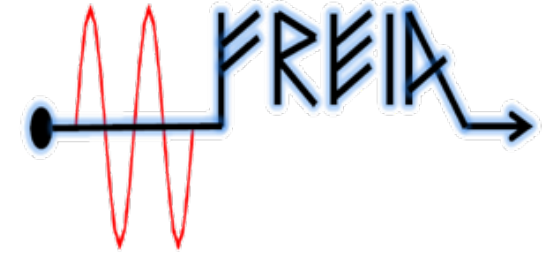




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FREIA Laboratory

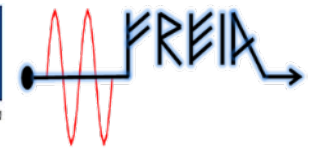
Facility for Research Instrumentation and Accelerator Development
Department of Physics and Astronomy

Projekt kalla magneter Möte om tillverkningsteknik

Roger Ruber

Uppsala, 10 February 2021





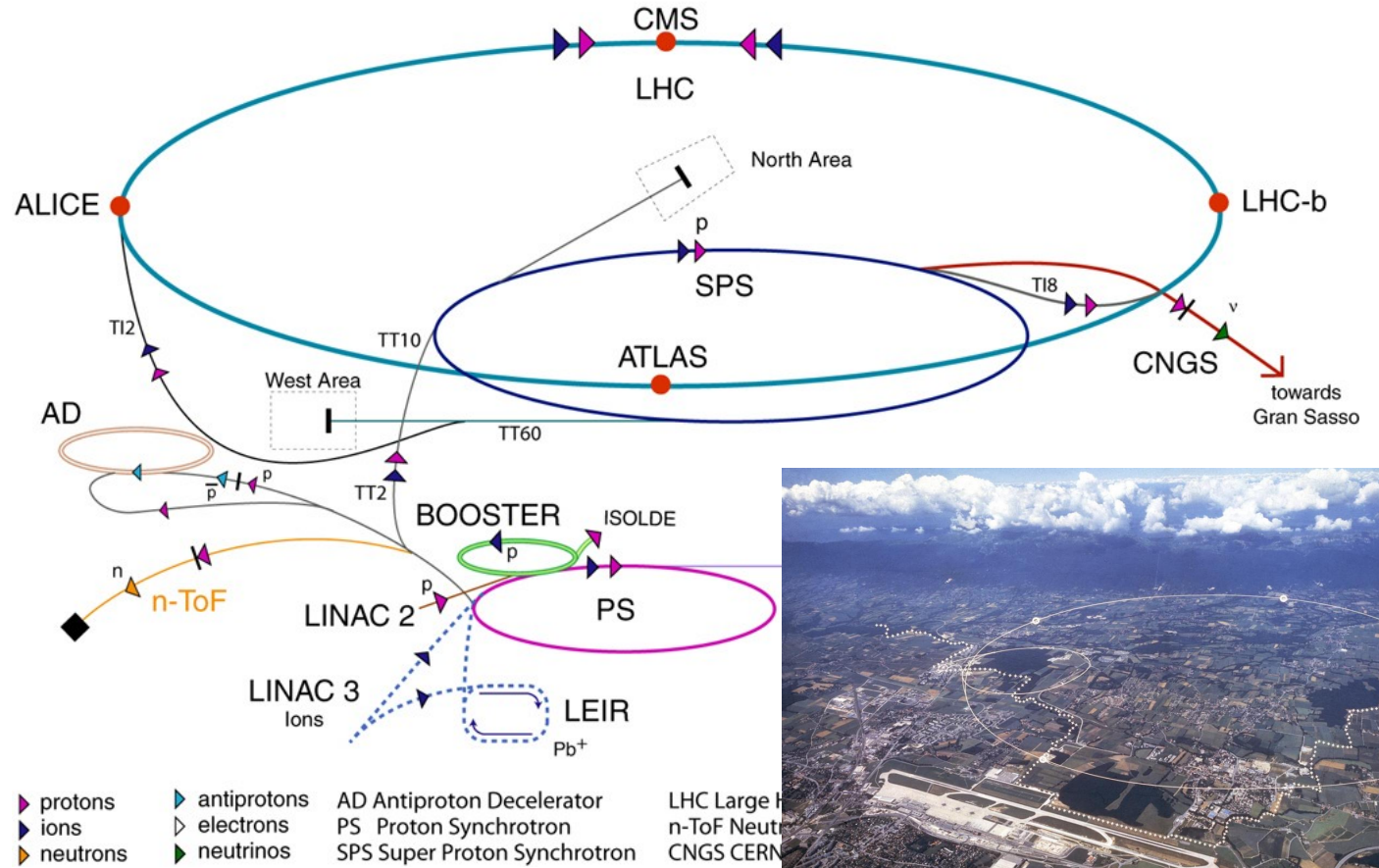
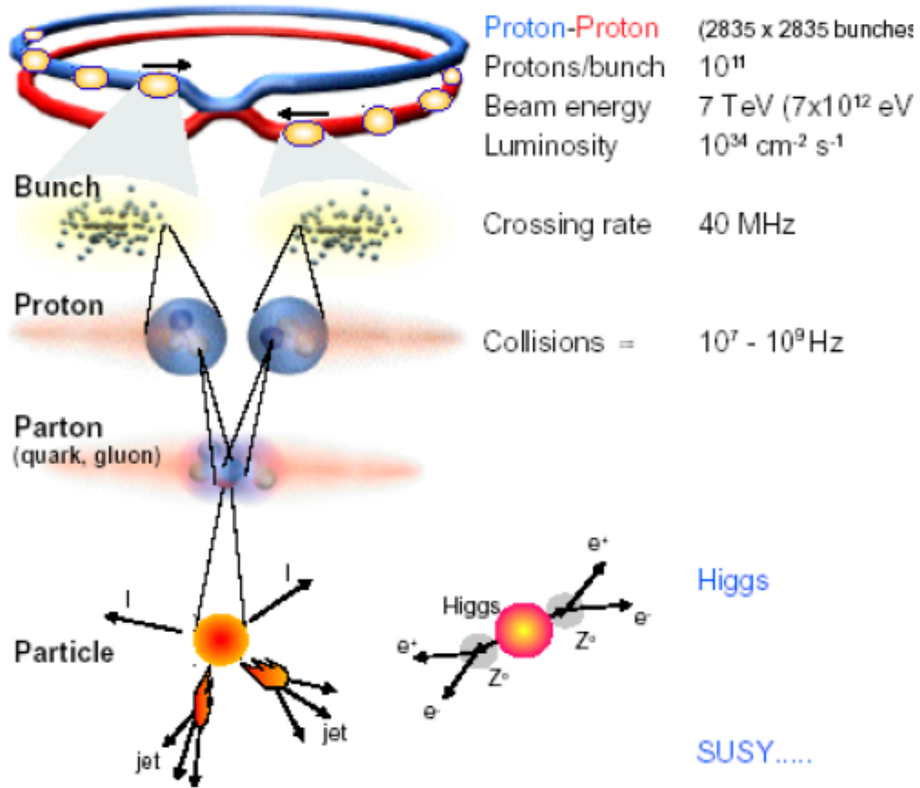
- **Uppgradering LHC acceleratoren vid CERN:**

- 2014: CERN och UU börjar diskussion om samarbete kring magnet test
- 2017: diskussion för att ersätta flera små dipol magneter (MCBC och MCBY orbit corrector)
 - inget stöd från Vetenskapsrådet
 - Kina erbjuder sig att bygga alla magnet på egen kostnad

- **CCT magnet**

- 2017: diskussion med magnet expert Glyn Kirby på CERN om ide att bygga CCT modell
- 2018: Vinnova stöder Scanditronix att bygga en 50 cm modell magnet
 - magneten byggs under 2018 – 2019
 - vänter hos CERN för montering i järn ok och test i Uppsala
- 2019: UU får kontakt med regionen och Tillväxtverket om utvecklingsstöd

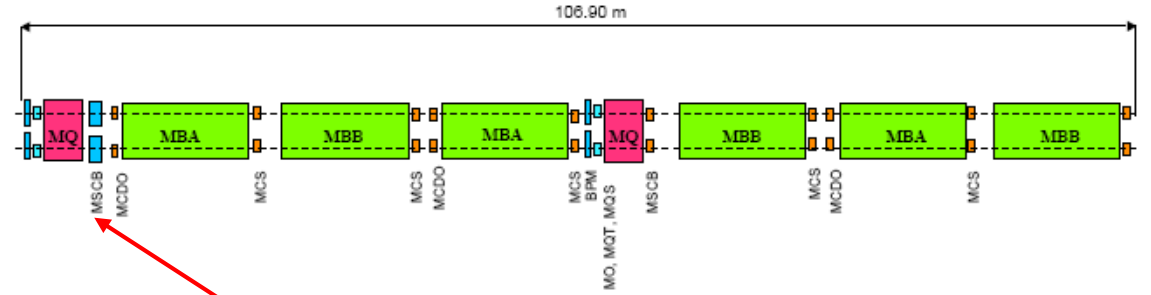
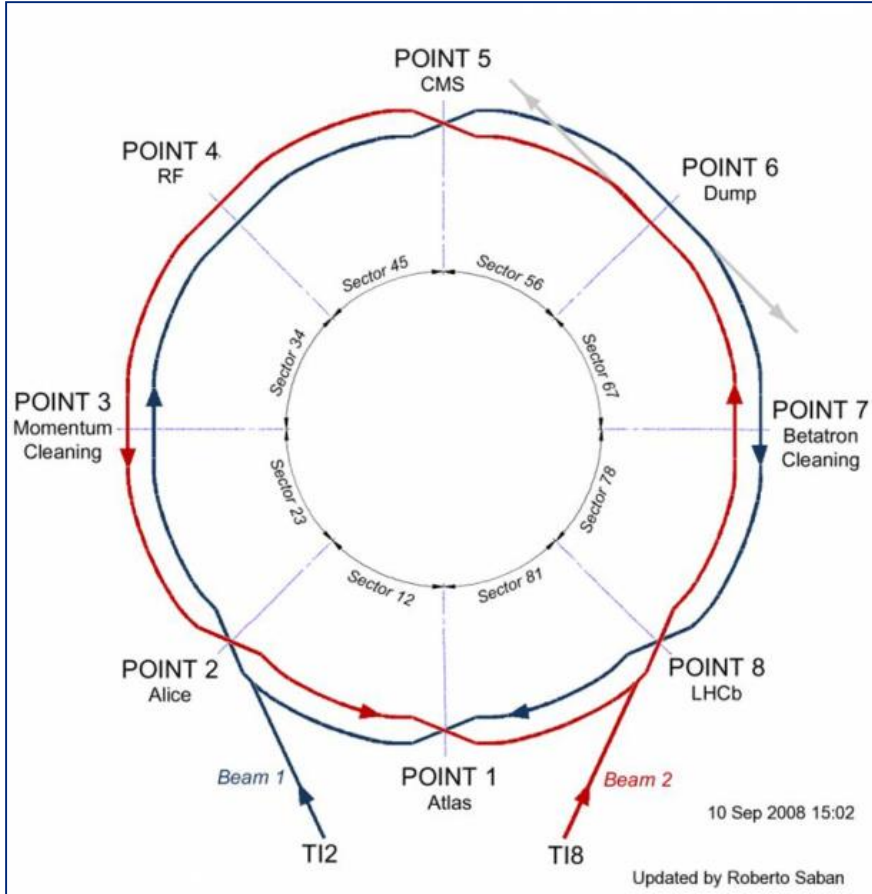
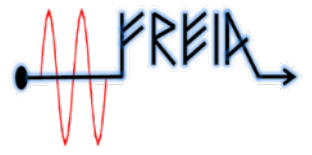
CERN och LHC



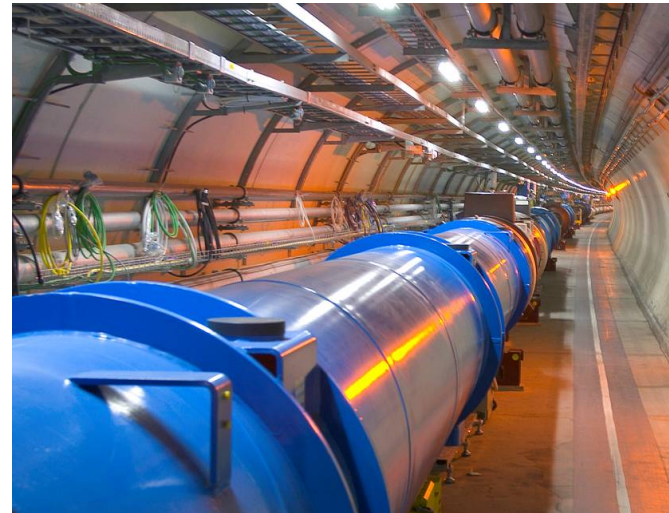
$$\ll E_{CM} = 2(E_{beam} + mc^2)$$



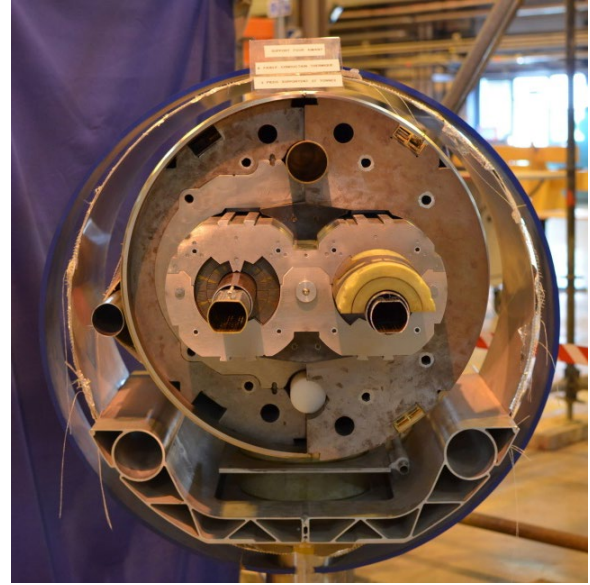
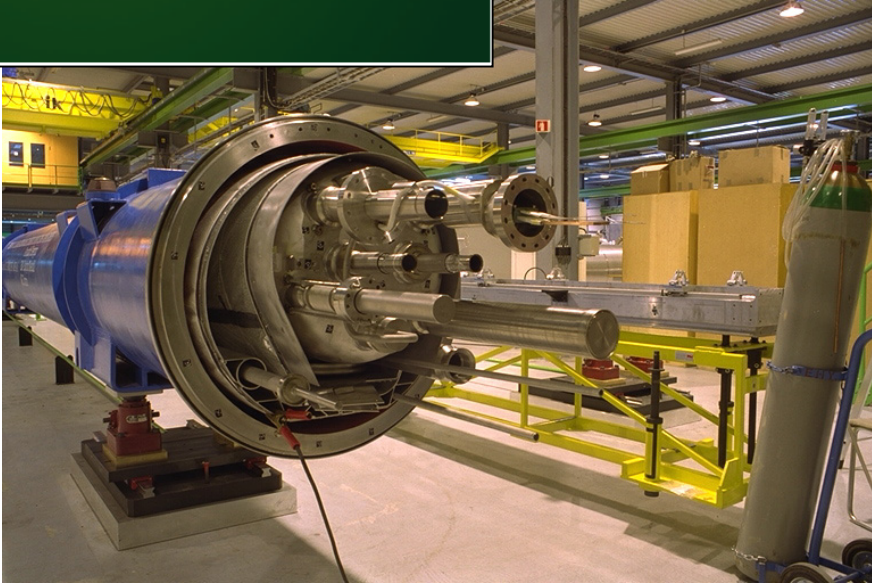
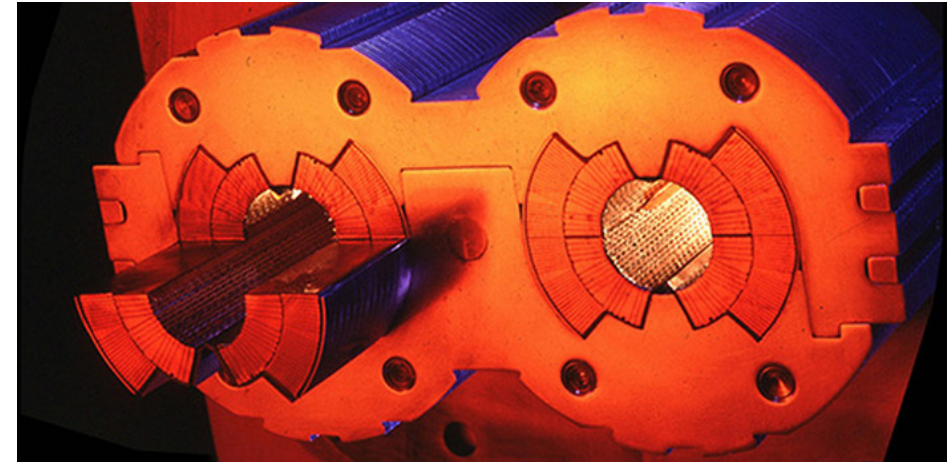
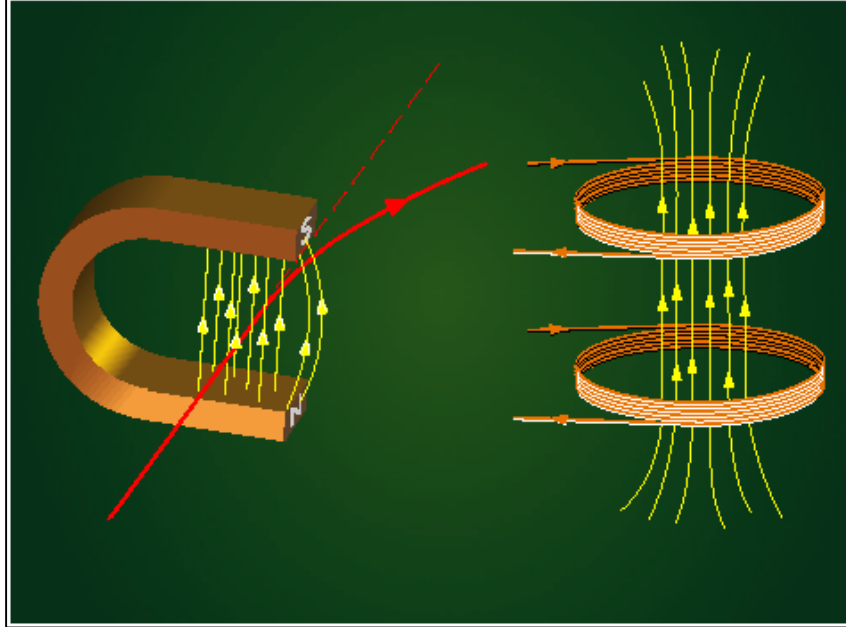
LHC Accelerator



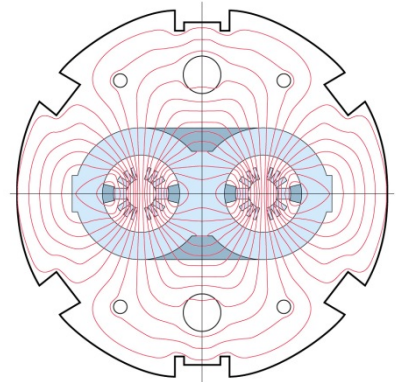
- MQT: trim quadrupole
- MCS: spool piece sextupole
- MQS: skew trim quadrupole
- MCDO: spool piece octupole + decapole
- MO: lattice octupole
- MSCB: sextupole (skew sextupole) + orbit corrector**



LHC Dipol Magnet



LHC dipole



Computed magnetic flux map at $B_0=10$ Tesla

Varför supraledande magnet

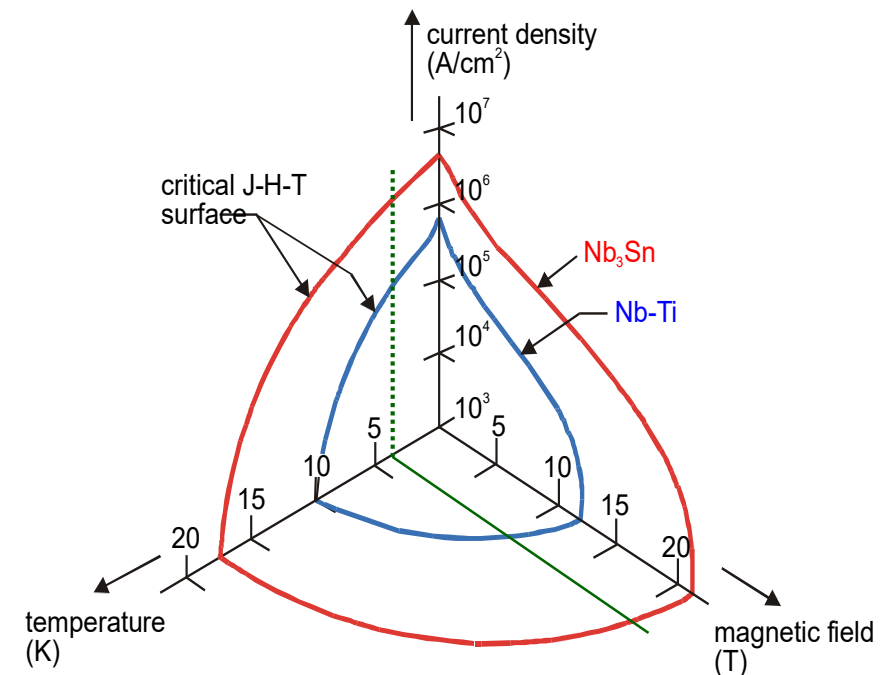
- **högre magnetfält**

- permanent magnet: 1 – 2 T
- normal ledande (kopper) magnet begränsad av järn ok: 2 T
- supraledande magnet begränsat av strömstyrkan: 9 – 15 T
- hybrid pulsade magnet upp till 100 T (ms)

- **högre effektivitet**

- normal ledande
 - exempel CERN SPS 315 GeV partikelenergi vid 52 MW elförbrukning
- superledande
 - exempel DESY HERA 800 GeV partikelenergi vid 6 MW elförbrukning

- alla metalliska superledare är spröda
 - undantag NbTi
 - kritisk ström täthet bero på bearbetnings process
- strömledare ska fungera nedanför kritisk yta
 - kritisk ström J_c
 - kritisk temperatur T_c
 - kritisk magnet fält B_{c2}
- **NbTi:**
 - $T_c(0) = 9.2 \text{ K}$; $B_{c2}(0) = 14.5 \text{ T}$
 - kritisk yta
 - $T_c(B) = T_c(0) \{1 - \{B/14.5\}\}^{0.59}$
 - $B_{c2}(T) = B_{c2}(0) \{1 - \{T/9.2\}\}^{1.7}$
 - typisk användning vid 4.2 K och 5 T
 - $T_c(5T) = 7.16 \text{ K}$; $B_{c2}(4.2K) = 10.7 \text{ T}$
- **Quench = förlorad supraledande tillstånd**



Iwasa table on the long route	
Criterion	Number
superconducting	~10'000
$T_c \approx 10 \text{ K}$ and $B_{c2} \approx 10 \text{ T}$	~100
$J_c \approx 1000 \text{ Amm}^{-2}$ at $B > 5 \text{ T}$	~10
magnet grade superconductor	~1

Temperatur marginal

- When a transport current flows, the onset of resistance is further reduced from T_c to T_{cs}

– $T_{cs}(B, I) = T_b + \{T_c(B) - T_b\} \{1 - I/I_c\}$ T_{cs} is the current sharing temperature

– $T_{cs}(5 T, 0.5I_c) = 5.7 K$

- So we lost a lot of margin from $T_c(0) = 9.2 K \rightarrow T_c(5T) = 7.2 K \rightarrow T_c(5T, 0.5I_c) = 5.7 K$

– 50% I_c and 5 T: $T_c(5T, 0.5I_c) = 5.7 K \rightarrow 1.5 K$ margin for $T_b = 4.2 K$

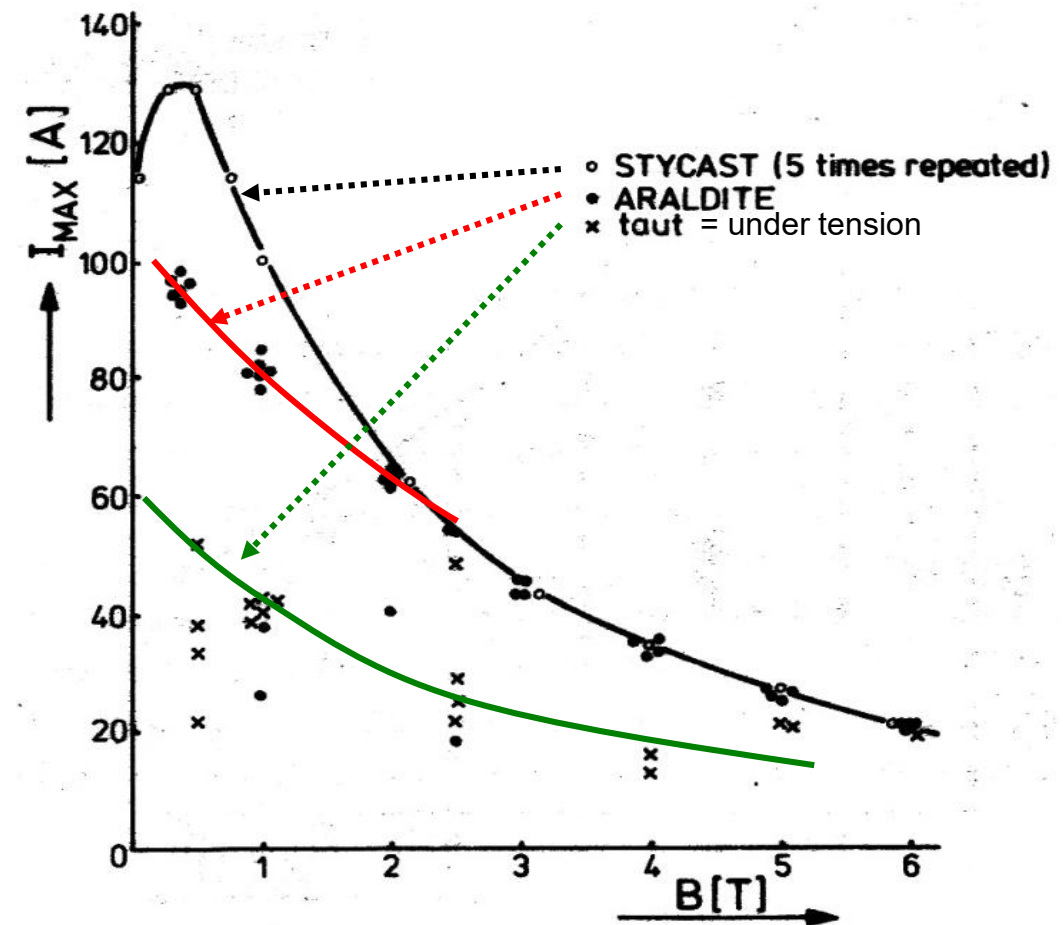
– 75% I_c and 5 T: $T_c(5T, 0.75I_c) = 5.0 K \rightarrow 0.8 K$ margin

→ **so we never can operate very near to I_c !**

- Following $\Delta T = Q / c(T)$ release of energy (heat) from various sources will cause a temperature rise and thus the superconducting state is very seriously in danger
- Increased temperature drops I_c ; causing flux motion, generates heat → **stability problem**
- The heat that can be absorbed without reaching T_{cs} is the enthalpy difference $\Delta H = \int c(T) dT$ between T_{cs} and T_o

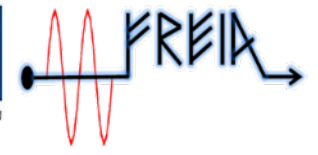
Example Wire Movement

- 2.5 μJ corresponds to a movement of 1 μm only in a 1 mm wire at 5 T and 500 A!
- NbTi/CuNi wire on sample holder, see picture:
 - The critical current of badly stable wires (no Cu matrix but CuNi for use in SC switches) can hardly be measured, resin cracking causes wires to quench.
 - A clear demonstration of how crucial suppression of cracking and wire movements is.

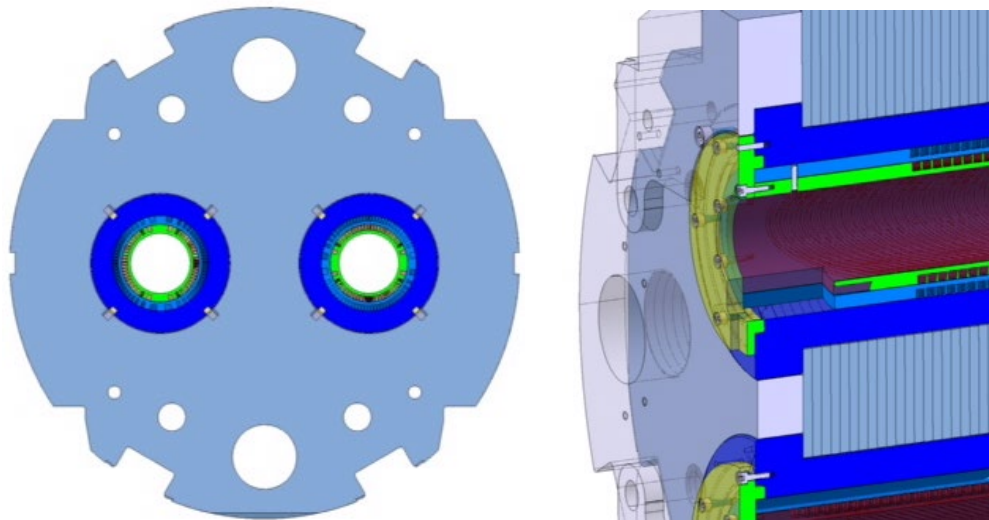




LHC MCBC/Y Magnet



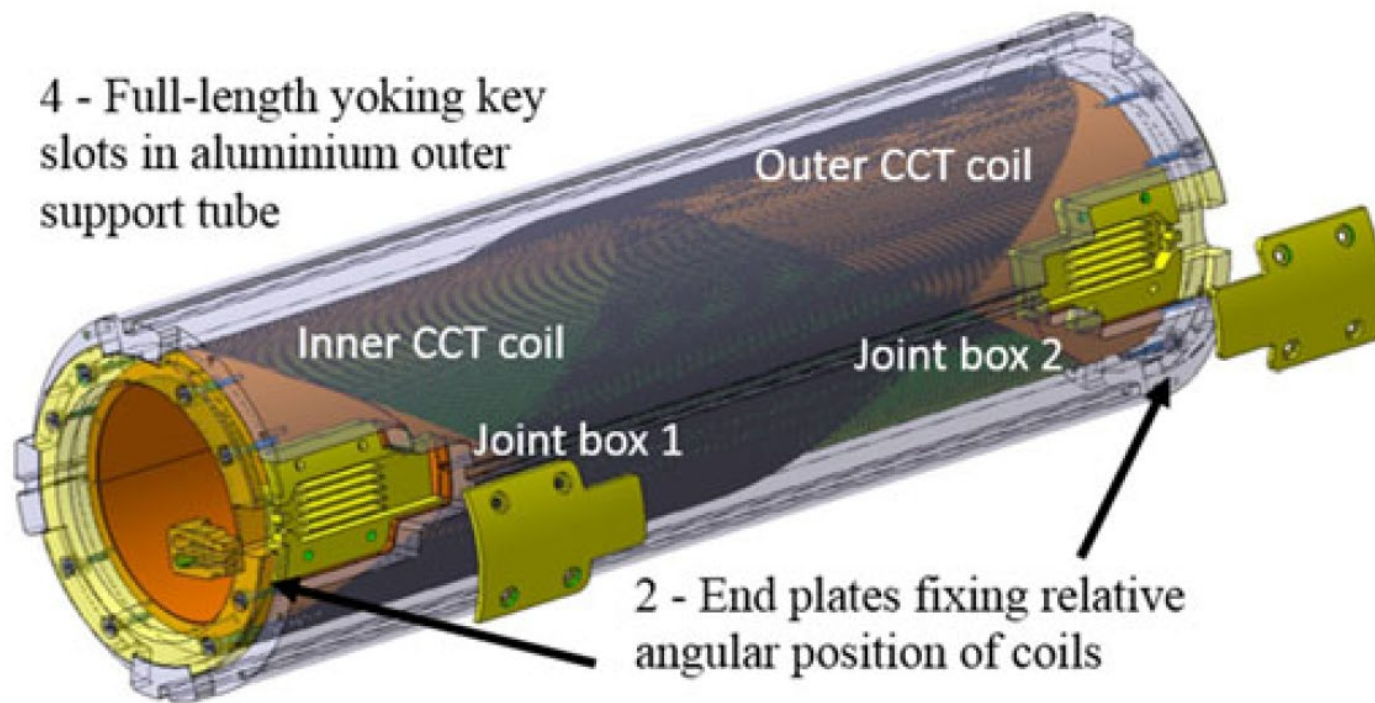
- **B = 3.11 T**
- **I = 100 A**
- **aperture diameter = 56 / 70 mm**
– double aperture (two-in-one magnet)
- **outer diameter = 452 / 475 mm**
- **total length = 1100 mm**



Parameters	MCBC	MCBY
Coil inner diameter	56 mm	70 mm
Magnetic length	0.904 m	0.899 m
Operating temperature	1.9 K	1.9/4.5 K
Nominal field (at 1.9/4.5 K)	3.11/2.33 T	3.00/2.5 T
Nominal current (at 1.9/4.5 K)	100/74 A	88/72 A
Peak field in coil (at 1.9/4.5 K)	3.65/2.68 T	3.60/2.96 T
Theoretical quench current (at 1.9/4.2 K)	172/127 A	162/120 A
Stored energy (at 1.9 K)	14.2 kJ	13.6 kJ
Self-inductance	2.84 H	5.27 H
DC resistance (RT)	375 Ω	501 Ω
Overall length	1100 mm	1100 mm
Outer diameter of assembly	452 mm	475 mm
Magnet module mass	203 kg	193 kg
Total mass including the support structure	1234 kg	1247 kg
Superconductor type	Nb-Ti in Cu matrix $0.73^{+0.00}_{-0.01} \cdot 0.38^{+0.00}_{-0.01} \text{ mm}^2$	Nb-Ti in Cu matrix $0.73^{+0.00}_{-0.01} \cdot 0.38^{+0.00}_{-0.01} \text{ mm}^2$
SC wire dimension	$0.73 \times 0.38 \text{ mm}$	$0.73 \times 0.38 \text{ mm}$
Ribbon construction	14 wire (glued)	15 wire (glued)

CCT Canted-cosine-theta magnet

- 2 lindningar (spindel) för en dipolmagnet
- spindel hjälpar ta hand om kraft på strömledaren
- kräver ingen fält optimalisering
- optimal vinkel 30° (pga. fältstyrka och längd)



G. Kirby et al., Trans. Appl. Superc. 27(4) 4002805 (2017)

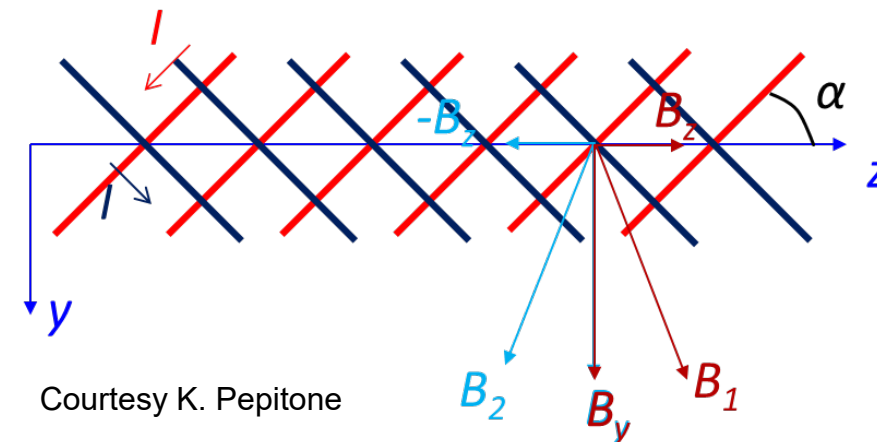
Individual turns are separated by Ribs

Ribs intercept forces transferring them to the spar

Individual turn

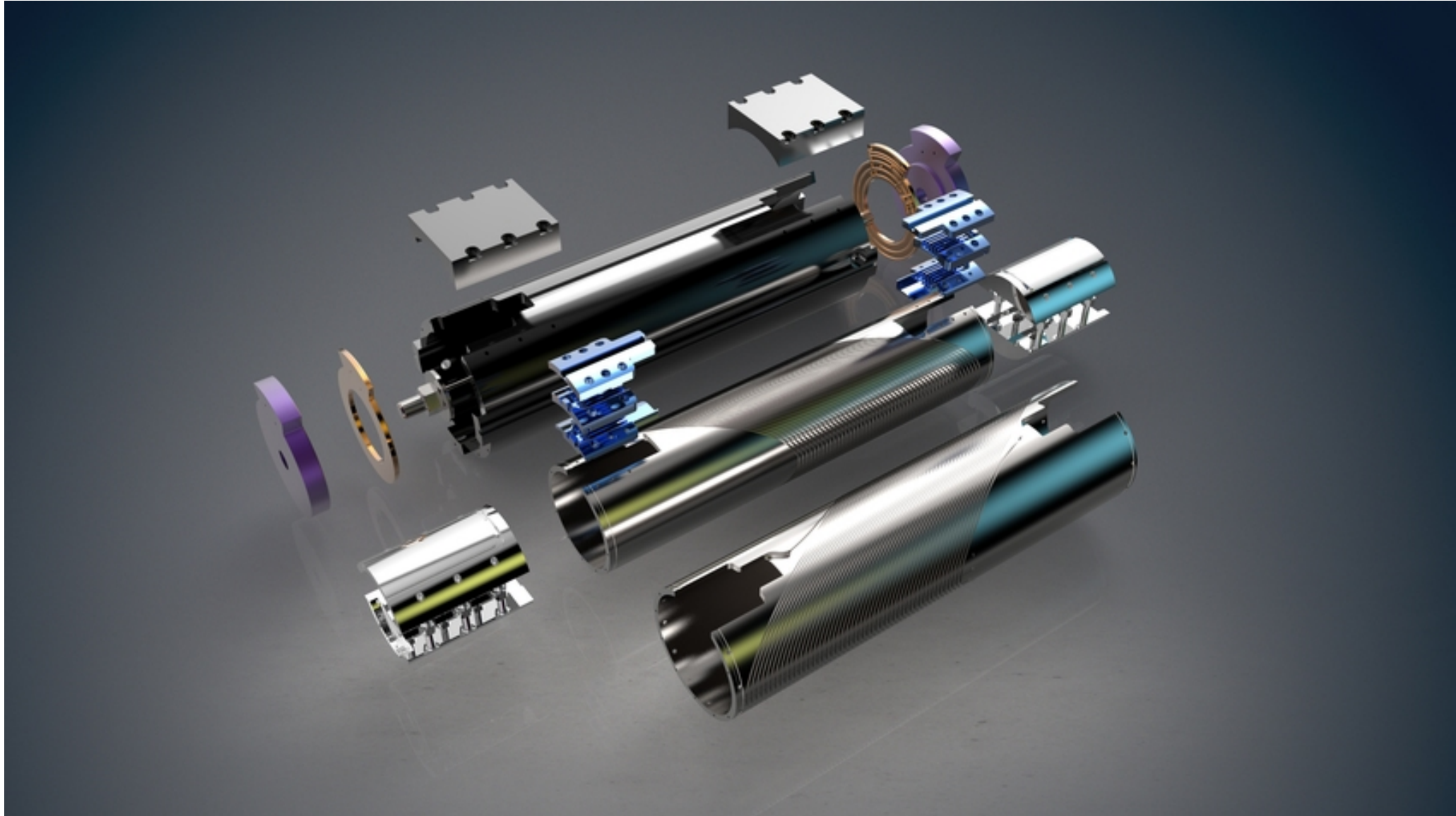
Spar

S. Caspi et al., Trans. Appl. Superc. 25(3) 4002304 (2015)



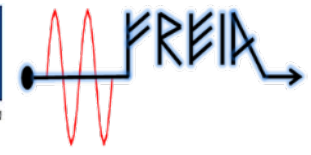
Courtesy K. Pepitone

Uppdelning av CCT magnet





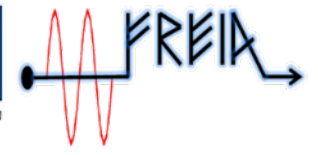
Information



- Föreläsning Glyn:
 - The State of the art with Canted Cosine Theta (CCT) magnets
 - <https://indico.cern.ch/event/1002941/>
- Glyn's sida på Research Gate
 - <https://www.researchgate.net/project/LHC-hi-Lumi-orbit-corrector-5Tm-CCT>
- Föreläsning om prototyp MCBRD
 - <https://indico.cern.ch/event/742082/contributions/3113840/attachments/1735646/2807203/HL-LHC-MCBRD-CCT-Oct-2018-GdR.pdf>
- Föreläsning Glyn från 2018
 - https://indico.cern.ch/event/753441/contributions/3120760/attachments/1713901/2764233/CCT_12th_sep_18_g_kirby.pdf



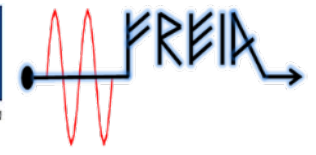
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SUPRALEDANDE KABEL

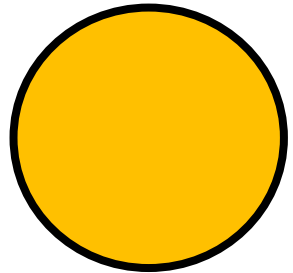


Elektrisk modell

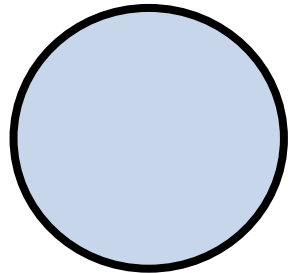


- Glyn Kirby, CERN, har utvecklat ett modell för 400 A
 - vi behöver dock anpassa till 100 A
 - pga. CERN vill återanvända befintliga superledande strömledare i LHC (max 100 A)
- Kevin arbetar på ett elektrisk modell
- **Rund kabel pga. böjning under lindning**
- Ide från Glyn
 - använd rep-kabel (nästa transparang)
 - 100 A per tråd ökas till 400 A per kabel
 - men kräver en hel del elektriska kopplingar ☹️
- Alternativ
 - flera lagar, dvs. flera magnetspindel
 - men ökar komplexitet och förhållande $B_{\text{peak}}/B_{\text{central}}$, och kräver eventuell ändring av sned-vinkeln

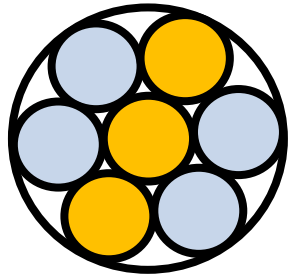
Ide om supraledande kabel



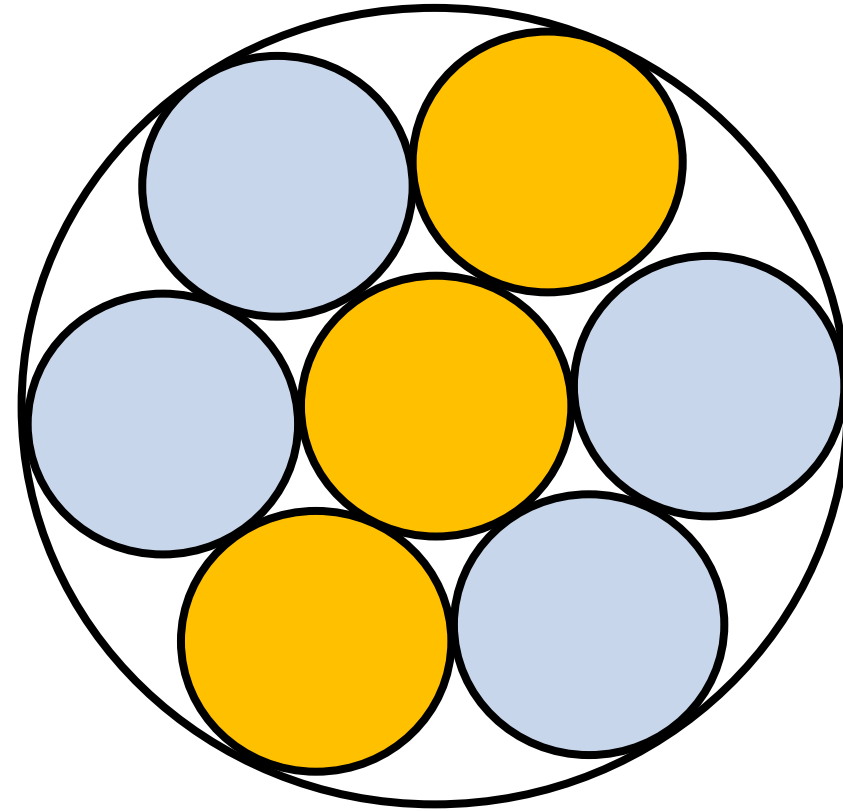
3x koppartråd
0.3 mm Φ
+ isolation



4x supraledandetråd
0.3 mm Φ
+ isolation



rep kabel
1 mm Φ
ej isolerad (inter-rep quench fortplantning)



1 mm



Problem / frågor

- **quench skydd**

- passiv = self protecting
- detta kan göras via quench-back heating av aluminium magnetspindel,
- eller med kall diod och motstånd på 2K

- krävs att göra quench beräkning

- UU har fått tillgång till CERNs mjukvara

- **lödning av supraledande tråd**

- kan blir många !





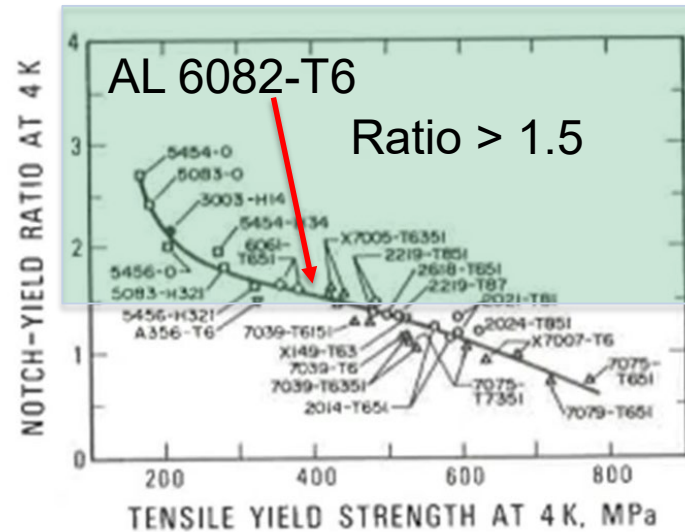
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MAGNETSPINDEL

Aluminium magnetspindel

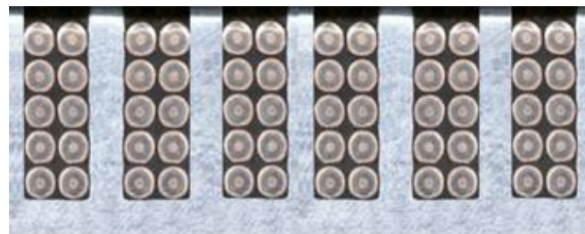
- A6082-T6
 - yield strength 400 MPa
 - operate below 120 MPa
 - high RRR (quench skydd)
- anodisera
 - ändrar elektrisk motstånd
 - ger extra isolation för kabeln
 - hjälper anknytning av epoxy resin
 - för 50cm modell magnet
 - 40 µm tjock
- **3 olika spindel**
 - 2 med spår och 1 yttre stöd-spindel
 - 3D step modell transfer från CAD till CNC
- **viktig med dimension kontroll**



**bilder 50cm CCT modell
Scanditronix 2018/19**

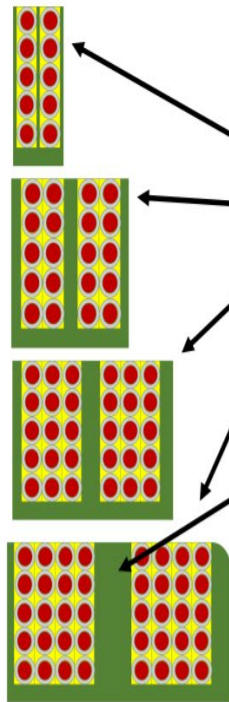
Spår för 10-12 lindningar

- Erfarenhet Glyn
 - spår max. 5 djup x 1 bred

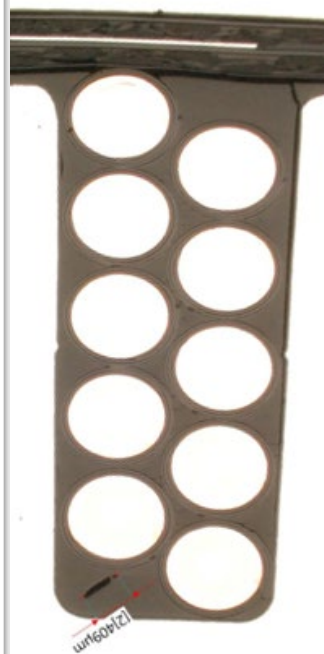
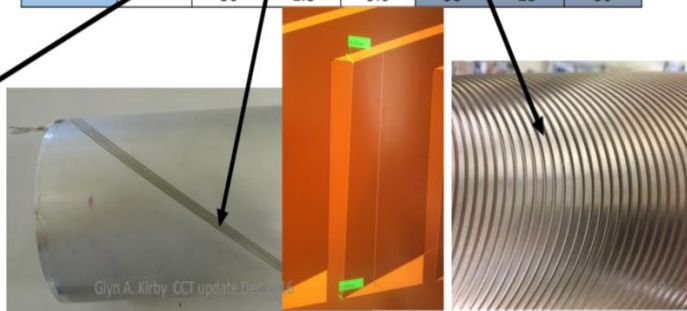
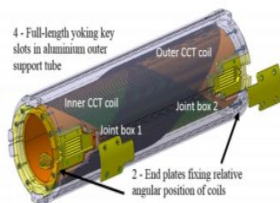


MCBRD proto: 10 wires in series

Cost Reduction Improvement Idea's

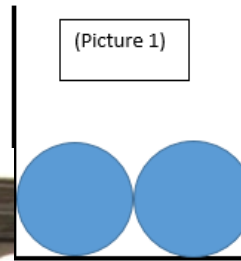


Slot and tool Ø	turns in former	Wires in each slot	Former min wall thickness [mm]	Former wall thickness at poles [mm]	Former		
					Joints total	lead end # joints	retrun end # joints
1	742	5	0.3	1.6	8	3	5
2	371	10	0.6	3.2	18	8	10
3	248	15	0.9	4.8	28	13	15
4	186	20	1.2	6.4	38	18	20
5	149	25	1.5	8	48	23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



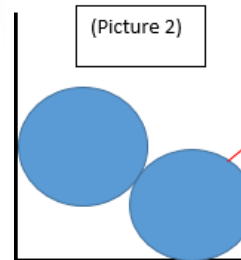
more stable stack for operation!

(Picture 1)



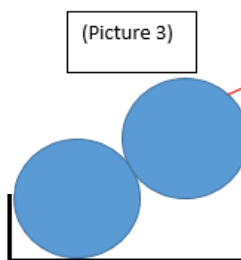
(Picture 1) if the wire are parallel in the bottom of the groove, they will stay parallel for all the 5 layers. (Picture 1). This is the optimum case.

(Picture 2)



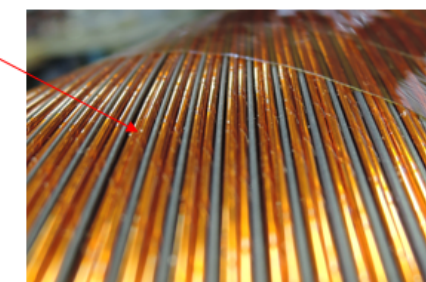
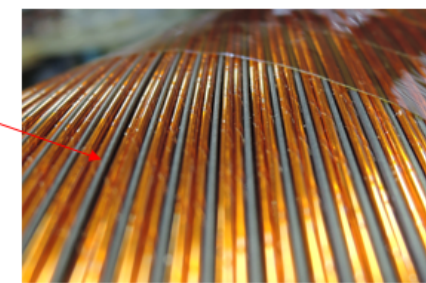
(Picture 2) If the groove is less wide, and if the wire on the right side of the groove go down first, it will be on the same place on the fifth layer.

(Picture 3)



(Picture 3) If the groove is less wide, and if the wire on the left side of the groove go down first, it will be on the same place on the fifth layer.

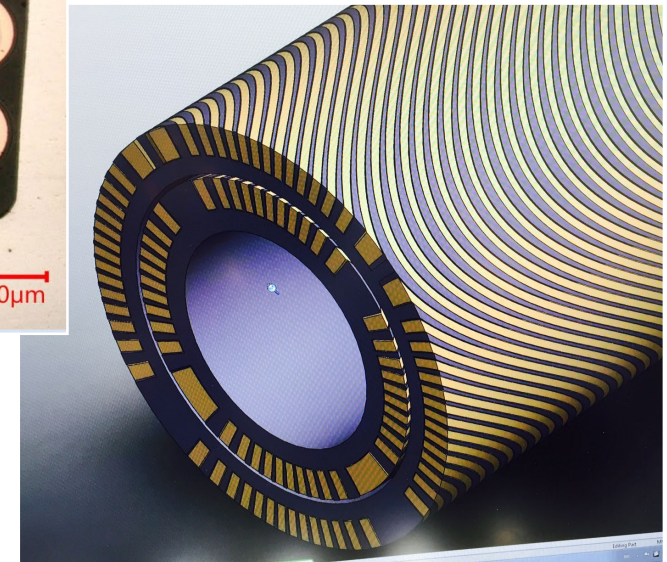
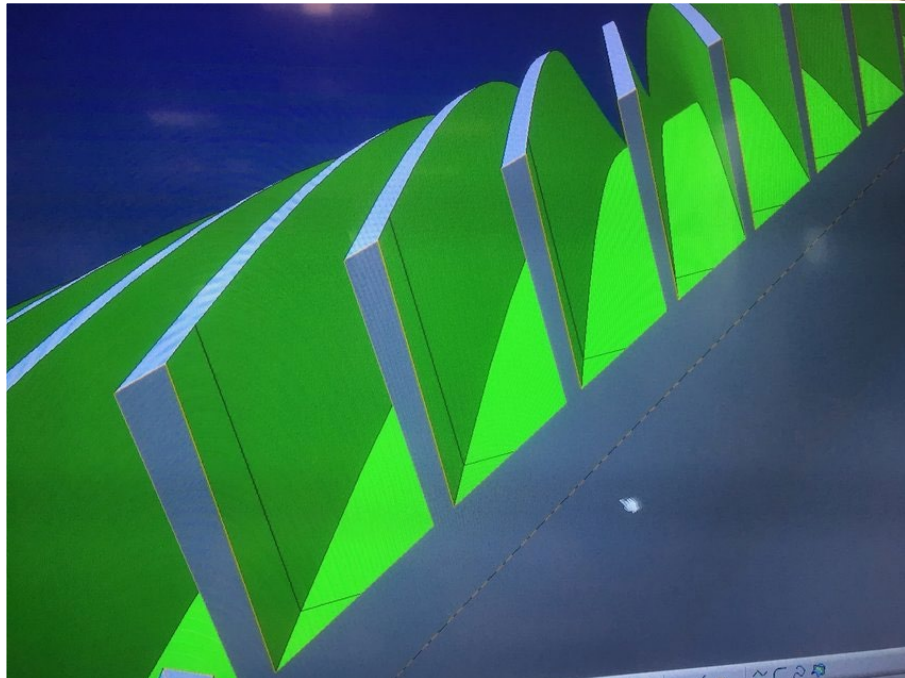
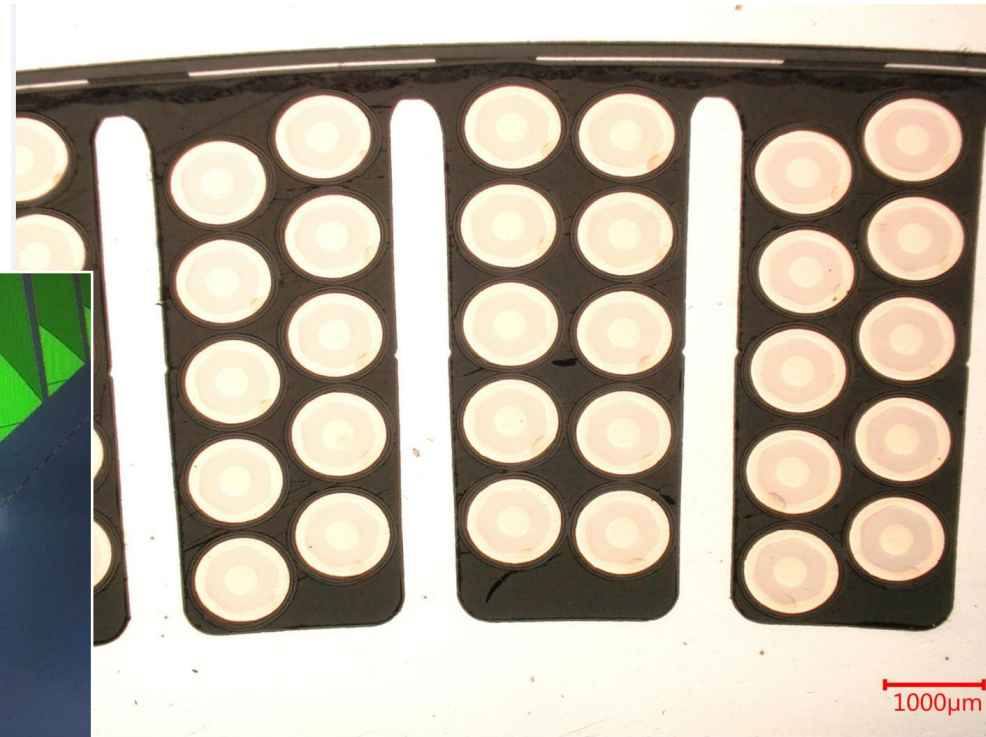
This could explain the different level you can see on the both layer (inner, outer)



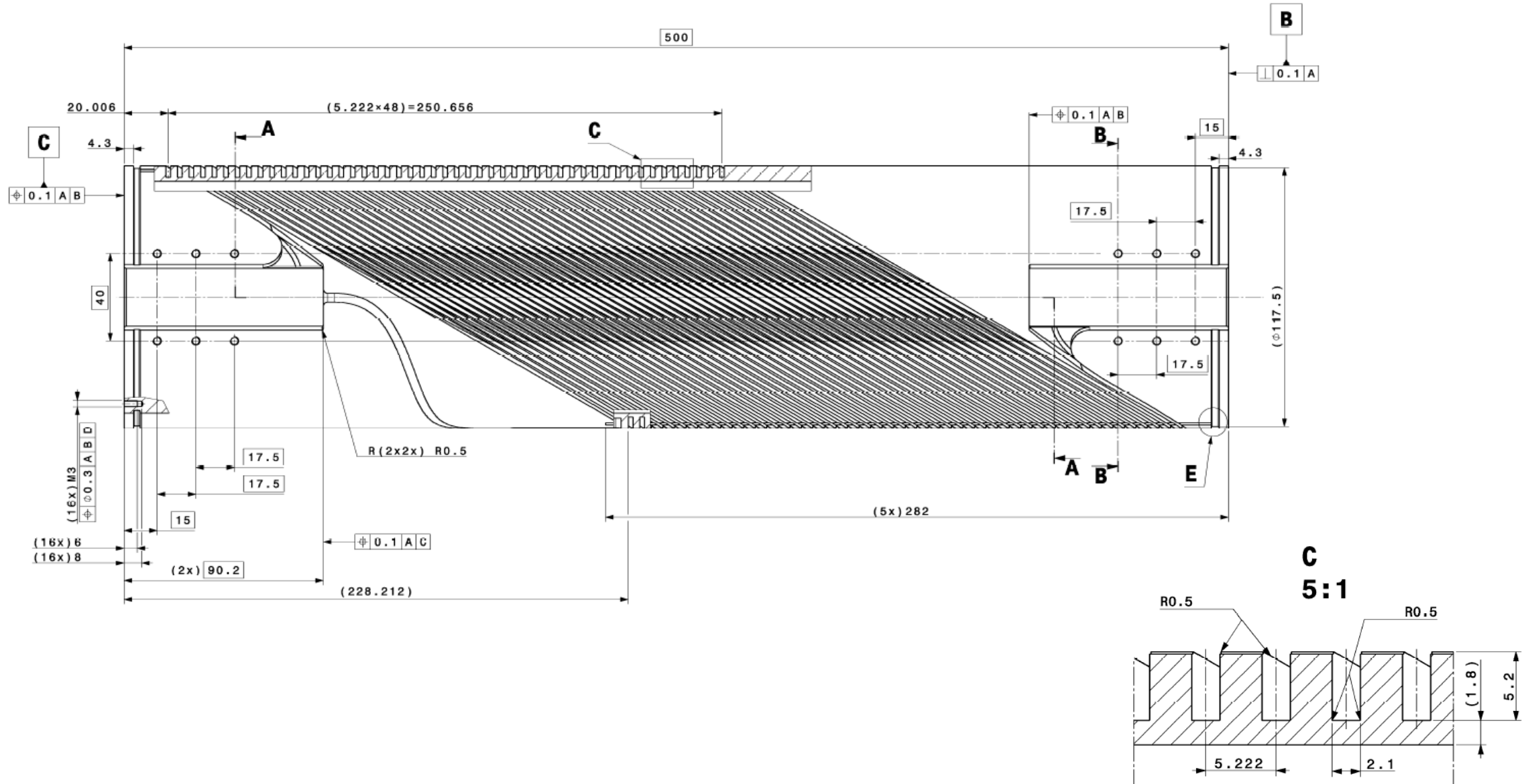


Tillverknings spår

- Botten och toppen av barriären har inte samma bred
– Glyns erfarenhet minst 0.3 mm bred i botten



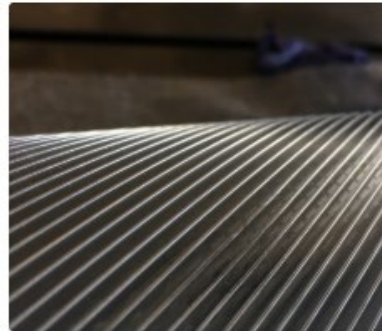
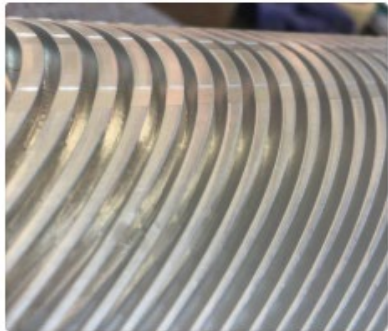
Del av produktsritning





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.

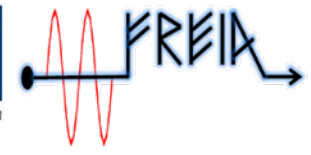




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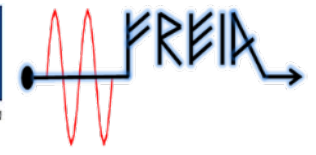
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JÄRN OK



Järn ok

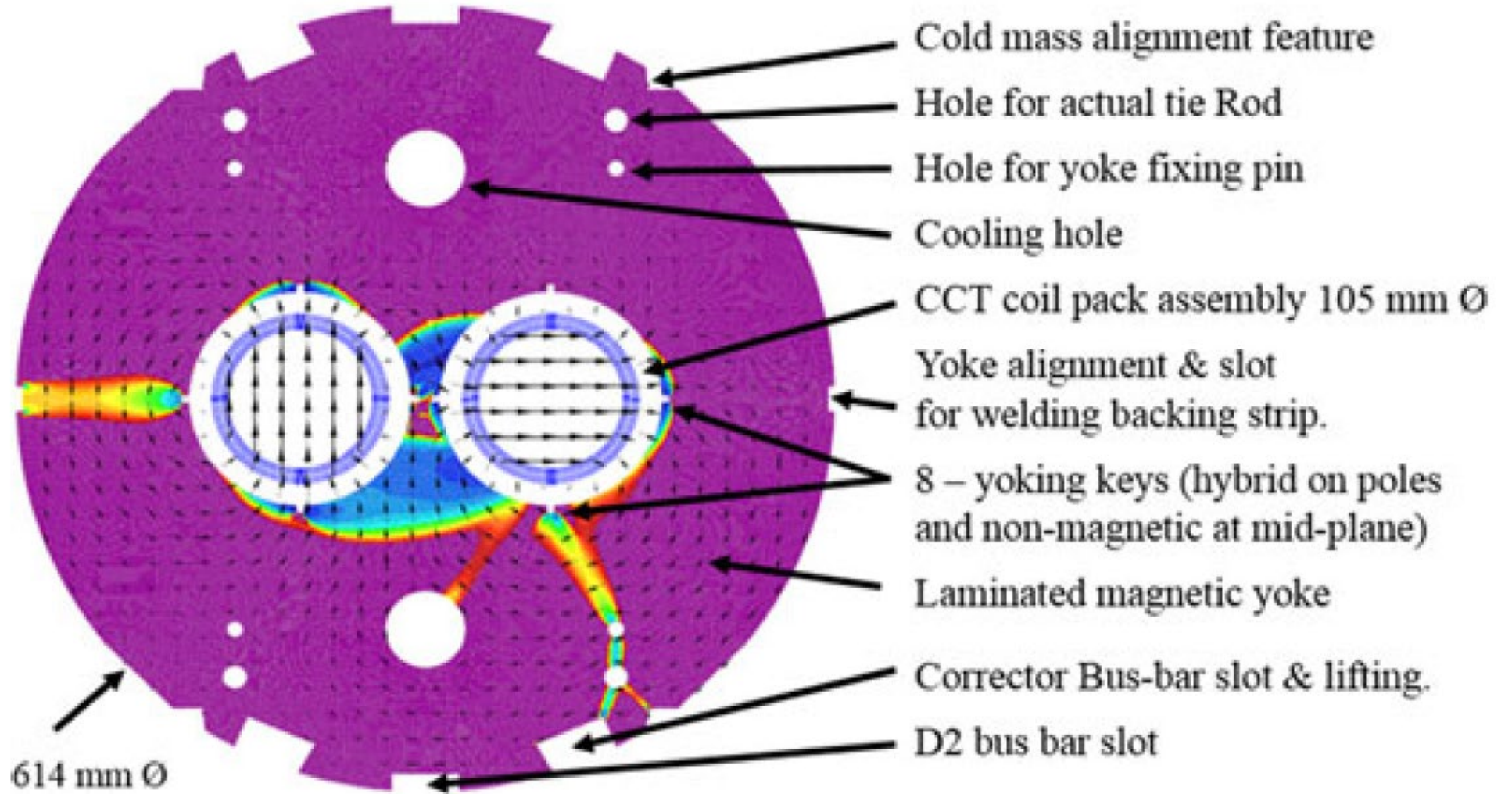
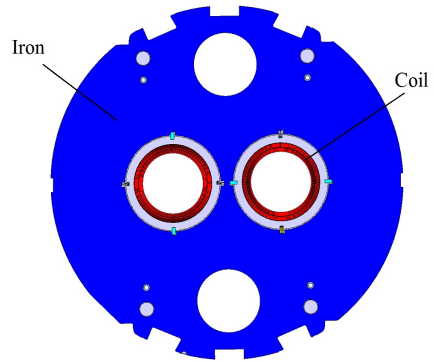


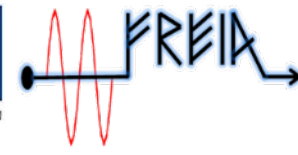
- austenitic stainless steel
 - t.ex. Sandvik
 - har levererad till CERN 350 mm bred, 3 mm tjock

- tjocklek mellan 1 och 6 mm
 - tjockare gör det lättare att montera oket pga. färre laminat
 - MCBRD använder t.ex. 5,8 mm

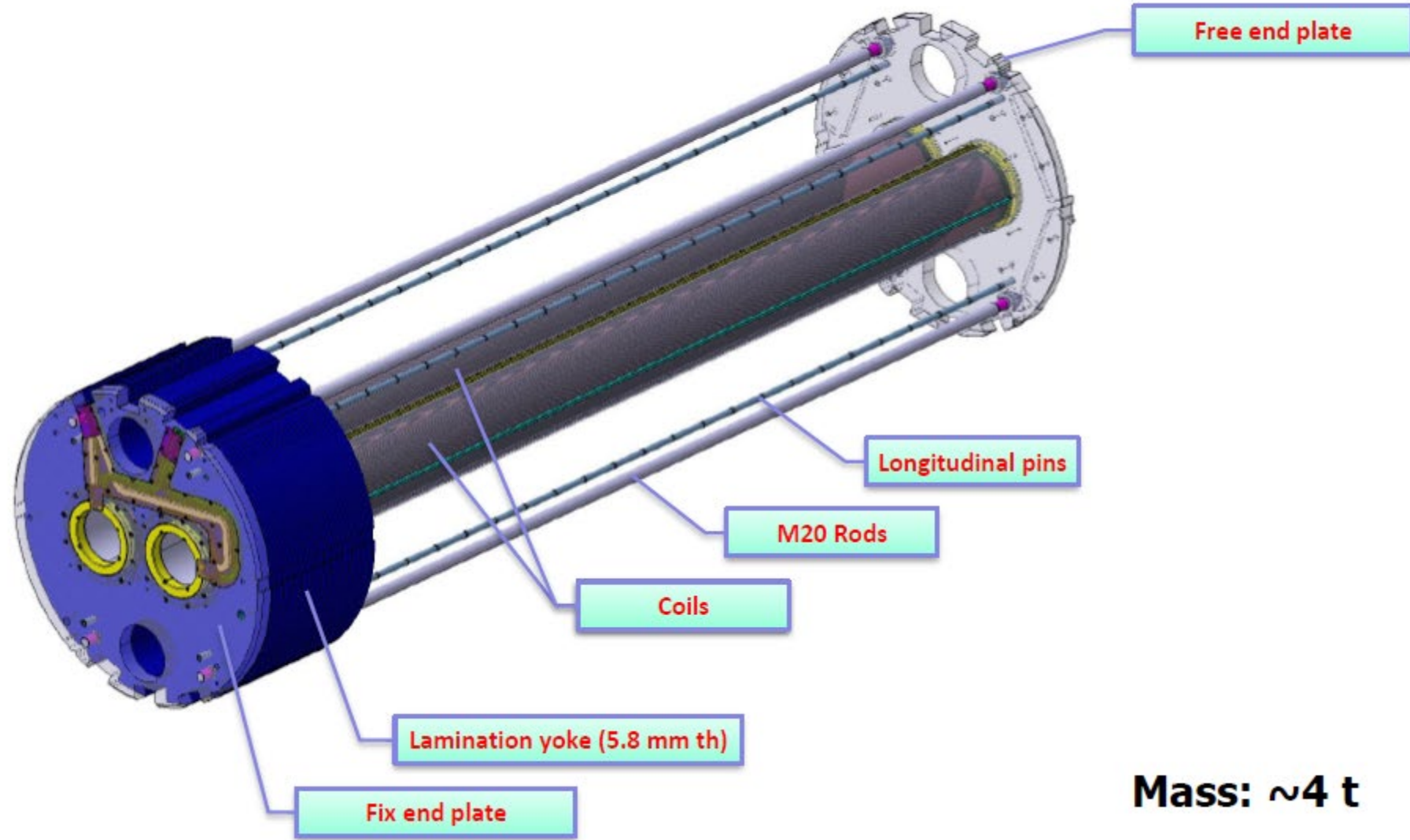
- förhoppningsvis kan vi få stål från CERN
 - diskussion pågår
 - 950mm X 2000mm X 1.5mm ACIER MAGNETIQUE COCKERILL
 - evt. köpa in för test lamineringar

MCBRC järn ok (105mm öppning, 2m lång)



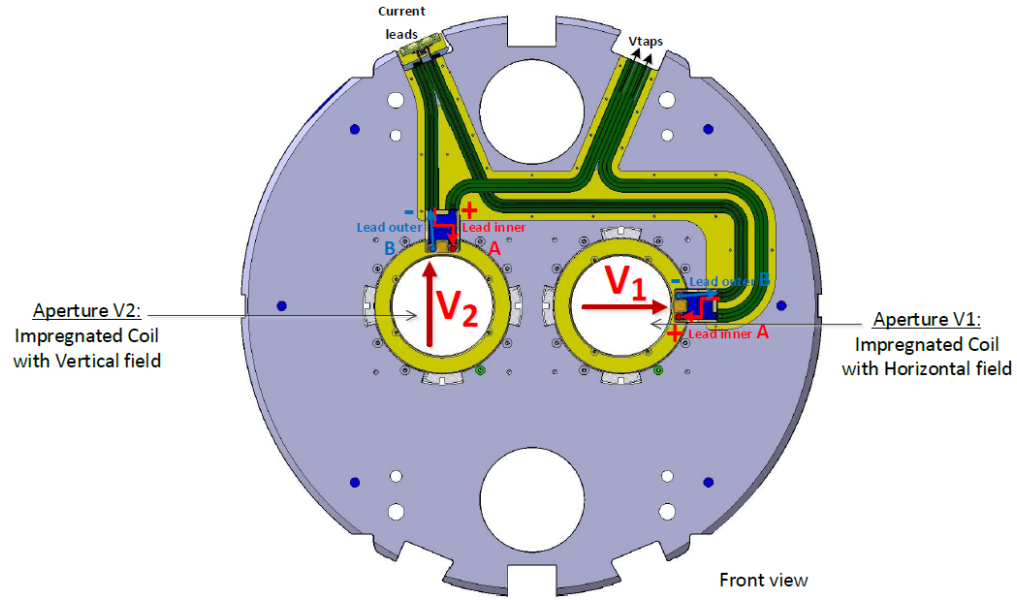


LINDNING OCH MONTERING

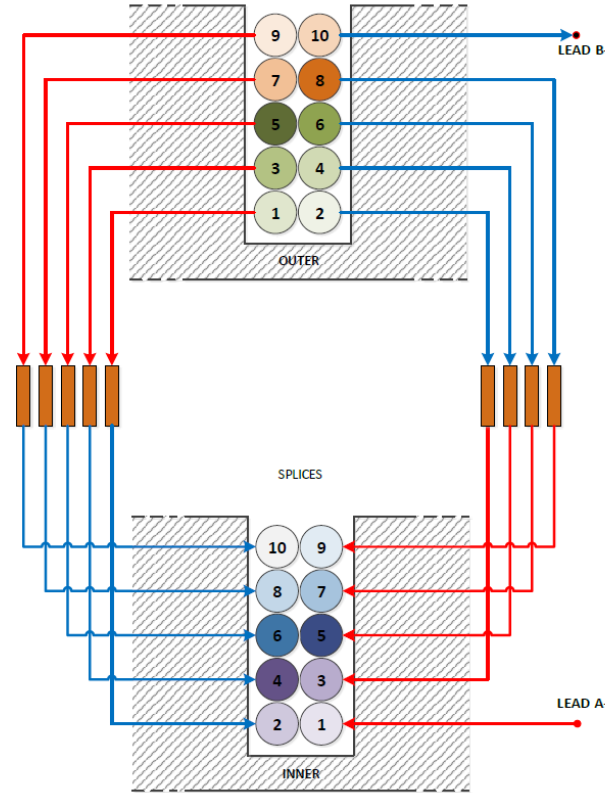


Mass: ~4 t

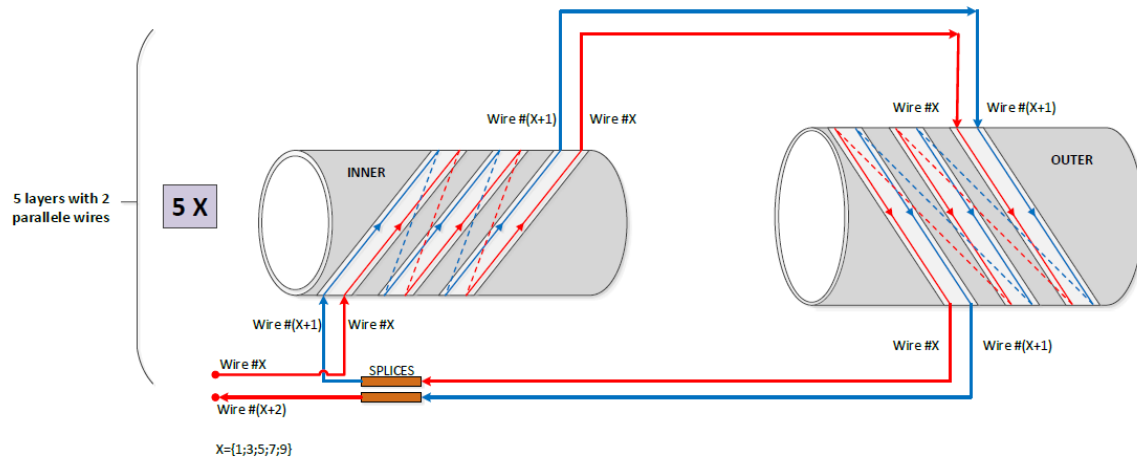
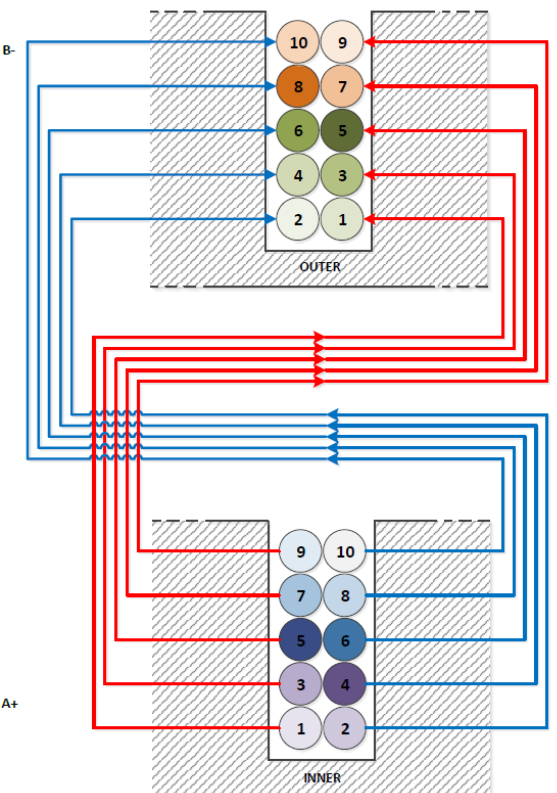
Elektrisk diagram (anpassas för repkabel)



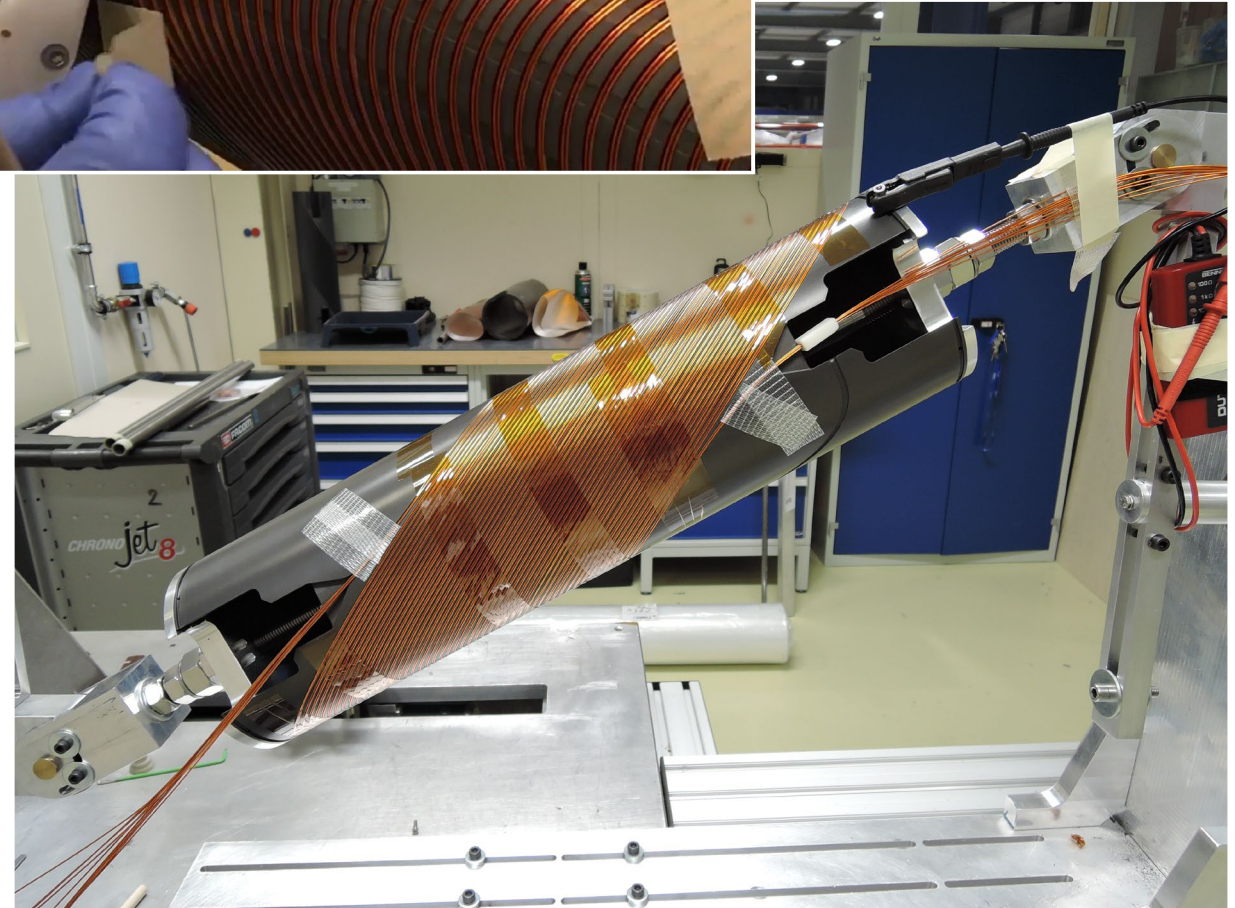
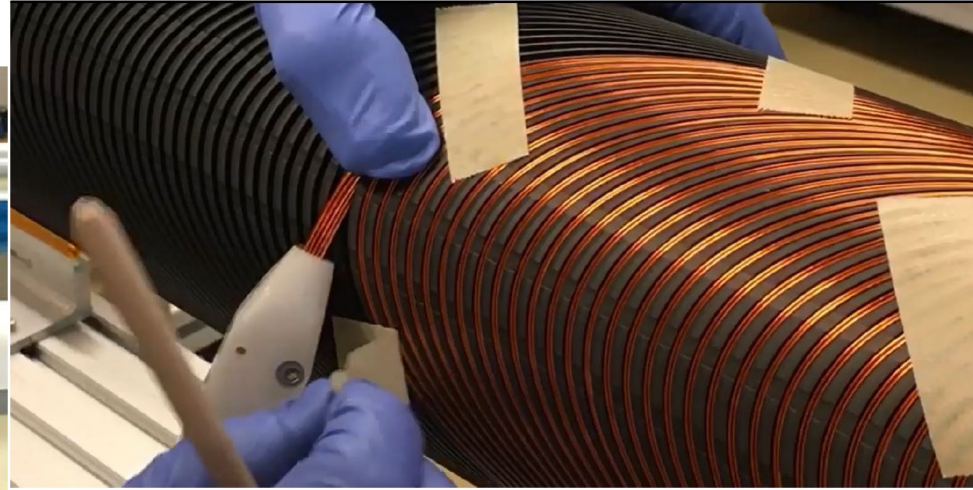
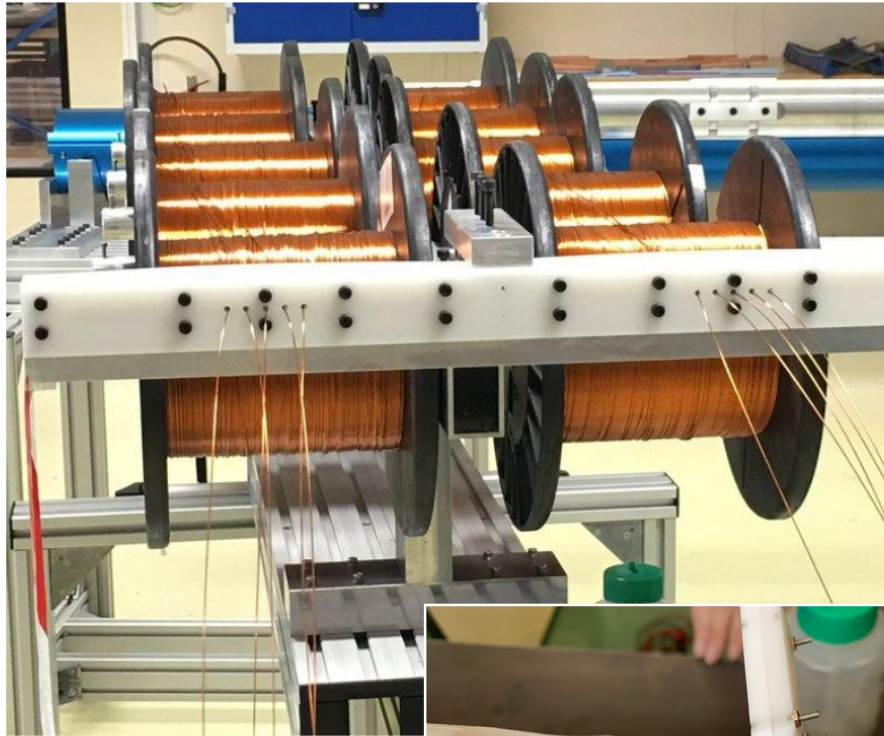
Transversal cross-section
Connexion Box CS view :



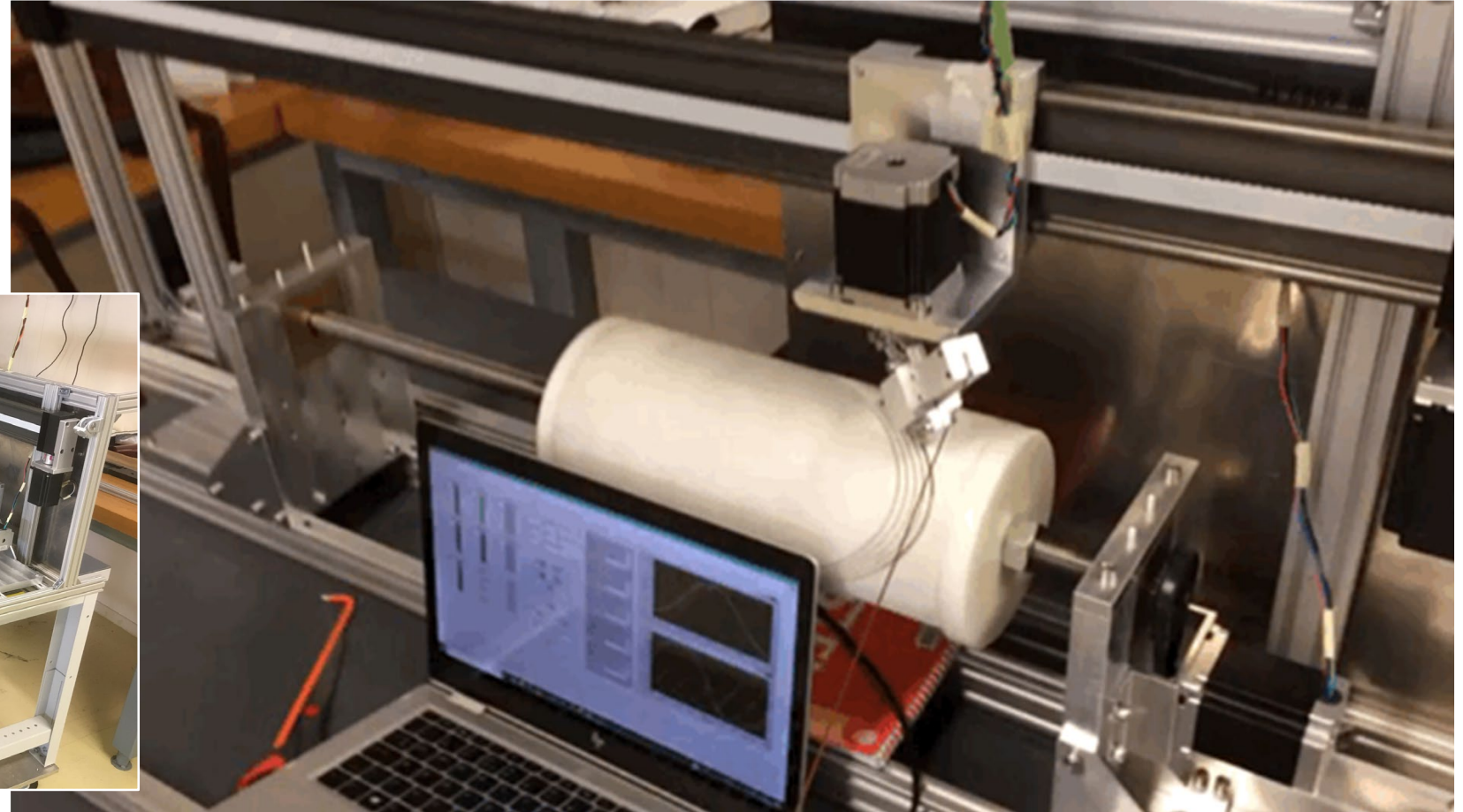
Transversal cross-section
Connexion Box NCS view :



Exempel lindningsverktyg vid CERN

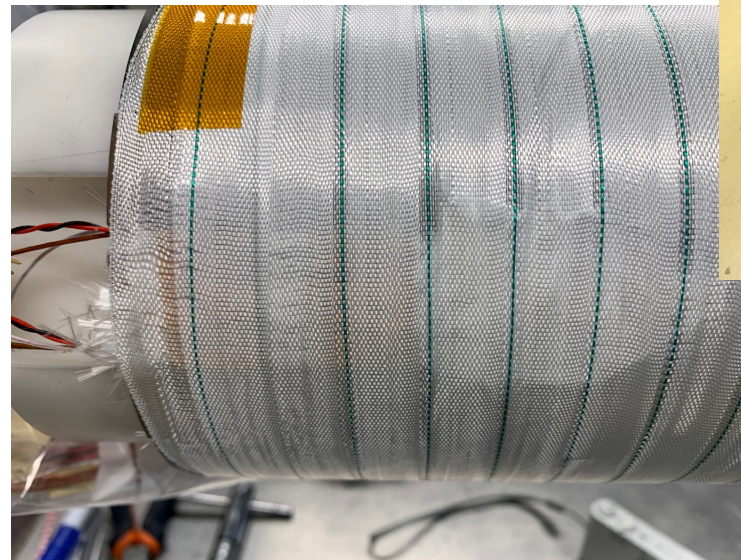
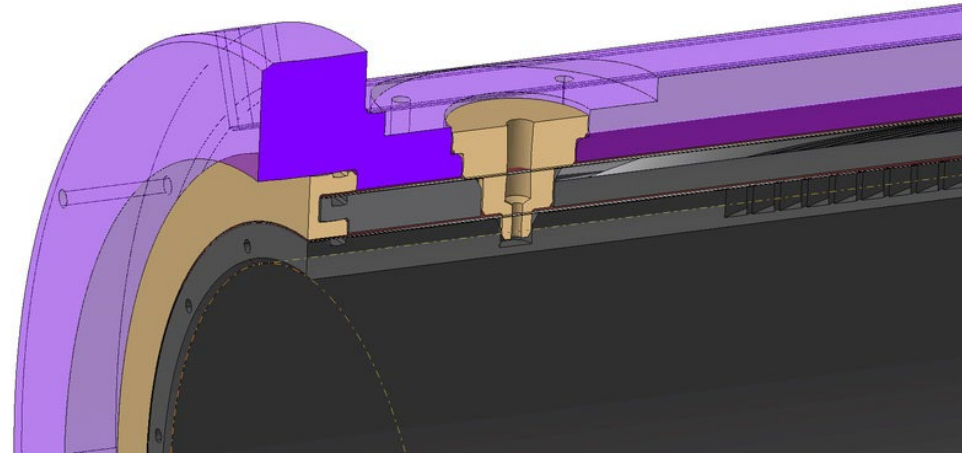


Lindningsrobot byggd av en student



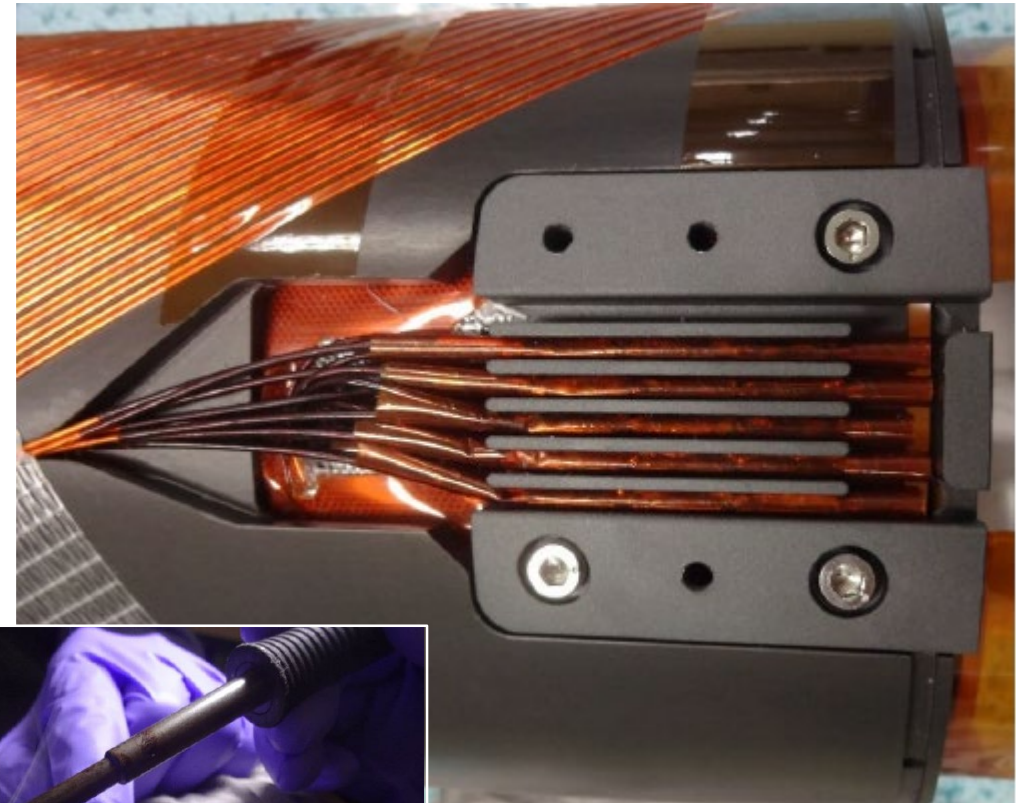
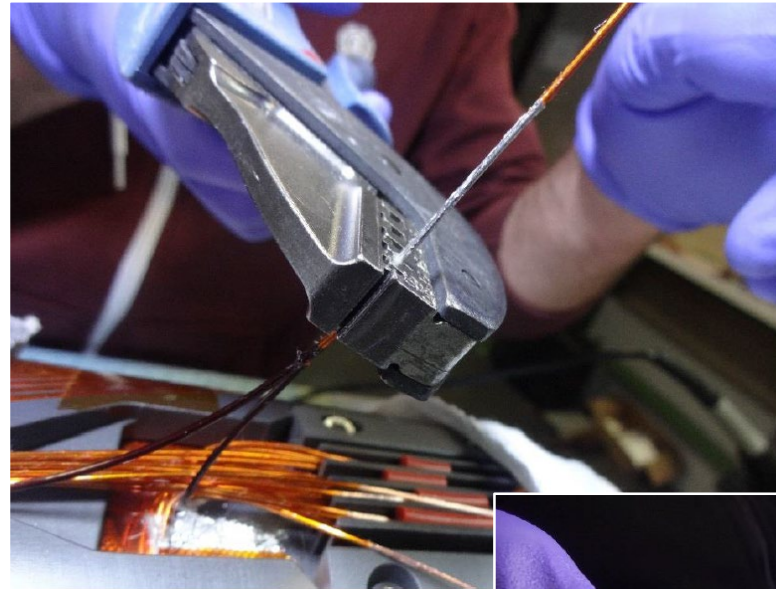
Elektrisk isolation mellan spindel

- glas tape (för resin)
- 2 lagar kapton folie
- glas fiber alignment pin
- slutändan skyddas med isolations ring



Splicing supraledande kabel

- process behövs anpassa för 7-tråds repkabel



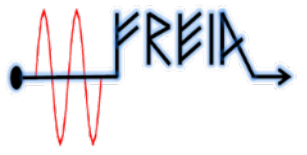
Inbakad temperatur givare

- ej obligatorisk
- intressant under kall test
 - monitor kylning
 - monitor quench-back värmning
- CCS sensor
 - prisvärd alternativ jämfört med Cernox





Impregnering



- Scanditronix expertis
- Glyn föreslår i sin föreläsning att det kan vara värd att undersöka alternativ
 - transparang 60 – 64, t.ex. bivax
 - transparang 74 – 91, hittat sprickor i resin, kräver mera test
- Behövs impregnering?

Järn ok montering vid CERN



MCBRD (2m):

- 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.