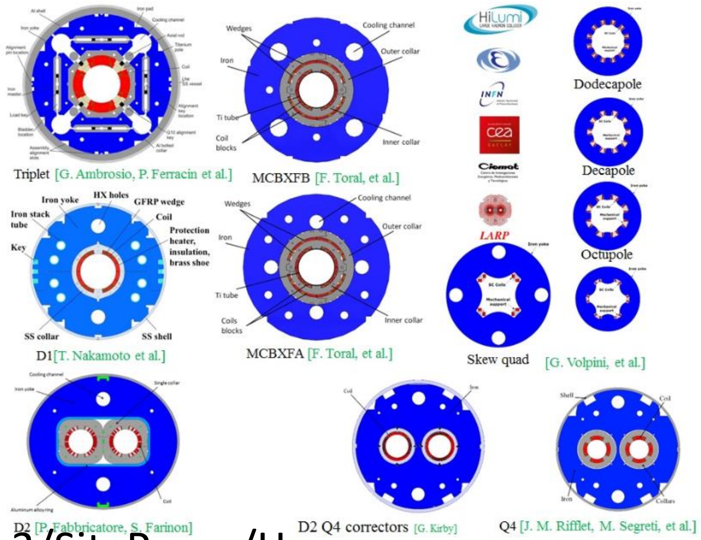
CERN CCT MCBRB-CORRECTOR

May 17th 2017

Glyn Kirby

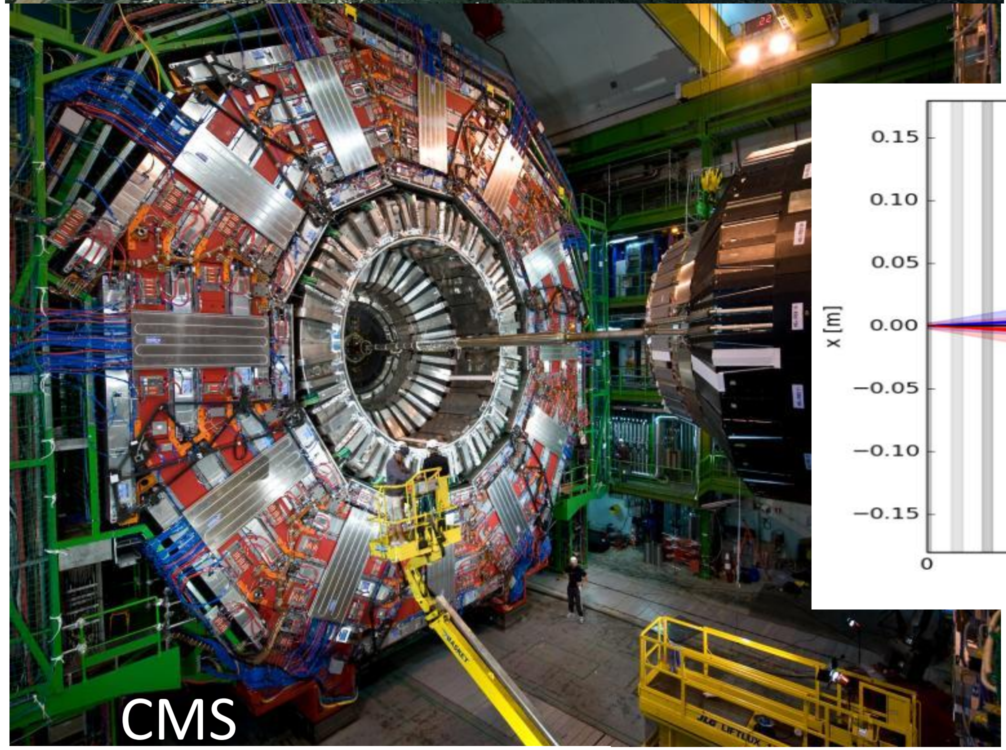
What is “High Luminosity LHC”

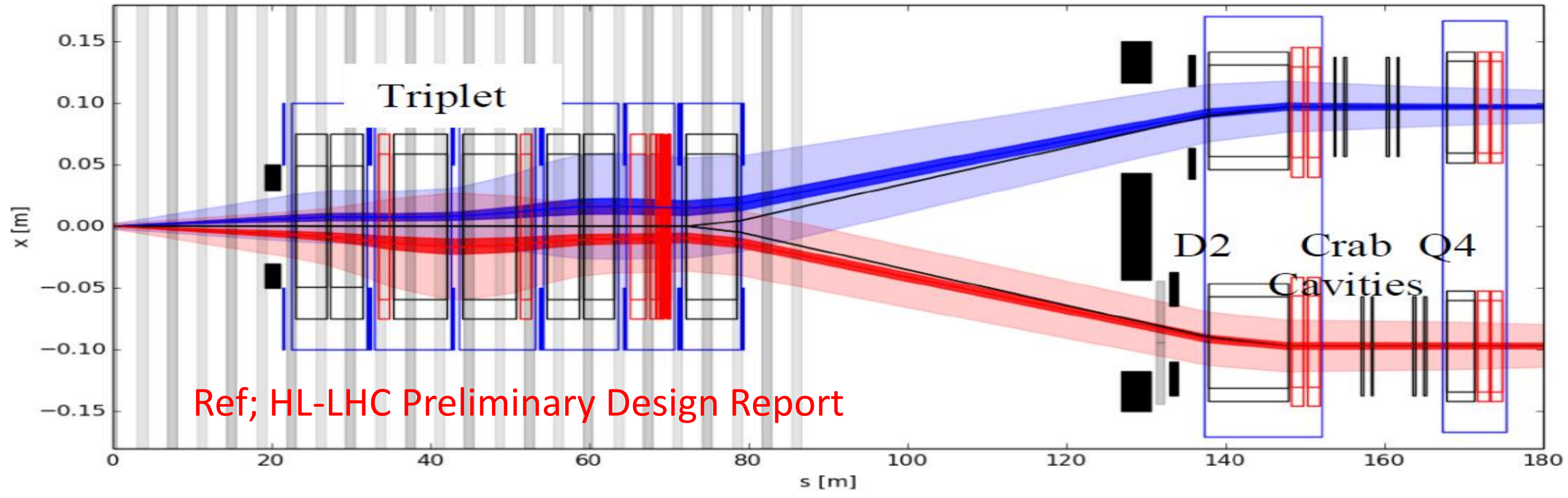
Goal of Hi-Lumi LHC increase Luminosity by factor ~10
In CMS and ALTAS
Installation Due 2024 - 2026

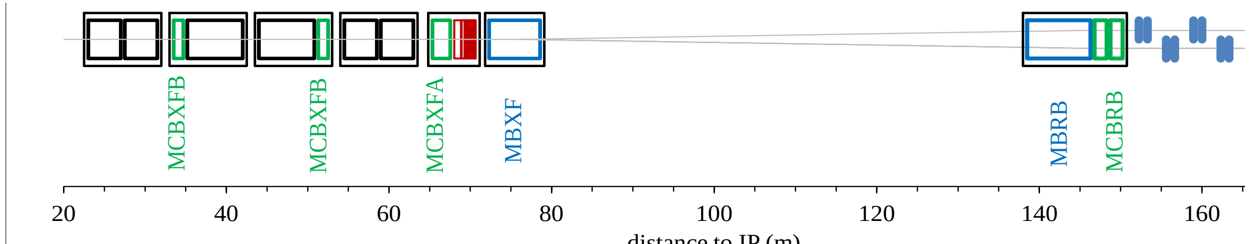


Upgrade Magnet Set

https://espace.cern.ch/HiLumi/wp3/SitePages/Home.aspx



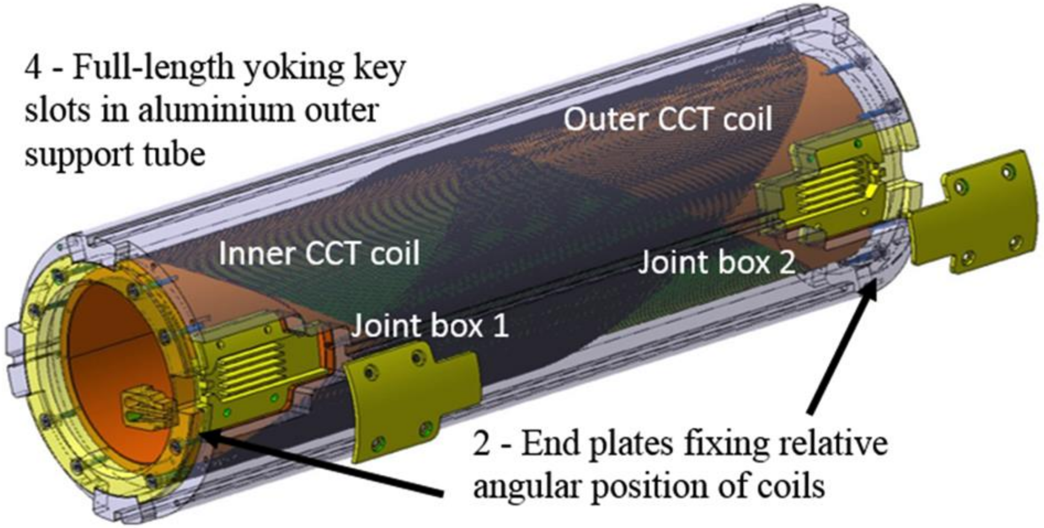


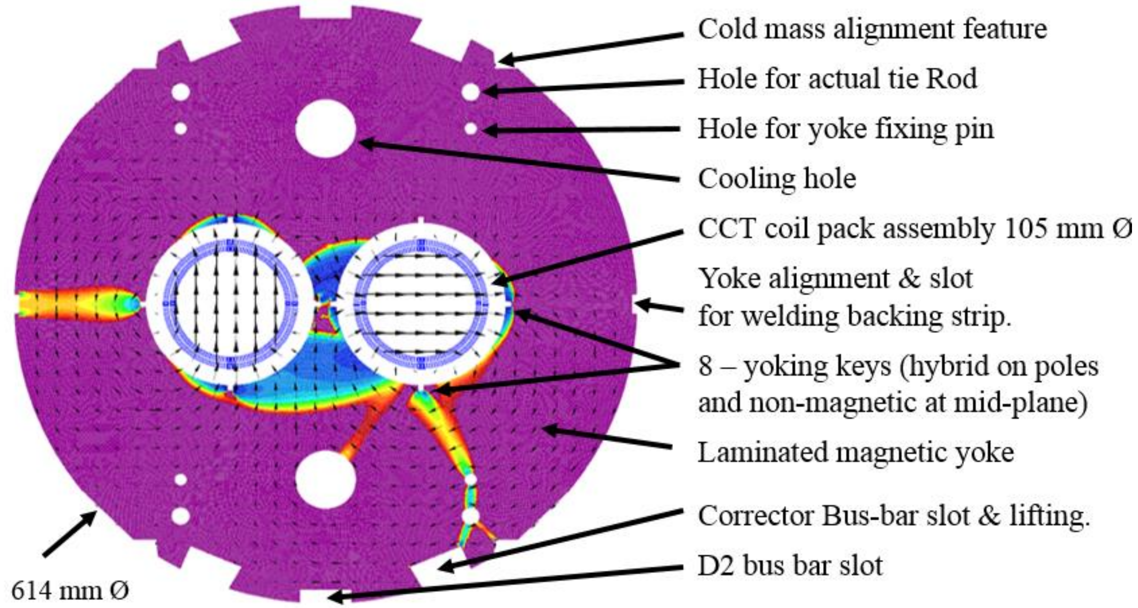


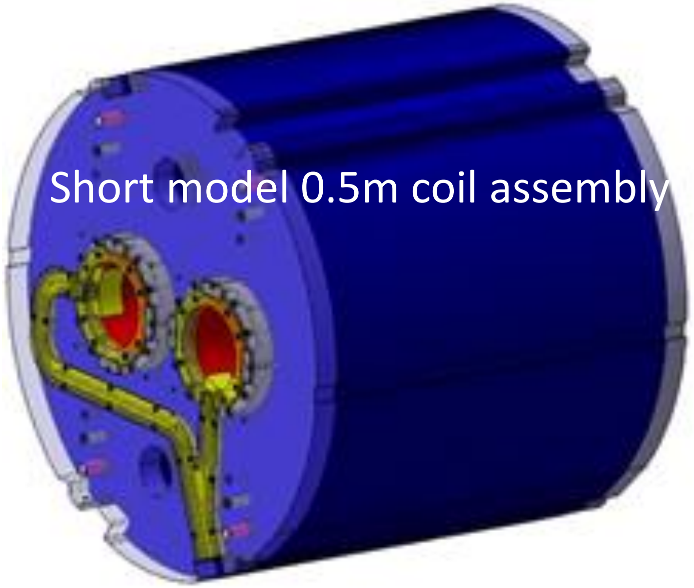
Magnet Spec.

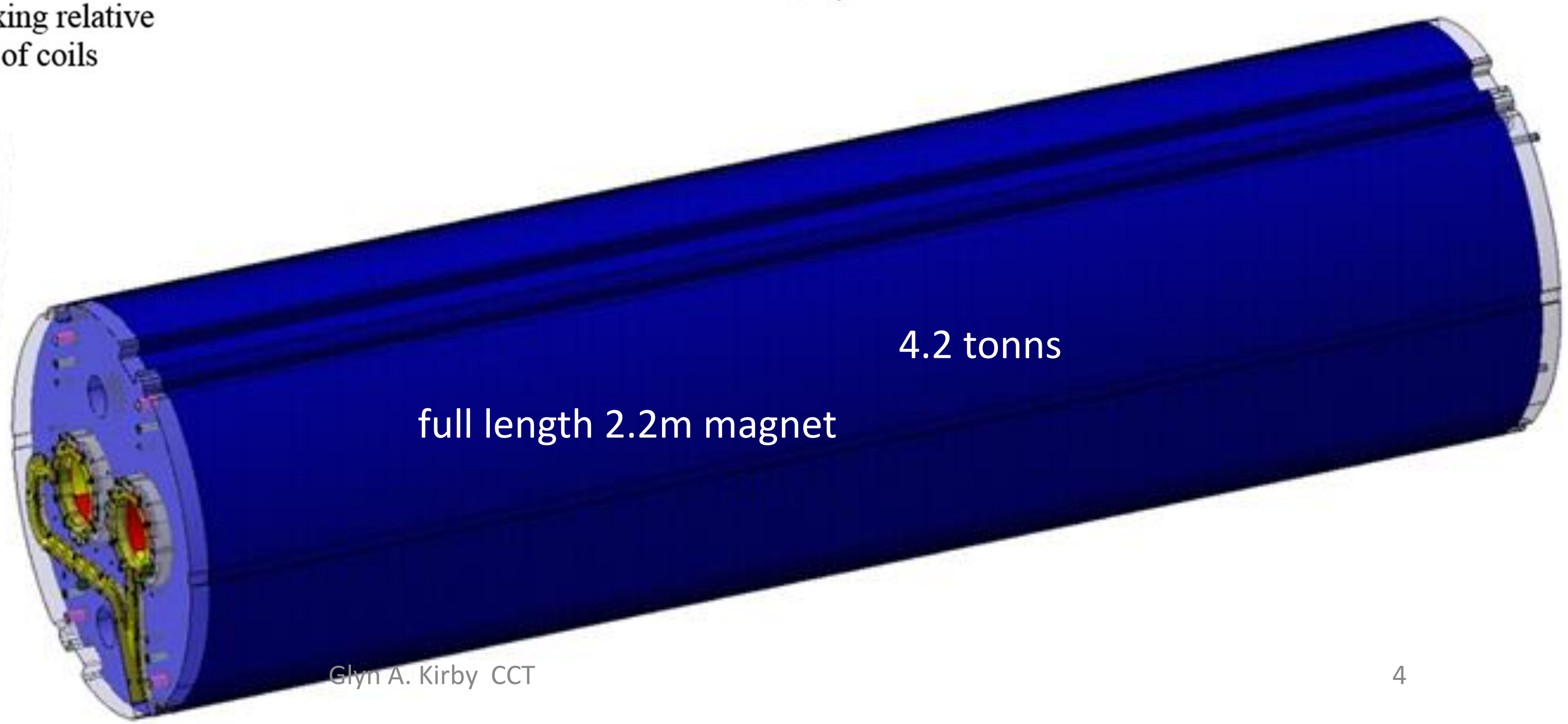
- Integrated field 5 Tm. Magnetic length ~ 1.92 m @ ~2.65T
- Magnet ~ 2.19 m long mechanical
- Multipoles ~< 10 units at all operational fields and configurations. Apertures independent.
- Aperture: 105 mm. (When cold)
- Beam distance: 188 mm.
- Faster Ramps rates ~100 s is the target value !
- Current < 600 A. Power supply (today 435A)
- Dose of 10 MGy so we need a radiation hard insulation.
- Yoke : Std LHC design: rotated yoke , yoke keys ,and spring pins. (614 mm dia)

Design


4 - Full-length yoking key slots in aluminium outer support tube
Outer CCT coil
Inner CCT coil
Joint box 2
Joint box 1
2 - End plates fixing relative angular position of coils

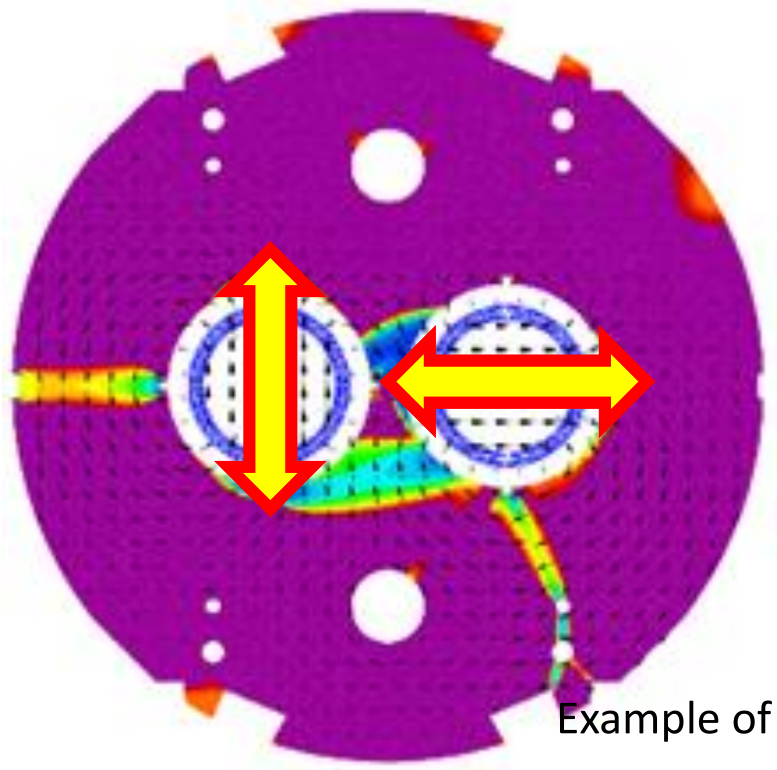

Cold mass alignment feature
Hole for actual tie Rod
Hole for yoke fixing pin
Cooling hole
CCT coil pack assembly 105 mm Ø
Yoke alignment & slot for welding backing strip.
8 – yoking keys (hybrid on poles and non-magnetic at mid-plane)
Laminated magnetic yoke
Corrector Bus-bar slot & lifting.
D2 bus bar slot
614 mm Ø

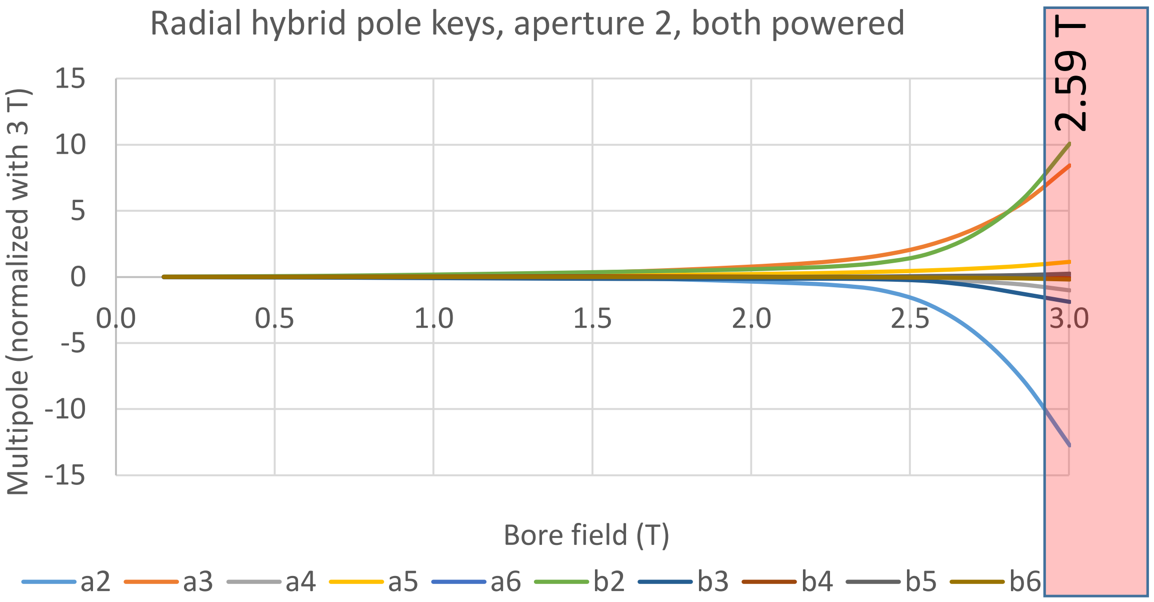

Short model 0.5m coil assembly


4.2 tonns
full length 2.2m magnet

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.

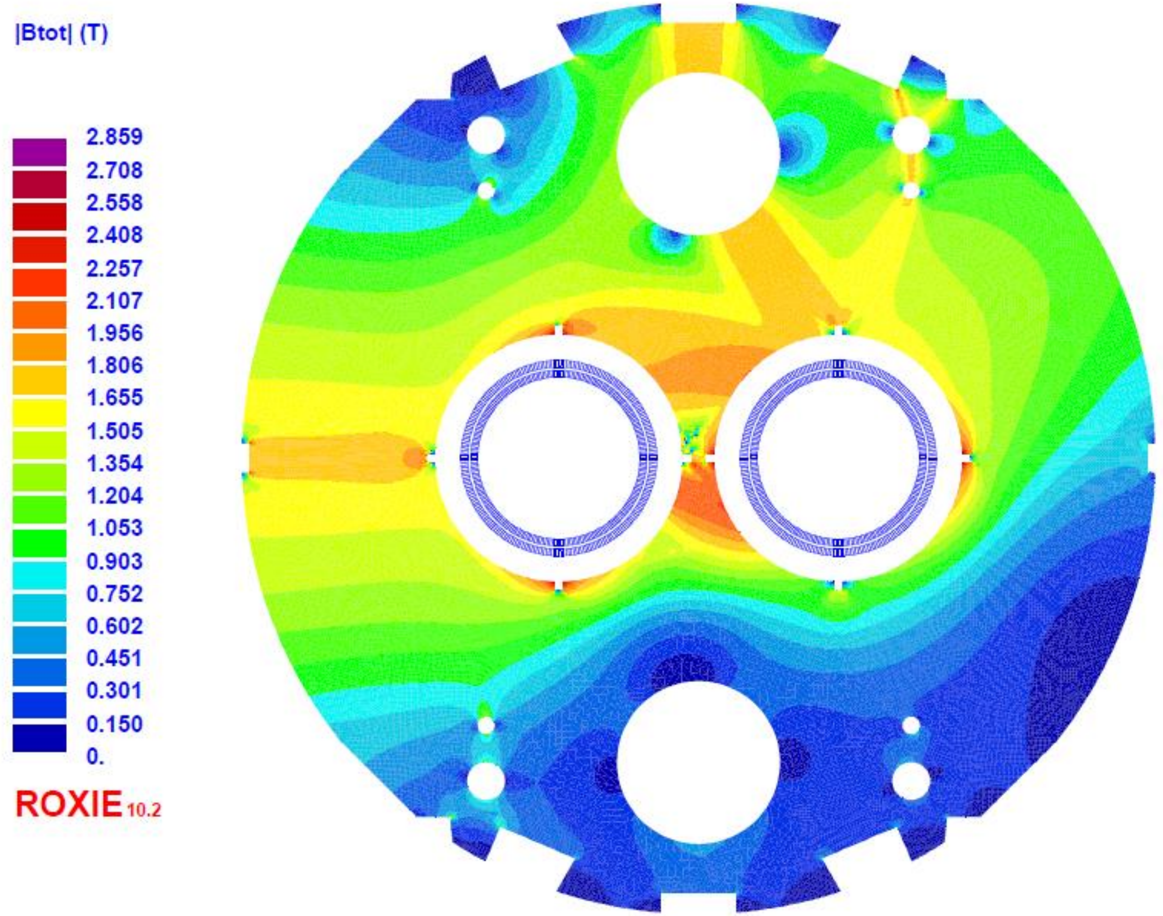


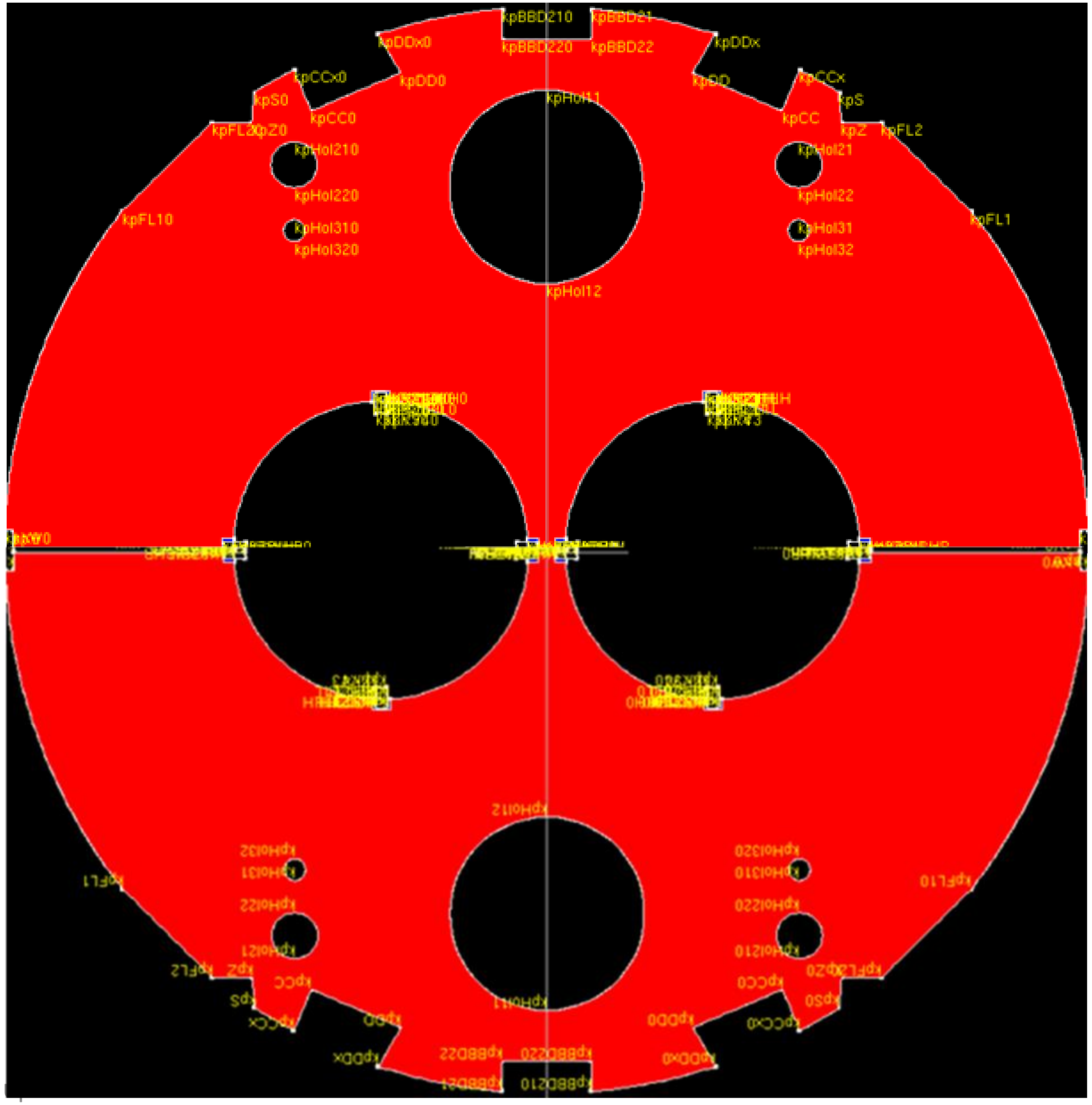


More complicated than one plot, Details to follow!

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

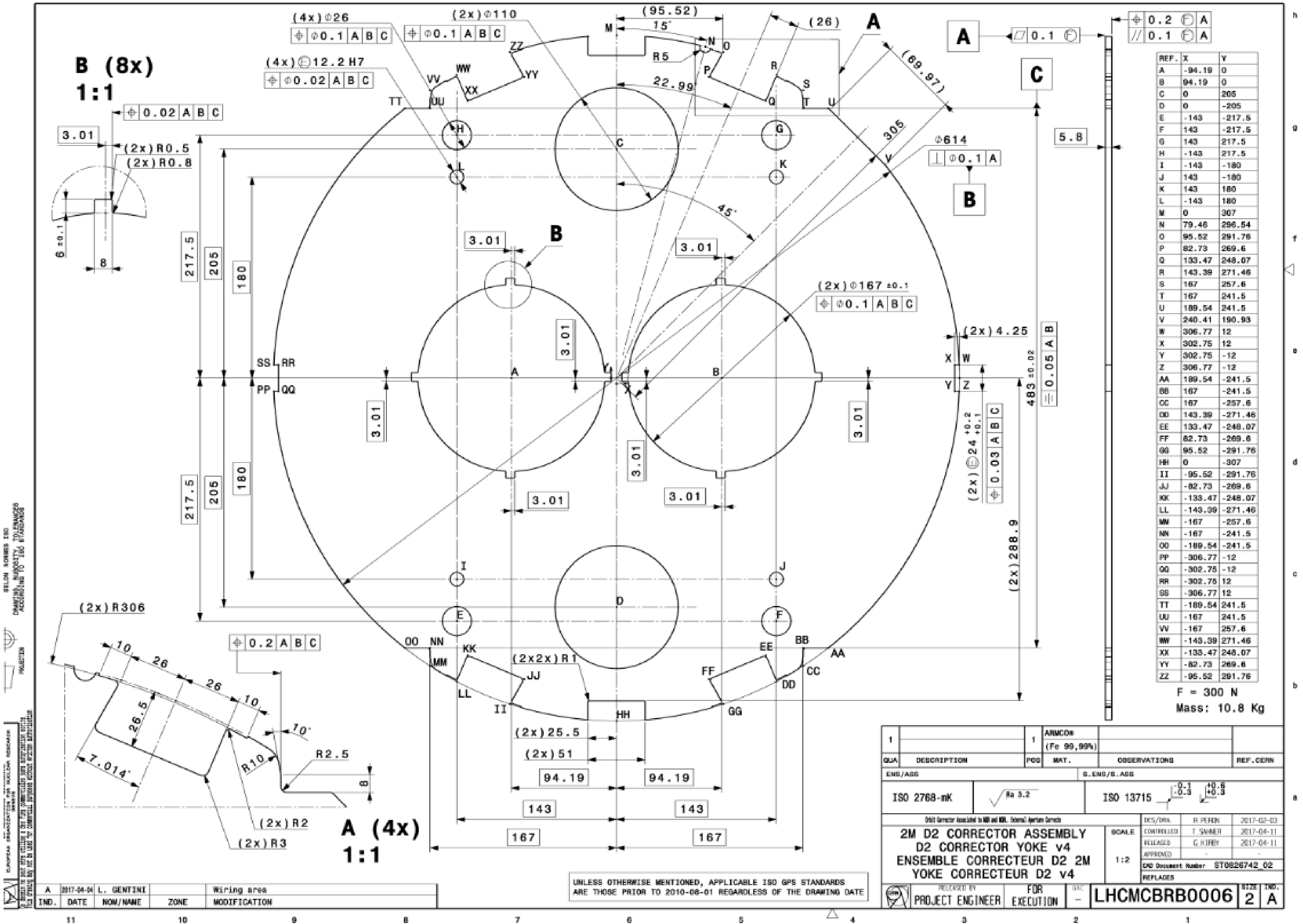
225 cm^2 clear cooling area through corrector



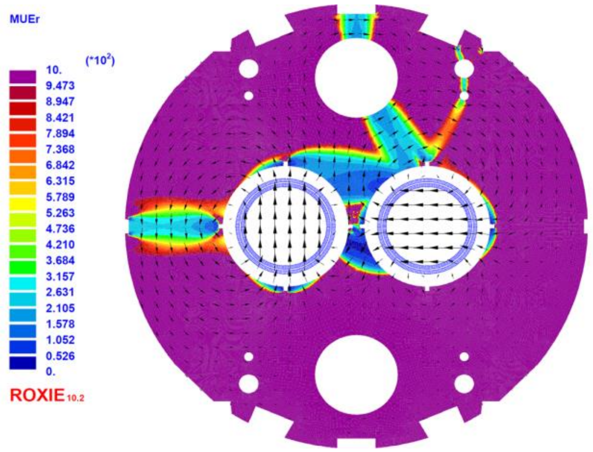


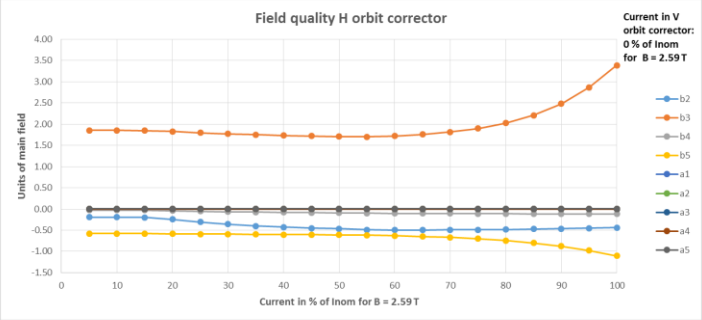
Yoke lamination

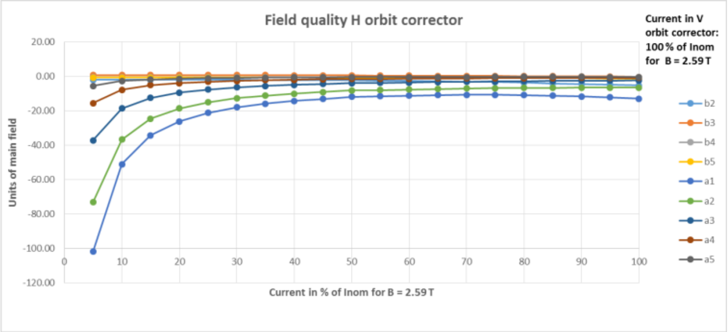
Interface yoke external profile with D2

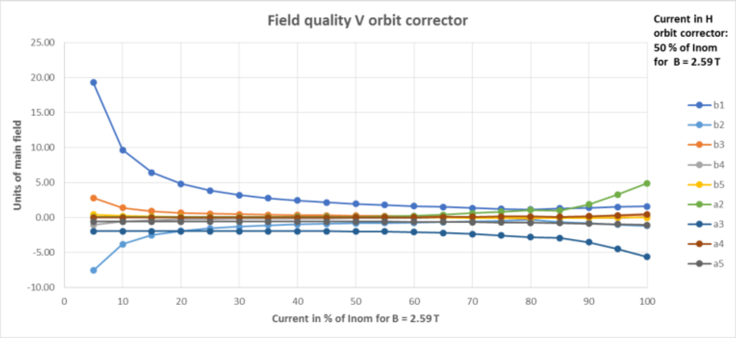


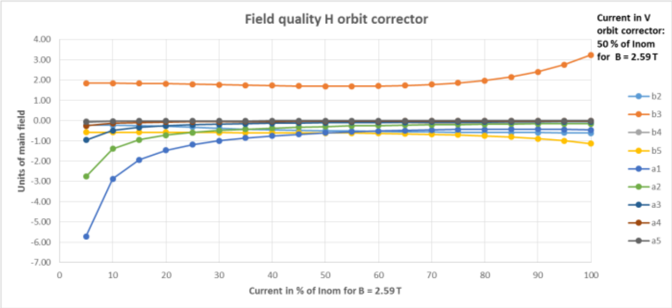
Modified yoke magnetic field check all ok with larger cooling holes

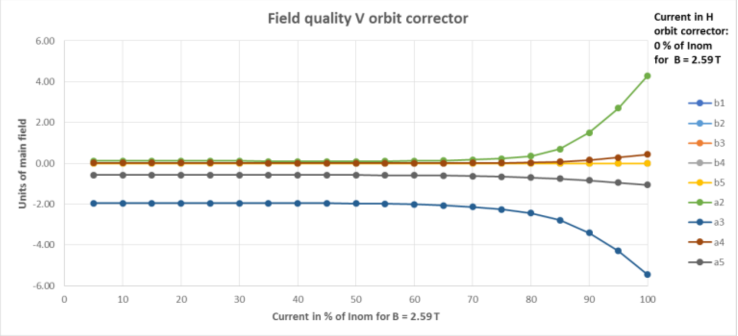


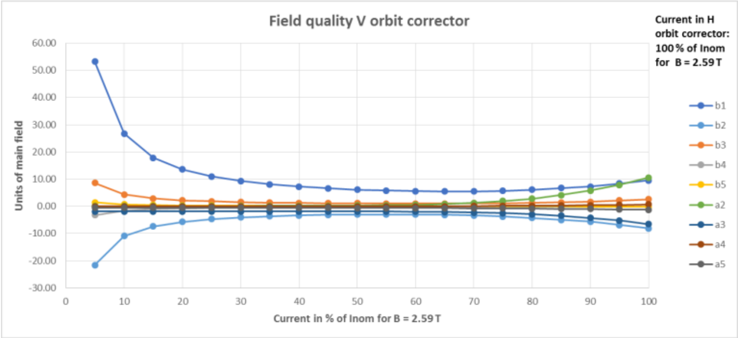


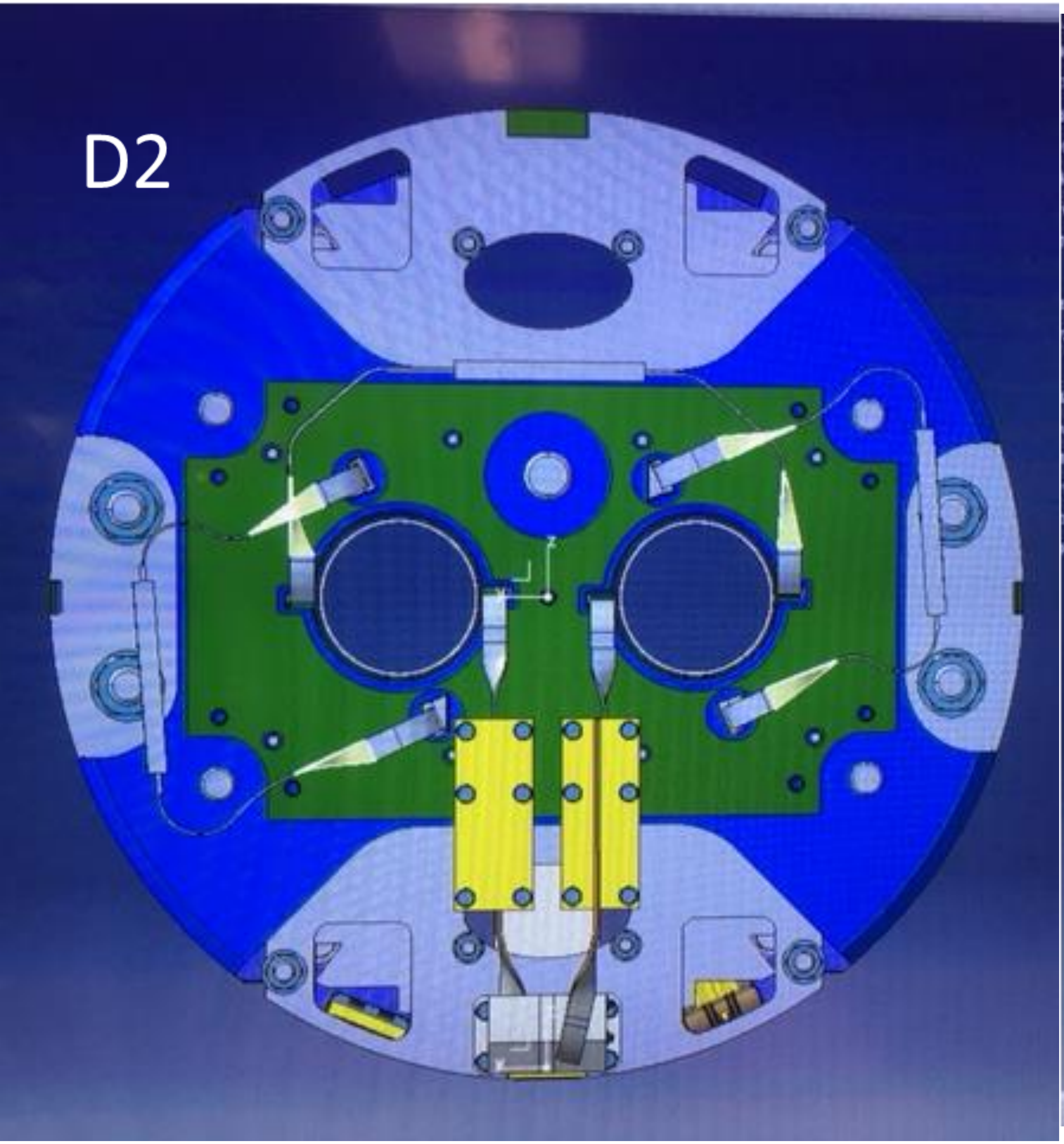


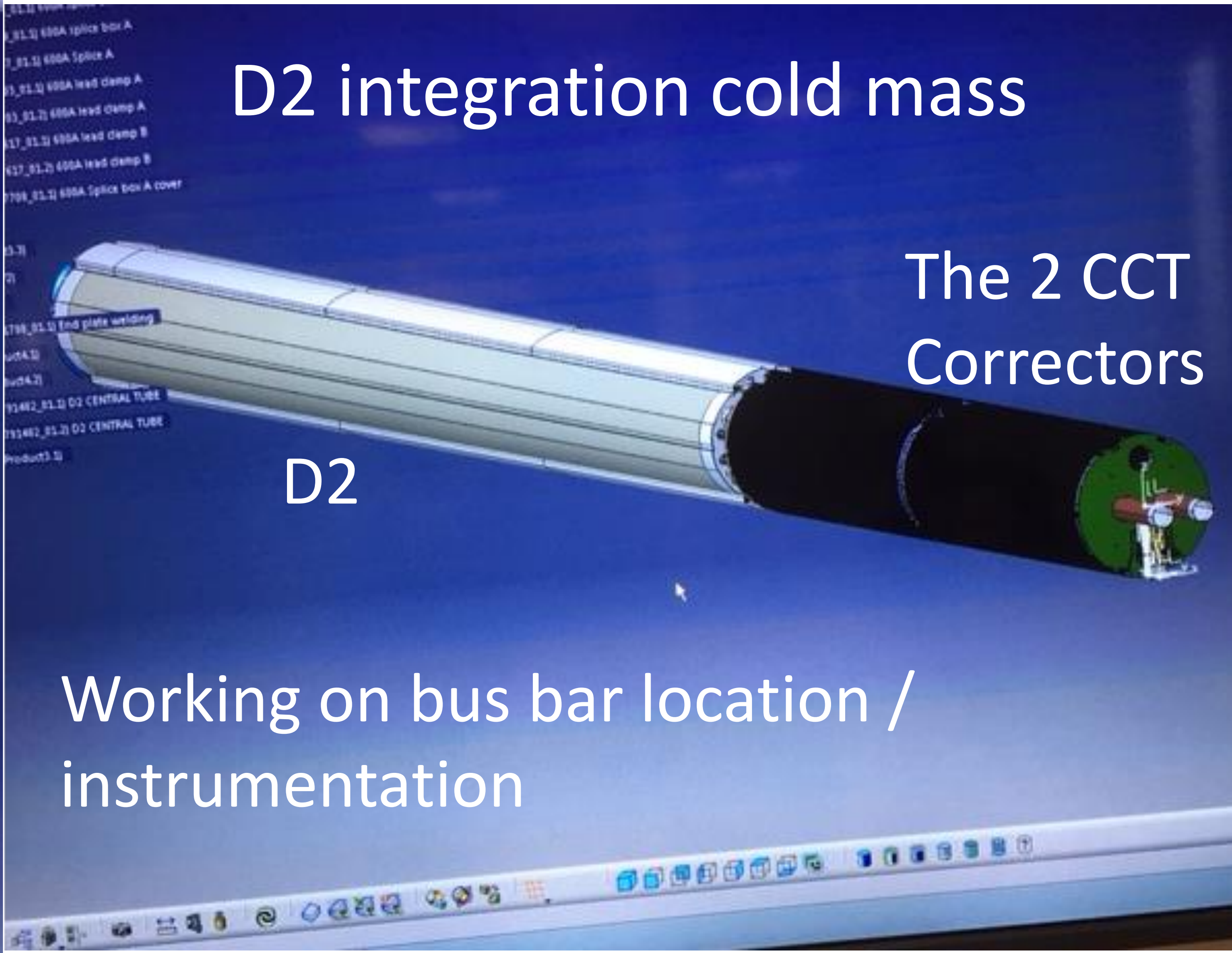




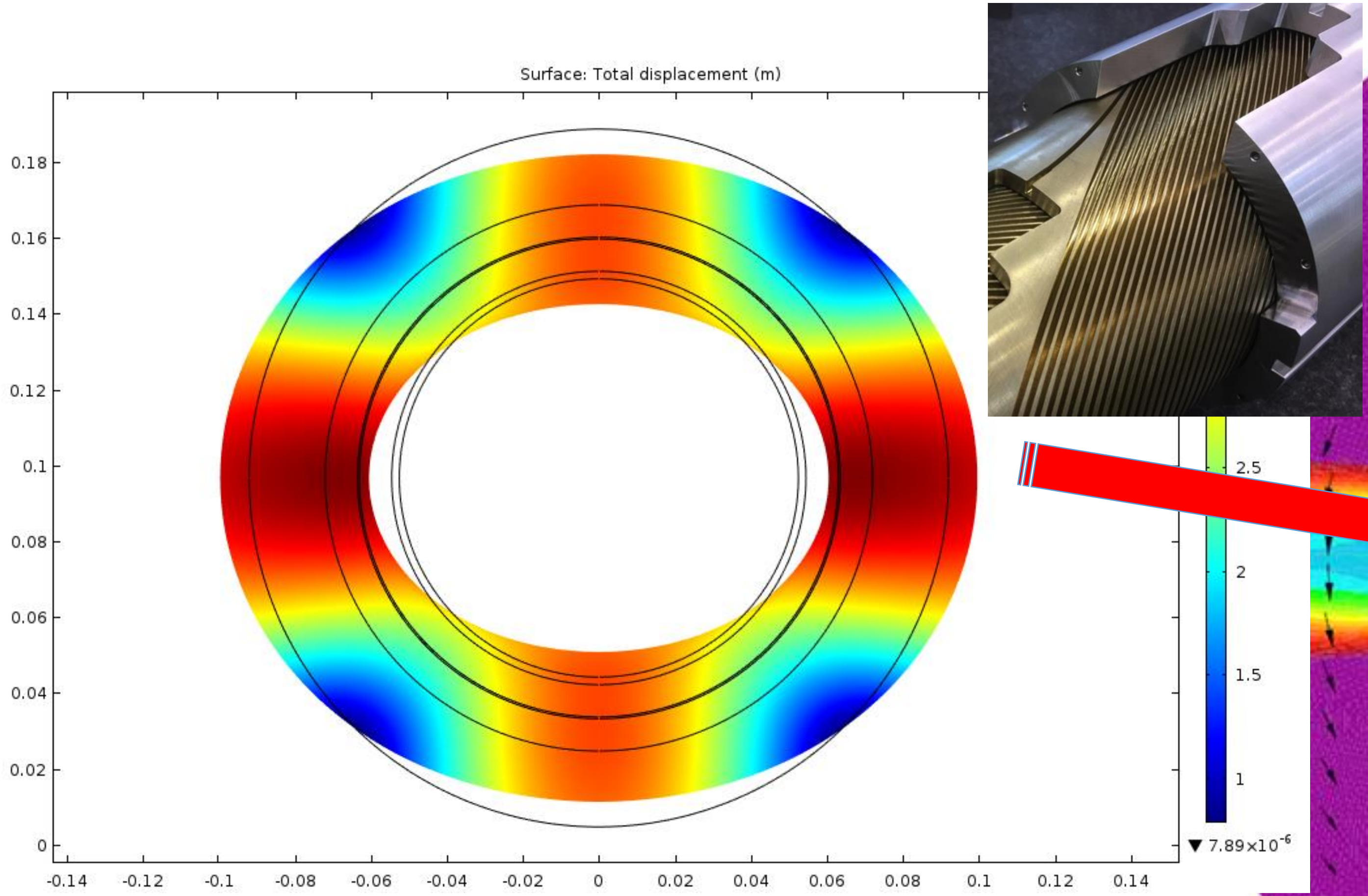


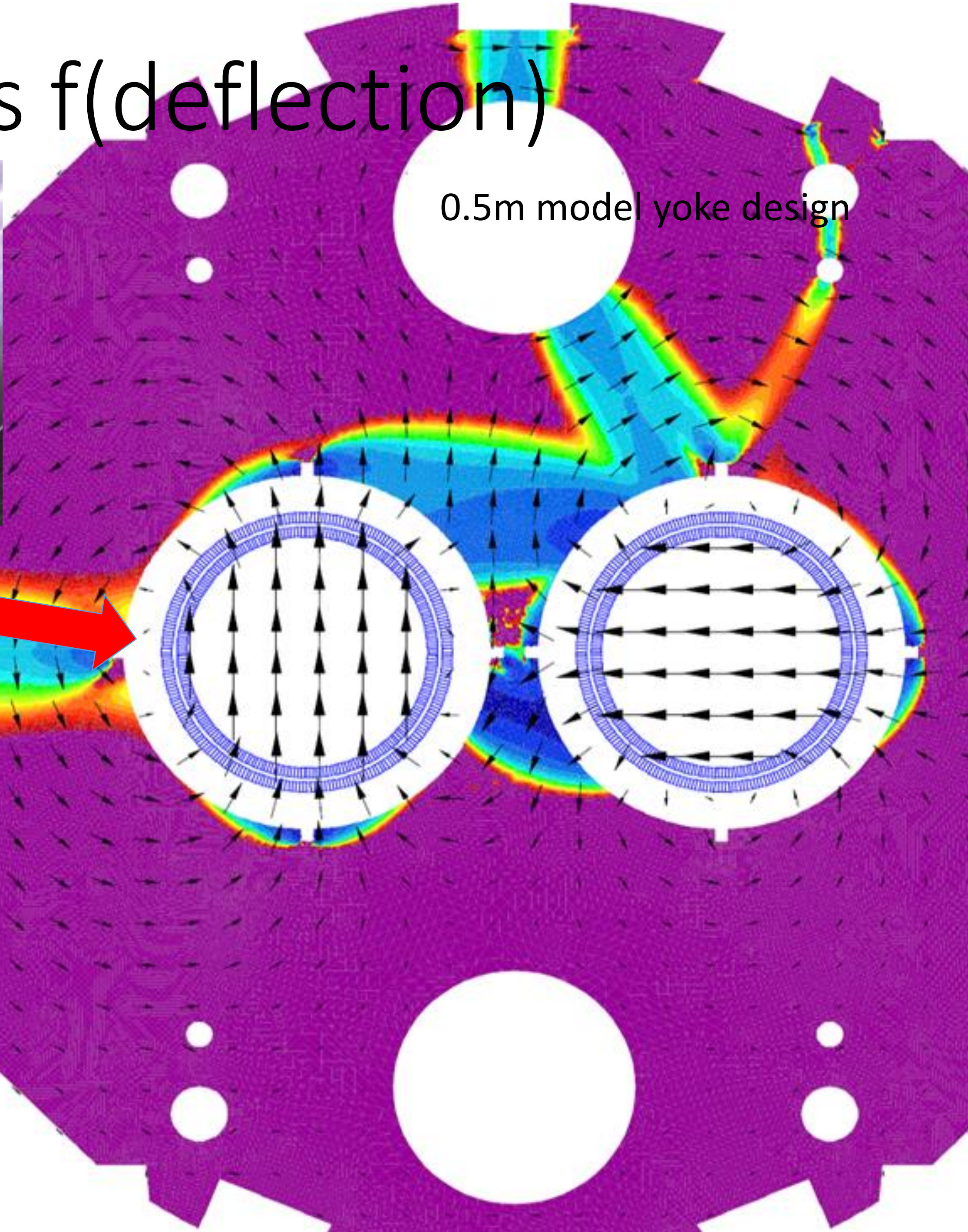



D2


D2 integration cold mass
The 2 CCT Correctors
D2
Working on bus bar location / instrumentation

Outer support collar thickness f(deflection)





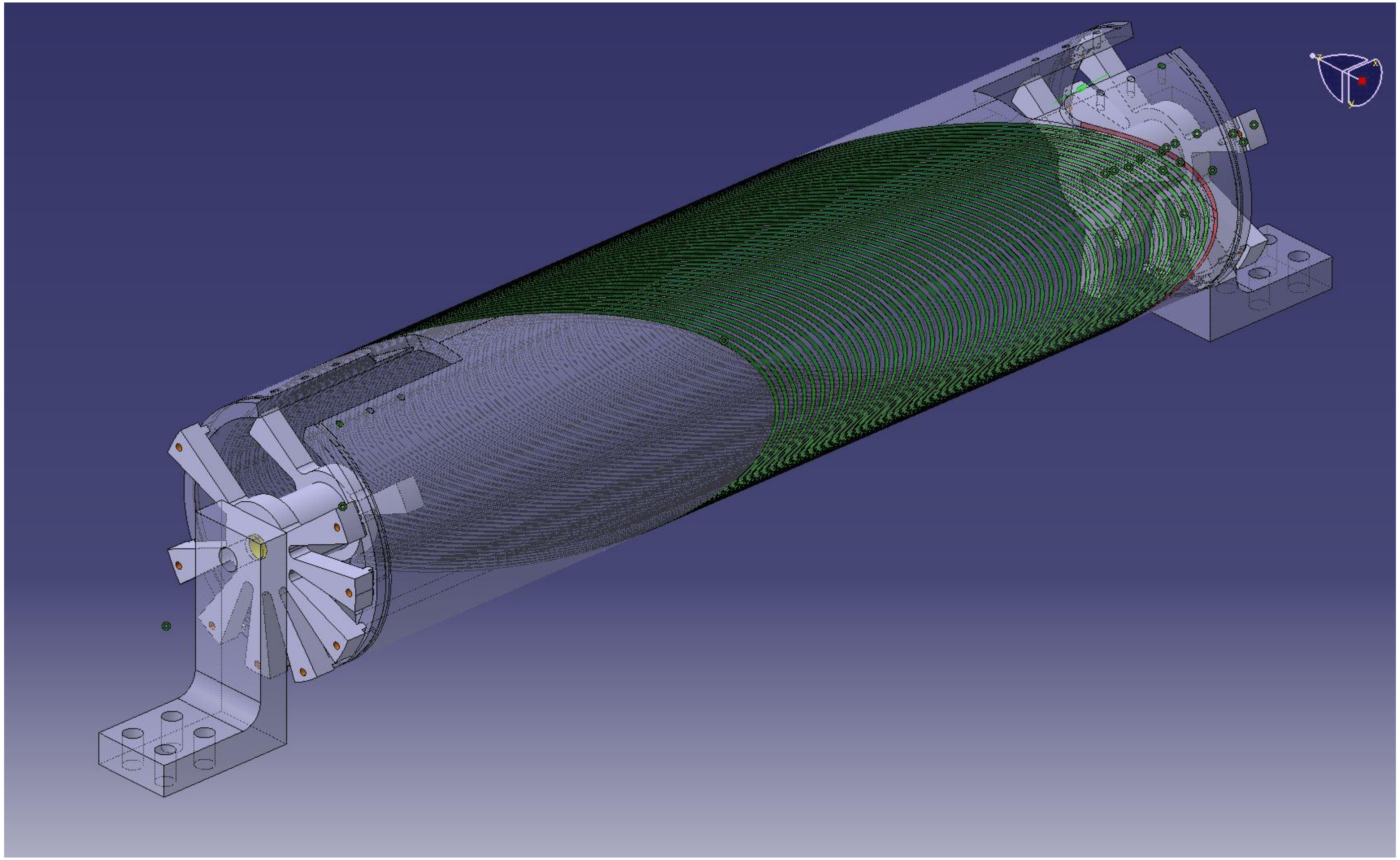
20 mm Al (70 GPa) & 3 T bore field deflection < 40 um
15 mm Al (70 GPa) & 3T bore field deflection < 50 um
With Inner support tube 2mm stst.

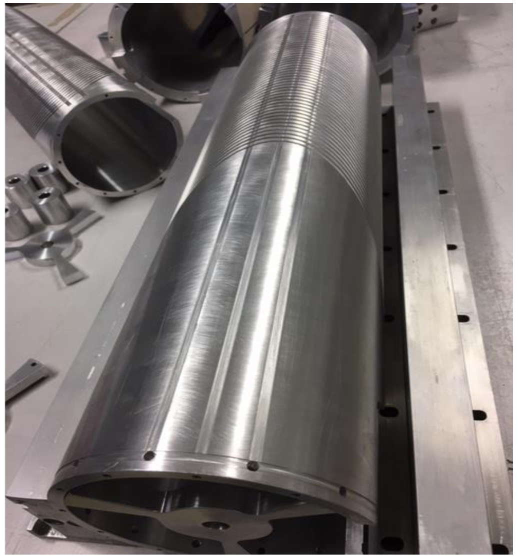
E_{coil} = 44 GPa E_{collar} = 70 GPa

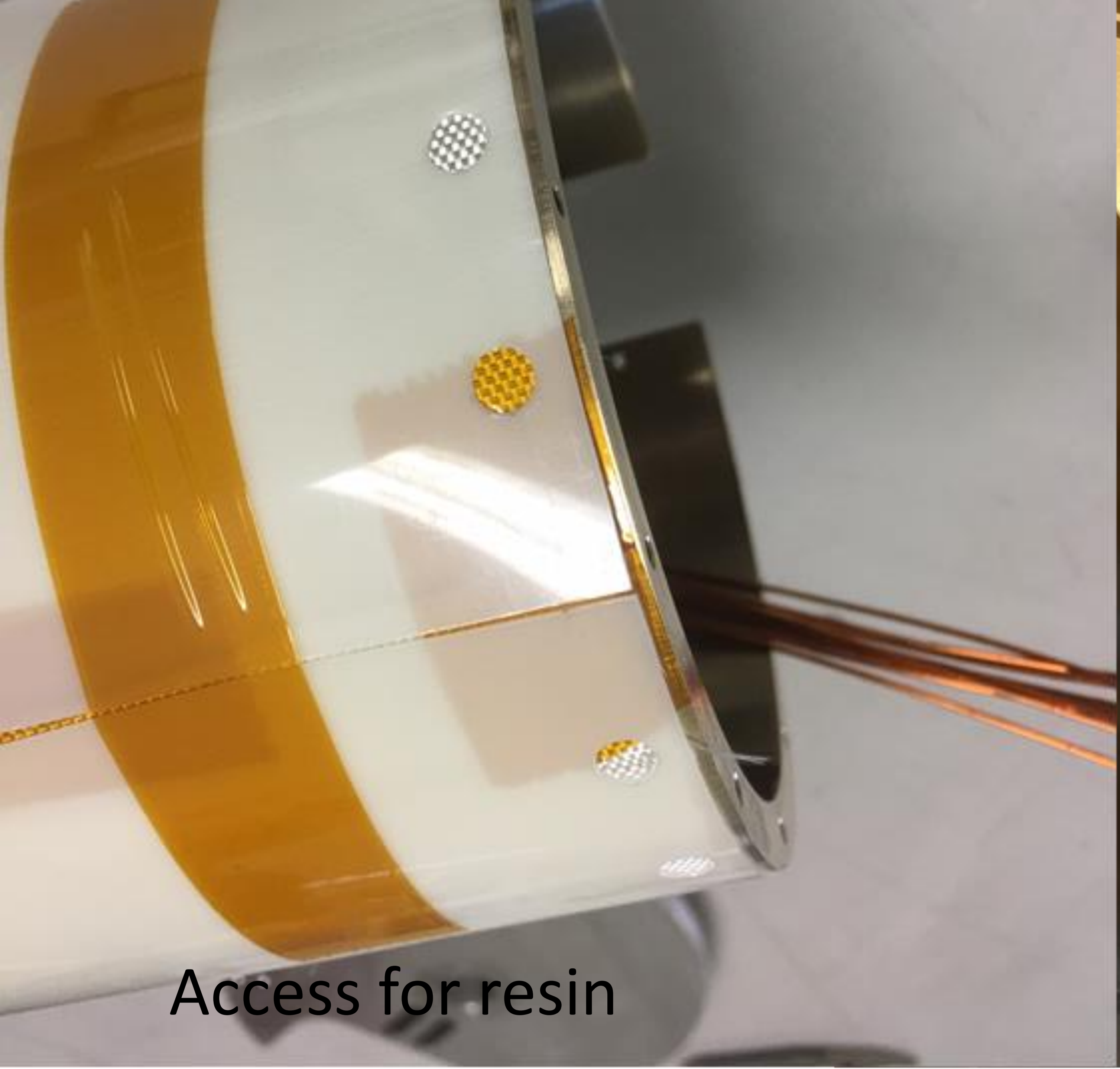
Outer Coil Former Support < 50 um deflection

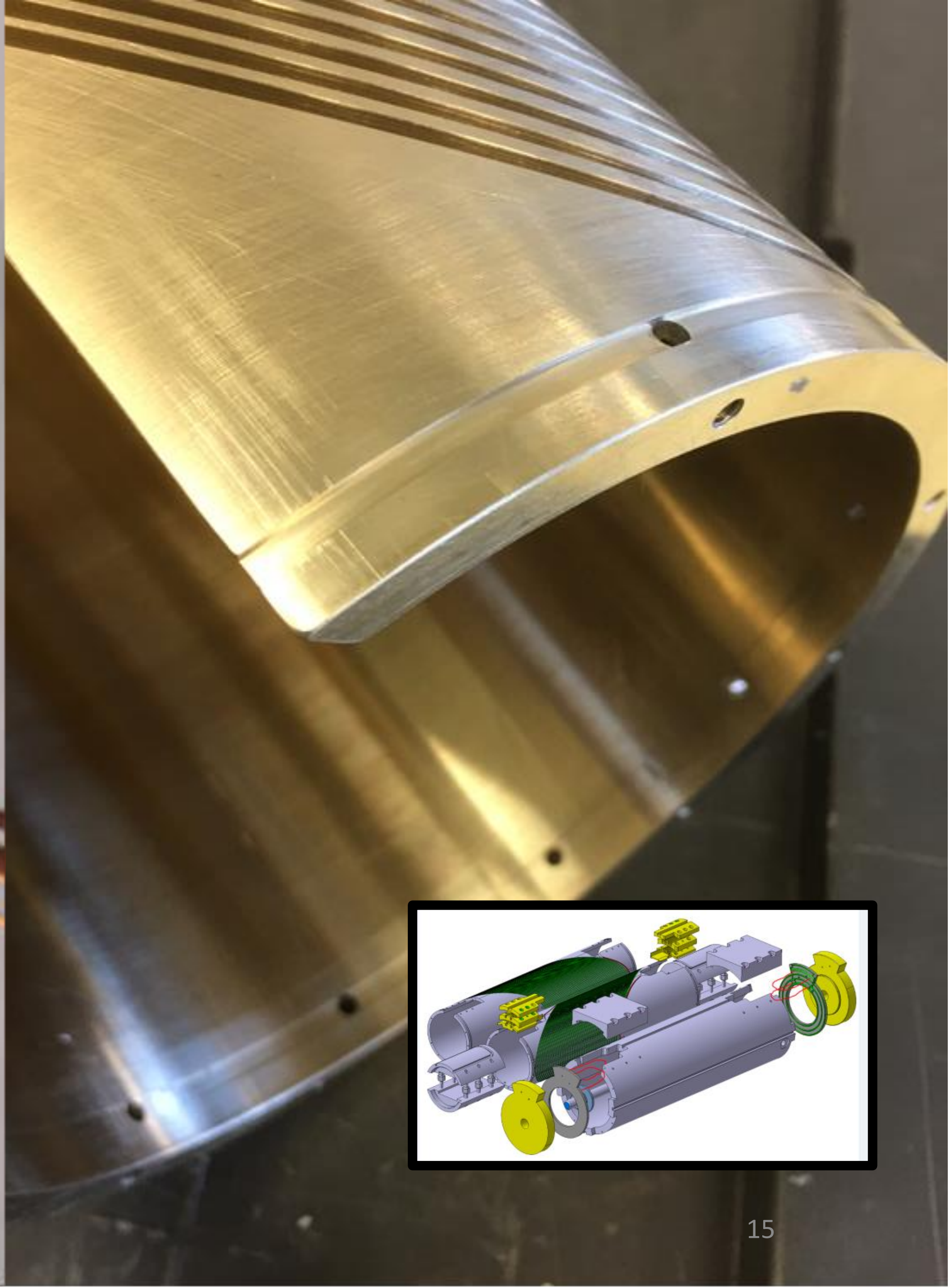
Aluminium formers 6082-T6 polishing test to de-burr? and then Hard Anodization (Micro-Machining)

Polishing support tool



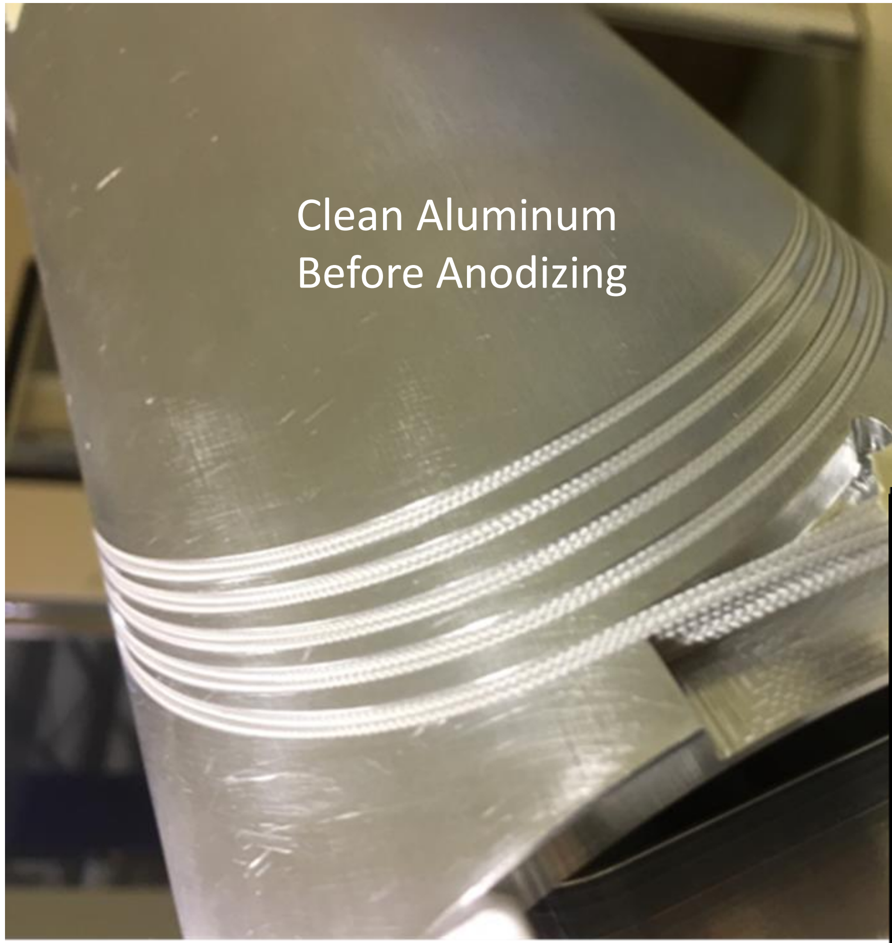


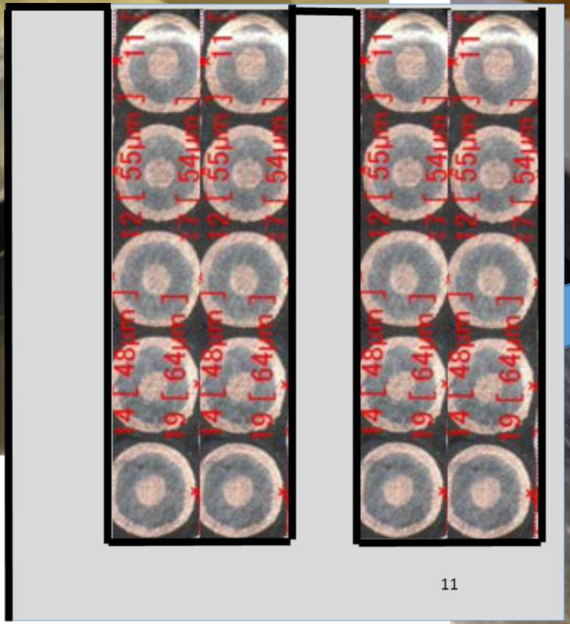



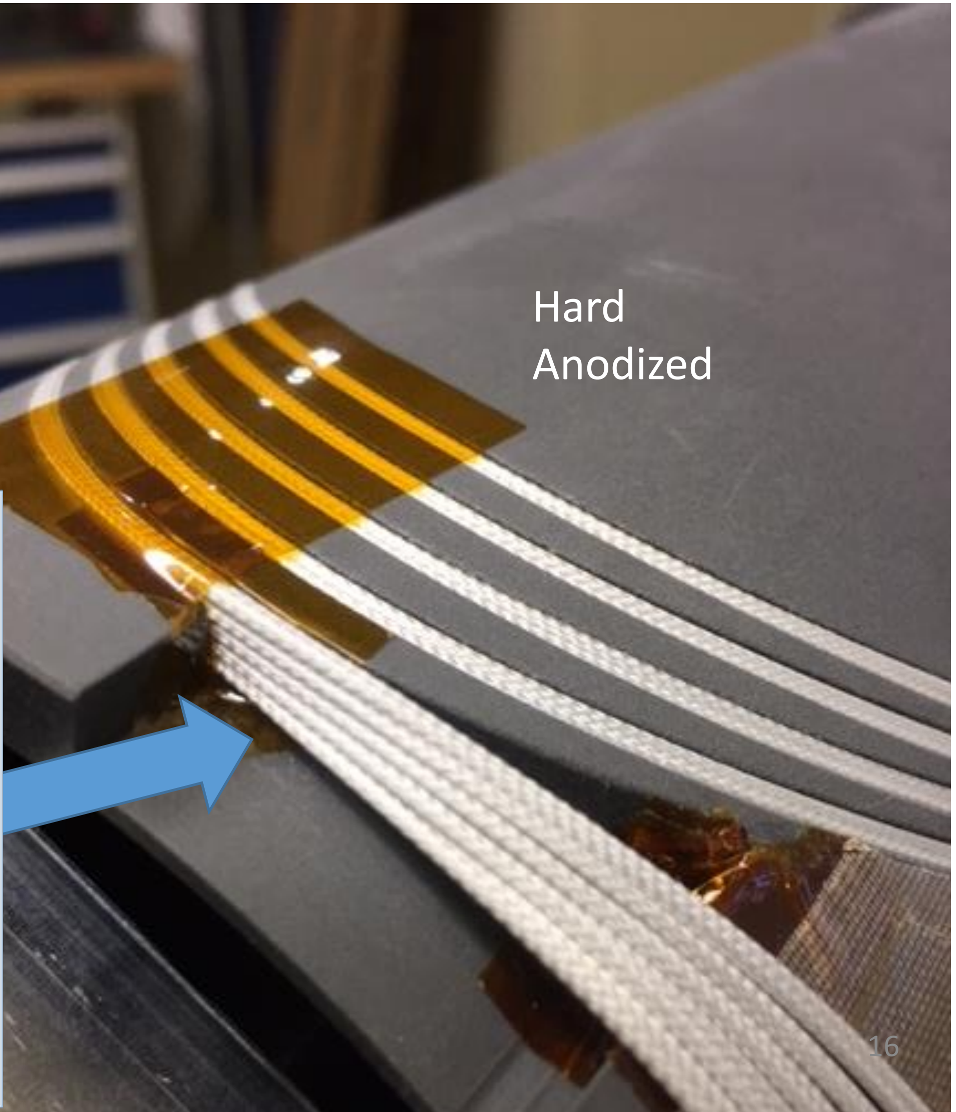


Access for resin

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







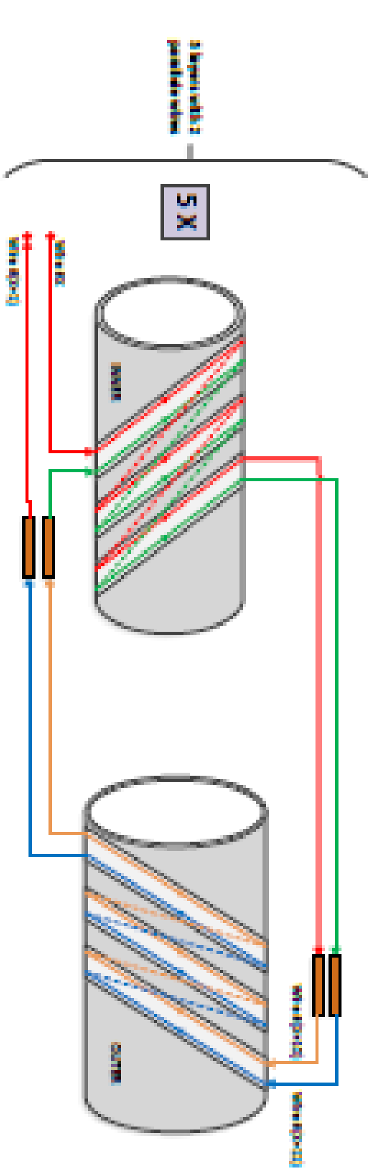
Manufacturing 2.2m long 105.35mm Inner Dia, CCT formers development.

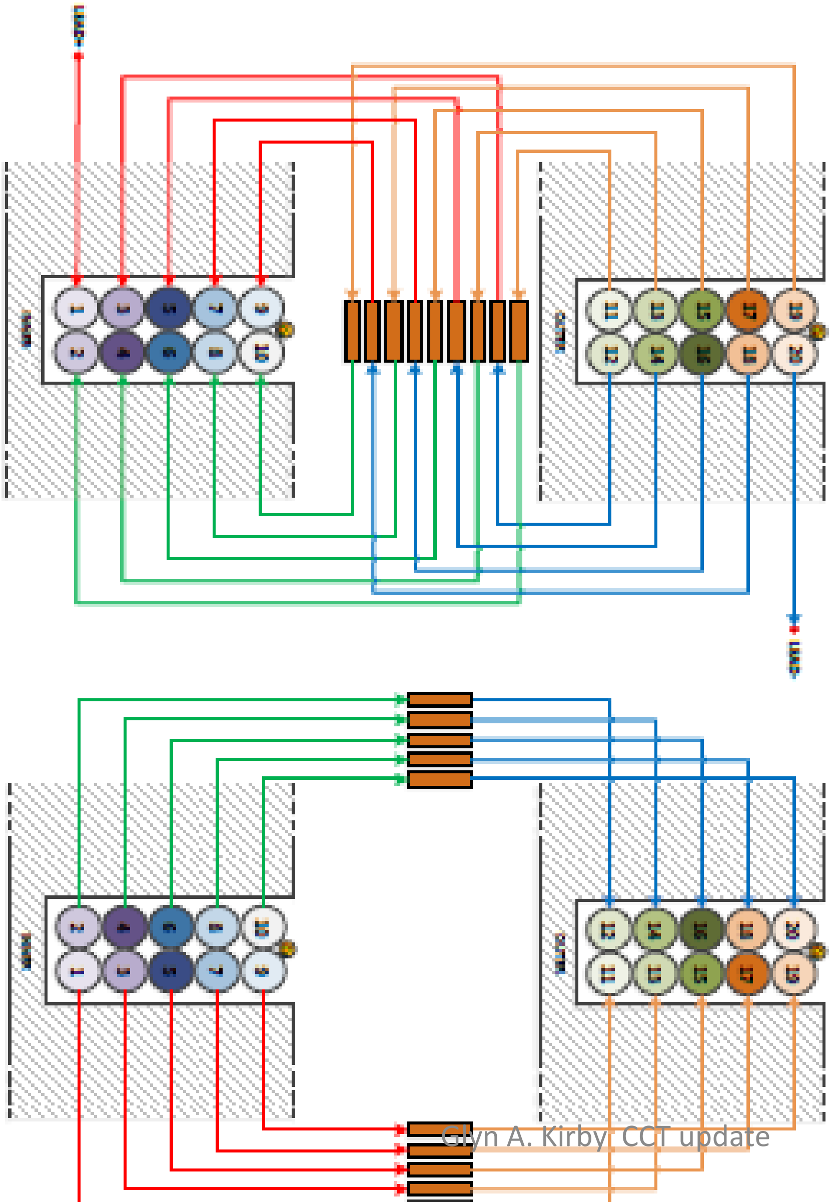
- CNC 4 axis machining 2mm wide x 5mm deep slot.
- Polishing / removing burrs and sharp edges
- Polishing to improve voltage brake down surface?
- Hard Anodizing

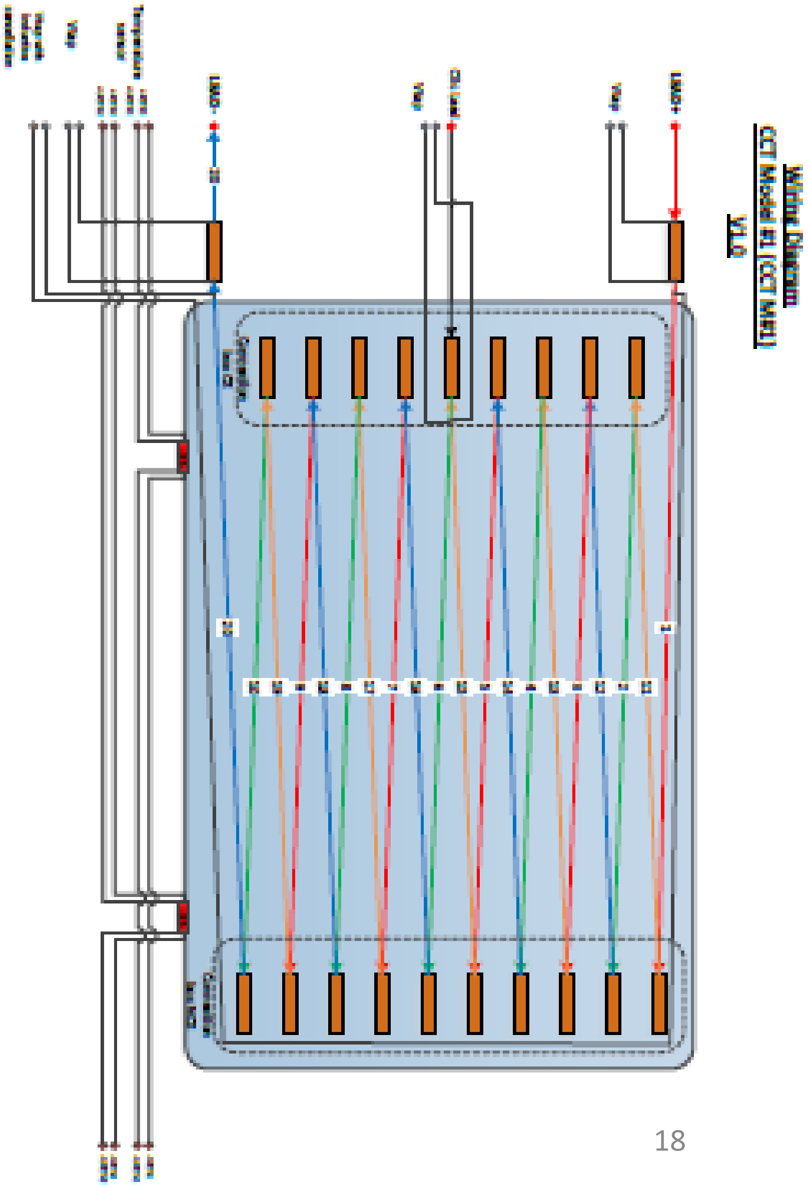
20 companies have been contacted

and we expect to open the bids on the 17th May

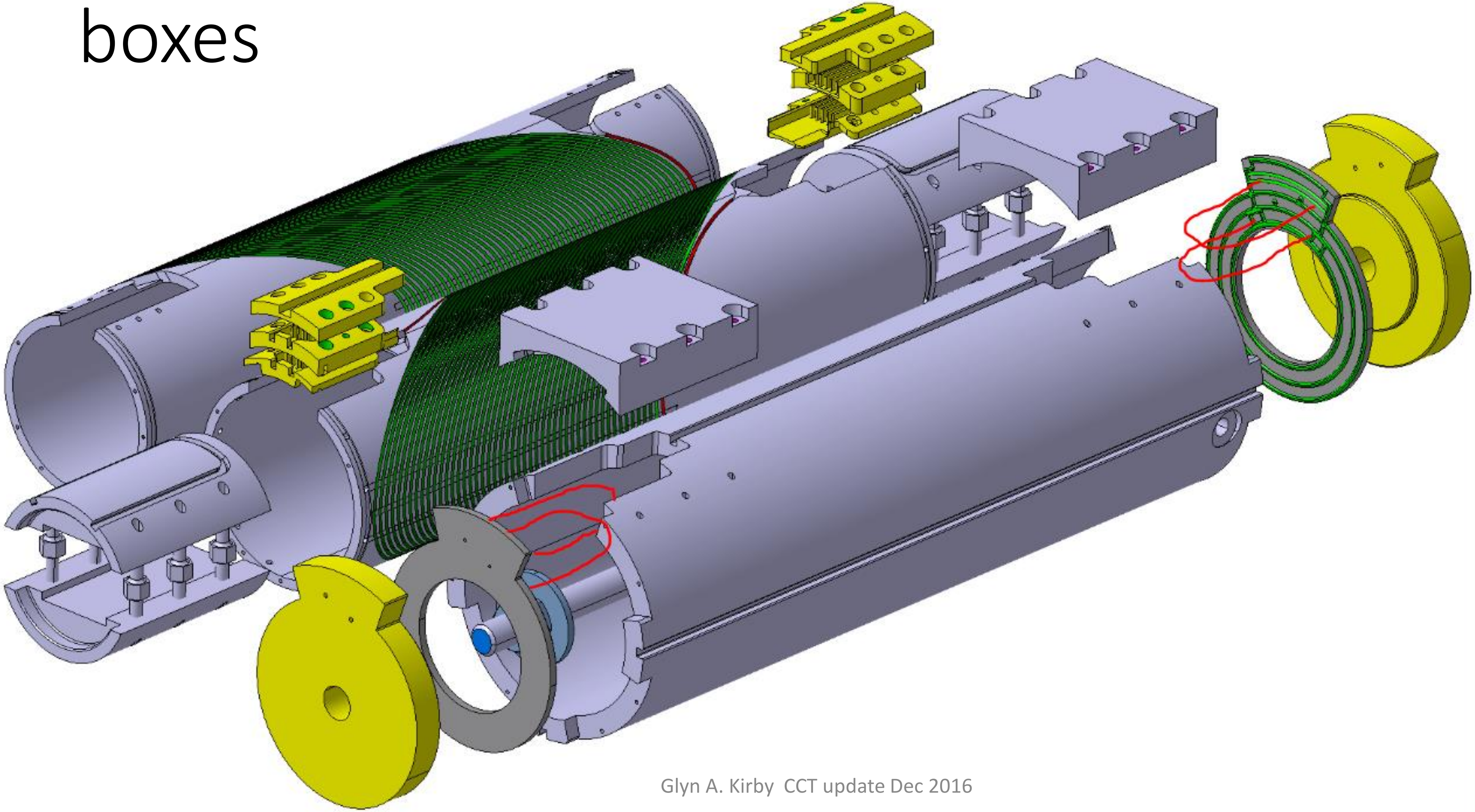
Wiring diagram one aperture

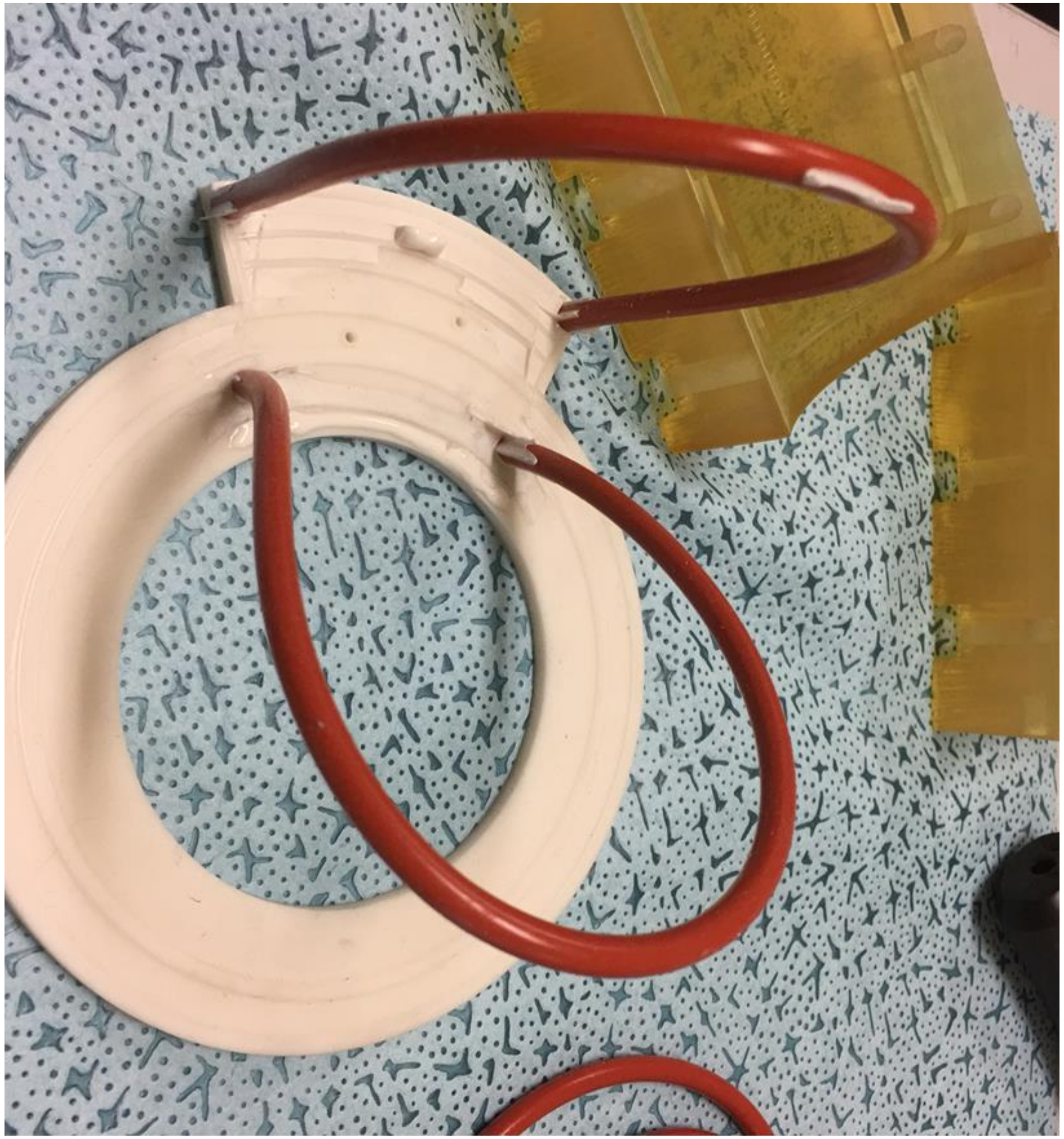


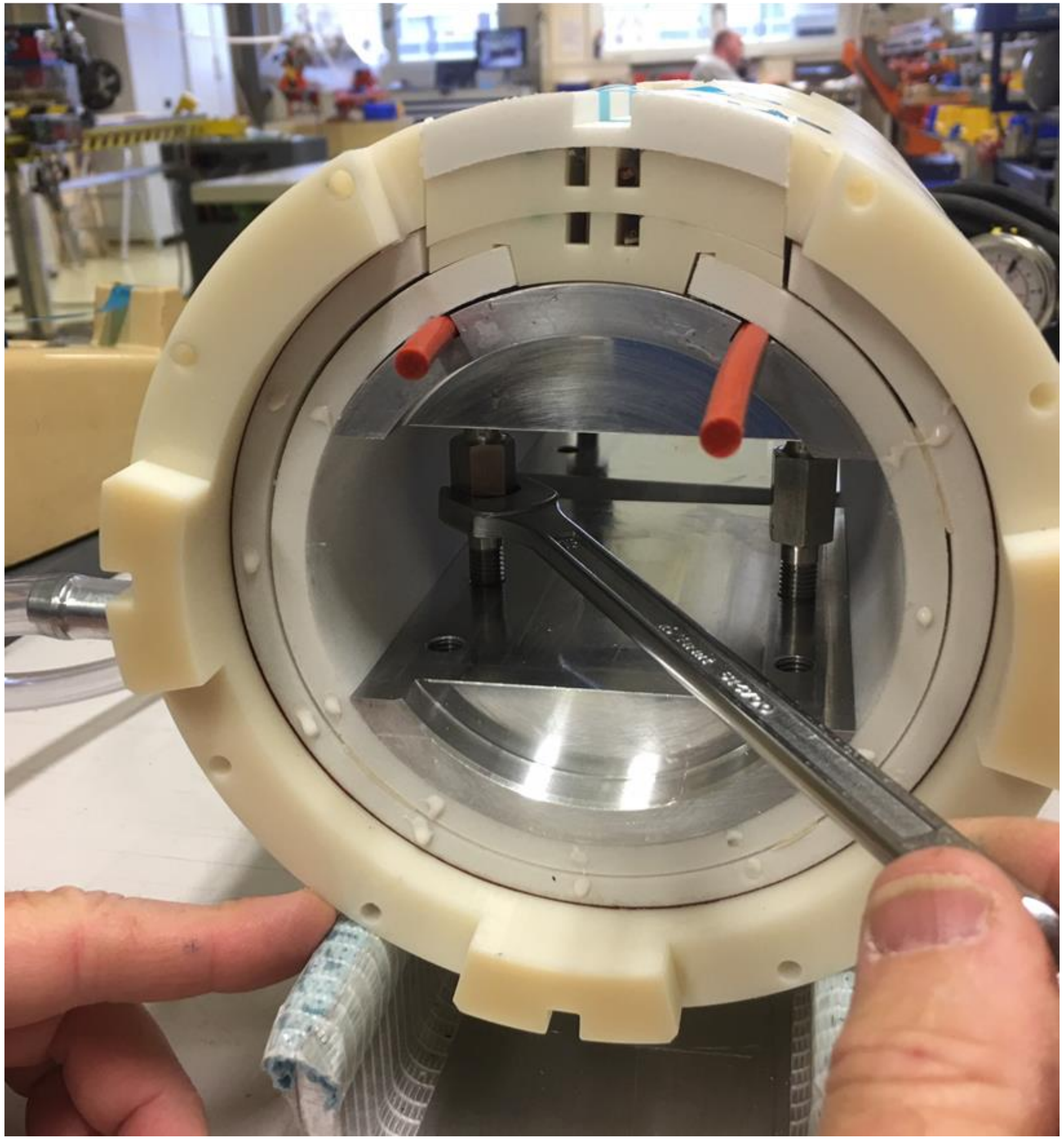


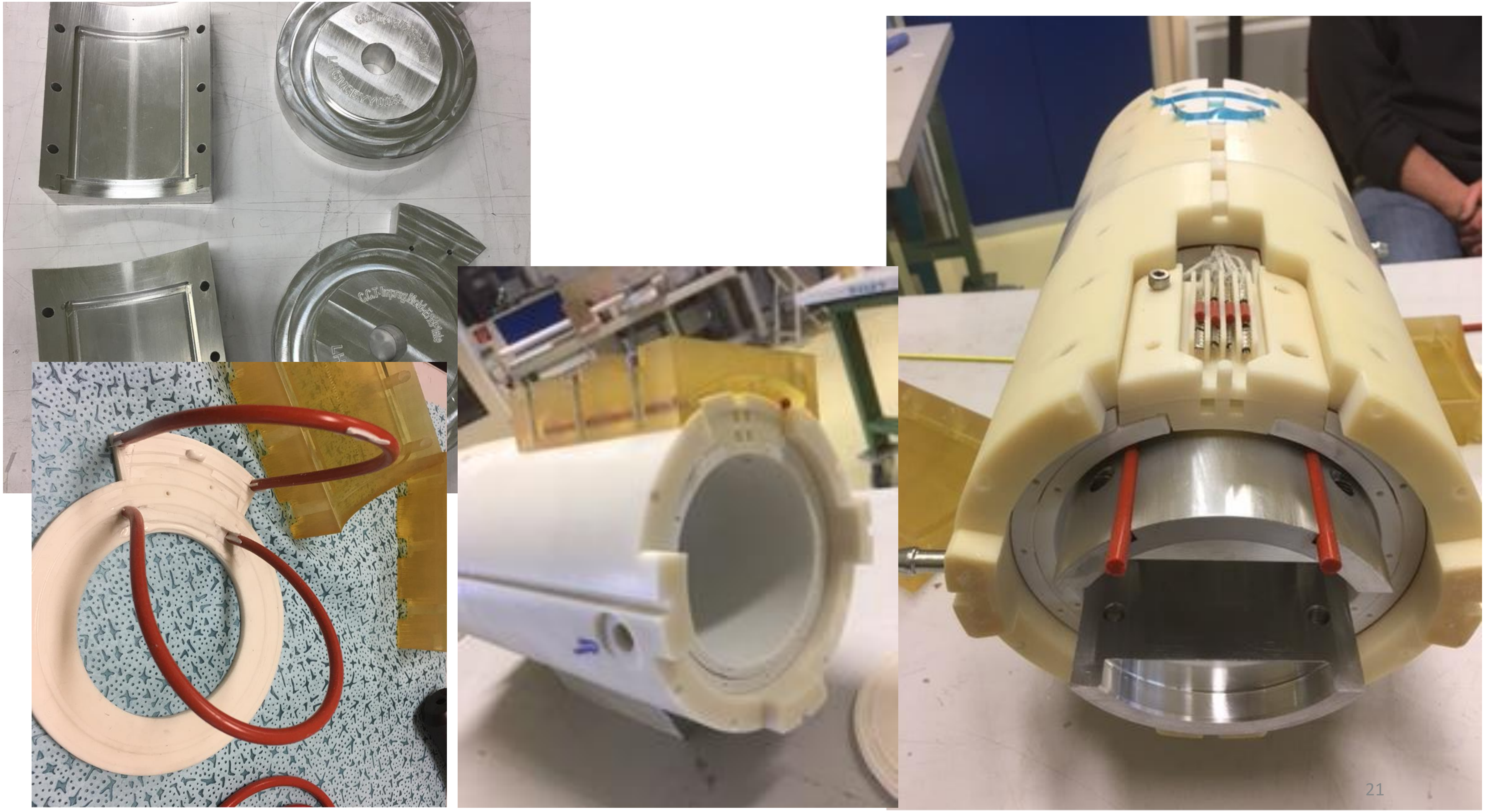


Coil formers , impregnation closures , joint boxes

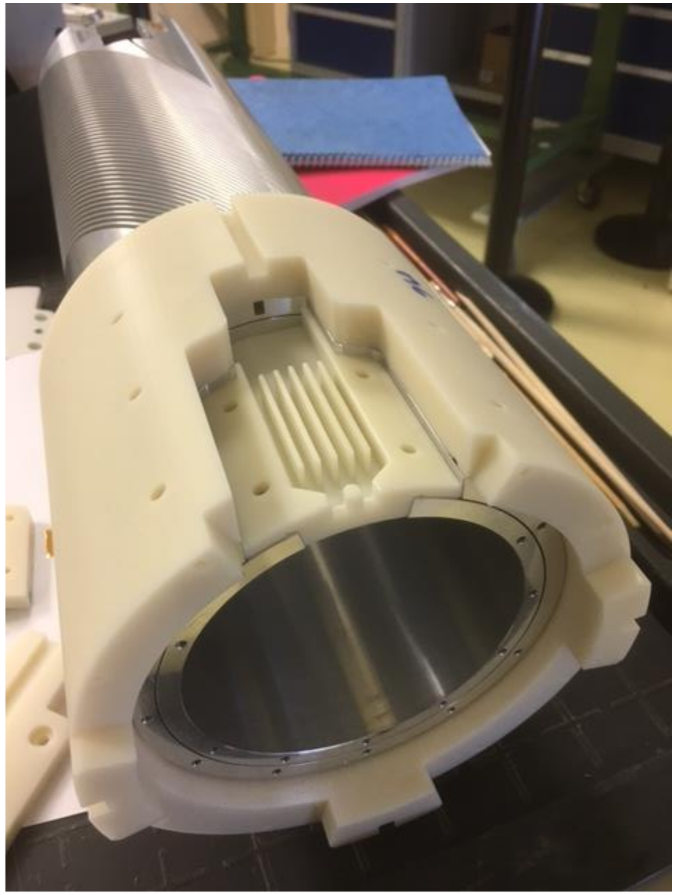


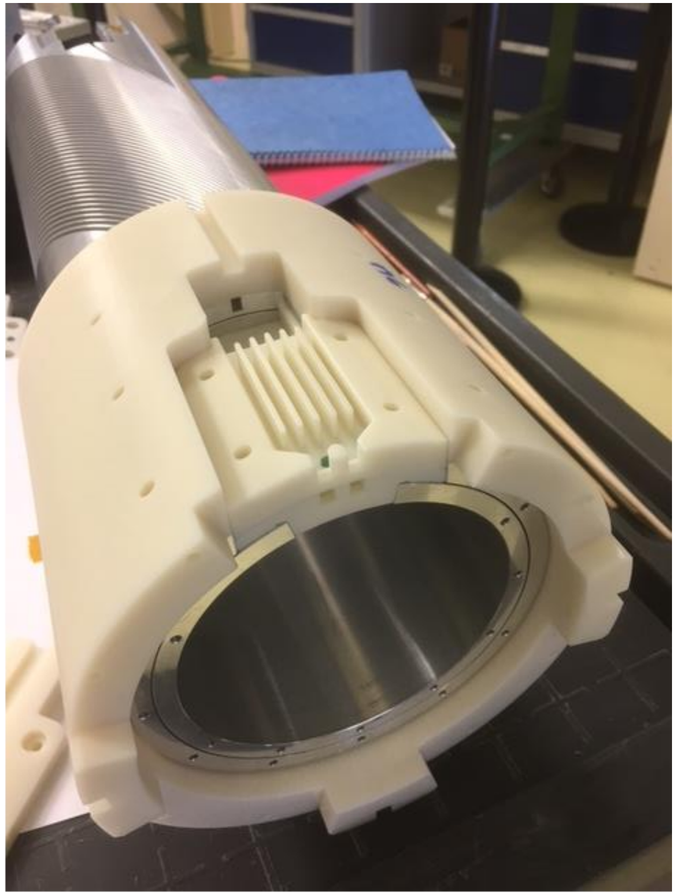


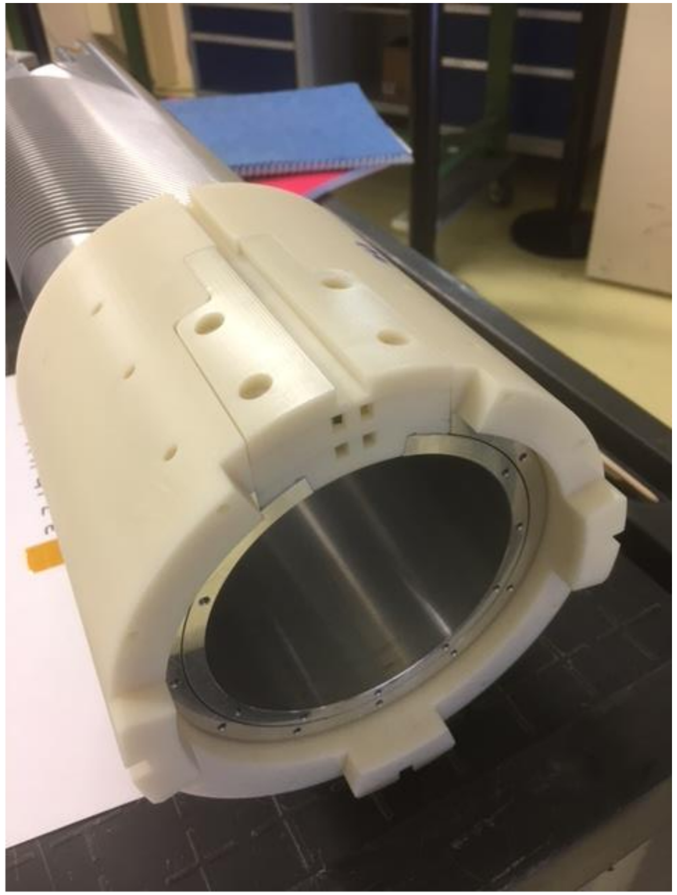




Two layer Joint box + cover

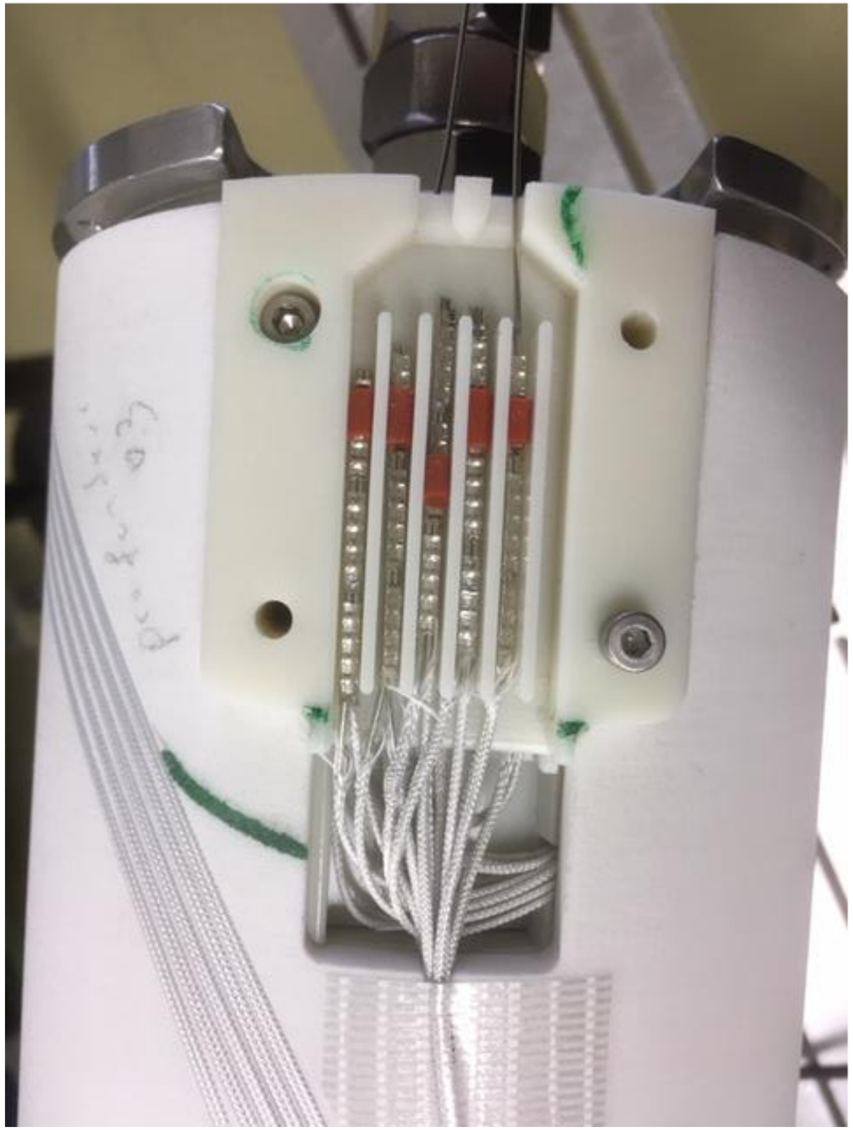


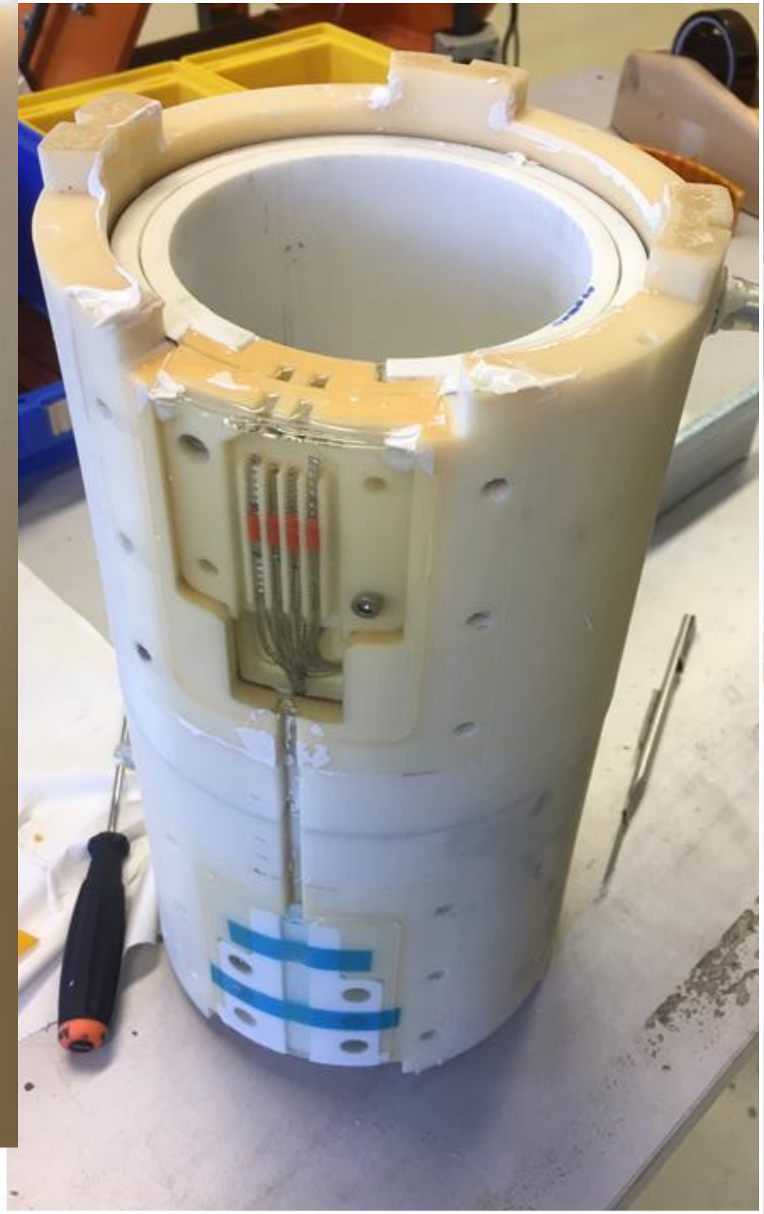


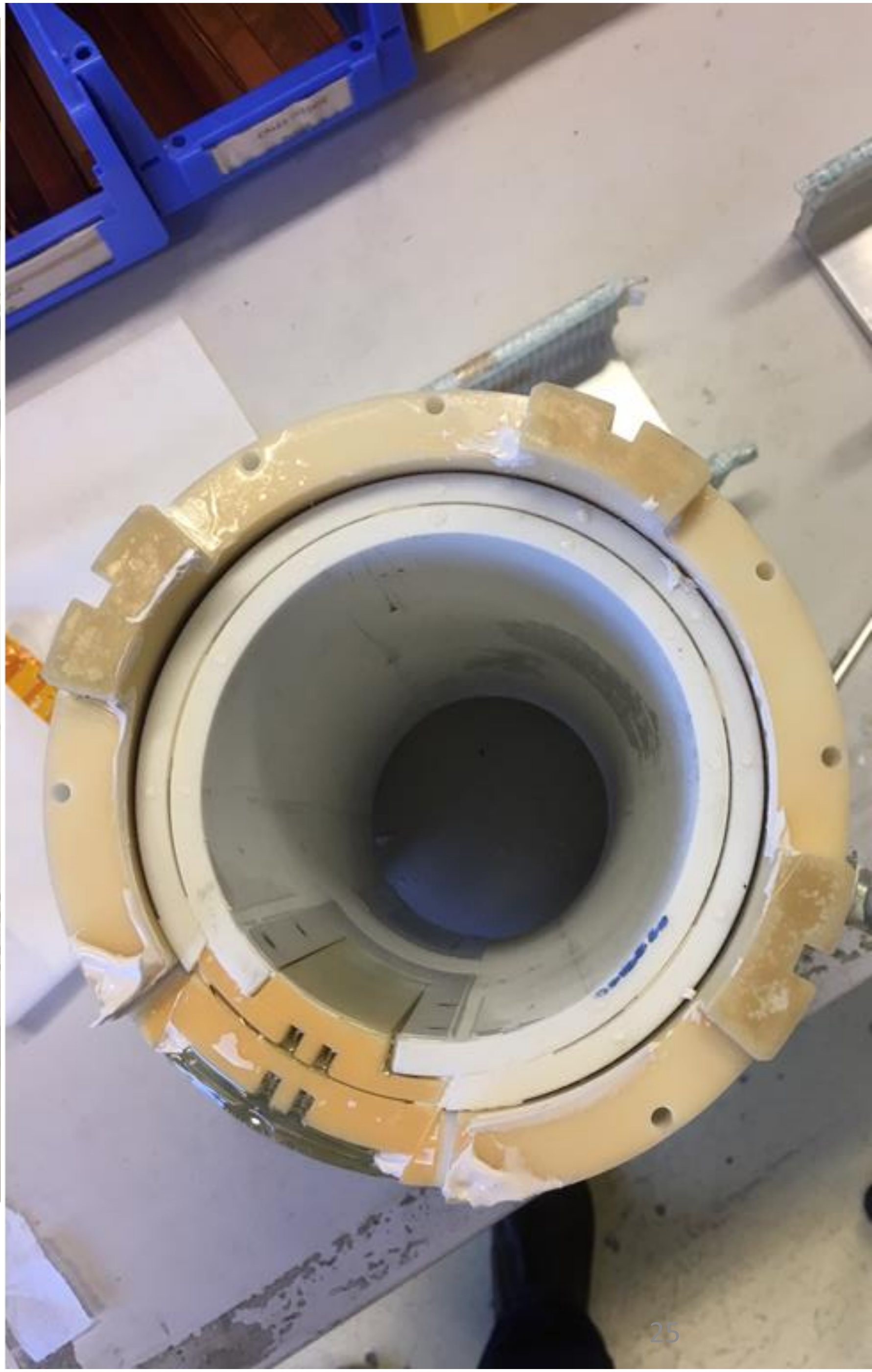


Joints : Crimped then soldered!

Total of 21 joints ,in 2 layer joint boxes



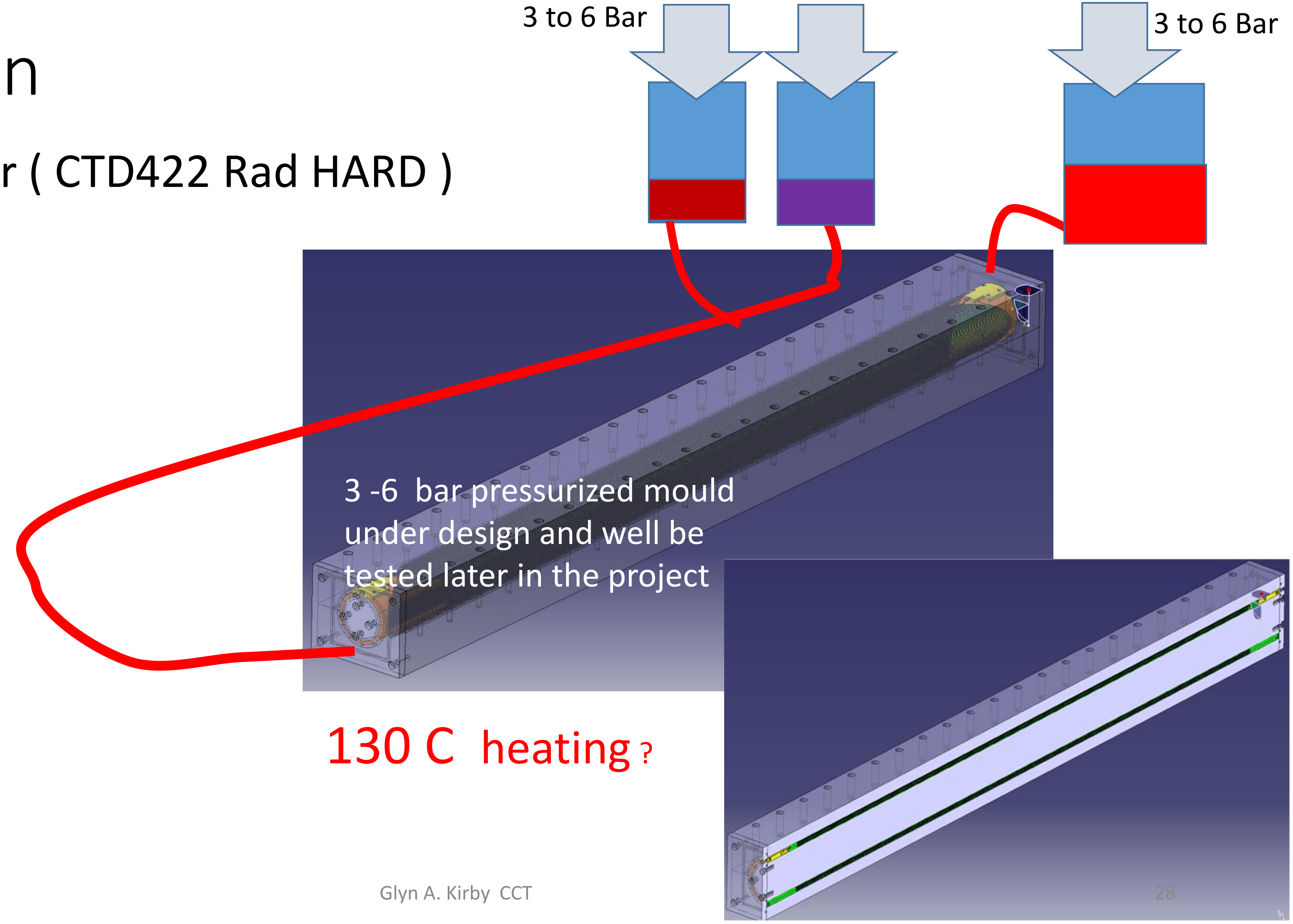




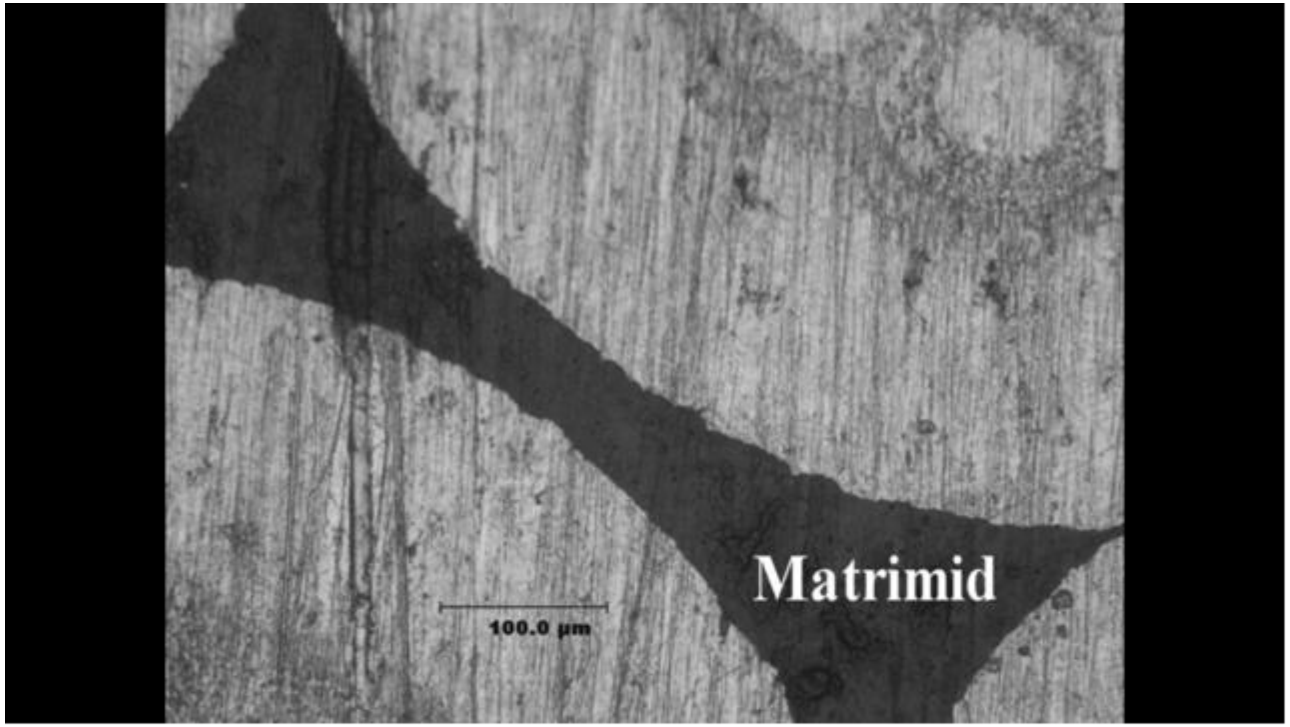
Impregnation test, the box will be filled with a glass filler, beads or chopped fibres for the final magnets

Impregnation

- CTD101K or later (CTD422 Rad HARD)
- 3 to 6 Bar
  - Process:
  - Vacuum out assembly
  - De-gas resign
  - Pre-heat assembly
  - Fill slowly from lower end
  - See resin exit
  - Allow resin to fill vacuum bubbles
  - Add 3 to 6 bar at both ends inert gas
  - Increase temp to cure resin



Looking at Matrimid impregnation a Polyimide in a solvent ?



Investigation of Alternative Materials for Impregnation of Nb_3Sn Magnets

Deepak R. Chichili, Jay Hoffman, and Alexander V. Zlobin

Abstract—Insulation is one of the most important elements of magnet design, which determines the electrical, mechanical, and thermal performance as well as lifetime of the magnet. The exposure to high radiation loads especially for the proposed LHC second-generation interaction region Nb_3Sn quadrupoles further limits the choices of the insulation materials. Traditionally Nb_3Sn magnets were impregnated with epoxy to improve both the mechanical and electrical properties. However, the acceptable radiation limit for epoxy is low which reduces the lifetime of the magnet. The paper presents the results of the feasibility study to replace epoxy with high radiation-resistant material during vacuum impregnation. The mechanical, thermal and electrical properties of samples impregnated with Matrimid were measured and compared with epoxy-impregnated samples.

Index Terms—Epoxy, Nb_3Sn, polyimides, radiation resistance.

I. Introduction

THE FIRST generation of low-β quadrupoles for LHC inner triplet based on NbTi superconductor technology are being produced at Fermilab and KEK [1], [2]. Based on the radiation dose, the estimated lifetime of these magnets at nominal luminosity of 10^{34} $cm^{-2}s^{-1}$ is about 6–7 years. Note that this estimate is in the high luminosity interaction regions. The limiting factor is the radiation strength of coil end-parts, which consist of substantial fraction of epoxy. The planned luminosity upgrades [3] will further reduce the lifetime of the magnets in the high luminosity regions to about 3 years.

In order to reach the highest possible machine luminosity without compromising the lifetime of the magnets, a new generation of quadrupoles made from superconductors with higher critical parameters than NbTi and structural materials with radiation strength higher than that of G11 are being investigated. Nb_3Sn is proposed as a choice of superconductor for 2nd generation LHC IR quadrupoles [4]. The lifetime of a magnet based on Nb_3Sn superconductor technology will depend on the choice of coil end-part material, cable insulation and the material used during vacuum impregnation. Since the coil end-parts are made from aluminum bronze and ceramic tape is used as cable insulation [5], the material used during vacuum impregnation will determine the lifetime of a Nb_3Sn magnet. Traditionally these magnets are impregnated with epoxy to improve both the mechanical and electrical properties of the coil. However, the acceptable radiation dose for epoxy is quite low. The paper presents the results of the study currently underway at Fermilab to replace epoxy with high radiation-resistant material like polyimides/bismaleimides.

Manuscript received August 5, 2002. This work was supported by the U.S. Department of Energy.

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Digital Object Identifier 10.1109/TASC.2003.812692

TABLE I
Effect of Temperature on the Viscosity and Potlife of Matrimid. The Data was Provided by the Manufacturer

Temperature, °C	Viscosity, cps	Potlife, min
75	5000	> 1000
100	800	1000
125	10	100
> 200	<10	< 1

II. Materials Investigated

Various polyimide/bismaleimides that are commercially available were investigated to replace epoxy as a medium of impregnation for Nb_3Sn magnets. The determining factors for the applicability of these solutions are the viscosity and potlife. An ideal solution for vacuum impregnation will have low viscosity and long potlife. Note that the viscosity of most of the available polyimide solutions is reduced through the addition of solvents. However, these solutions cannot be used under vacuum due to out-gassing. On the other hand, solvent-less polyimide solutions usually have high viscosity at room temperature making them unsuitable for vacuum impregnation. However, raising the temperature, the upper limit of which is determined by the potlife, can reduce viscosity. Note that the potlife is inversely proportional to the temperature.

A list of commercially available bismaleimide products from various manufacturers is given in [6]. In this study we will concentrate on Matrimid® 5292, by Vantico (spin off of CIBA-GEIGY). Future work will include more products and comparisons between these products.

A. Matrimid® 5292

Matrimid® 5292 is a two-component bismaleimide system which when combined and used in controlled environment is suitable for vacuum impregnation. Table I gives the properties as provided by the manufacturer. For comparison the epoxy CTD-101K, which Fermilab is currently using to impregnate the Nb_3Sn dipole models, has a viscosity of about 500 cps at 60 °C with a potlife of about 40 hrs [7].

Matrimid part A and B were mixed in proper proportions (1 : 1.13 pbw) in a mixer equipped with heating capability and mechanical stirrer. The components were heated to 100 °C with continuous stirring until a clear solution was obtained. The temperature has to be maintained within ±5 °C to obtain the polyimide solution with the right viscosity and potlife as indicated in the Table I. A temperature of 100 °C was chosen because it

Matrimid

Fig. 2. Cross-section of a sample impregnated with Matrimid 5292.

C. Testing Procedure

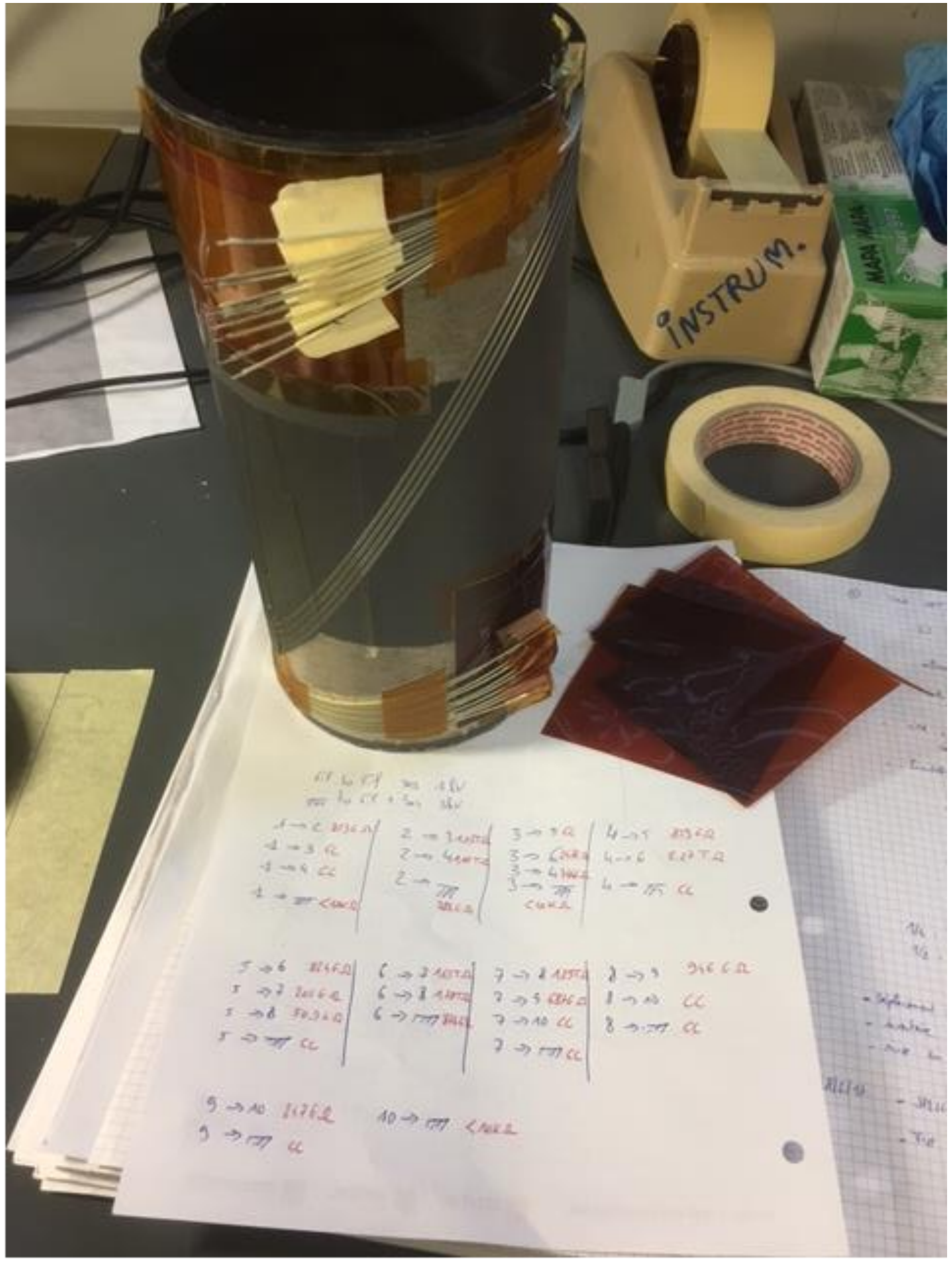
Once the samples were impregnated, they were sectioned,

Looking at Bees wax as an impregnation material

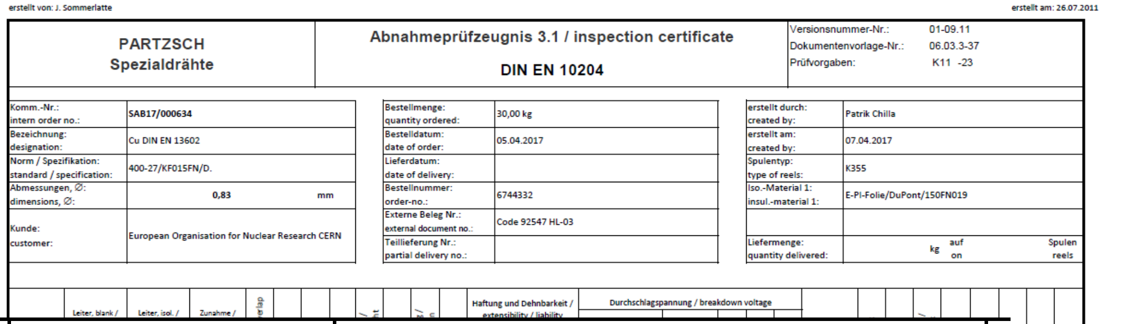
Voltage Testing std.

- Turn to turn Design value 150 V
- Voltage to ground, Design value 435 V

- Test CERN spec.
- At cold = Nominal x 2 + 500V = 1370 V
- At room temp = Cold value x 2 = 2740 v



Insulation testing
8.2kV x 1.4=11.5 kV DC

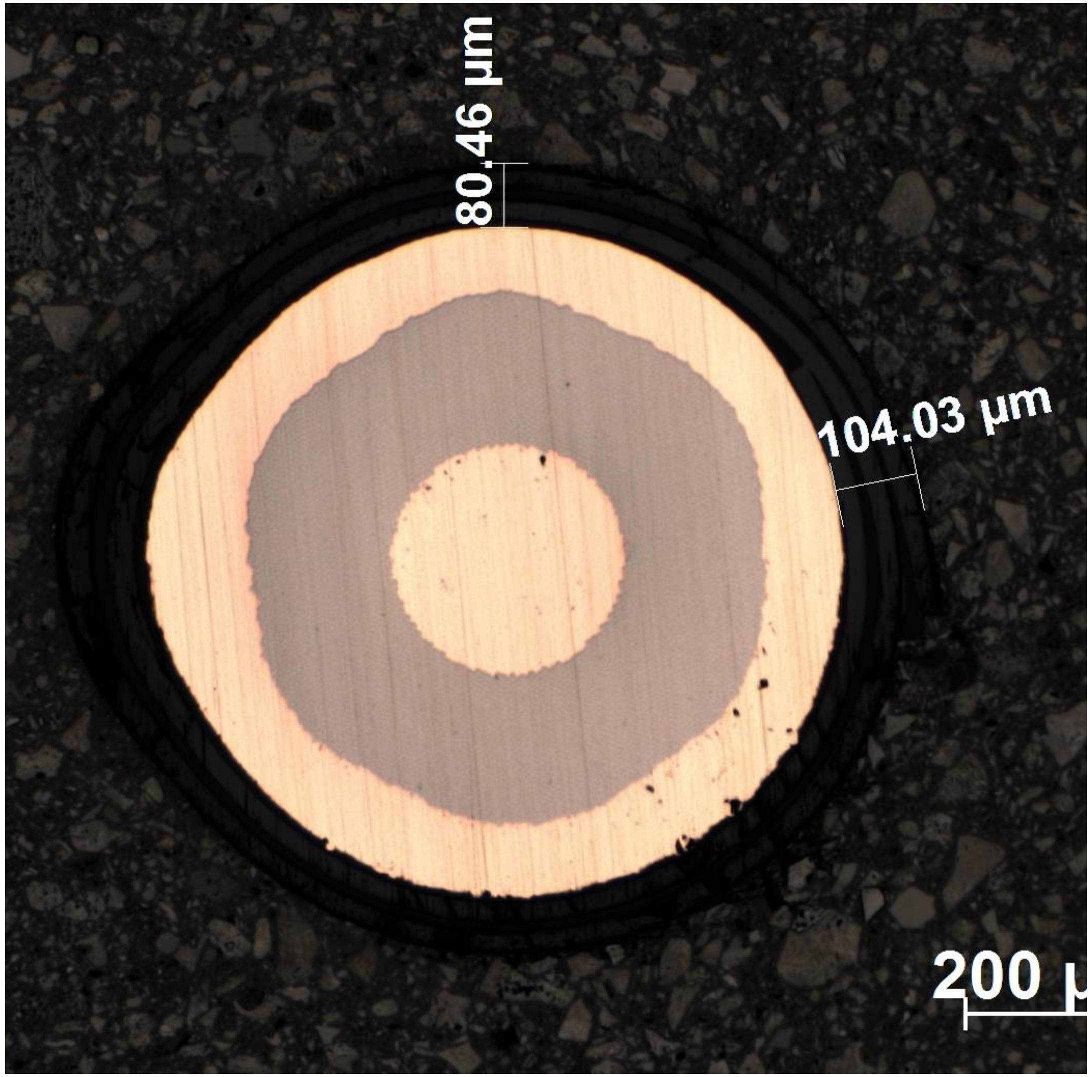

erstellt von: J. Sommerlatte | erstellt am: 26.07.2011

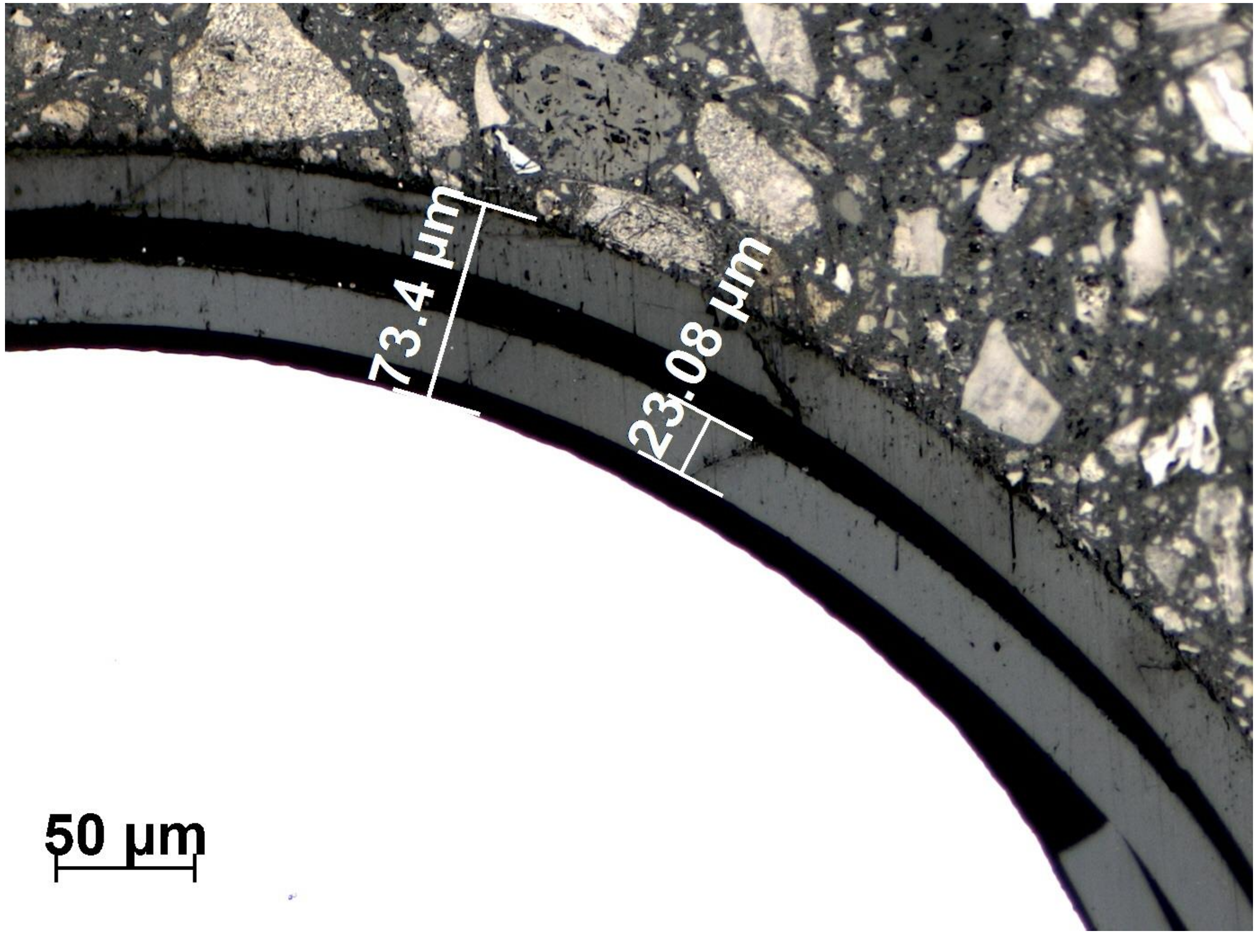
PARTZSCH Spezialdrähte	Abnahmeprüfzeugnis 3.1 / inspection certificate DIN EN 10204	Versionsnummer-Nr.: 01-09.11 Dokumentenvorlage-Nr.: 06.03.3-37 Prüfvorgaben: K11 -23

Komm.-Nr.: intern order no.:	SAB17/000634	Bestellmenge: quantity ordered:	30,00 kg	erstellt durch: created by:	Patrik Chilla
Bezeichnung: designation:	Cu DIN EN 13602	Bestelldatum: date of order:	05.04.2017	erstellt am: created by:	07.04.2017
Norm / Spezifikation: standard / specification:	400-27/KF015FN/D.	Lieferdatum: date of delivery:		Spulentyp: type of reels:	K355
Abmessungen, ∅: dimensions, ∅:	0,83 mm	Bestellnummer: order-no.:	6744332	Iso.-Material 1: insul.-material 1:	E-PI-Folie/DuPont/150FN019
Kunde: customer:	European Organisation for Nuclear Research CERN	Externe Beleg Nr.: external document no.:	Code 92547 HL-03		
		Teillieferung Nr.: partial delivery no.:		Liefermenge: quantity delivered:	kg auf on Spulen reels

	Leiter, blank / conductor, bare ø	Leiter, isol. / conductor, insul. ø	Zunahme / increase	Überlappung / overlap				Zugfestigkeit / tensile strenght		Bruchdehnung / fracture strain		Haftung und Dehnbarkeit / extensibility / liability				Durchschlagspannung / breakdown voltage							
																ca. 20°C			220°C / 30'				
												Dorn 2 x d				straight	Dorn 2 x d		Dorn 2 x d				
limit / min max	0,822 0,838	0,960 1,000	0,130 0,170	48 50				≥200		≥1		pass				≥5,0	≥4,0		≥3,5				
low	0,82	0,98	0,15													10,00	9,10		8,20				
mean	0,82	0,98	0,15	52				684		11		pass				10,00	9,57		8,47				
max	0,82	0,99	0,16													10,00	9,90		8,70				
unit	mm	mm	mm	%				MPa		%		-				kV	kV		kV				

Close look at the insulation cross section





Superconductor Ic test at 1.8 and 4.5 K in 2-5T



To test the wire performance after the high temperature that it saw during the insulation process 420 C / 30 s we will re-test the insulated wire at 4.5 and 1.8K over the range 2 to 5 Tesla. Above we see the test preparation.

Insulation material Kapton CR

Technical Information

DuPont Films

High Performance Films

Kapton®

polyimide film

Corona Resistant Kapton® CR Takes Electrical Insulation Design and Reliability to New Levels

Improved Margin of Operational Safety

DuPont Kapton® CR polyimide film was developed specifically to withstand the damaging effects of "corona," which can cause ionization and eventual breakdown of an insulation material or system when the voltage stress reaches a critical level.

In development and testing by DuPont with ABB Industrie AG Switzerland (a subsidiary of the multinational ABB group) and Siemens AG, two of the world's foremost traction motor manufacturers, Kapton® CR shows corona resistance or voltage endurance of greater than 100,000 hr at 20 kV/mm (500 V/mil) at 50 Hz. Kapton® CR also provides twice the thermal conductivity (0.385 W/m·K) of standard Kapton®. These substantial property improvements increase the margin of operational safety and open the door to new electrical design possibilities in traction motors, transformers, and electrical rotating machines.

Table 1 shows the properties of Kapton® CR and **Table 2** shows the properties of the heat-sealable version, Kapton FCR®, which is laminated to DuPont Teflon® FEP film. As you can see, these next-generation insulation materials retain all the other excellent electrical, thermal, mechanical, and physical properties for which standard Kapton® is known.

Excellent Results in Corona Resistance Testing

Figure 1 compares the corona resistance of Kapton® CR to that of standard Kapton® HN. At a voltage stress of 20 kV/mm (500 V/mil) AC at 50 Hz, for example, Kapton® CR has a life endurance in excess of 100,000 hr (11½ yr), compared to 200 hr for Kapton® HN. Similar substantial improvements in corona resistance are seen at other voltages as well. Testing was performed independently by DuPont, ABB Industrie AG Switzerland, and Siemens AG according to IEC 343.

Figure 1. Comparison of Corona Resistance of Kapton® 100 CR versus Kapton® 100 HN. Based on measurements performed by DuPont, ABB Industrie AG Switzerland, and Siemens AG according to IEC 343.

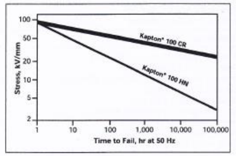


Table 1
Typical Properties of Kapton® Type 100 CR Polyimide Film, 25 μm (1 mil)

Property	Typical Value at 23°C (73°F)	Test Method
Electrical		
Corona Resistance, hr at 20 kV/mm at 50 Hz	>100,000	IEC-343
Dielectric Strength, kV/mm (V/mil)	291 (7,400)	ASTM D-149-81
Dielectric Constant	3.9	ASTM D-150-81
Dissipation Factor	0.003	ASTM D-150-81
Volume Resistivity, ohm·cm	2.3×10^{16}	ASTM D-257-78
Surface Resistivity, ohm/sq	3.6×10^{16}	ASTM D-257-78
Mechanical		
Ultimate Tensile Strength, MPa (psi)	152 (22,100)	ASTM D-882-91
Yield Point at 3%, MPa (psi)	66 (9,500)	ASTM D-882-91
Stress to Produce 5% Elongation, MPa (psi)	86 (12,500)	ASTM D-882-91
Ultimate Elongation, %	40	ASTM D-882-91
Tensile Modulus, GPa (psi)	3.2 (463,000)	ASTM D-882-91
Tear Strength—Propagating, N (lbf)	0.03 (0.007)	ASTM D-1922
Tear Strength—Initial, N (lbf)	11 (2.5)	ASTM D-1004-90
Density, g/cm³	1.54	ASTM D-1505-90
Yield, m²/kg (ft²/lb)	25.5 (125)	—
Thermal		
Coefficient of Thermal Conductivity, W/m·K	0.385	Univ. of Delaware Method
Flammability	94 V-0	UL-94 (Tested by DuPont)
Shrinkage, % at 150°C (302°F)	0.2	ASTM D-5214-91
400°C (752°F)	0.6	

Table 2
Typical Properties of Kapton® Type 150 FCR 019 Polyimide Film, 37.5 μm (1.5 mil)

Property	Typical Value at 23°C (73°F)	Test Method
Electrical		
Corona Resistance, hr at 20 kV/mm at 50 Hz	>100,000	IEC-343
Dielectric Strength, kV/mm (V/mil)	173 (4,400)	ASTM D-149-81
Dielectric Constant	2.9	ASTM D-150-81
Dissipation Factor	0.001	ASTM D-150-81
Volume Resistivity, ohm·cm	5.3×10^{16}	ASTM D-257-78
Surface Resistivity, ohm/sq	1.6×10^{15}	ASTM D-257-78
Mechanical		
Ultimate Tensile Strength, MPa (psi)	117 (17,000)	ASTM D-882-91
Yield Point at 3%, MPa (psi)	48 (7,000)	ASTM D-882-91
Stress to Produce 5% Elongation, MPa (psi)	62 (9,000)	ASTM D-882-91
Ultimate Elongation, %	43	ASTM D-882-91
Tensile Modulus, GPa (psi)	2.4 (348,000)	ASTM D-882-91
Tear Strength—Propagating, N (lbf)	0.05 (0.012)	ASTM D-1922
Tear Strength—Initial, N (lbf)	5.3 (1.2)	ASTM D-1004-90
Density, g/cm³	1.72	ASTM D-1004-90
Yield, m²/kg (ft²/lb)	15.79 (77.4)	—
Bonding, N/cm (lb/in)		
Teflon® FEP to Kapton® CR	7.7 (4.4)	DuPont Test
Teflon® FEP to Copper	7.9 (4.5)	DuPont Test
Laminate Bond as Received	1.2 (0.7)	DuPont Test

2

Figure 2 compares the corona resistance of Kapton® FCR, a heat-sealable version laminated to Teflon® FEP film, with that of standard Kapton® FN, which is also laminated to Teflon®. As expected, the corona resistance of Kapton® FCR is substantially more than that of standard, laminated Kapton® FN.

Excellent Insulating Properties for Magnet Wire

Throughout the development program, Swiss Insulating Works performed a series of magnet wire tests comparing next-generation to standard Kapton®. These results are summarized in **Table 3**. Kapton® FCR exhibits properties almost identical to those of Kapton® FN, both of which are well in excess of typical specifications.

Figure 2. Comparison of Corona Resistance of Kapton® 150 FCR 019 versus Kapton® 150 FN 019. DuPont testing performed according to IEC 343.

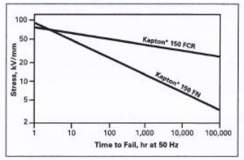


Table 3
Comparison of Magnet Wire Insulating Properties for Kapton® Type 150 FCR 019 Polyimide Film and Kapton® Type 150 FN 019 Polyimide Film*

Property	Kapton® 150 FN 019	Kapton® 150 FCR 019	Kapton® 150 FN 019	Kapton® 150 FCR 019
Number of Wraps	1	1	1	1
Lapping, %	50	50	53	53
Insulation Increase, mm	0.15	0.15	0.21	0.21
Breakdown Voltage, Straight, IEC 851-5, kV				
Min.	4.5	4.0	6.0	6.0
Avg.	6.0	5.5	7.0	7.0
Bend Test, IEC 851-3				
2× Width Edgewise, kV				
Min.	4.5	4.0	5.0	5.0
Avg.	5.5	5.0	6.0	6.0
2× Thickness Flat, kV				
Min.	4.5	4.0	5.0	5.0
Avg.	5.5	5.0	6.0	6.0
Bend Test After Heat Shock (30 min at 220°C [428°F]), IEC 851-6, kV				
Min.	4.5	4.0	5.0	4.5
Avg.	5.5	5.0	6.0	5.5

*Data provided by Swiss Insulating Works.

3

Excellent Resistance to Voltage Breakdown

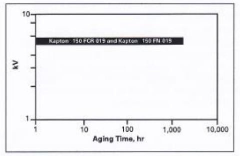
Using magnet wire prepared by Swiss Insulating Works, Siemens AG compared the voltage breakdown of Kapton® FCR versus standard Kapton® FN in a shot bath according to IEC 251-3. The magnet wire was aged at 250°C (482°F), placed in a lead shot bath, and a voltage was applied. The results in **Figure 3** show that even after 2,000 hr at 250°C (482°F), there is no degradation for either Kapton® FCR or Kapton® FN.

Applications and Availability

Traction motor manufacturers are in the process of evaluating Kapton® CR, and it has already been adopted by ABB Industrie AG Switzerland for use in its Veridur®-Plus insulating system. It can also be used in transformers, electrical rotating machines (for example, in generators), and any other insulation application where corona is a concern.

Kapton® CR is available in a variety of widths, 3.0 mm to 1,200 mm, in 25 μm thickness. Thicker versions are planned and custom gauges can be discussed. A heat-sealable version, consisting of 25 μm Kapton® CR laminated to 12.5 μm Teflon® FEP film, is also available.

Figure 3. Comparison of Voltage Breakdown of Kapton® 150 FCR 019 and Kapton® 150 FN 019 in a Shot Bath (IEC 251-3). Magnet wire was immersed in lead beads and thermally aged at 250°C (482°F) by Siemens AG. No degradation was seen up to 2,000 hr for either Kapton® FCR or Kapton® FN. Both magnet wires gave excellent results within the band shown in the chart.



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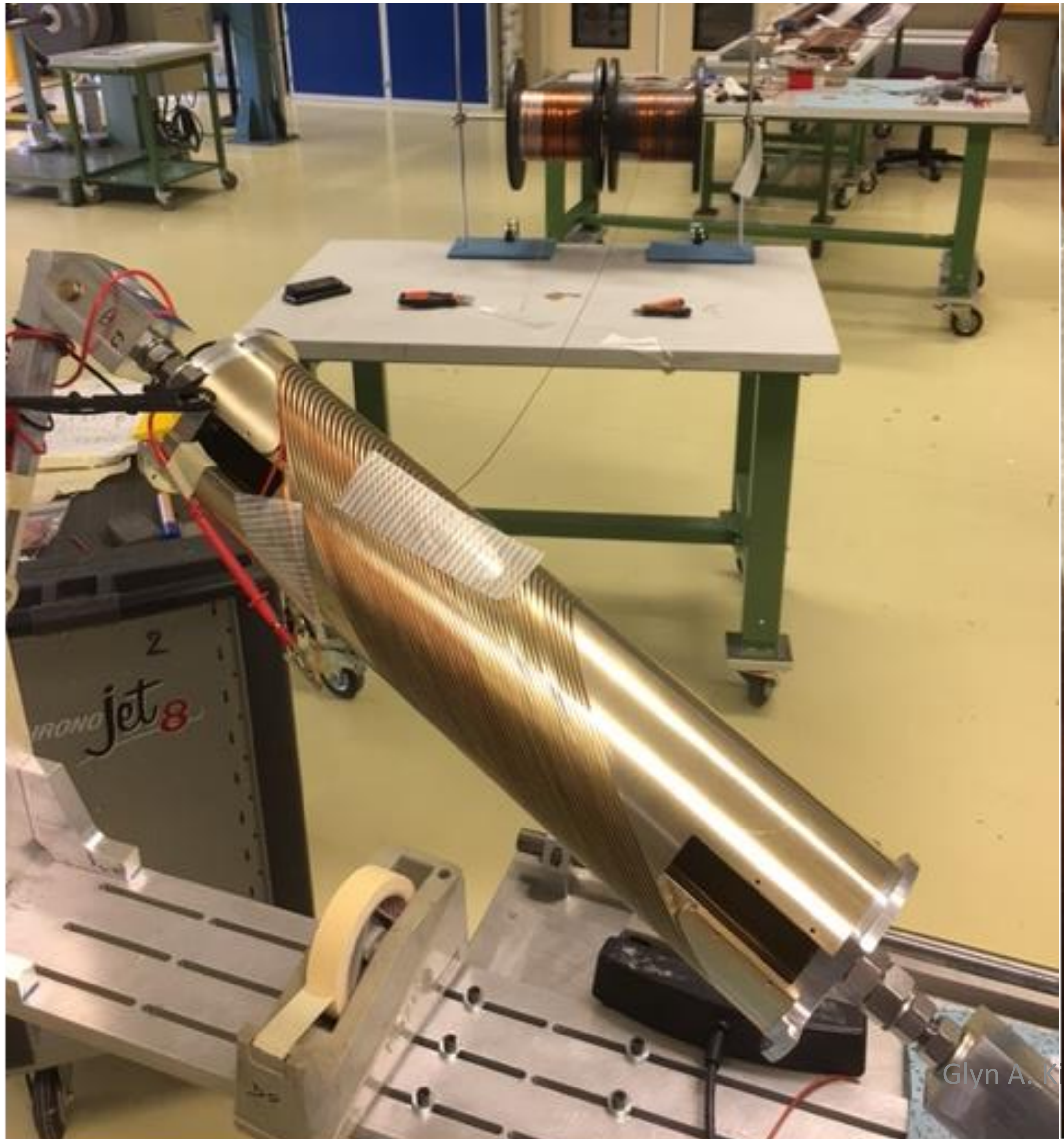
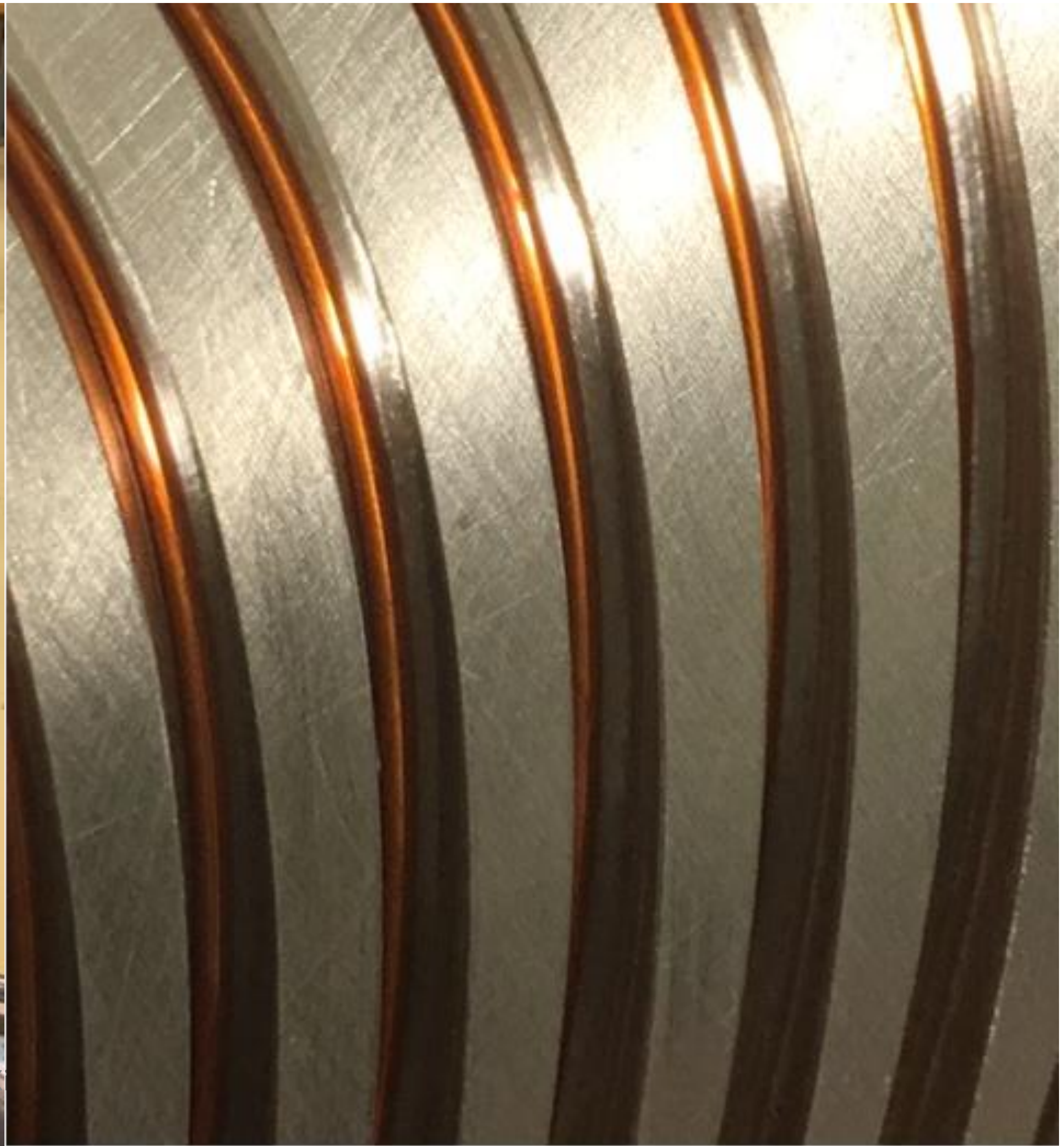
DuPont Films

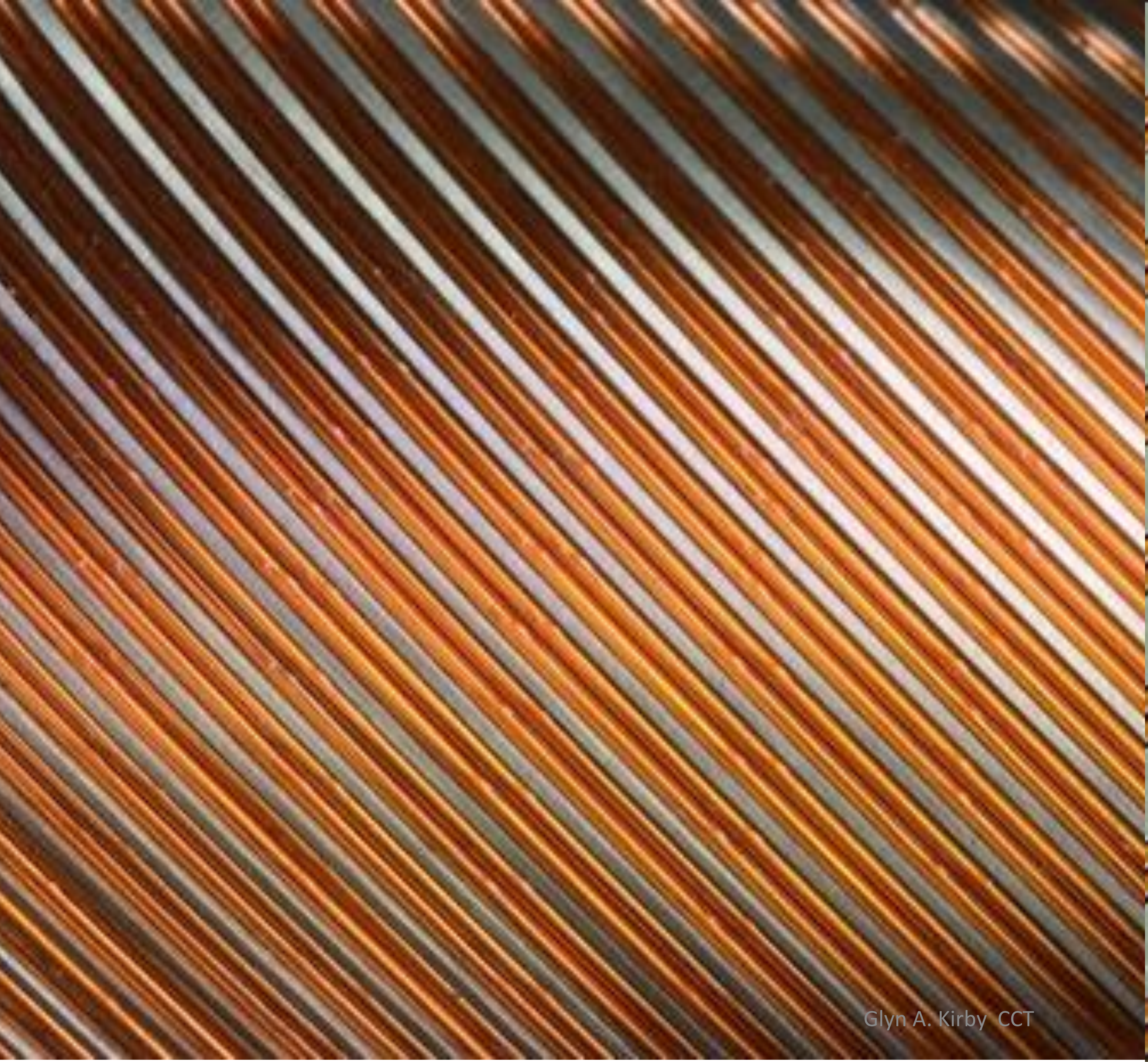
Winding started , first wire in the slot!

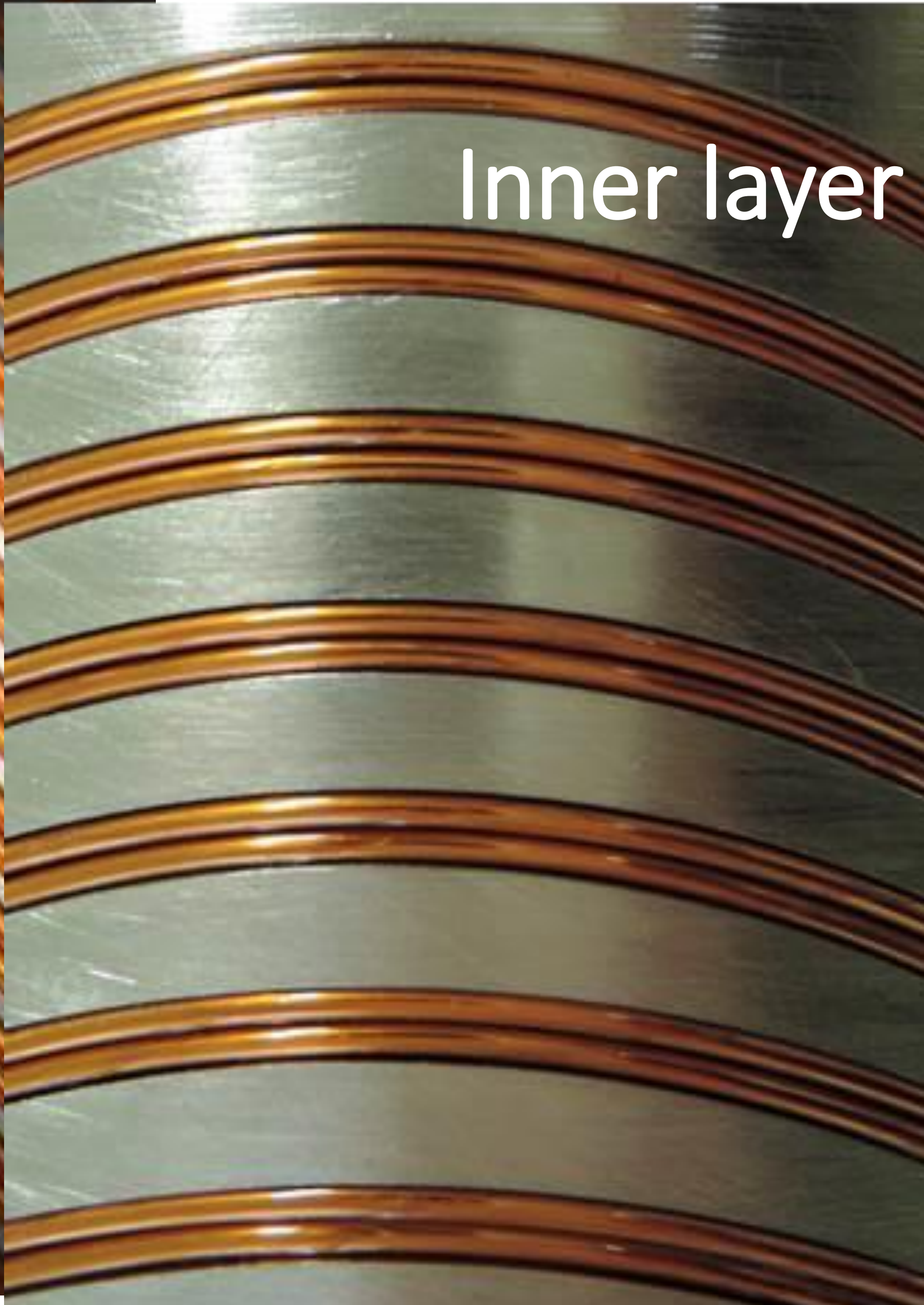
Aluminium-Bronze former with CERN wire Polyimide wrapped insulation





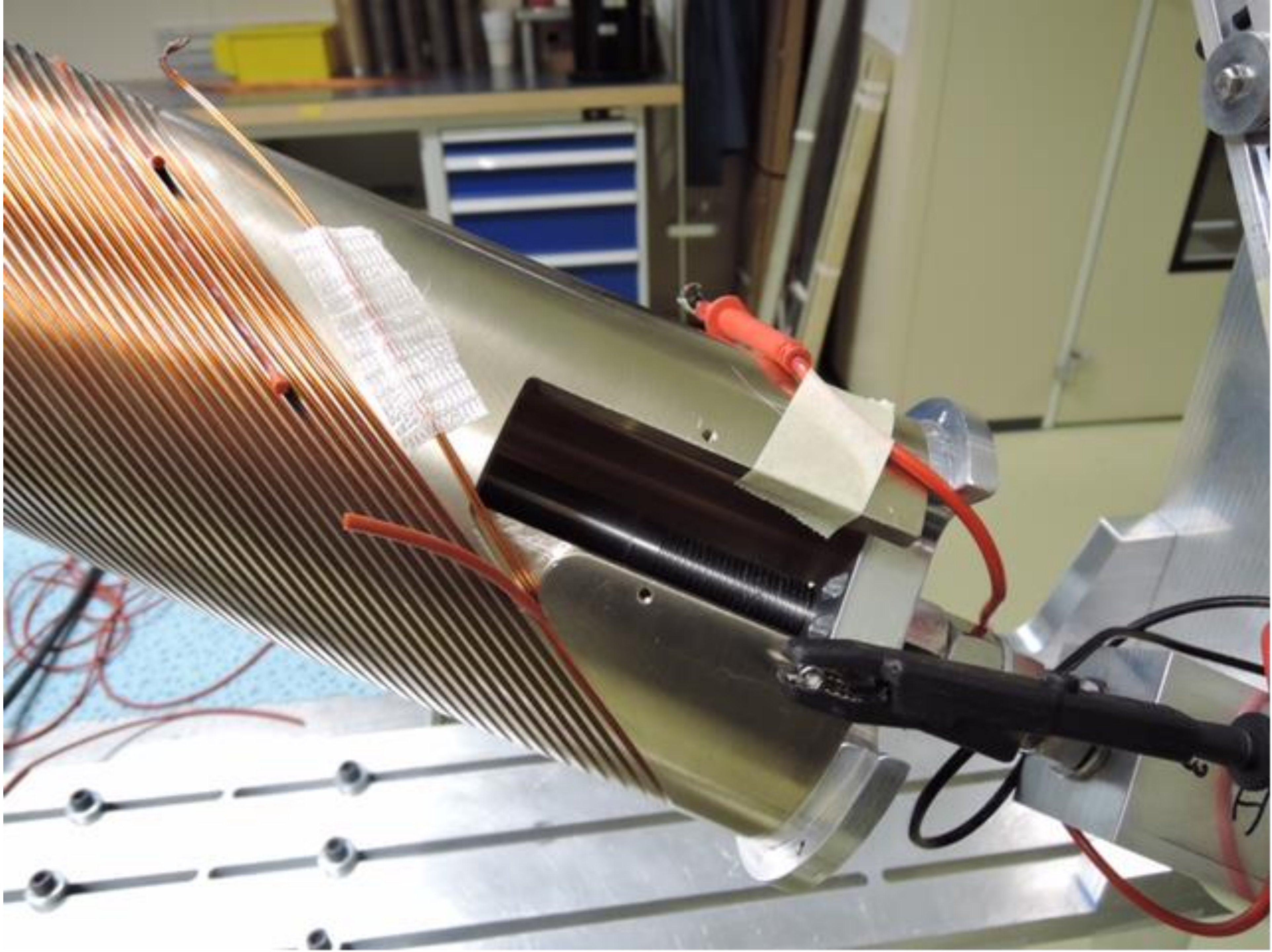
Inner layer





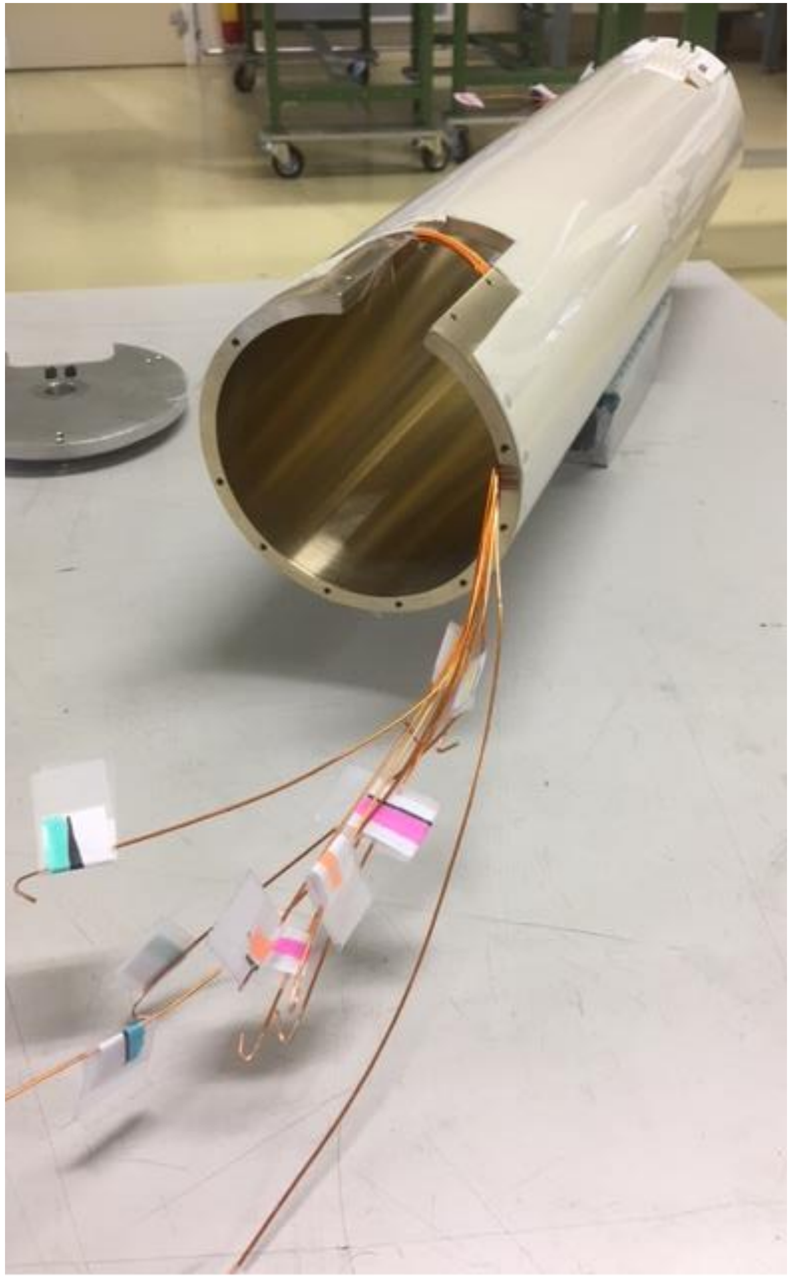
Winding:
Holding wires in place with O-ring's later we will use winding tension.

Continues shorted turns Monitoring.

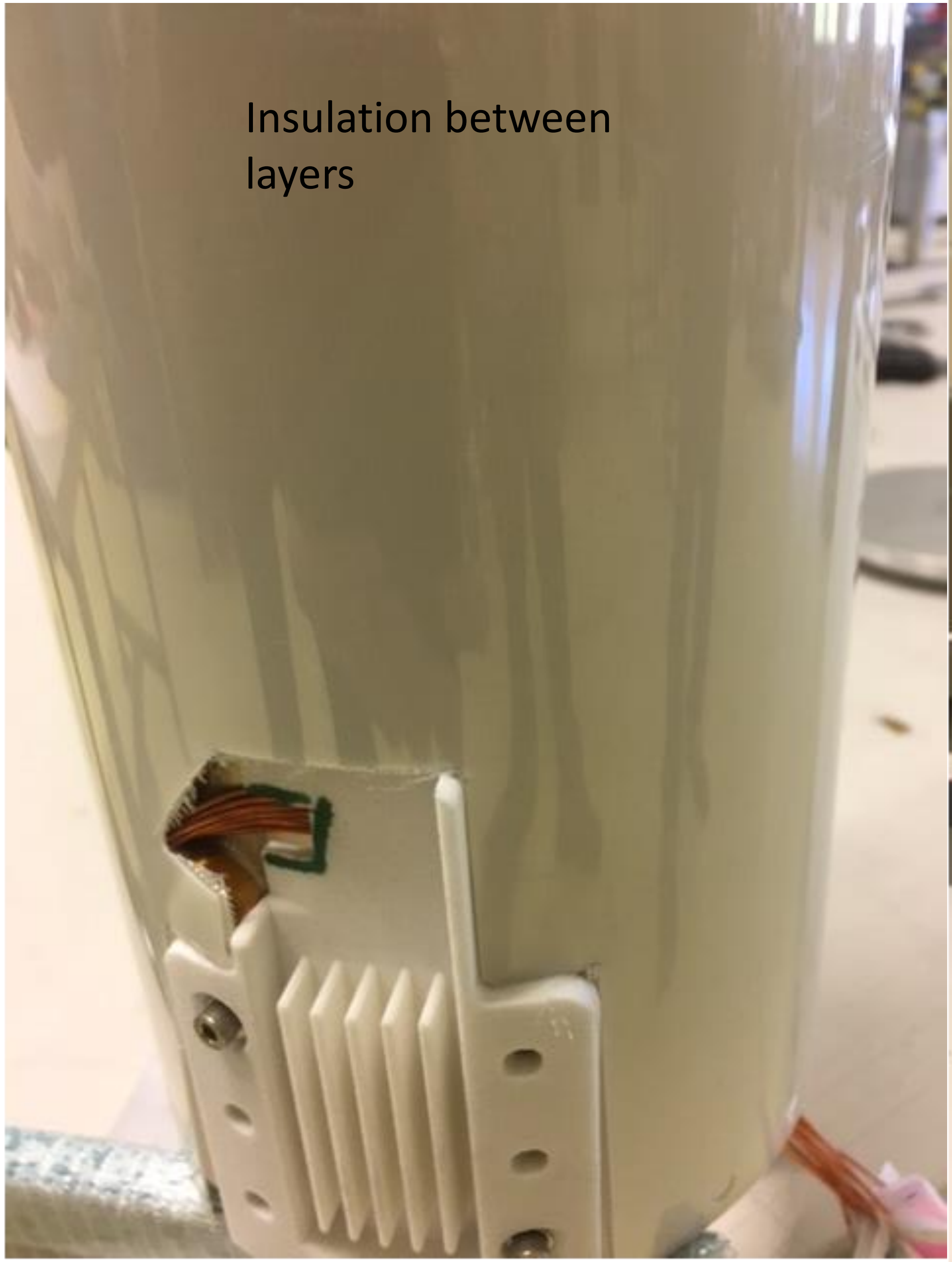


Glass mat to let impregnation flow in

Insulation sheets



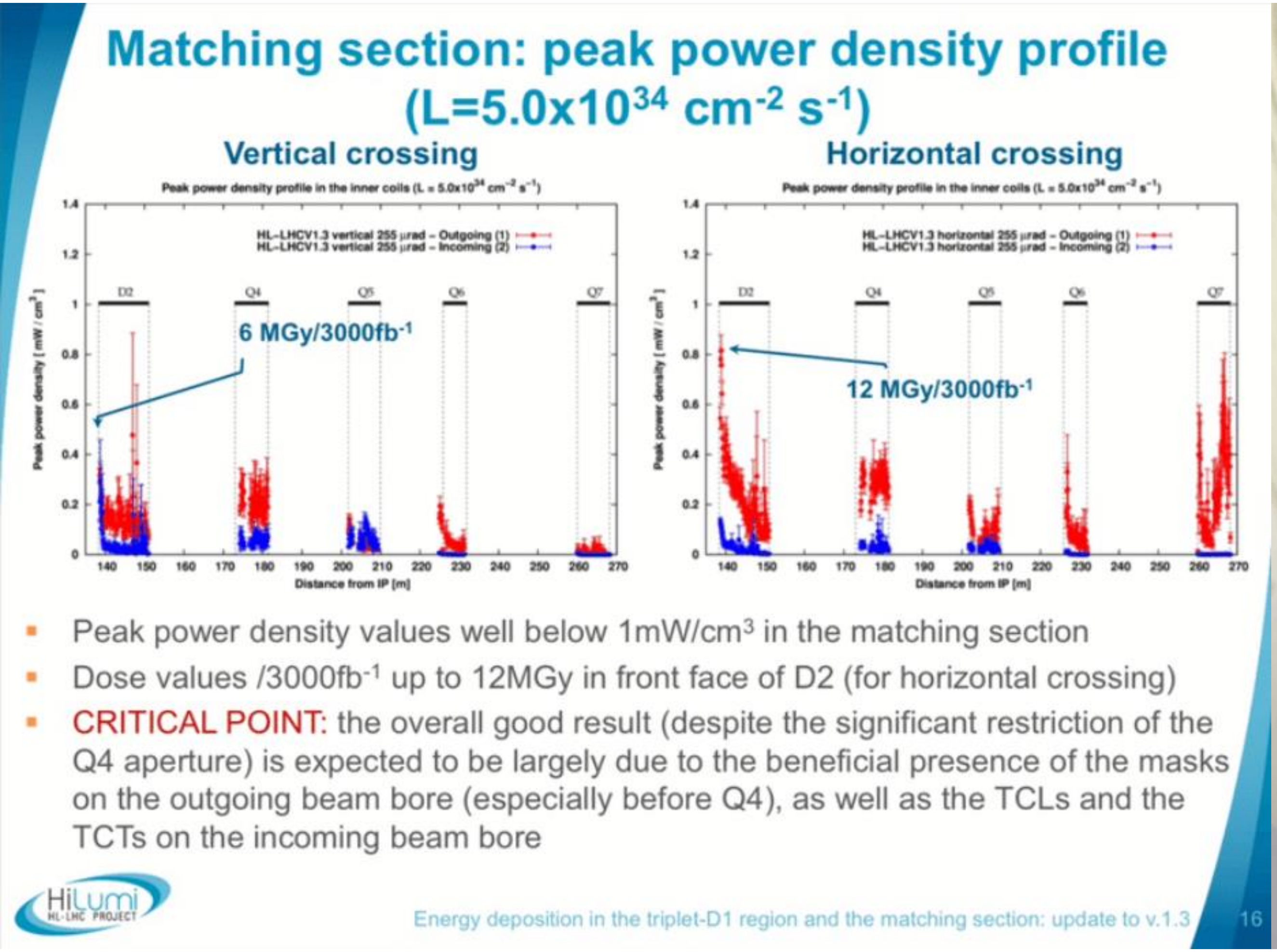
Former + glass mat + insulation
You also see the colour coding to identify the individual wires

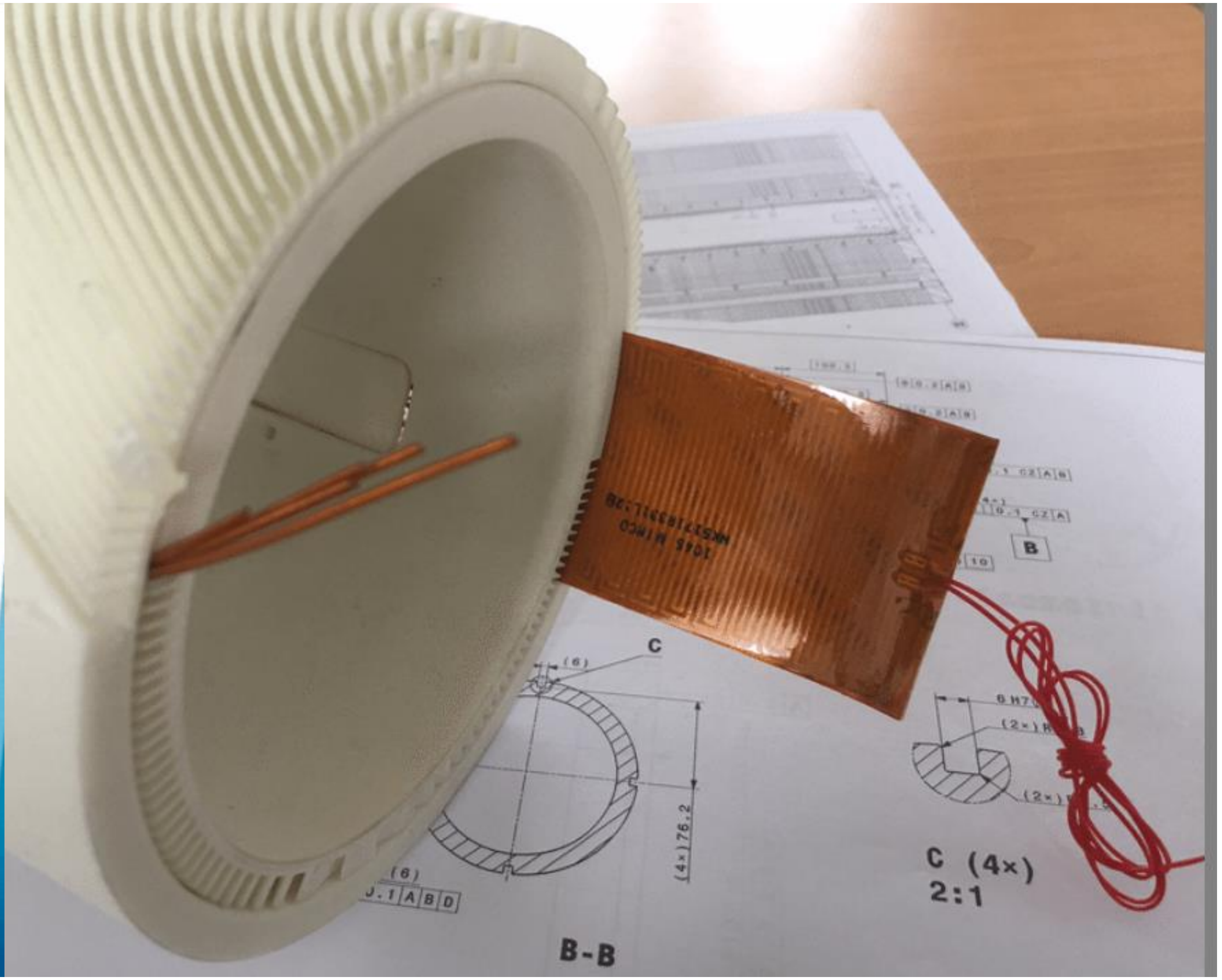


Insulation between layers

Fixing the 10 wires at both ends of the CCT former still needs some work.

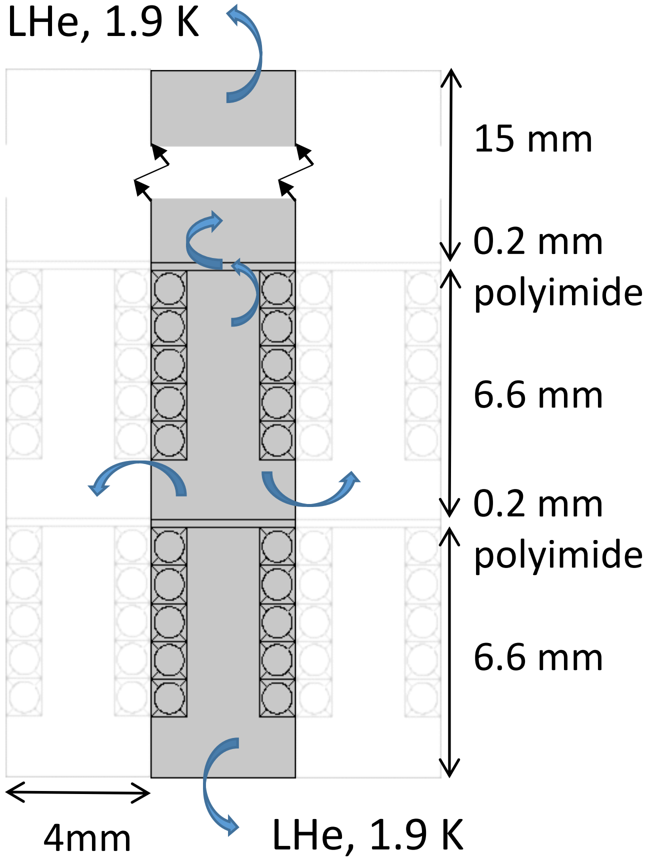
Heat Extraction test,   1mW/cm^3

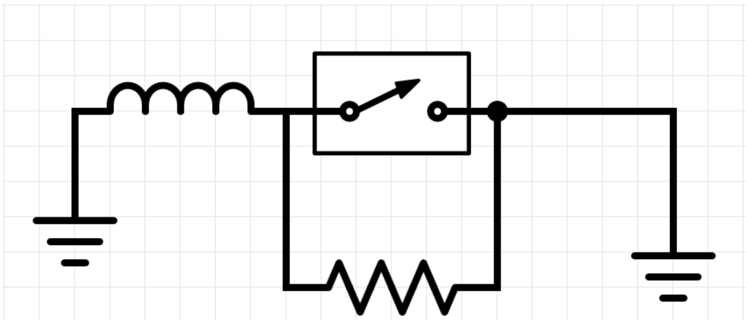




CCT coil, d*I*/dt

Transverse heat transfer model
(see: https://indico.cern.ch/event/616774/ for details)



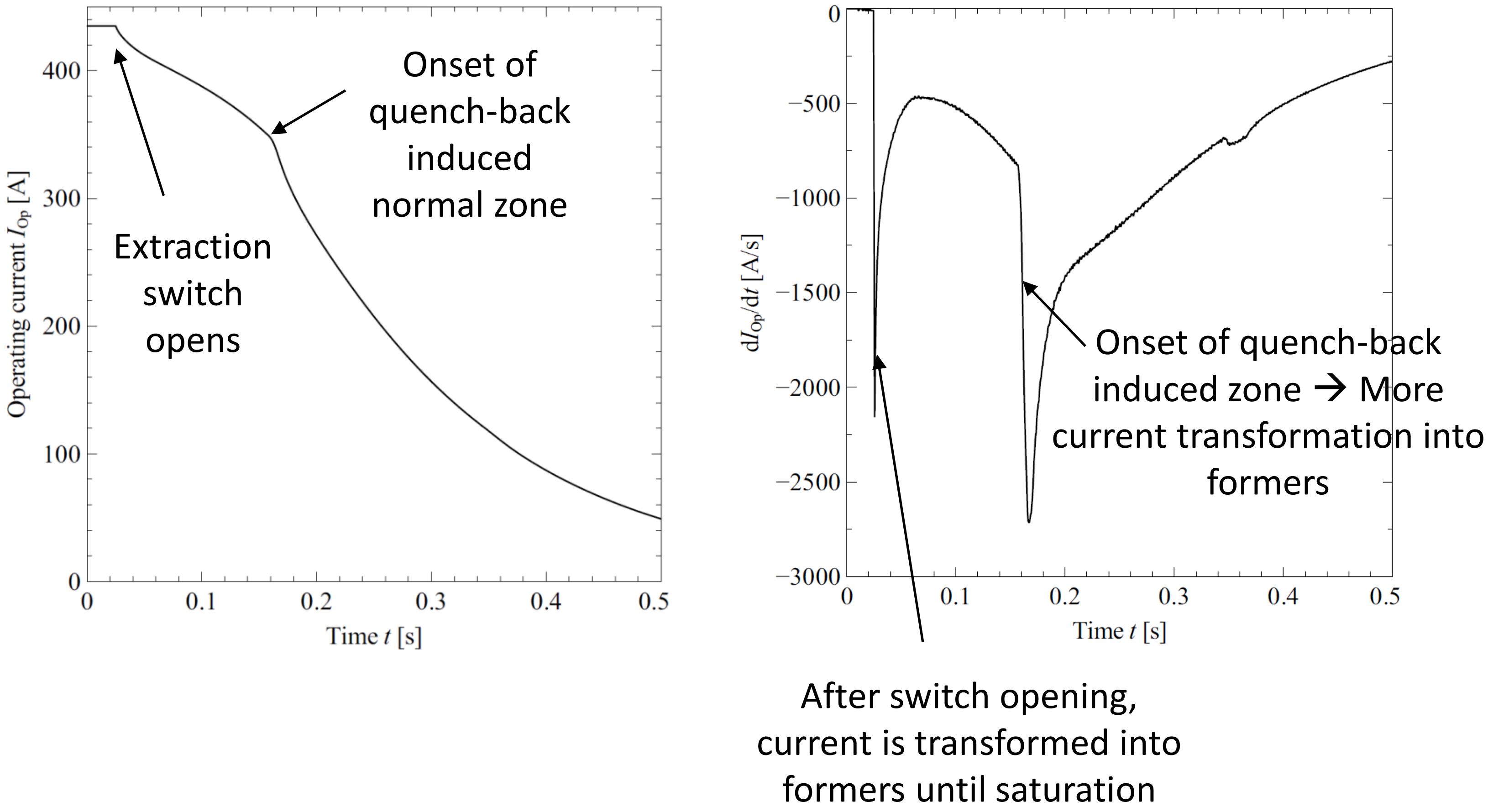


CCT coil, quench model

- CCT coil (2.2m) switched in series with a dump resistor after 25 ms
- Internally, current is transformed into aluminum formers (Quench back)

Thanks to Matthias Mentink for the quench analysis!

CCT coil, dI/dt, R_{dump} = 0.7 Ω, t_{delay} = 25ms



- Assumed coupling to aluminum formers is somewhat pessimistic, i.e. likely the degree of quench back is higher
- dI_{op}/dt shown here is thus indicative of magnitude, and cannot be taken as an upper limit
- Peak hotspot temperature = 198 K depending on variable can be much lower !

Thanks to Matthias Mentink for the quench analysis!

0.5 m model magnet quench, different to the 2.2m

Operating current [A]	PS switch-off delay [ms]	Dump resistor after 25 ms [Ohm]	Peak temperature [K]
422	0	0	99
422	60	0	103
422	0	0.7	44
600	0	0	168.3
600	60	0	197.9
600	0	0.7	86

- The short magnet is self protecting, but we will use the 0.7 ohm dump to check voltages.
- The first test will check training, voltage resistance , and quench back in the former .
- The full length 2.2 m magnet needs the dump. And will measure field quality

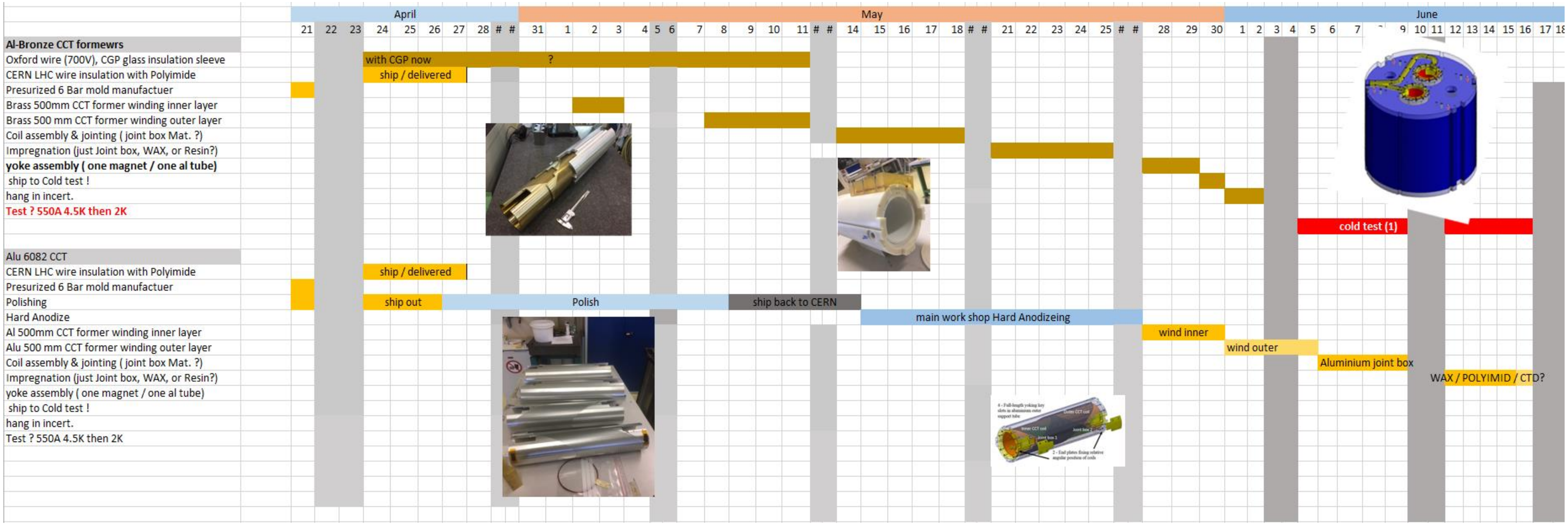
Planning

0.5m models

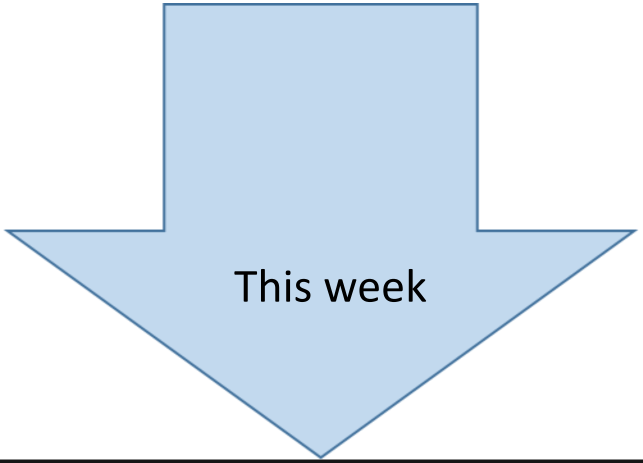
move to cold test mid June?

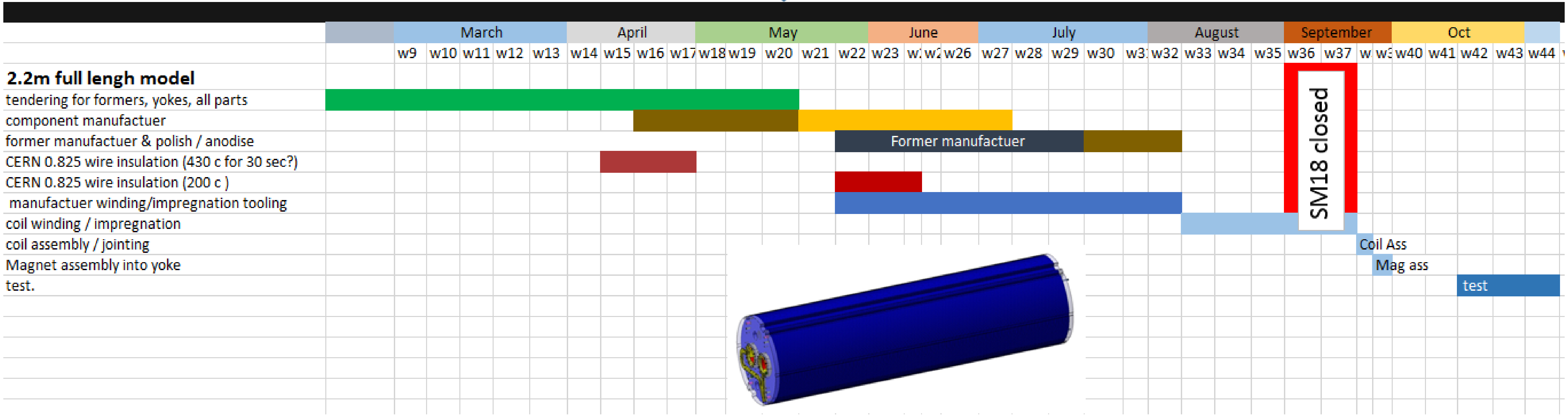
or wait for second aperture mid July?

today



Planning
2.2 m prototype





Project summary

- We are winding the first 500mm model aperture:
  - Aluminium Bronze former.
  - CERN dipole wire- insulated with Polyimide tape
- Next former arrives in 3 weeks
  - Aluminium former- polishes and hard-anodized.
- All other components for the500 mm model are at CERN
- 2.2 m model we open bids for formers this week. All other parts ordered.
- 500 mm model Test in June/July
- Order for insulating 25km length of wire in progress. Needed for 2.2m magnet.
- We are still to select the final resin type


Glyn A. Kirby
The END

Follow the project progress

https://www.researchgate.net/project/LHC-hi-Lumi-orbit-corrector-5Tm-CCT