CERN R&D Magnets

Susana Izquierdo Bermudez and Juan Carlos Perez

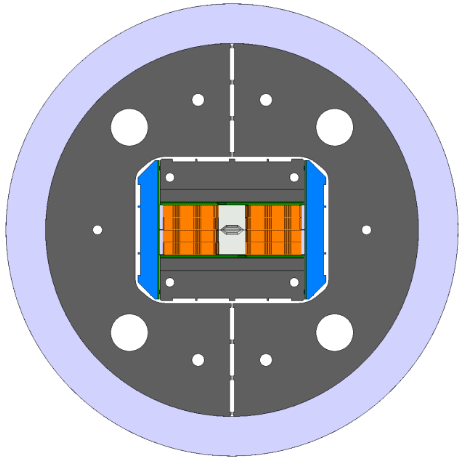
N. Bourcey, A. Carlon Zurita, R. De Paz Ludena, C. Fernandes, P. Ferracin, J. Ferradas Troitino, M. F. Garcia Perez, J. Massard, G. Maury, J. Mazet, J. Osieleniec, D. Tommasini, P. Moyret, C. Petrone

Overview

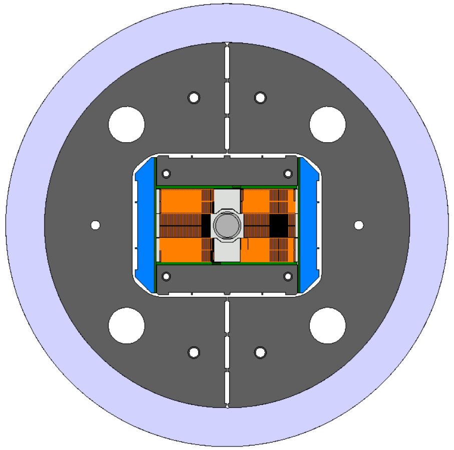
- Introduction
- Non-graded magnet design and construction
- Graded magnet design

The eRMC and RMM program

eRMC
Enhanced Racetrack Model Coil
16 T midplane field
- Demonstrate field on the conductor
- Coil technology development



RMM
Racetrack Model Magnet
16 T in a 50 mm cavity
- Demonstrate field on the aperture
- Mechanics (including inner coil support)



Base for the development of the technology needed for the 16 T dipole program

Nb_3Sn HFM development @ CERN

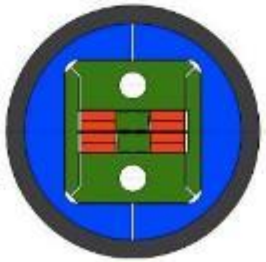
SMC

OD = 530 mm
L = 500 mm
No Ap.
B_{op}= n.a.
B_{ult} = 14 T

RMC

OD = 570 mm
L = 820 mm
No Ap.
B_{op}= n.a.
B_{ult} = 16 T

Hi-Lumi R&D



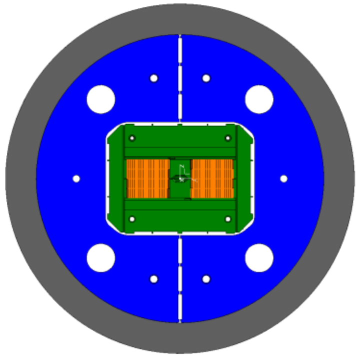
eRMC

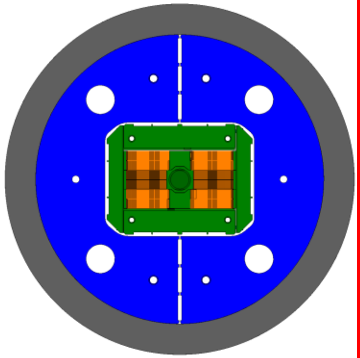
OD = 800 mm
L = 1.2-1.4 m
No Ap.
B_{op}= 16 T
B_{ult} = 18 T

RMM

OD = 800 mm
L = 1.2-1.4 m
50 mm closed Ap.
B_{op}= 16 T
B_{ult} = 18 T

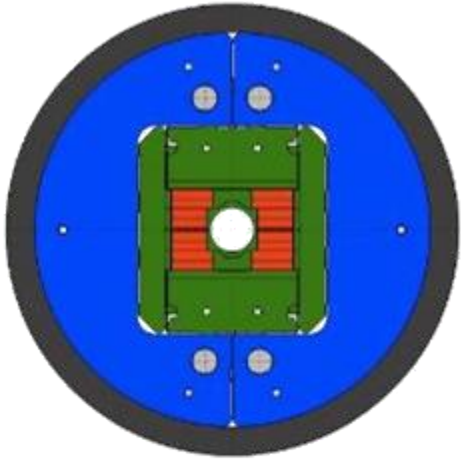
FCC R&D





FRESCA2

OD = 1.03 m
L = 1.6 m
100 mm Ap.
B_{op}= 13 T
B_{ult} = 15 T



OD = Outer diameter
L = Magnet length
AP = Aperture
B_{ult}= Ultimate field, defined as the maximum design field for the magnet structure

eRMC & RMM design strategy

Stage 1 priorities:

1. Demonstrate the field
   - Design based on the “available” critical current density (~20% lower than FCC target at 18 T, 4.2 K)
   - As field quality is not an objective, profit from the use of an iron pole to decrease the ratio between the field in the aperture and in the coil to ~ 1
2. Study the mechanics

Non graded design

- Construction started!

Stage 2 priorities:

1. Coil size → Grading
   - Design based on the target FCC critical current density
   - High Field Nb_3Sn splice development needed
2. Field quality (b_n<10 units, including iron saturation)
   - Still, it will need to be accommodated within the same structure, changing only the coil pack assembly

Graded design

- 2D magnetic and mechanical design done
- Activity launched on splice development, but further feedback needed before starting the engineering design.

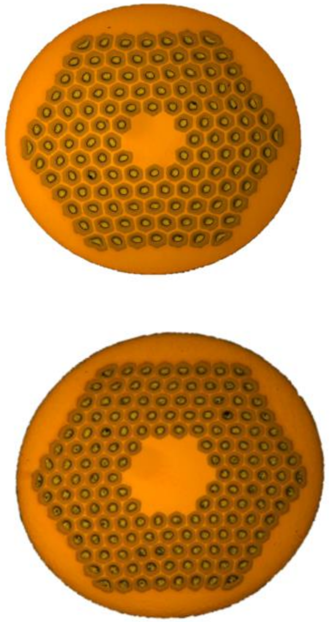
CERN

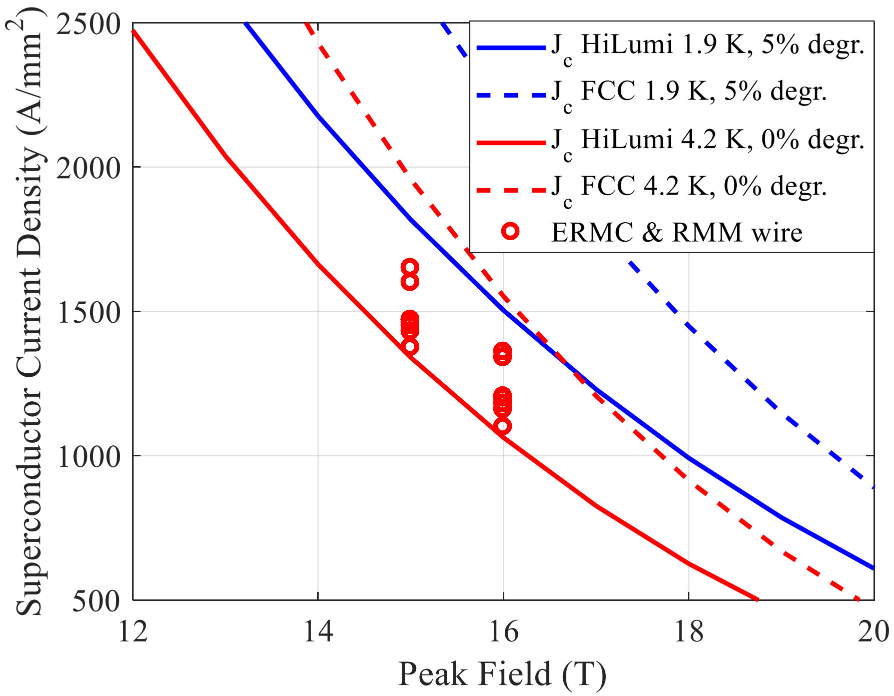
Non-Graded Magnet Design and Construction

B. Bordini, J. Fleiter & A. Bonasia

Strand and Cable Parameters

- 1 mm diameter wire, cu/sc =1
- Wire received in 2016:
  - 4 billets RRP 120/127
    - 62-64 µm
  - 5 billets RRP 150/169
    - 54-55 µm





- 40-strand cable
  - Bare width x thickness: 20.9 x 1.82 mm
  - SS core 14 mm wide and 25 µm thick
- Assumed growth during HT : 3% (thickness), 1% (width)

Magnetic Design

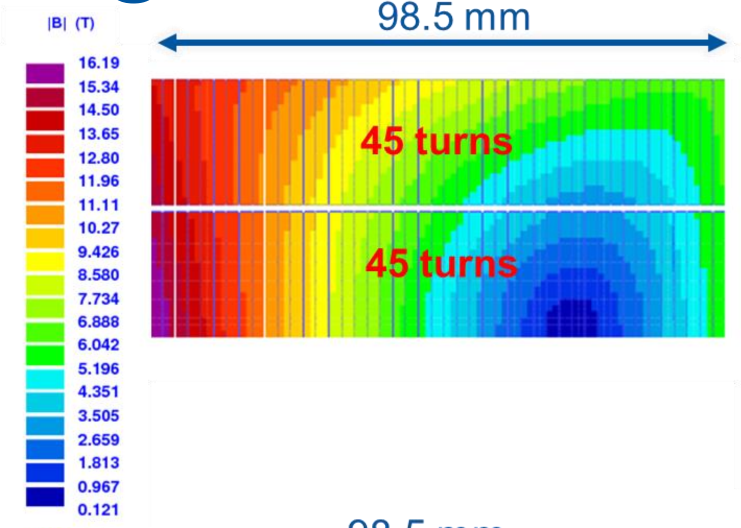
eRMC

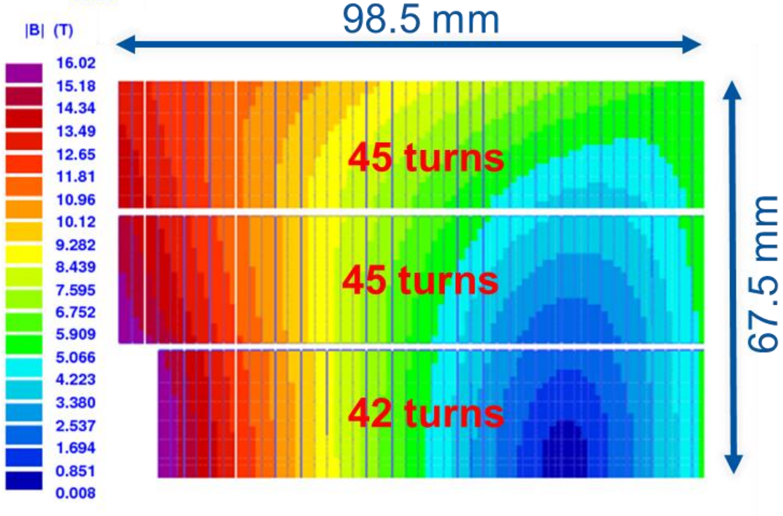
- Two double-layers with 45 turns each wounded around a magnetic pole
- B_p/B_o = 1.097

RMM

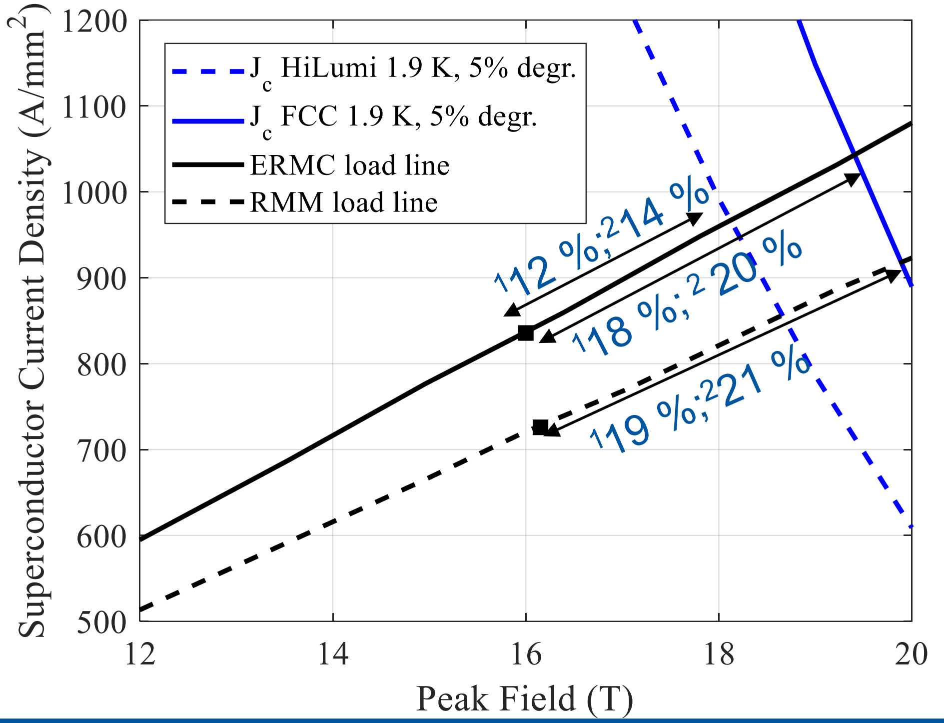
(eRMC double layers +)

- Middle double layer with 42 turns each wound around a titanium closed cavity
- Coil aperture radius = 31 mm
- Closed aperture radius = 25 mm
- B_p/B_o = 1.097





	Units	eRMC	RMM
Nominal current (I_{nom})	**kA**	13.1	11.4
Overall current density	**A/mm²**	282	245
Bore field	**T**	15.7	16.0
Peak field at I_{nom}	**T**	16.0	16.2
Stored energy at I_{nom}	**MJ/m**	1.5	2.1



[1]1-I/I_{ss}

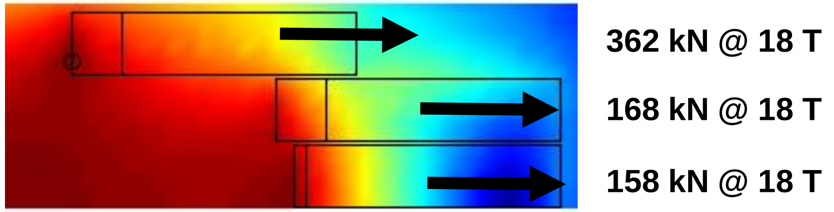
[2]1-B/B_{ss}

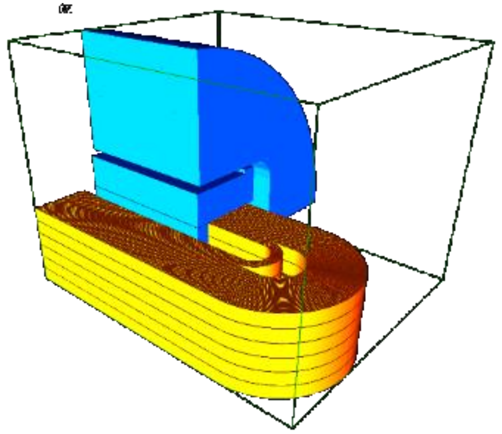
3D Magnetic Design

Optimized solution 1

- No end-spacer → simpler manufacturing
- Shifted layer → minimum peak field
- Unbalanced electromagnetic forces in the top layer

ΔBpeak = 1.1T



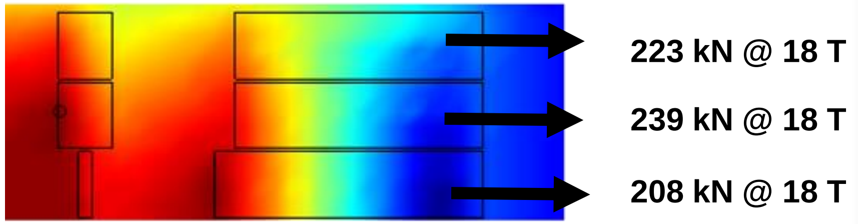


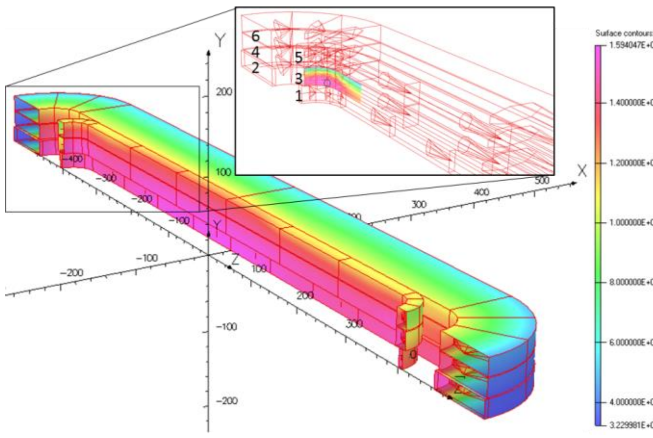
Selected option

Optimized solution 2

- Requires coil end spacers
- The peak field in the coil ends is only 0.5 T lower than in the straight section
- Balanced electromagnetic forces

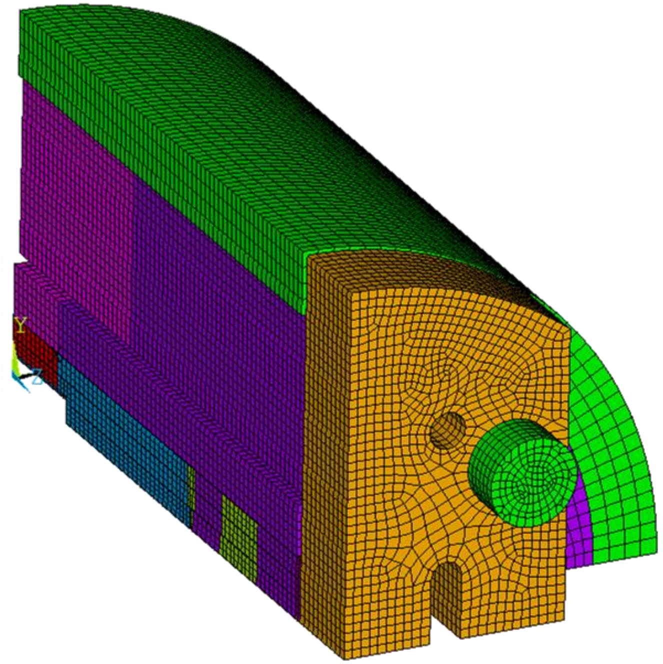
ΔBpeak = 0.5 T

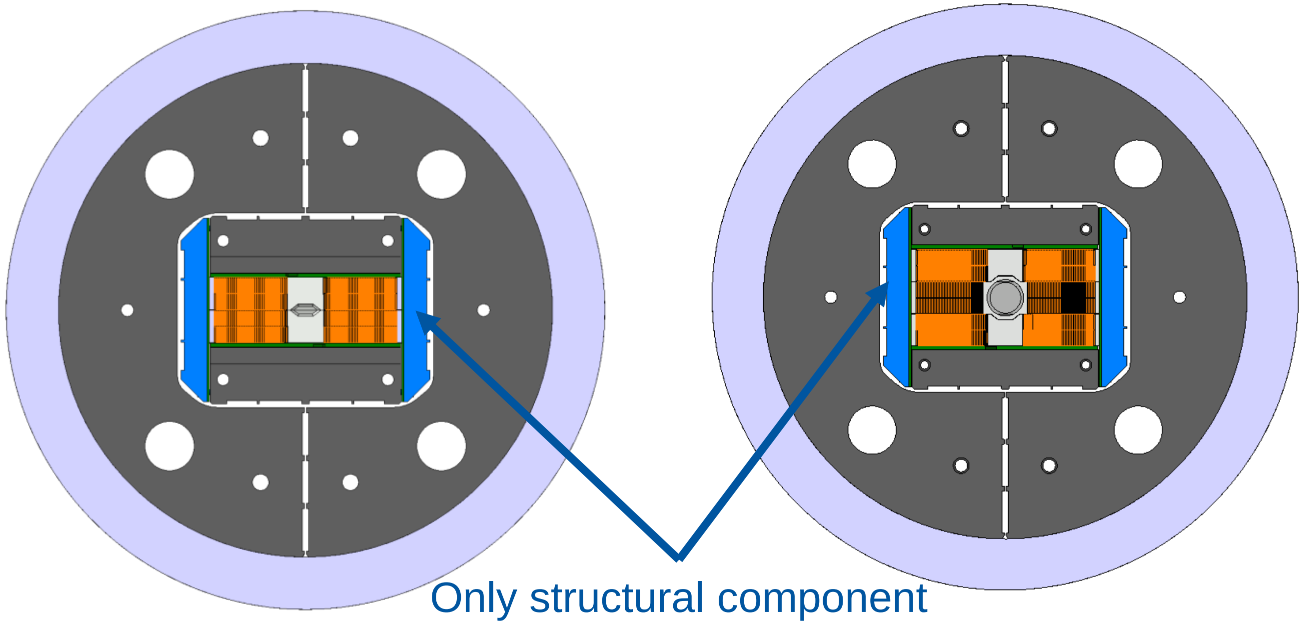




Mechanical design

- Mechanical structure capable to load the magnet up to 18 T, with enough margin to perform an experimental exploration of the different parameters relevant to magnet performance.
- Critical structure components during optimization:
  - Yield strength of the iron yoke during assembly (design criteria σ_{eq_warm} < 180 MPa) and tensile strength at cold (σ_{1_cold} < 200 MPa)
    - After a mechanical characterization of ARMCO samples, these limits have been raised to σ_{eq_warm} < 230 MPa; σ_{1_cold} < 370 MPa)
  - Bending of the horizontal pads during bladders operation (Nitronic).





Only structural component different in eRMC and RMM

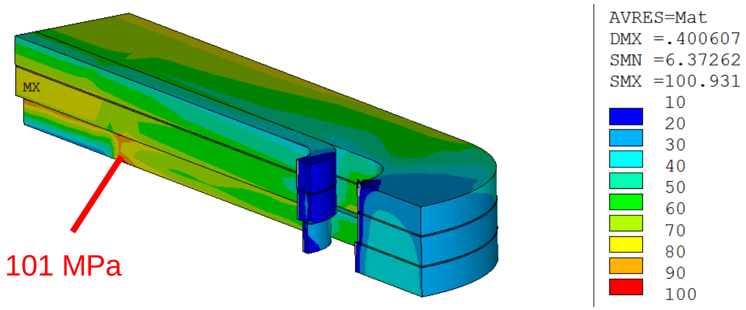
3D Mechanical Analysis

- Axial support structure dimensioned to provide up to 100 % of the electromagnetic forces at 18 T.
  - In any case, tension (or gap) in the pole turn at maximum field.
- Stainless steel and aluminium rods variants studied.

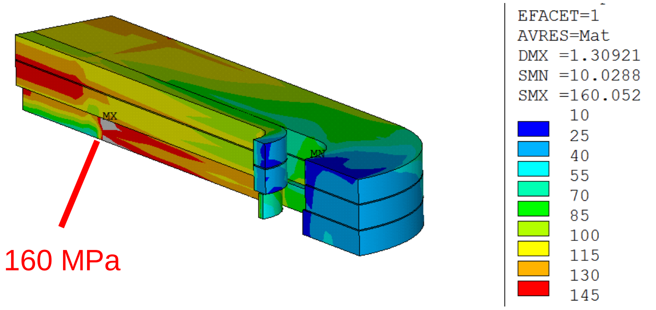
Different possible axial pre-loads using Aluminium Rods

	Rod Pre-load Fz [% L. F.]	Rod Cool-Down Fz [% L. F.]	Energization: Max. Tension [MPa]	Energization: Max. Gap [µm]
16 T	14	76	64	106
18 T	11	**56**	90	135
16 T	27	**100**	56	94
18 T	20	75	80	133
16 T	72	139	46	76
18 T	53	**104**	66	110
16 T	**97**	167	40	62
18 T	72	125	72	99
16 T	135	208	30	44
18 T	**100**	155	66	85

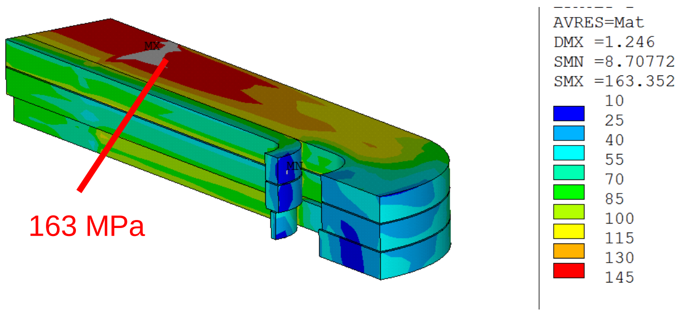
Assembly



Cool Down



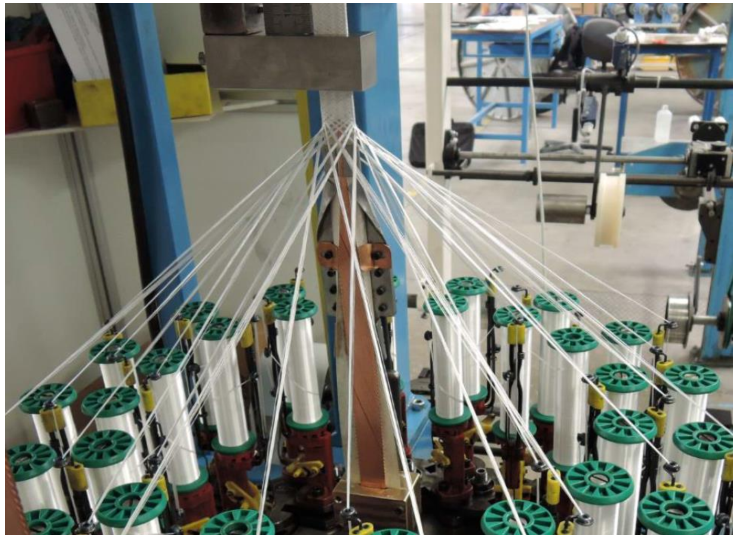
Powering at 18 T



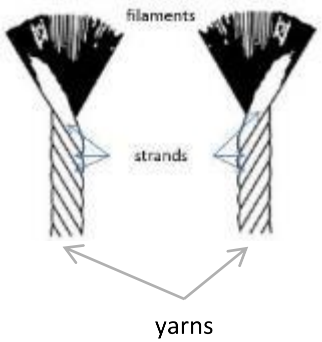
E. Rochepault, et. Al., “3-D Magnetic and Mechanical Design of Coil Ends for the Racetrack Model Magnet RMM”, IEEE Appl. Sup., Vol 28, No. 3, April 2018

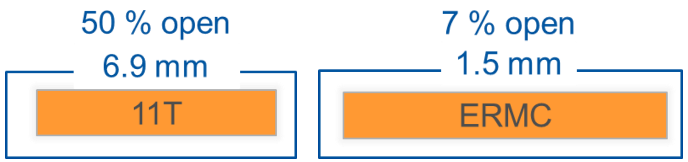
Cable Insulation

- Baseline: 0.150 $^{+0.00/-0.02}$ mm Mica-Glass Insulation
- Insulation tests preformed to define the best parameters:
  - S2 glass 636 11 TEX yarn
  - 14 yarns (ply) per bobbin
  - 32 bobbins
  - Speed (angle) set to guarantee full coverage and appropriate thickness



Sample ID	Insulation thickness at 5 MPa (μm)
Coil 101 – S1	150
Coil 101 – S2	149





Remark: plots not on scale

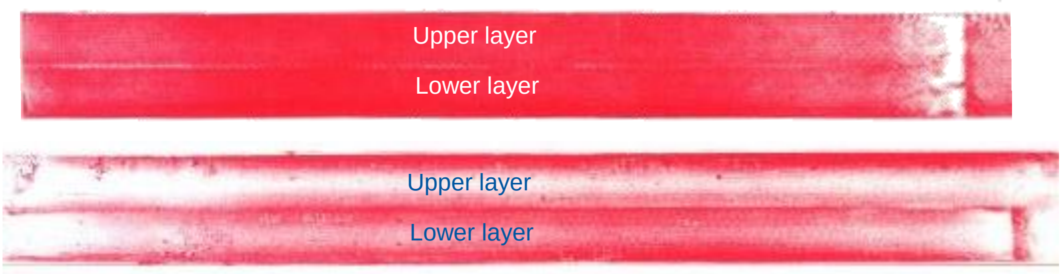
Cable Insulation - Mica

- Some evidences on 11 T and SMC 11 T that the C-Shape mica can have a negative impact on the uniformity of the pressure distribution.

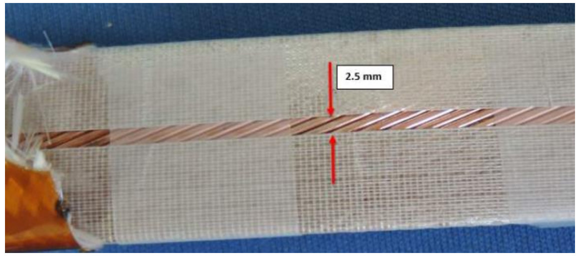
Contact pressure on outer coil turns, SMC11T under 50 MPa compression

SMC11T-1 (no mica)

SMC11T-3 (mica)



- After some iterations, braiding with wider mica tapes (44 mm) feasible.
- Three unit lengths have been insulated, no problems have been identified.



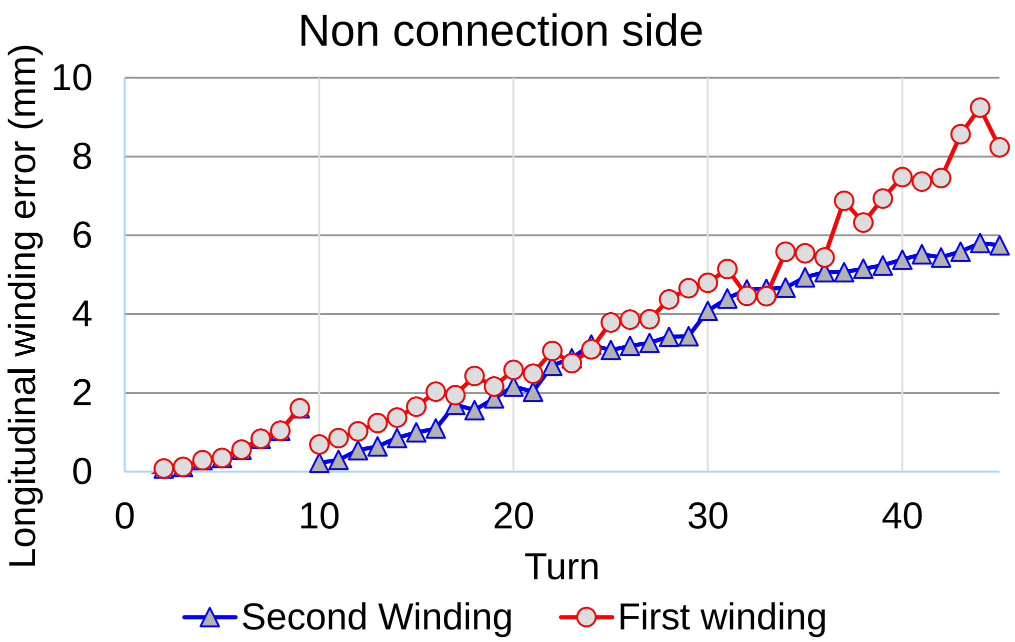
https://indico.cern.ch/event/641884/
https://indico.cern.ch/event/659541/contributions/2689641/attachments/1507432/2349396/Visite_CGP_ERMC.pdf

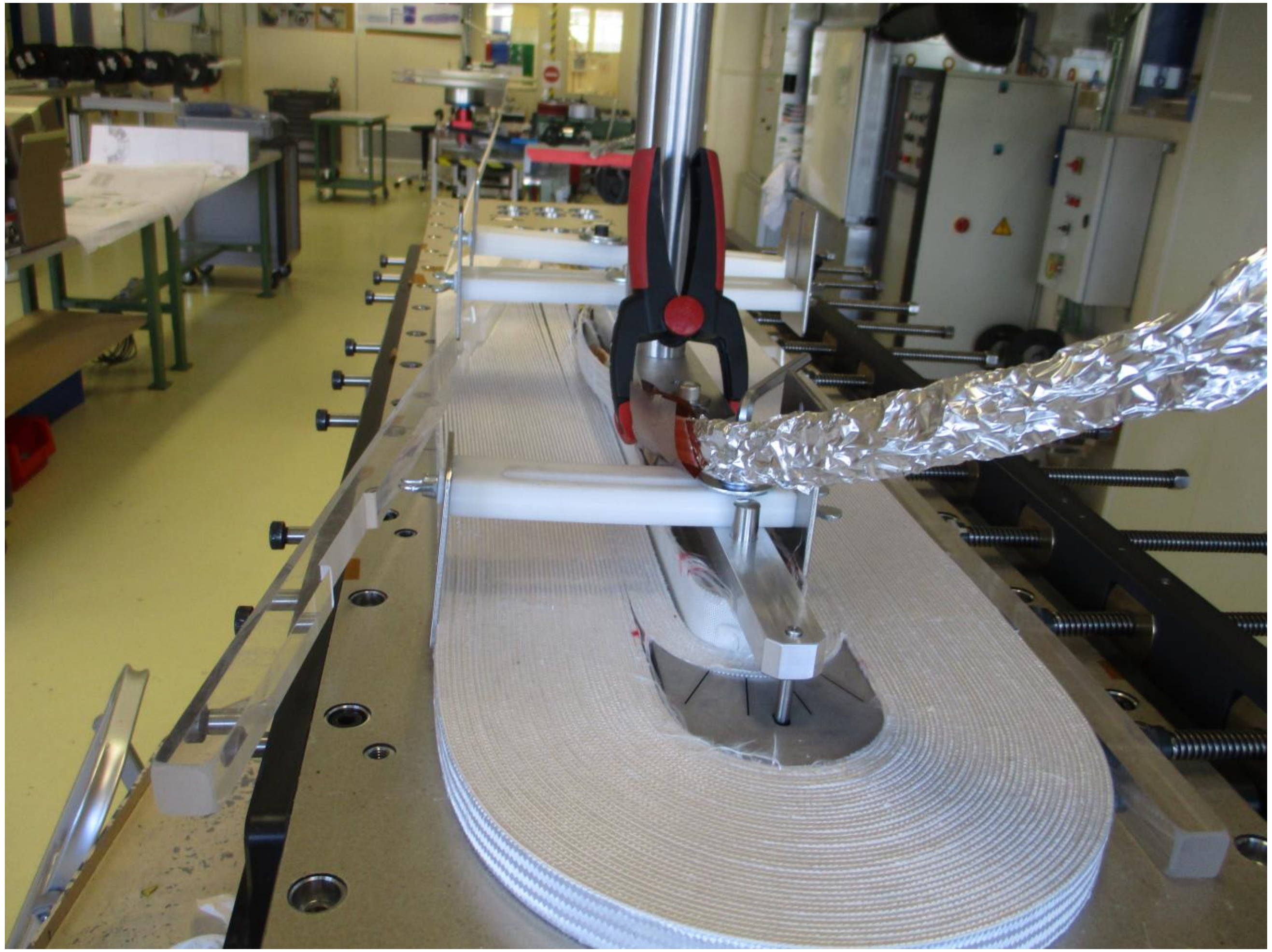
Coil Winding – eRMC coil 101

- First coil has been wound
- "Novel" features:
  - Mica around the pole, to minimize the bonding strength between cable and pole.
  - End spacers polished to maximize the bonding strength between cable and end parts.
  - End parts not coated, but 0.5 mm of extra S2 glass between cable and metallic parts to enhance the electrical insulation.

Coil Winding – eRMC coil 101

- Main challenge: good clamping of the cables during winding for a good coil compaction, particularly difficult in the coil ends
  - At the end of the winding, coil is around 12 mm longer than nominal (6 mm per side)



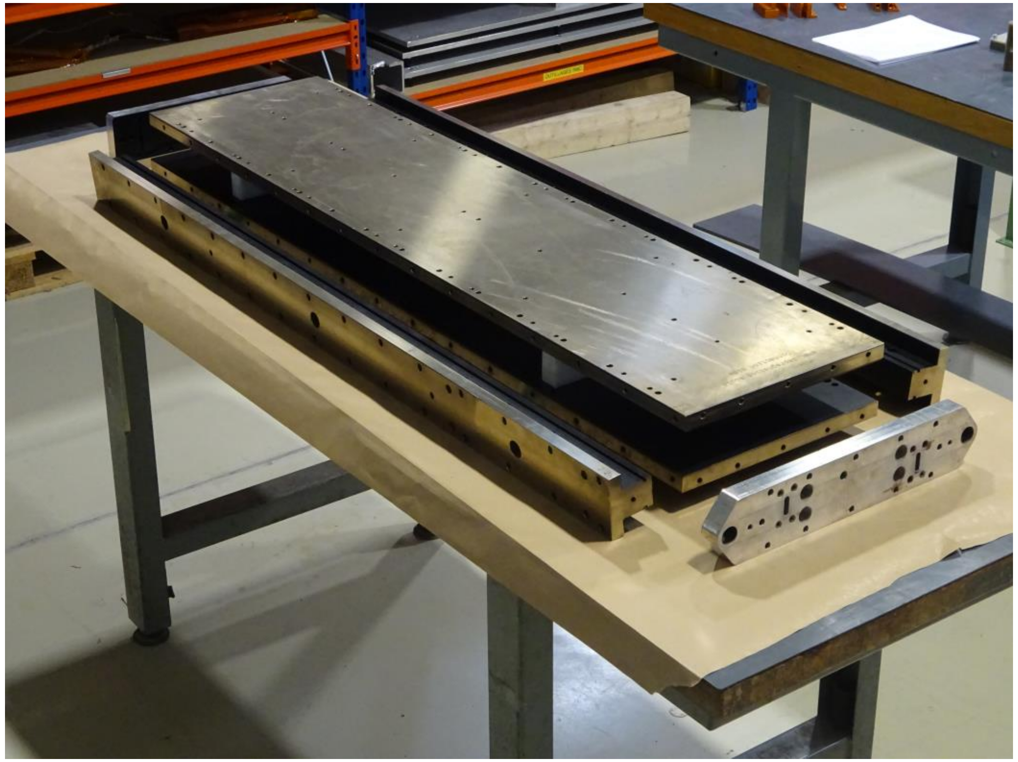


Reaction

- Gap between poles:
  - During winding: 1.5 mm
  - After releasing the winding tension: 1.5 mm
  - After heat treatment: (our expectation: gap “almost” closed)
- The first coil is ready for reaction

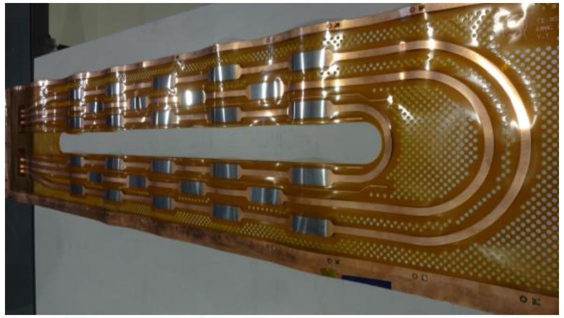
Impregnation

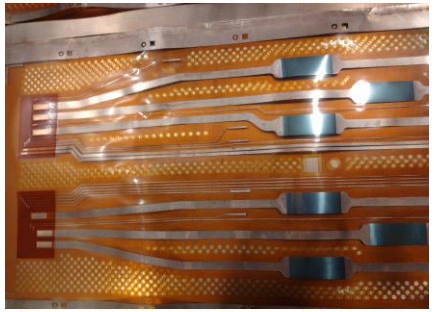
Two set of impregnation tooling are ready

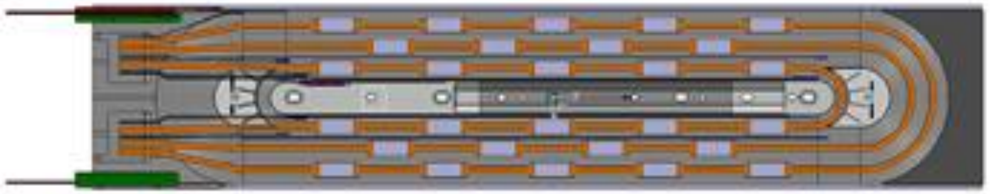


Instrumentation

- Quench heaters and voltage taps integrated in the so-called trace, using the same technology as for MQXF/11 T/SMC/RMC/FRESCA2…
    - Trace has been designed accounting with the possibility to install a spot heater for quench protection studies.

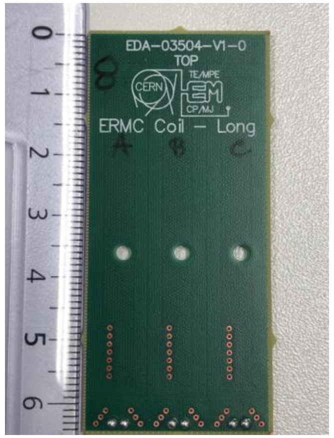


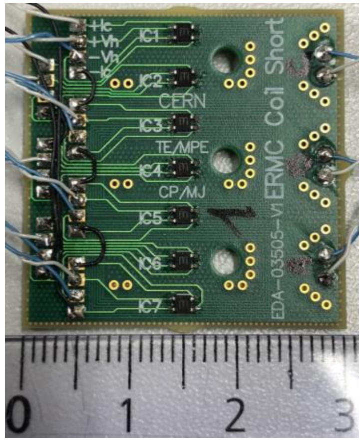


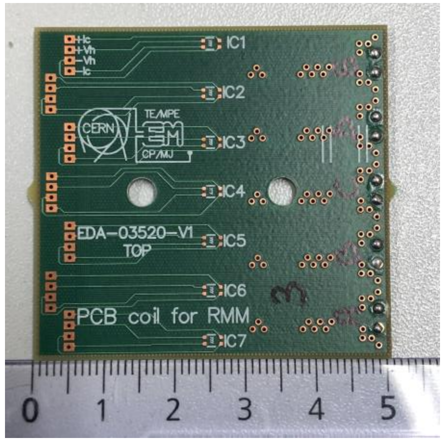


C. Petrone

- Hall sensors and PCB probes have been produced, both for eRMC and RMM configuration to characterize the field.
    - Additional PCB will be probes will be installed in the magnet, in an attempt to use them as quench antenna.







Magnet Structure

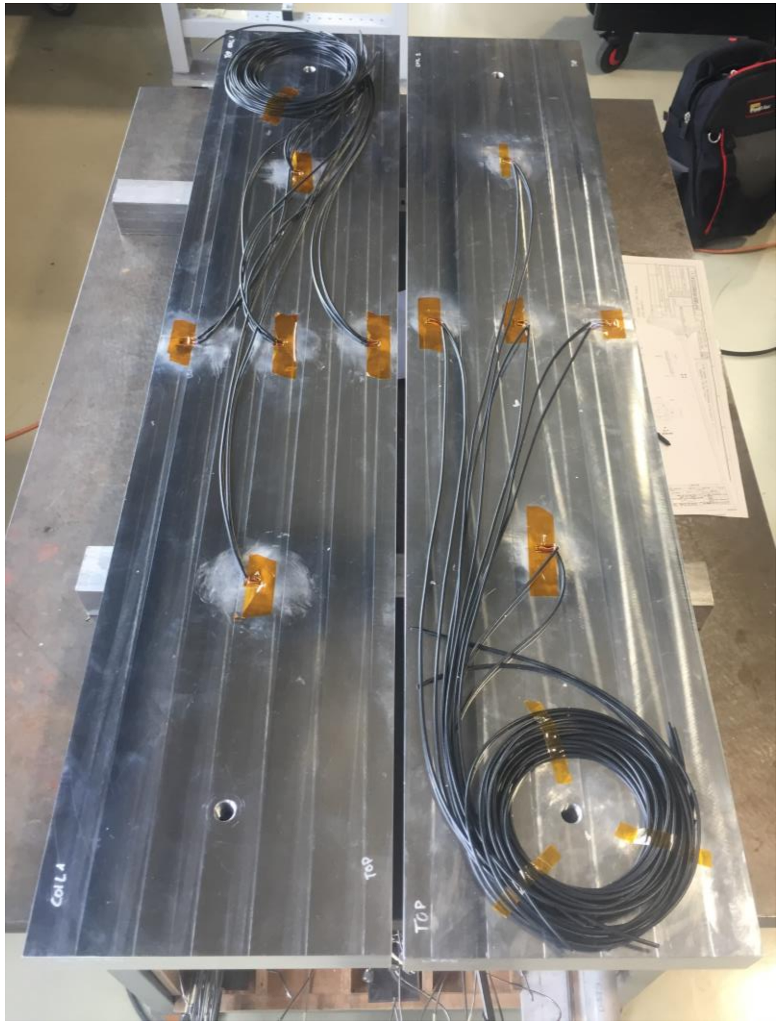
- All magnet components (except end plate) received and ready for assembly.
- In order to explore different assembly parameters:
  - Full aluminum shell and half length shell options available.
  - Aluminum and Stainless Steel rods available for the longitudinal loading.



Mechanical Test Assembly

- Aluminium dummy coils, rods and shells are instrumented, ready to start the dummy assembly test.
- Plan: Perform an assembly test, including cool down, with three pre-load levels.

Aluminum Dummy Coils

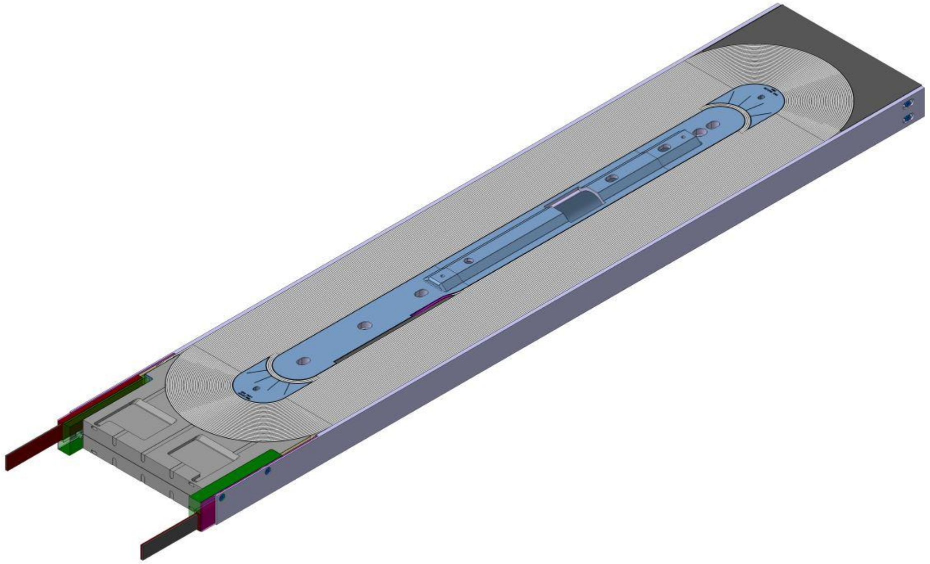


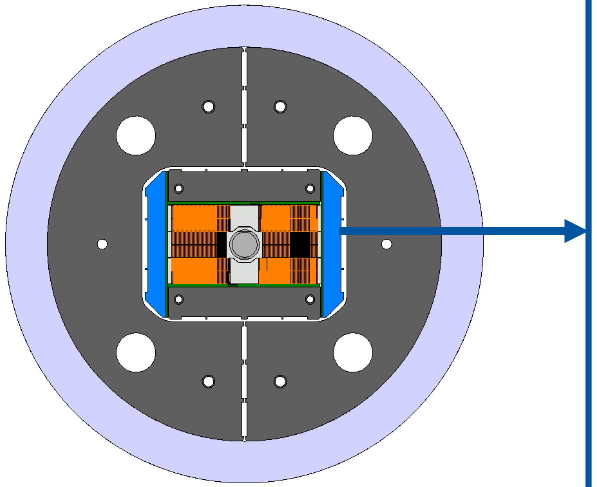
Assembly table

Axial loading system

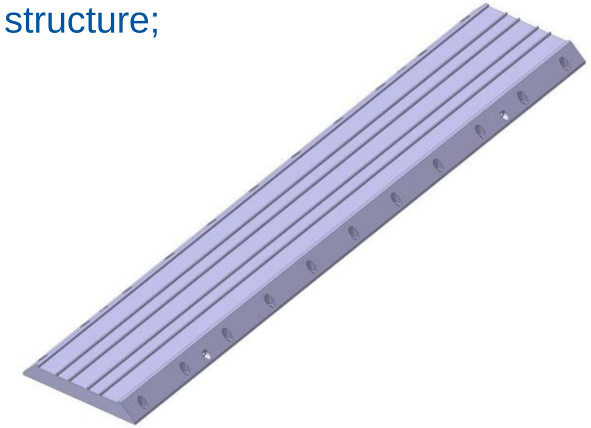
Preparation activities for RMM

- Same magnet structure for eRMC and RMM, only few items need to be procured:
  - Cable (strand available, cabling planned in summer)
  - Coil parts (procurement being launched)
  - Lateral pad (procurement being launched)





Lateral Pad: Only component not in common with eRMC structure;



Graded Magnet Design

Strand and Cable

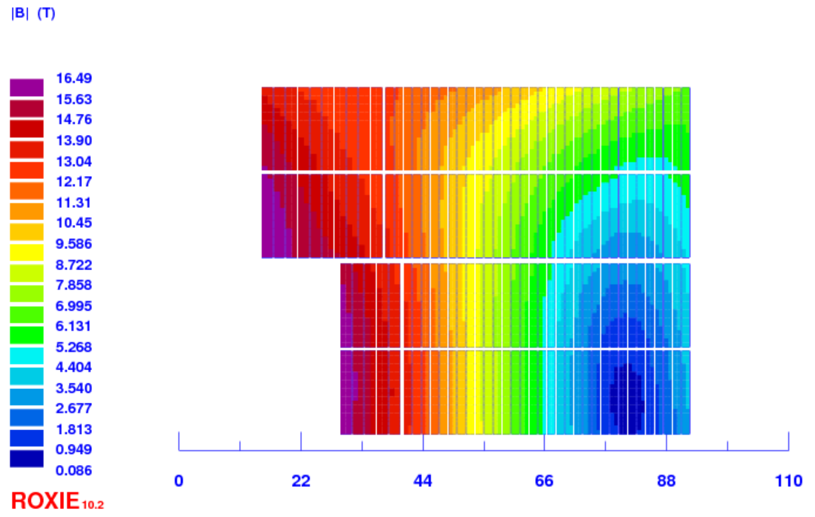
- Guidelines for the selection of the strand and cable:
  - If possible, choose a diameter that can be easily procured in the short term
    - 0.7 mm (11T), 0.85 mm (MQXF) and 1 mm (FRESCA/eRMC)
  - Stay within CERN technical limitations for the cable production (max. strands = 40)
- Cable for eRMC-RMM graded magnet:
  - Low field: 0.7 mm x 40 strands (SMC11T cable)
  - High field: 1.0 mm x 28 strands

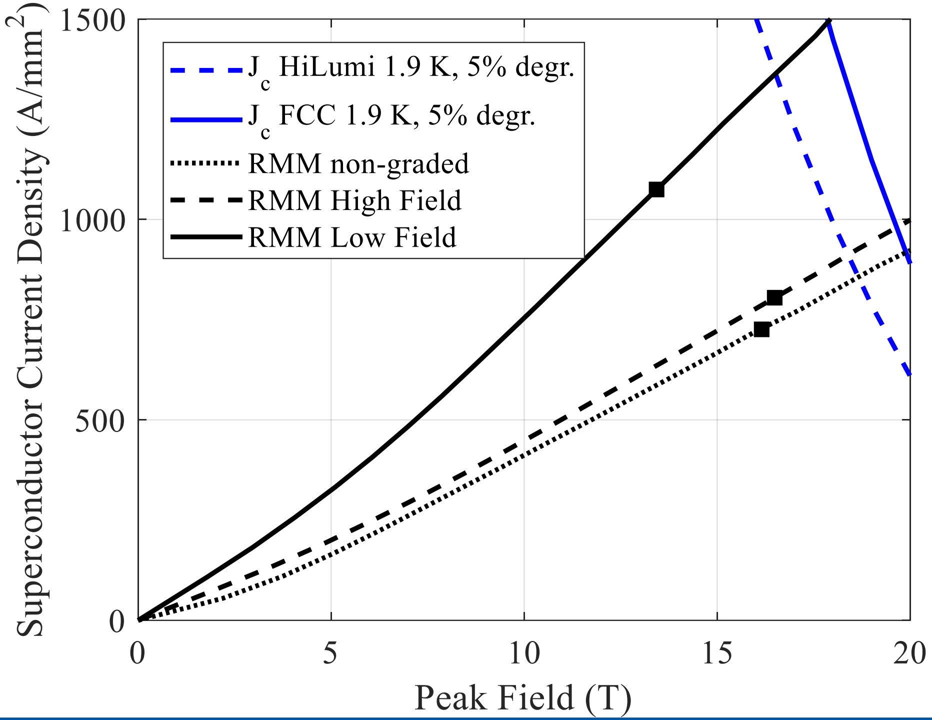
Parameter	UNIT	HF	LF
Strand diameter	mm	1	0.7
Copper to superconductor ratio (Cu/SC)	--	1*	1.15
J_c(12T, 4.2K), with self-field correction	A/mm^2	3260	3260
J_c(16T, 4.2K), with self-field correction	A/mm^2	1355	1355
J_c(18T, 4.2K), with self-field correction	A/mm^2	774	774
Number of strands	--	28	40
Cabling degradation	%	5	5
Cable bare width (before/after HT)	mm	14.70/14.847	14.70/14.847
Cable bare thickness (before/after HT)	mm	1.786 /1.839	1.250/1.288
Insulation thickness per side	mm	0.150	0.150

*Can be reduced to 0.8, which would translate on 2.5 % increase of the load line margin.

Magnetic Design

- Strong synergy with the EuroCirCol Block design option, slightly more conservative in some aspects:
  - 16 T bore field, with 14 % margin, using “available” critical current density (16 % margin assuming FCC Jc; 10 % assuming HiLumi Jc)
  - 20 % margin in the low field region, as the impact on coil size is relatively small (25 % margin assuming FCC Jc; 19 % assuming FCC Jc)
  - Inner support thickness of 4 mm. In a later stage, coil with 2 mm inner support can be produced to study the impact of the inner support on the performance.
  - Minimum available copper to superconductor ratio 1 instead of 0.8

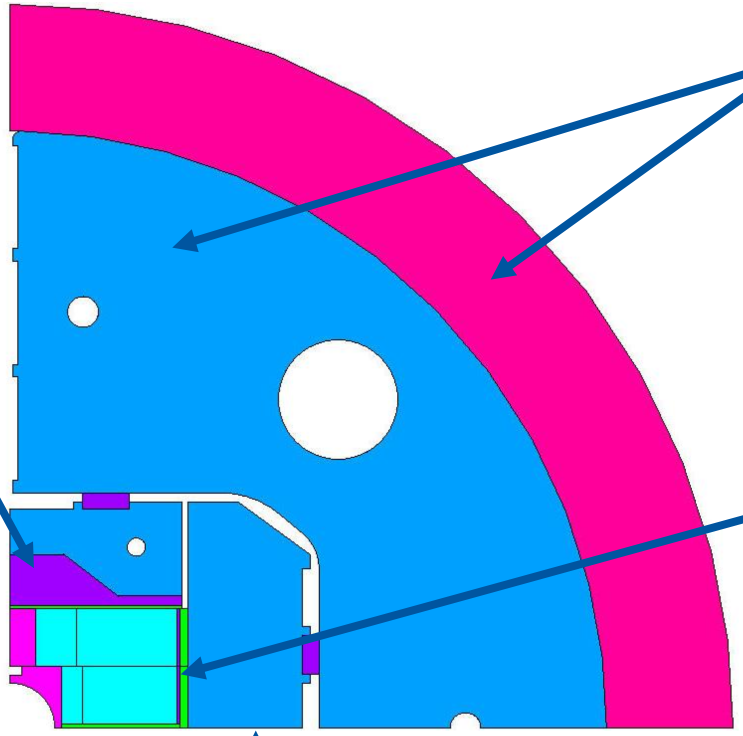




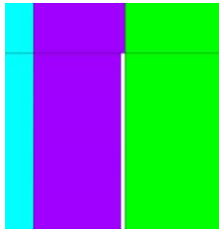
Mechanical Design

Stainless steel part for field quality requirements (iron saturation effect within 10 units from injection to nominal). Contact to the iron pad to be more carefully studied.

Yoke, shell and axial support is the same as for the non-graded magnet



Notch on the lower coil decreases peak stress by 10 MPa (small gain, but we might profit from this to put strain gauges on the upper coil)

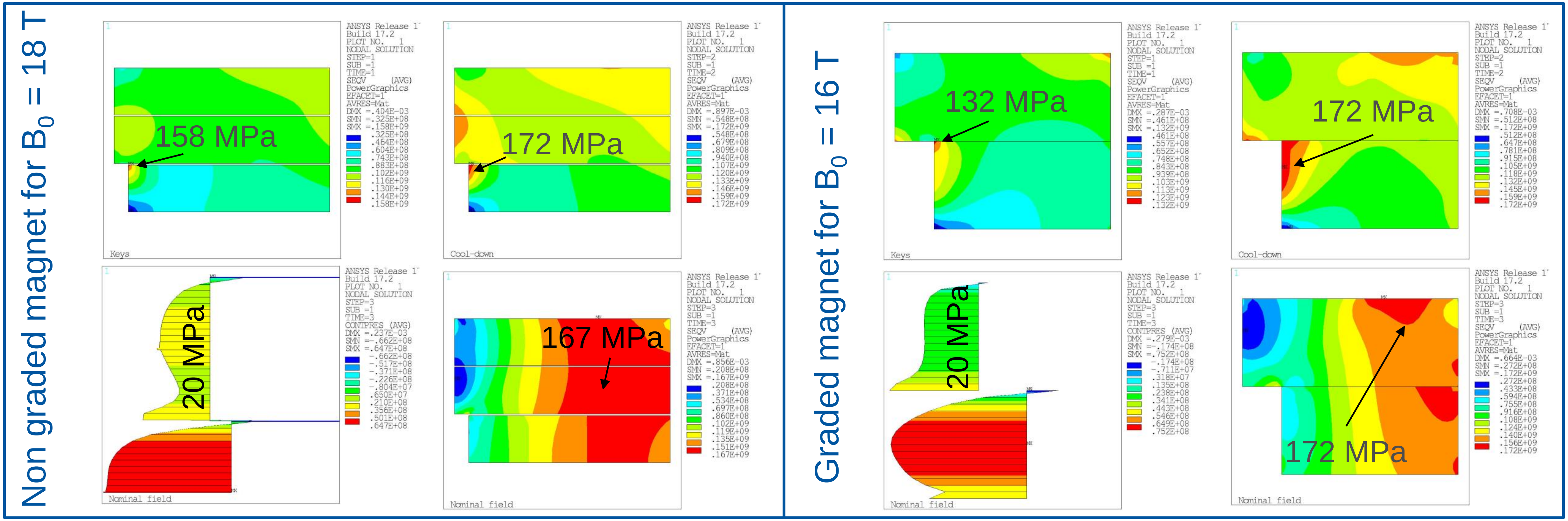


If we can engineer a good sliding plane in between the two coils, potential of gaining ~ 10 MPa at cold, 25 MPa at warm shimming slightly less the bottom coils

Lateral Pad of ARMCO (since we are re-using the non-graded structure, enough room available to have a magnetic pad)

Mechanical Design

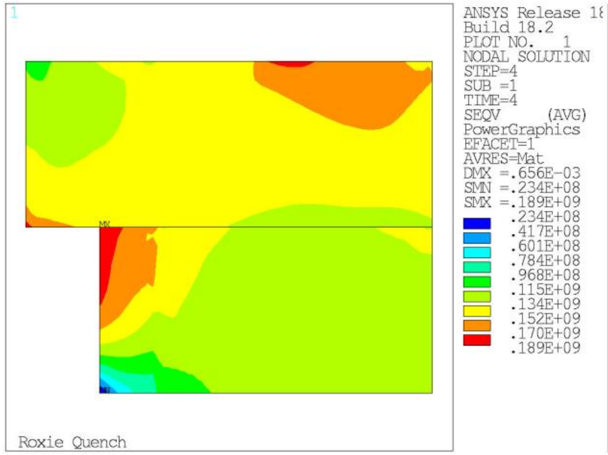
- Fulfills EuroCirCol Criteria (using EuroCirCol Material properties and stress limits).
- In terms of peak stress, non-graded magnet at 18 T comparable to the graded magnet at 16 T.



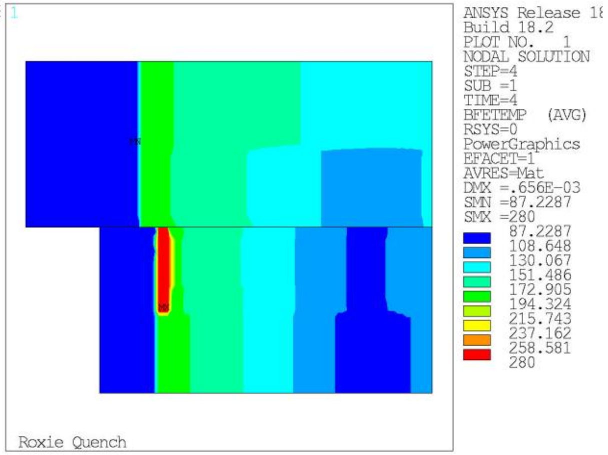
Quench Protection

- Preliminary analysis show that the stress distribution after a quench is close to the stress after cool down (around 10 MPa higher)
- Based on SMC and 11 T experience, an adiabatic temperature of ~ 430 K does not have an impact on the magnet performance.

Expected stress and temperature profile in RMM after a quench at nominal current

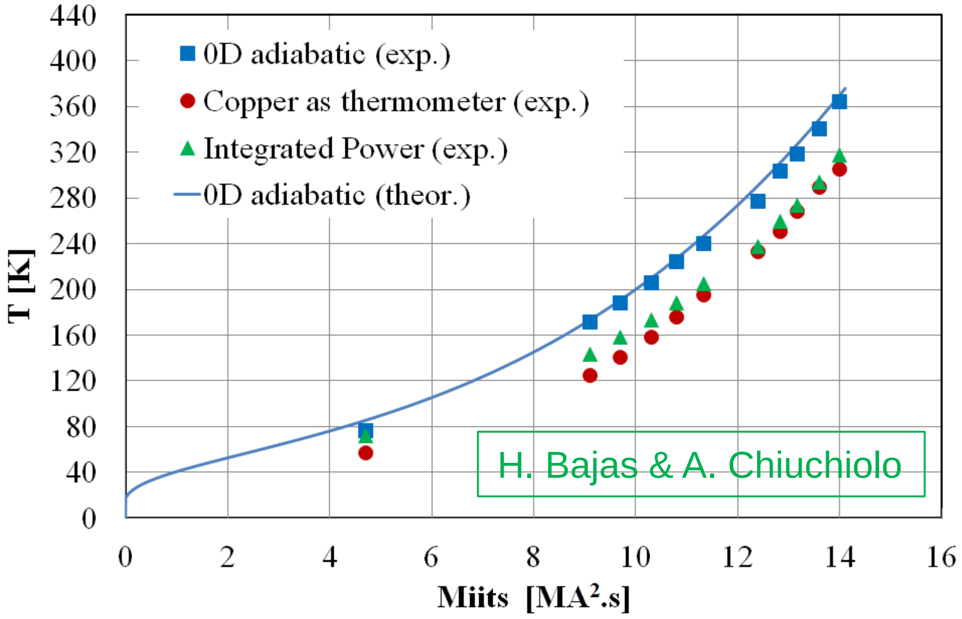


Stress Distribution After Quench [MPa]



Temperature profile [K] assuming all conductors quenched at 40 ms (excluding T_{hot})

SMC4 – Spot Heater Tests



Summary – where we are

- Conductor and cable
  - *Non-graded*: Strand, cable and insulation parameters defined. Three cable unit lengths have been produced, and strand available for producing two additional unit lengths.
  - *Graded*: Strand and cable parameters defined to minimize the risk, procurement time and cable R&D required; Synergy with CEA-16 T model
- Non-graded coils
  - The first coil has been wound!
  - All coil production tooling available.
- Graded coils
  - Conceptual 2D design for ERMC and RMM
  - Relaying on EPFL activities on High Field Nb_3Sn Splice Development to start the engineering design of a graded coil.
- Structure
  - All structural components except the end-plate are in-house.
  - Dummy assembly to characterize the magnet structure with Aluminum coils on-going.

Summary – what we want to study

- Explore the maximum allowable stress in a simplified coil geometry with respect to an accelerator magnet.
  - Step by step approach. First, 18 T, big coils. Little by little, going towards accelerator quality magnets.
- Define the optimal assembly parameters (longitudinal and azimuthal pre-load levels)
- Develop coil technology
  - A large part of the training we observed in the magnets is probably resin cracking. How do we demonstrate this is the case? What can we use to limit this phenomena? Where do we want sliding surfaces? Where do we want glued surfaces?
- Explore the limits in terms of peak temperature and stress enhancement during quench.
- Learn as much as possible in terms of field quality

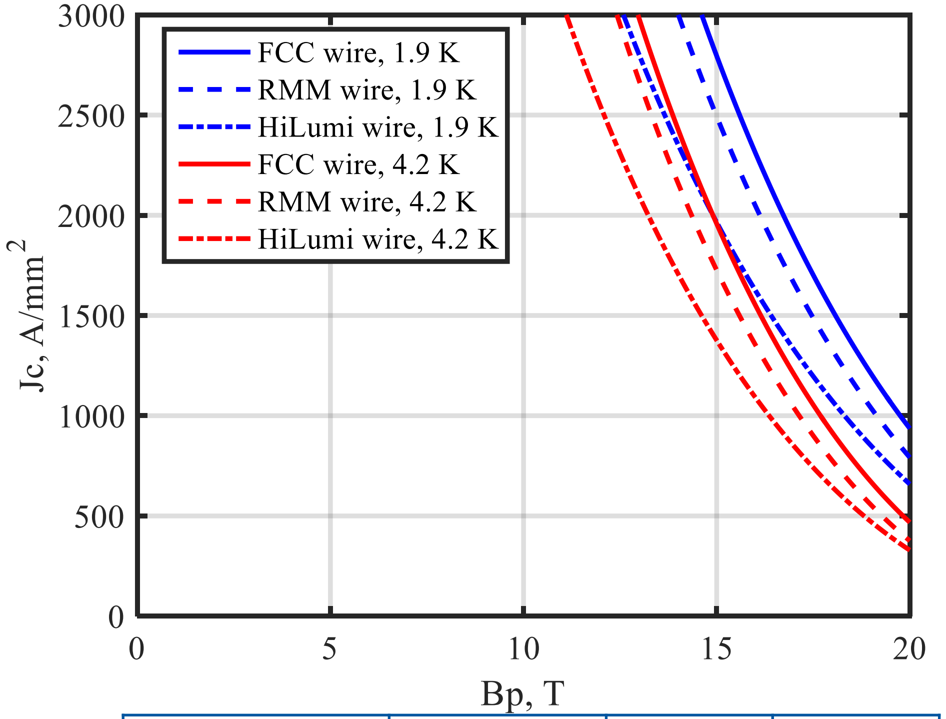
Thank you for your attention

Superconductor parametrization

$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$

$$J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1-b)^2$$

$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$

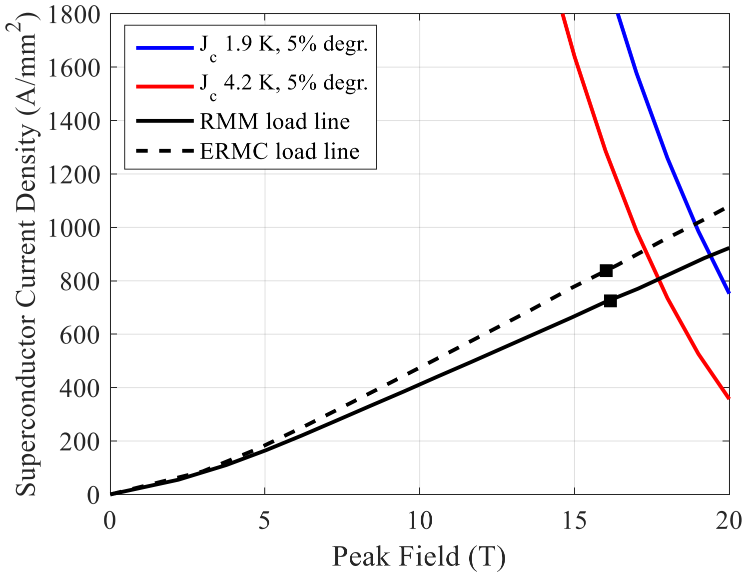


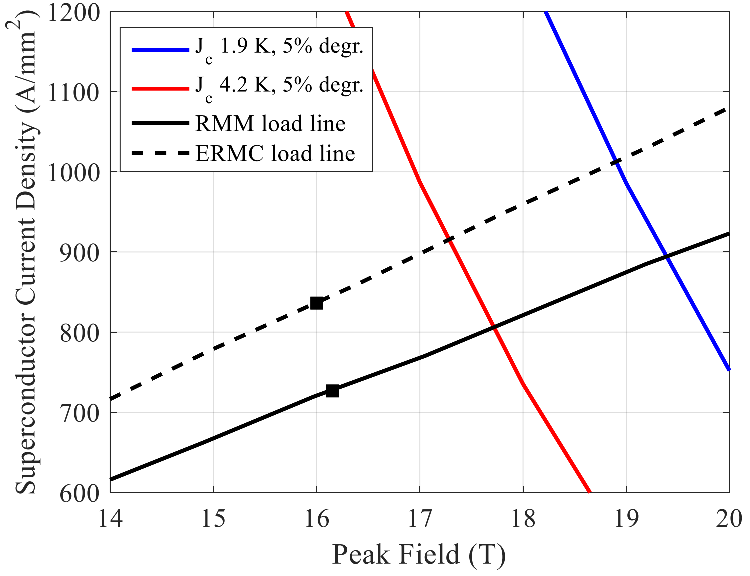
	Hi-Lumi	RMM	FCC
T_{c0} (K)	16	16	16
B_{c20} (T)	29.38	28.8	29.38
α	0.96	0.96	0.96
$C_0(A/mm^2T)$	188870	255230	275880

J_c at 4.2 K	Hi-Lumi	RMM	FCC
12 T	2500	3250	3610
15 T	1340	1725	1960
18 T	625	775	915

Non-graded magnets

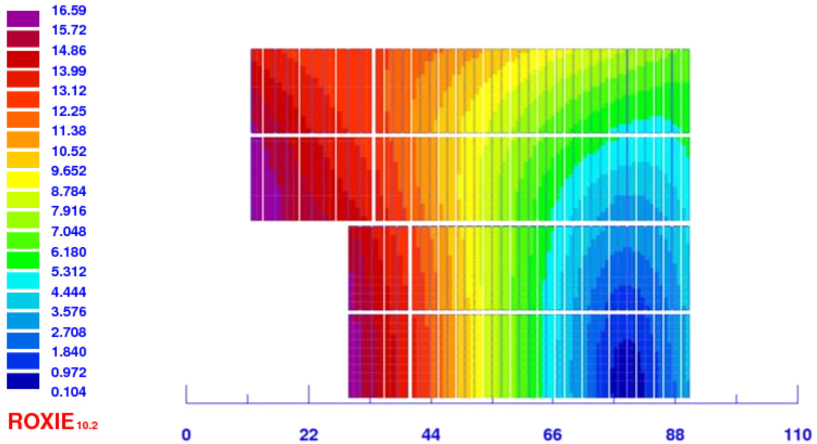
	Units	ERMC	RMM
Nominal current (I_{nom})	**kA**	13.1	11.4
Overall current density	**A/mm²**	282	245
Bore field	**T**	15.7	16.0
Peak field at I_{nom}	**T**	16.0	16.2
Stored energy at I_{nom}	**MJ/m**	1.5	2.1
Differential inductance at I_{nom}	**mH/m**	16.6	31.1
Short sample field at 4.2 K	**T**	17.3	17.7
Short sample field at 1.9 K	**T**	18.9	19.4
Short sample current at 4.2 K	**kA**	14.4	12.7
Short sample current at 1.9 K	**kA**	15.9	14.1
$(1-I/I_{ss})$ at 1.9 K	**%**	18	19
$(1-B/B_{ss})$ at 1.9 K	**%**	15	16



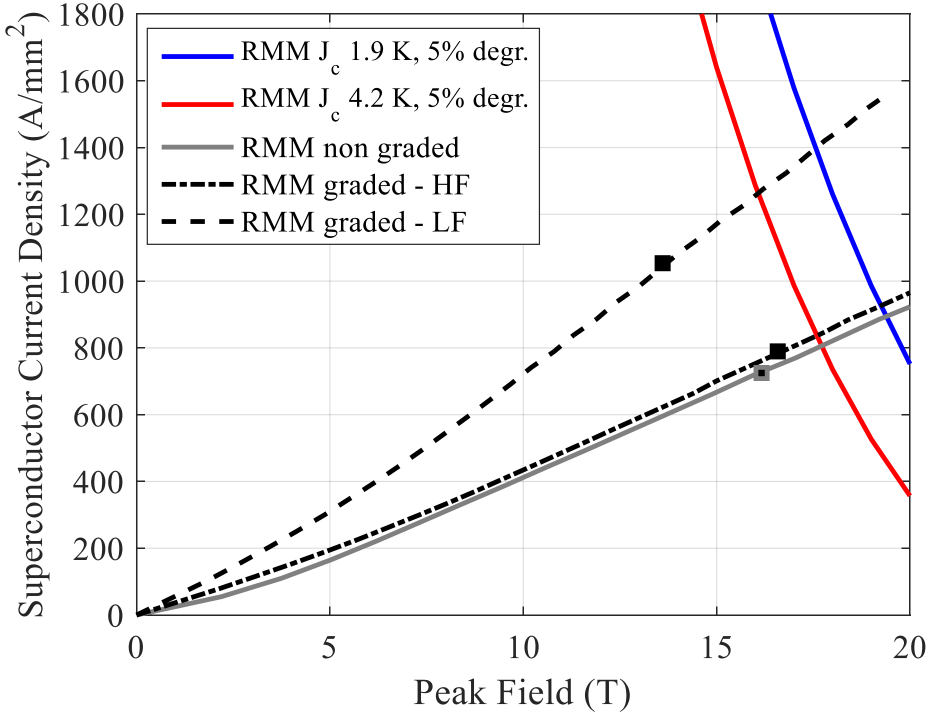


Graded magnet

- 20 % reduction on the coil size (17 mm out of 86 mm) thanks to grading.
- Operating conditions of the high field conductor close to RMM graded magnet.



Parameter	Unit	Non Graded	Graded	
			HF	LF
strand diameter	mm	1	1	0.7
Cu/SC	--	1	1	1.15
# of strands/cable	--	40	28	40
# turns/quadrant	--	132	30	132
coil width	mm	86	69	
I_{nom}	A	11546	8695	
$J_{overall}$	A/mm²	248	264	357
Ratio LF/JF	--	n.a.	1.35	
B_0 at I_{nom}	T	16.0	16.0	
B_p at I_{nom}	T	16.1	16.6	13.6
$1-B_p(I_{nom})/B_{ss}(1.9\ K)$	%	18.5	14	23
F_x/h at I_{nom}	MPa	141	145	
F_y/w at I_{nom}	MPa	-49	-55	

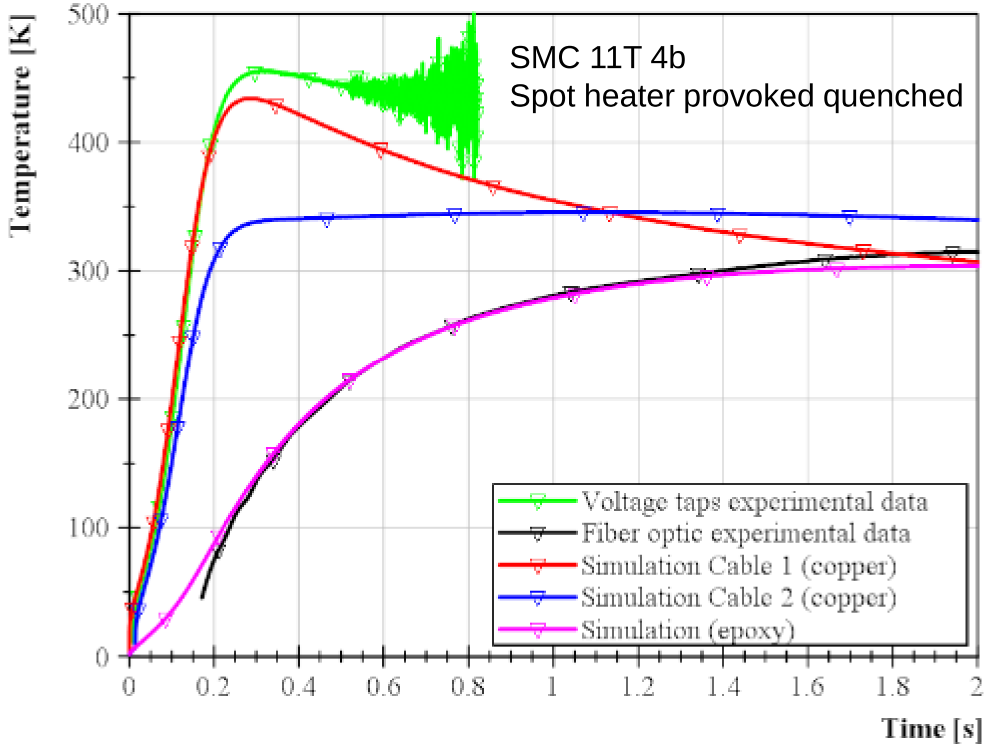


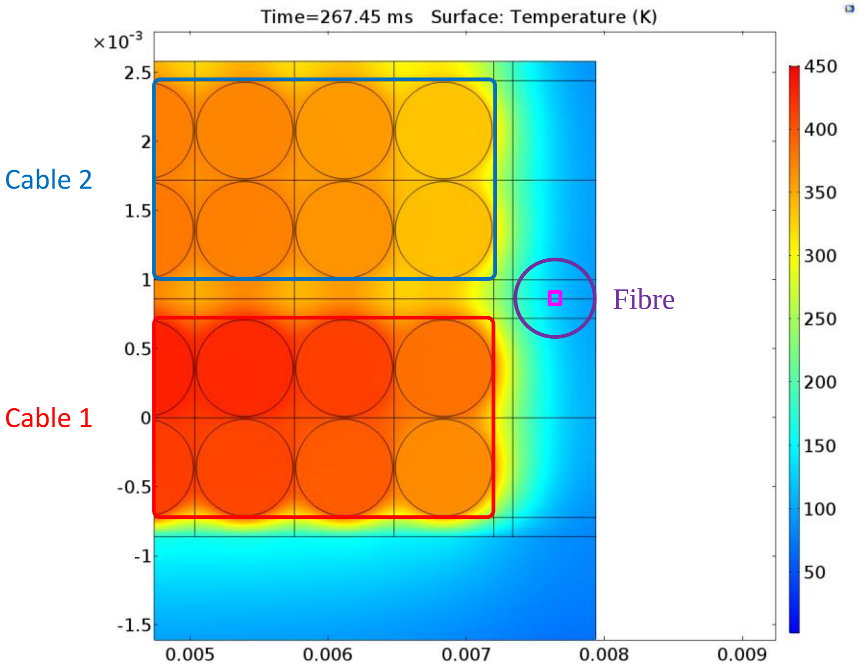
H. Bajas, J. Lorenzo & A. Chiuchiolo

Quench protection studies

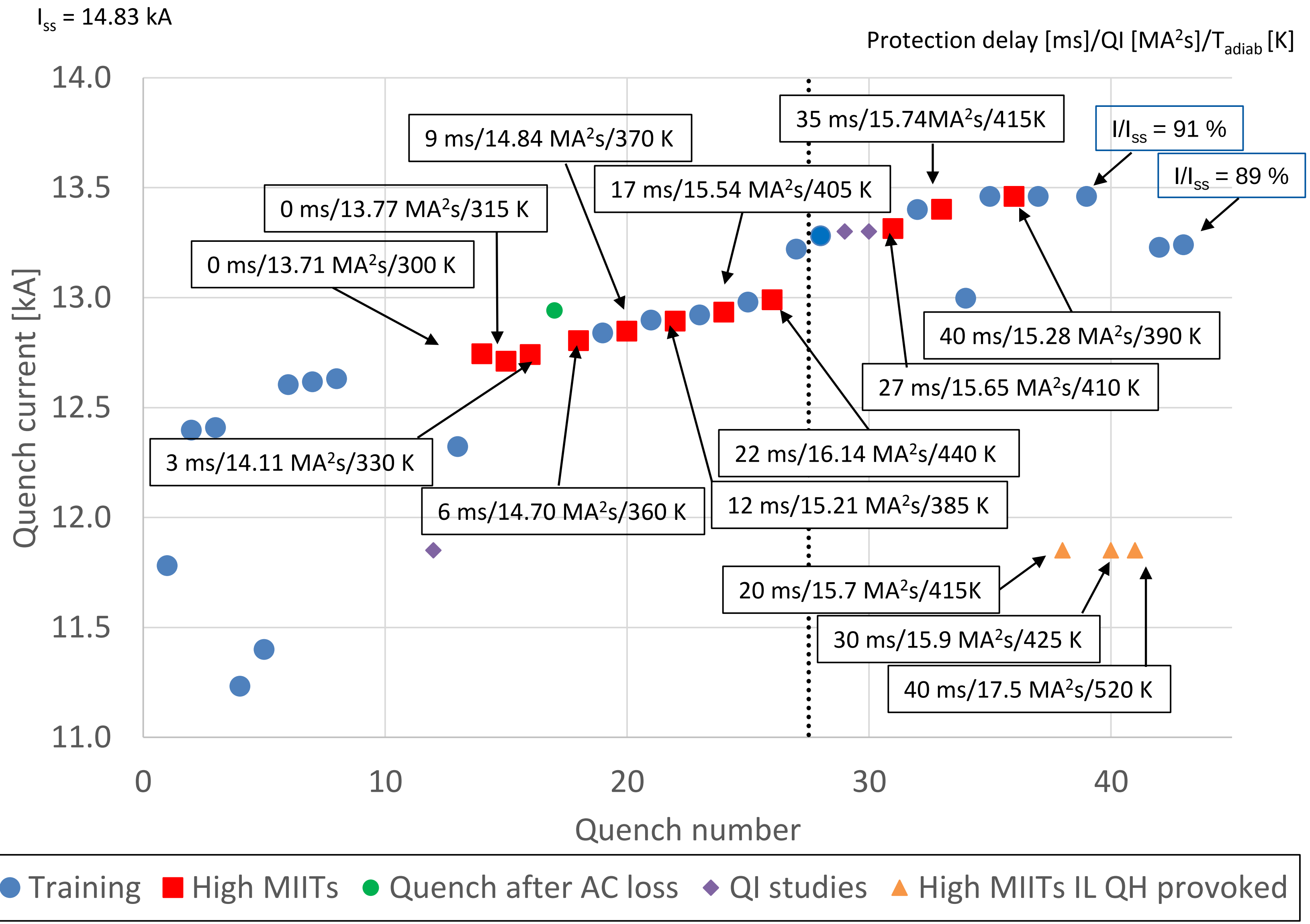
Voltage taps and fiber optic allow a better characterization of the temperature rise to validate models and explore limits.

Quench Propagation Velocity and Hot Spot Temperature in Nb_3Sn Racetrack Coils – to be published on IEEE TAS



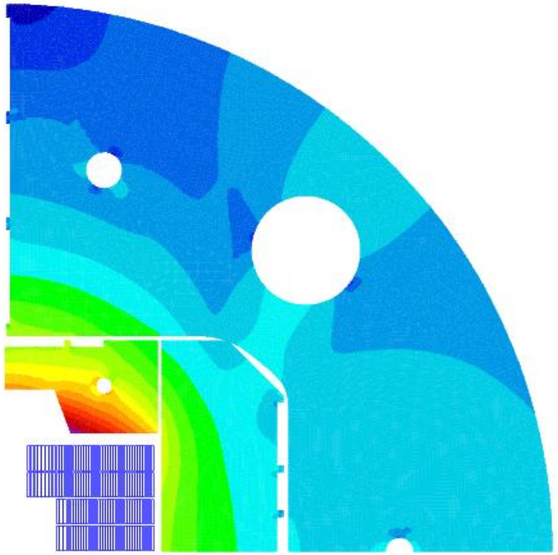


MBHSP106 – G. Willering, F. Savary



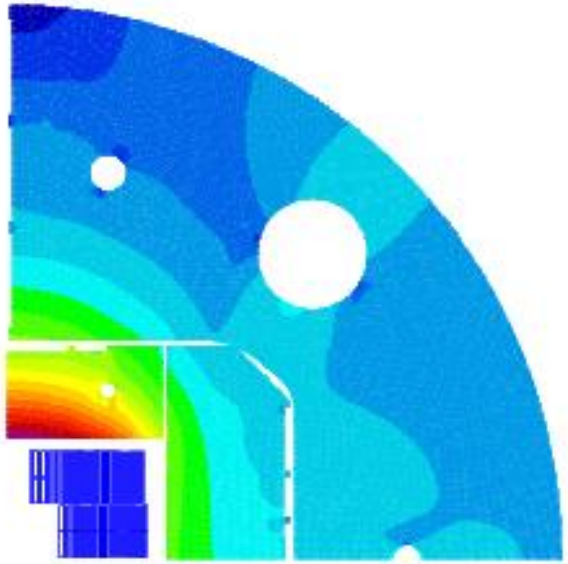
The price of field quality

Iron saturation effect on b_3 = 10 units



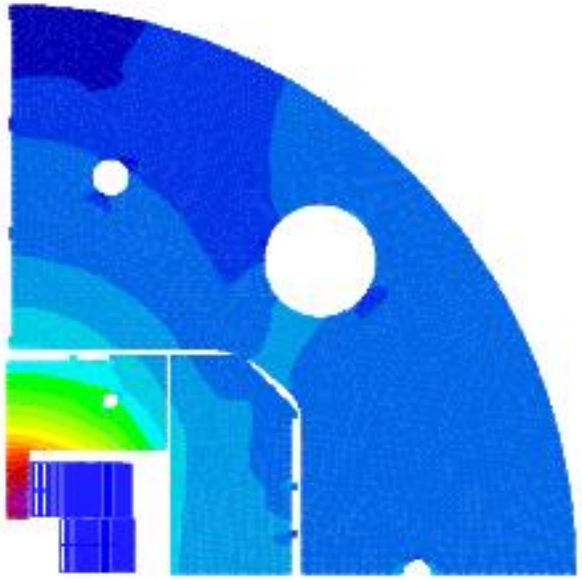
67 mm

Iron saturation effect on b_3 = 40 units



62 mm

Iron saturation effect on b_3 = 150 units



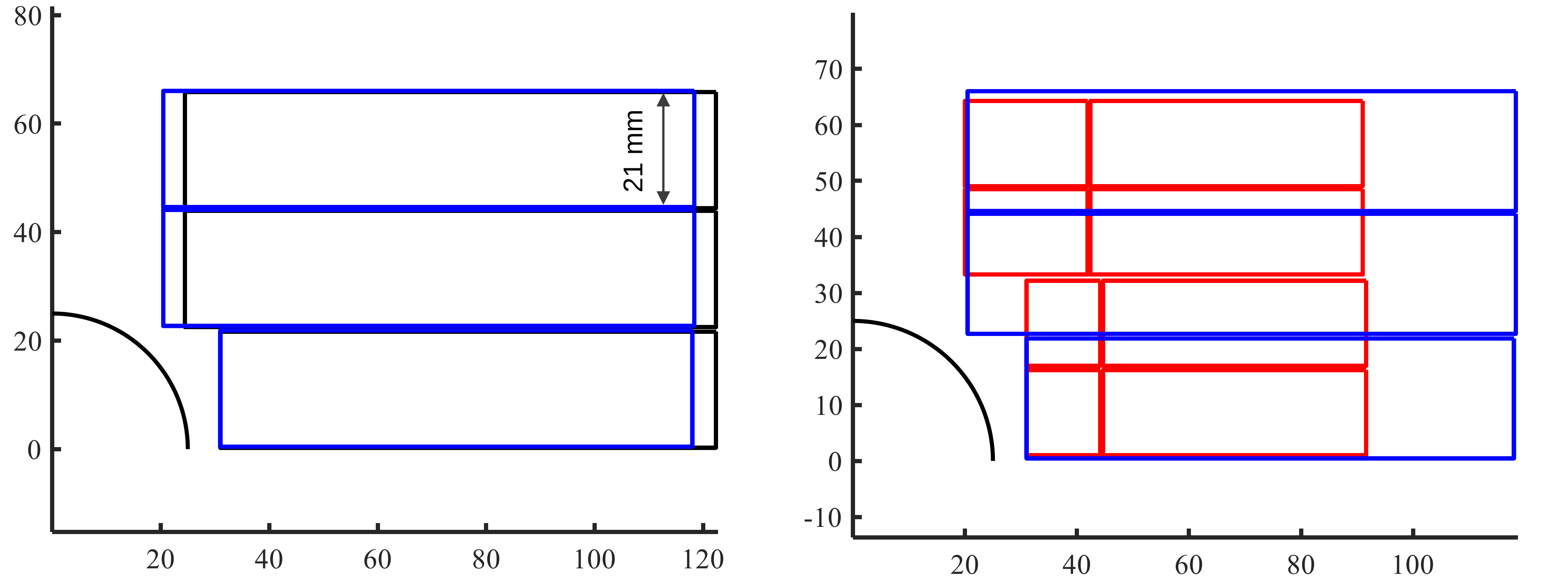
55 mm

- Kept constant: RMM Jc, Inner support = 6 mm, 14 % margin

The gain of grading

RMM not graded, no field quality (18 % margin)
RMM not graded, field quality (14 % margin)

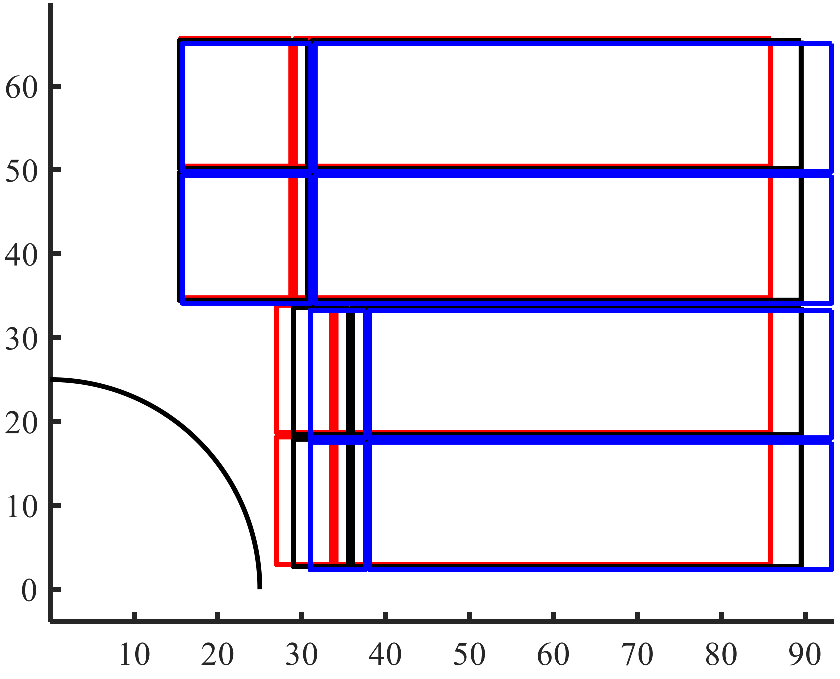
RMM graded, field quality (14 % margin)
RMM not graded, field quality (14 % margin)



- Kept constant: RMM Jc and Inner support = 6 mm

Inner support

- Inner support =
  2 mm; 4 mm; 6mm

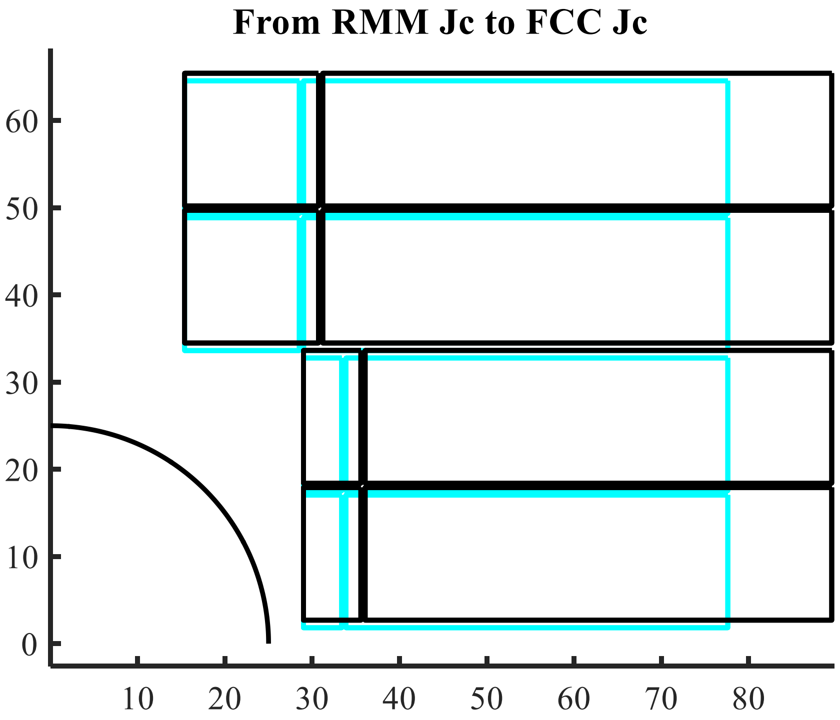


file version		2 mm		6 mm	
		HF	LF	HF	LF
strand diameter	mm	1	0.7	1	0.7
Cu/SC	--	1	1.2	1	1.2
# of strands/cable	--	28	40	28	40
# turns/quadrant	--	18	134	20	144
coil width	mm	65		68	
I_{nom}	A	9020	9020	8750	8750
$J_{overall}$	A/mm²	271	366	263	355
Ratio LF/JF		1.35		1.35	
B_0 at I_{nom}	T	16.02		16.00	
B_p at I_{nom}	T	16.44	14.65	16.55	14.79
$B_p(I_{nom})/B_{ss}(1.9\ K)$	%	14	14	14	14
F_x/h at I_{nom}	MPa	142		146	
F_y/w at I_{nom}	MPa	-63		-67	

- Kept constant: RMM Jc and Good Field Quality

Critical current density

RMM Jc; FCC Jc



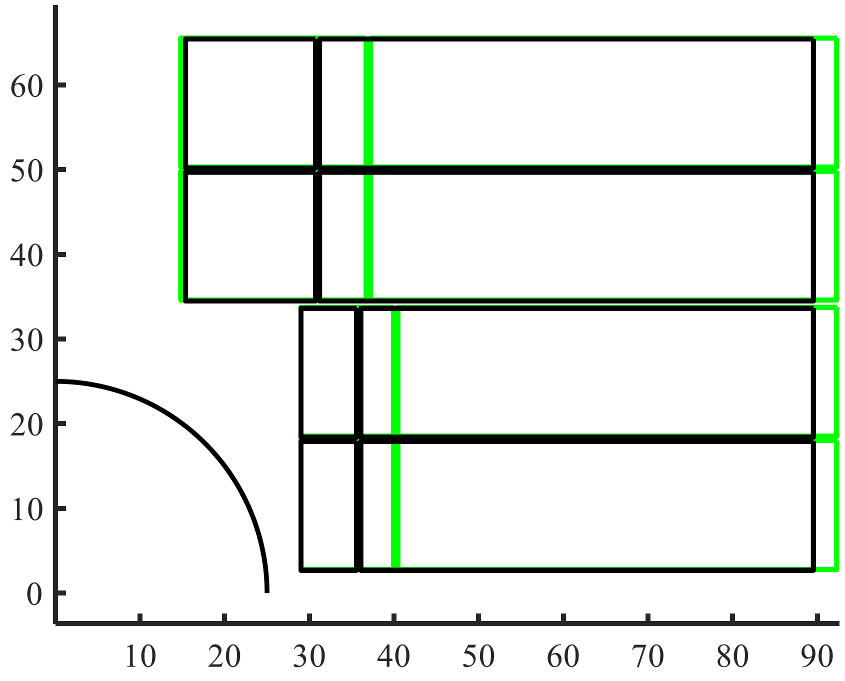
file version		RMM Jc		FCC Jc	
		HF	LF	HF	LF
strand diameter	mm	1	0.7	1	0.7
Cu/SC	--	1	1.2	1	1.2
# of strands/cable	--	28	40	28	40
# turns/quadrant	--	20	138	16	114
coil width	mm	67		59	
I_{nom}	A	8887	8887	10150	10150
$J_{overall}$	A/mm²	267	360	305	412
Ratio LF/JF		1.35		1.35	
B_0 at I_{nom}	T	16.00		16.01	
B_p at I_{nom}	T	16.50	14.53	16.65	14.85
$B_p(I_{nom})/B_{ss}$(1.9 K)	%	14	14	14	14
F_x/h at I_{nom}	MPa	144		140	
F_y/w at I_{nom}	MPa	-65		-77	

- Kept constant: Inner support = 4 mm and Good Field Quality

Low Field Margin

- Low field margin = 20 %; 14 %

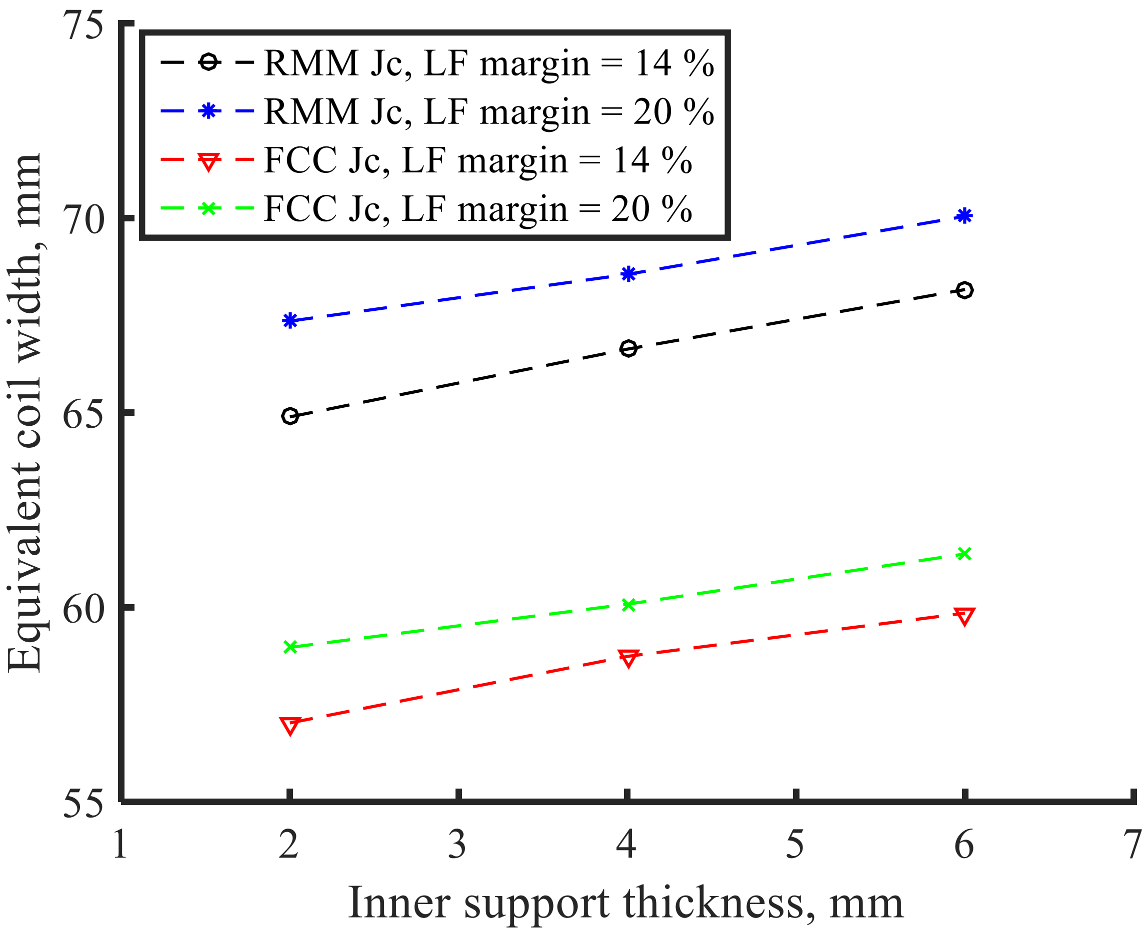
Low field margin 14 % or 20 %



file version		LF 14 %		LF 20 %	
		HF	LF	HF	LF
strand diameter	mm	1	0.7	1	0.7
Cu/SC	--	1	1.2	1	1.2
# of strands/cable	--	28	40	28	40
# turns/quadrant	--	20	138	30	132
coil width	mm	67		69	
I_{nom}	A	8887	8887	8625	8625
$J_{overall}$	A/mm²	267	360	259	350
Ratio LF/JF		1.35		1.35	
B_0 at I_{nom}	T	16.00		16.00	
B_p at I_{nom}	T	16.50	14.53	16.60	13.67
$B_p(I_{nom})/B_{ss}(1.9\ K)$	%	14	14	14	20
F_x/h at I_{nom}	MPa	144		145	
F_y/w at I_{nom}	MPa	-65		-66	

- Kept constant: RMM Jc, Inner support = 4 mm and Good Field Quality

Summary



RMM Jc, LF margin = 14 %
RMM Jc, LF margin = 20 %
FCC Jc, LF margin = 14 %
FCC Jc, LF margin = 20 %
Equivalent coil width, mm
Inner support thickness, mm
75
70
65
60
55
1
2
3
4
5
6
7