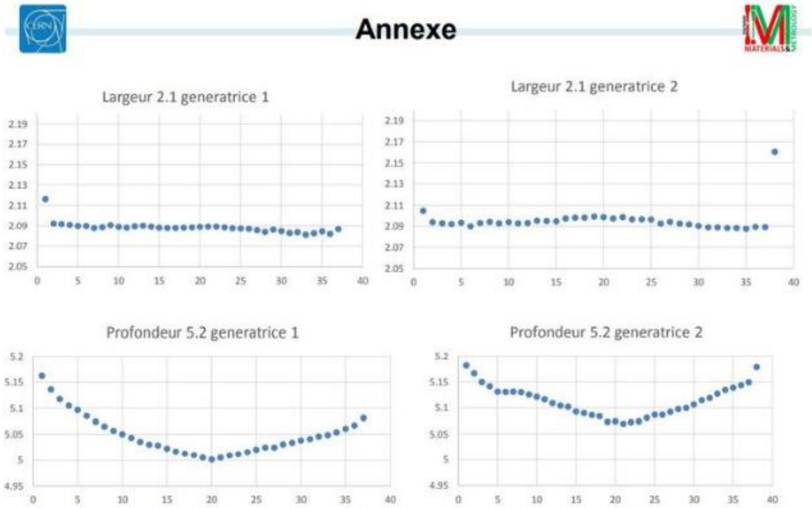
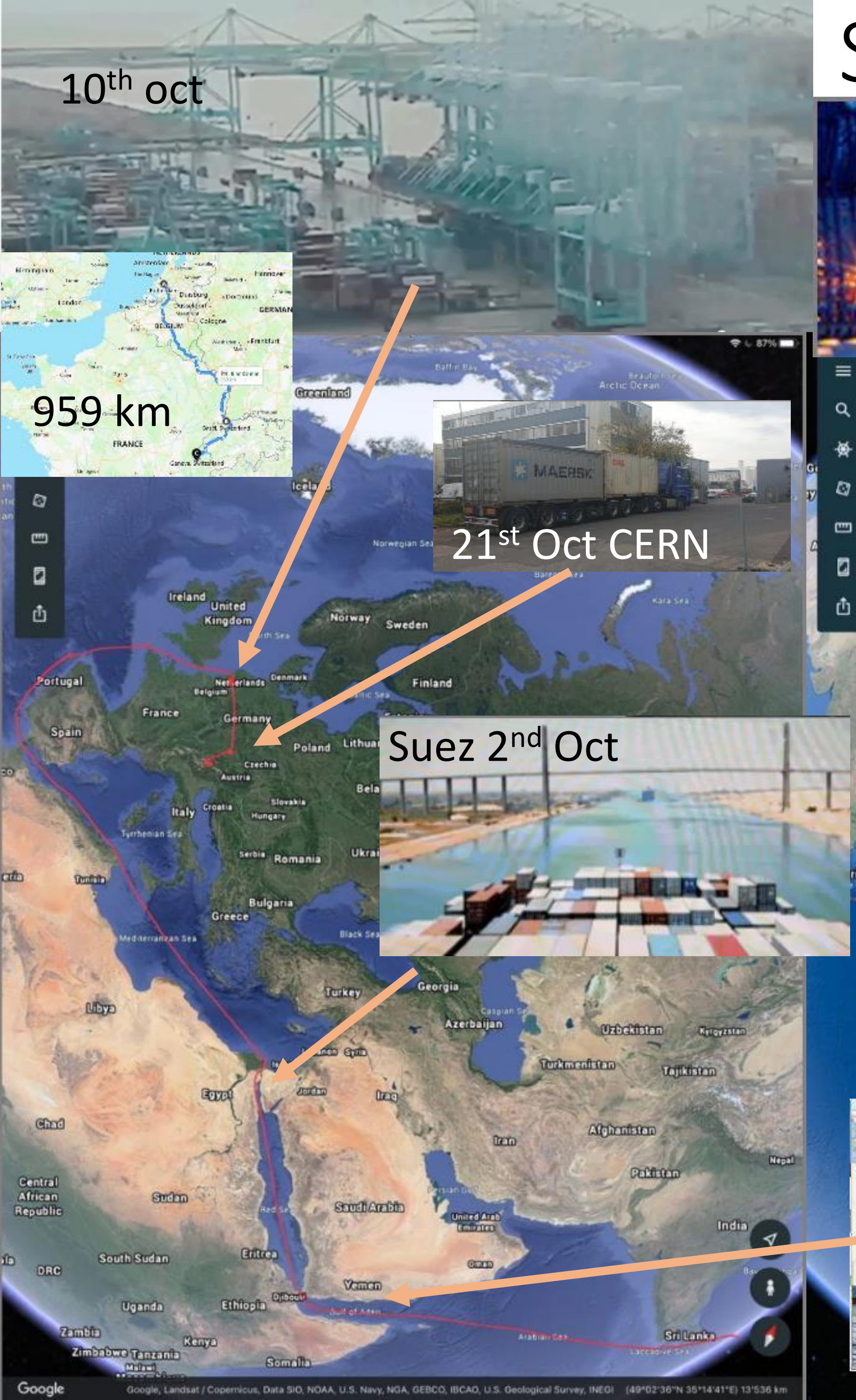


Fig3. Measuring Points of each Groove



Shipping from china to CERN 8 weeks



Measured Errors

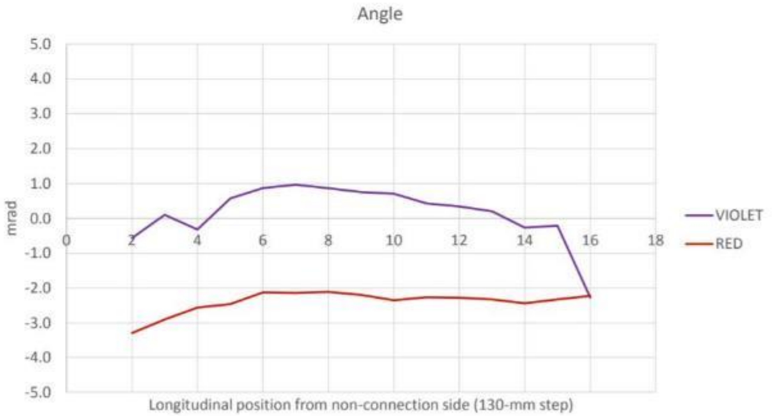
Apertures without yoke

Multipoles within 2 units

Rref = 35 mm

Magnetic angle with respect to key slots

MCBRDP2 with yoke at room temperature



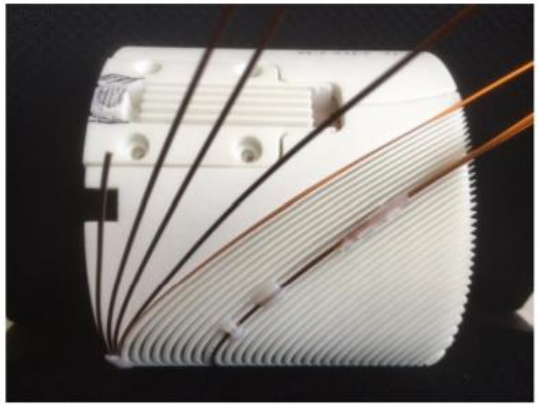
Angles within ± 3 mrad

Field errors in aperture ~ 2 units only !

Field angle +- 3 mrad that's 0.05 mm tolerance in position of wires in m/c formers.

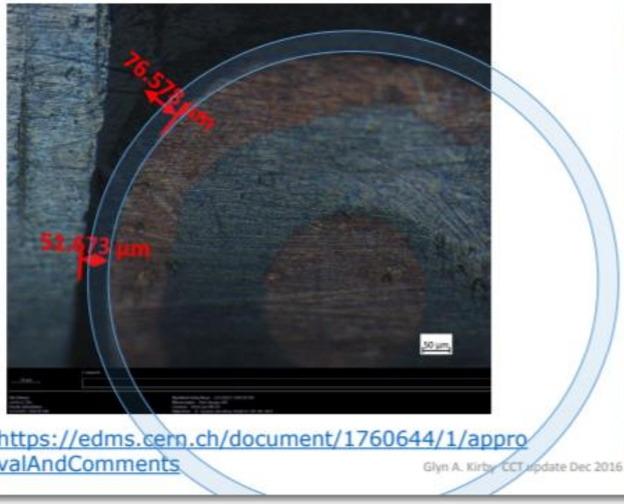
Transfer Function < 5 units

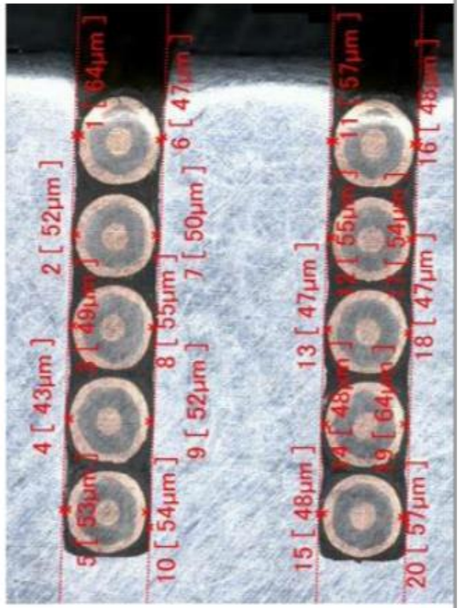
1st winding test with the rectangular wire !!!!failed!!!



The enamel rectangular wire rotated as we tried to wind and finally was impossible to wind into the slot!

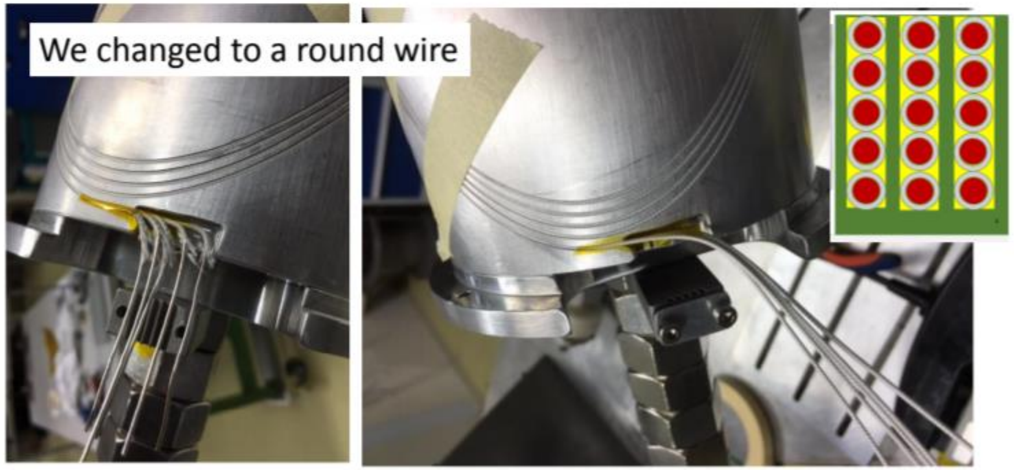
1mm x 5mm slot with 0.05mm glass impregnated insulation





https://edms.cern.ch/document/1760644/1/approvalAndComments

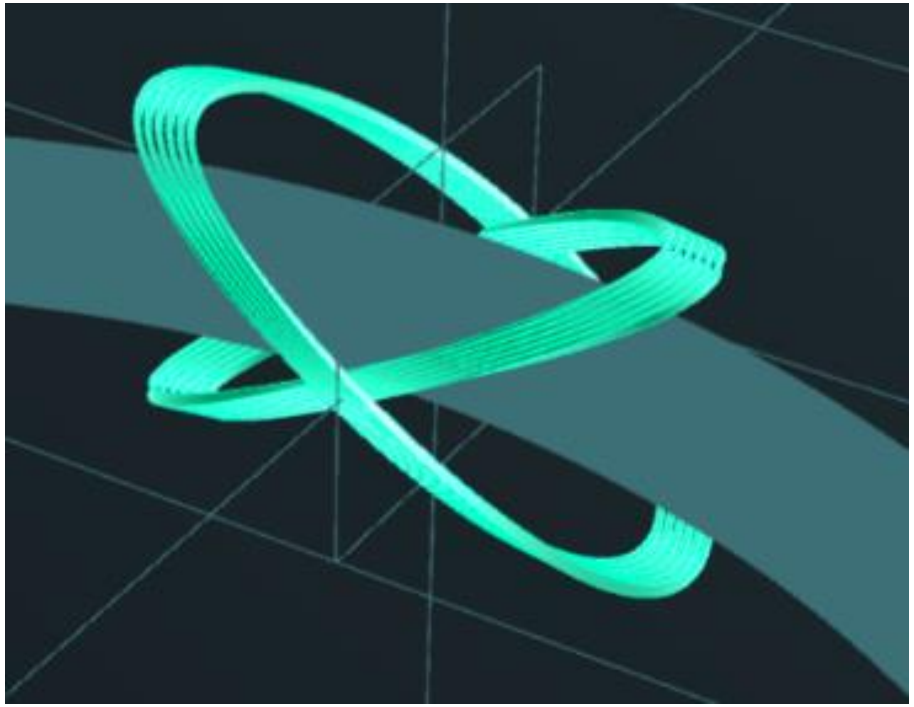
We changed to a round wire

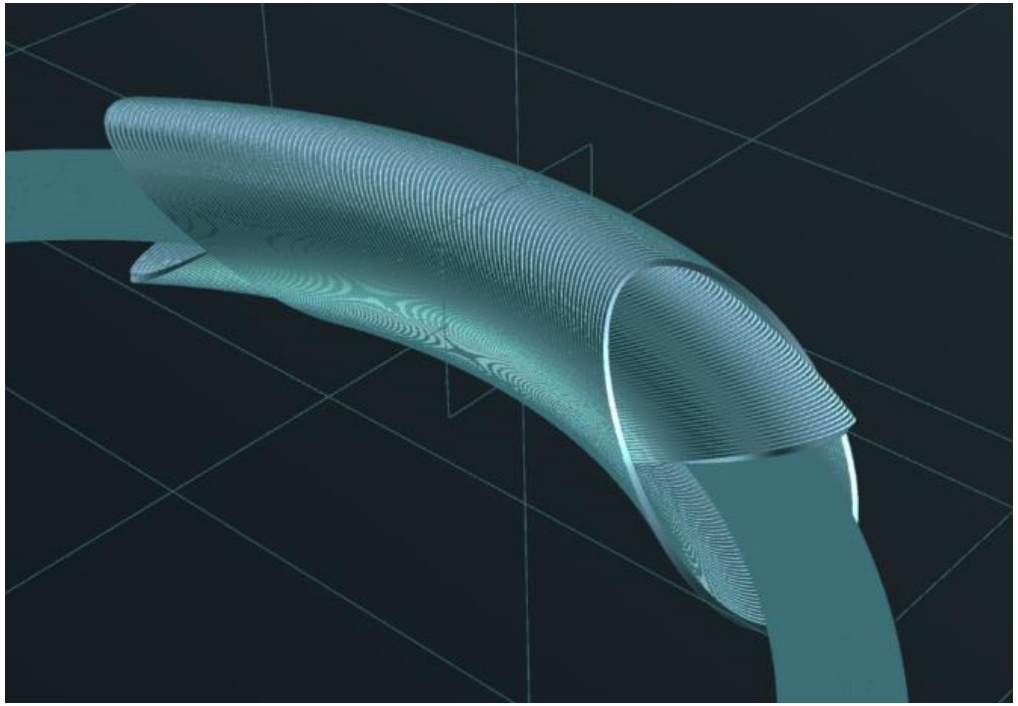


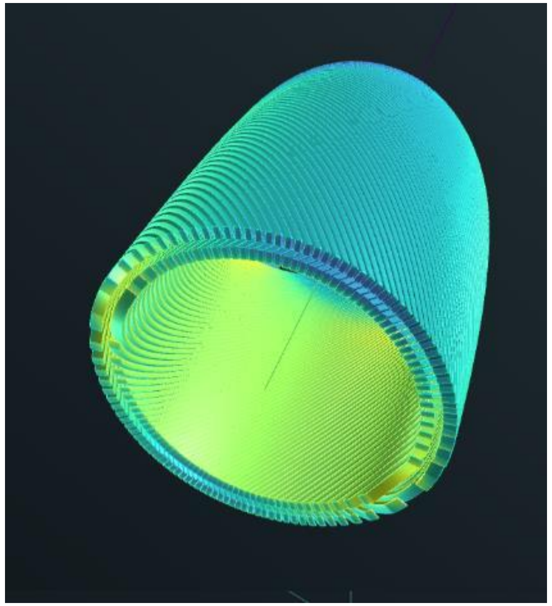
Version 1 , 1mm x 5 mm deep winding test.
Tight to get glass insulated wire into slot without damaging the insulation but was achieved!
Former has some sharp edges. That will need removing on next models.

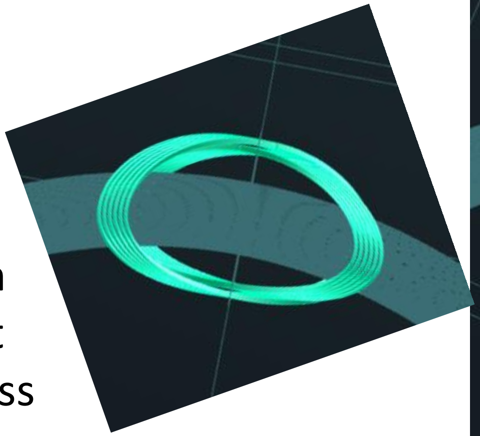
Version 2 ,
Changing from 1x5 wires to 2x5 wires
1) Reduces machining time.
2) Increases machine tool size!
3) Increases number of joints

Machining model









Two or three turns in a coil can be used to test the full magnet design to its full operating stress and conductor limits!