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Overview of ERMC-RMM Magnet Technology Program

Acknowledgments: Bernardo Bordini, Paolo Ferracin, Friedrich Lackner,
Ezio Todesco, Davide Tommasini, Daniel Schoerling,

Content

1. Introduction
2. Electromagnetic design
3. Mechanical design
4. Engineering design
5. Main technical developments needed
6. Summary and next steps

Content

1. **Introduction**
2. Electromagnetic design
3. Mechanical design
4. Engineering design
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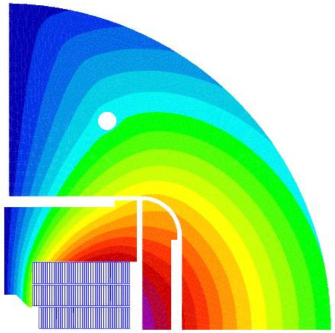
1. Introduction: ERMC/RMM

ERMC/RMM : A two stages project

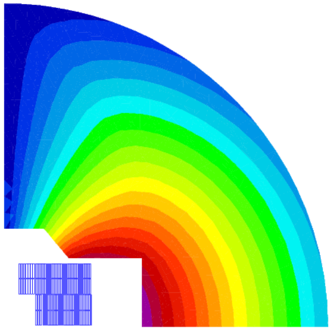
Stage 1 priorities:

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



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 collar pack assembly



1. Introduction

Stage 1 priorities:

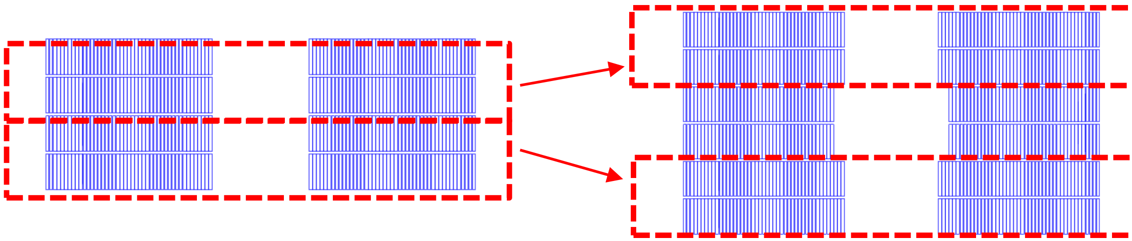
1. Demonstrate the field
    - Design based on the "available" critical current density (~20% lower than FCC target at 18 T, 4.2 K)
    - As field quality is not an objective, profit from the use of an iron pole to decrease the ratio between the field in the aperture and in the coil to ~ 1
2. Study the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

Stage 1 approach:

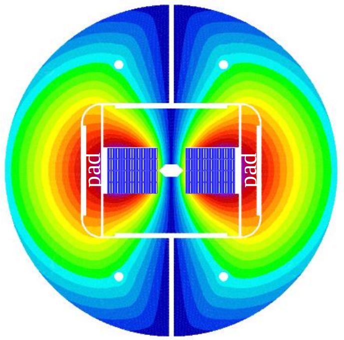
In order to optimise time and resources:

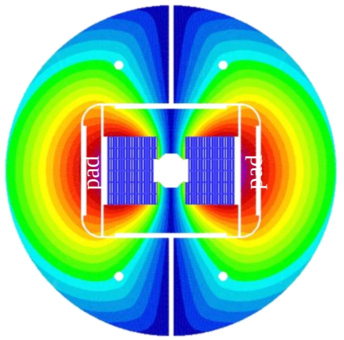
- ERMC double pancakes will be used at top/bottom RMM coils.
- Same structure for both magnets
    - Keeping the possibility of having two set of pads to optimize the stress distribution on the coil.

ERMC RMM



Remark: Possibility to test also a single coil configuration





Details:
https://indico.cern.ch/event/446669/

1. Introduction

Stage 2 priorities:

1. Coil size → Grading
   - Design based on the target FCC critical current density
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   - Still, it will need to be accommodated within the same structure, changing only the collar pack assembly

KEY ISSUE: Development of Nb_3Sn High field internal splices

Strategy:

- Magnet design following FCC targets in terms of critical current density and field quality
- ERMC will be the base to test the coil technology development:
  - It should allow the test of a single pancake

Content

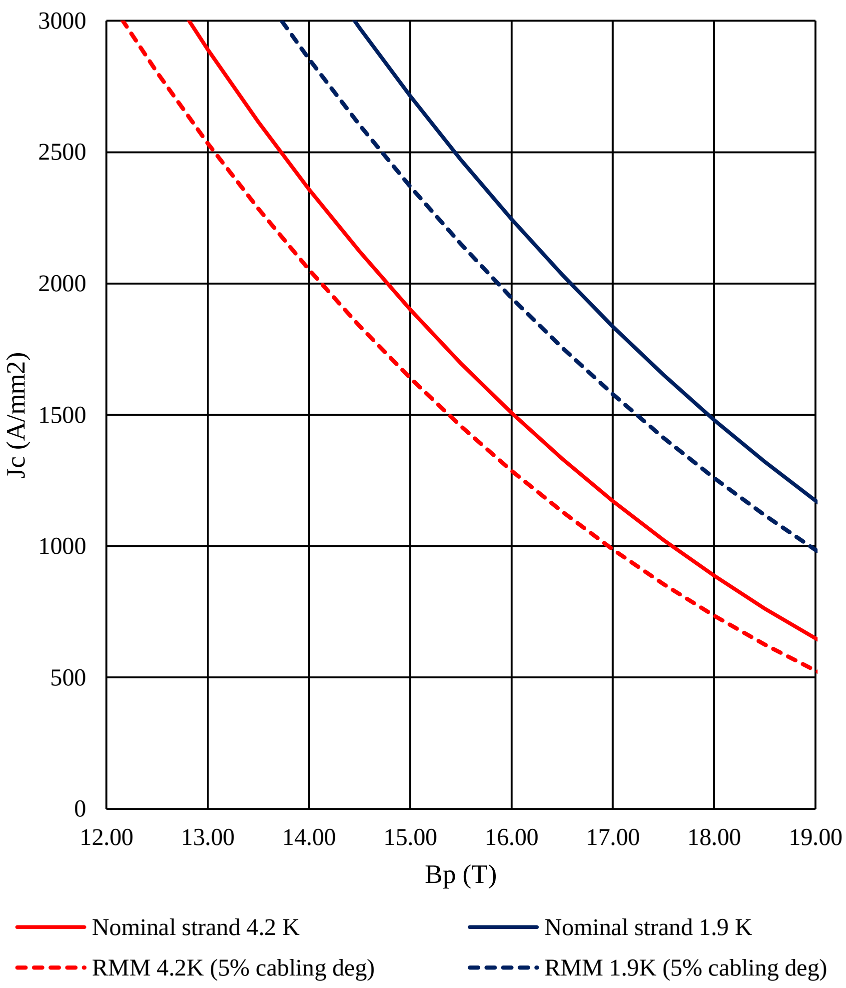
1. Introduction
2. **Electromagnetic design**
3. Mechanical design
4. Engineering design
5. Main technical developments needed
6. Summary and next steps

Strand

- Strand diameter:
  - From **0.7** to **1.1 mm**
- Copper to superconductor **> 1**
  - **Time margin** for protection **≥ 40 ms**
- Strand critical current density:
  - **ERMC/RMM non graded design:**

    T_{c0} = 16 K, B_{c20} = 28.8 T,
    C_0 = 255230 A/mm^{2}T,
    5 % cabling degradation
    J_c(4.2K,16T) = 1287 A/mm^2
    J_c(4.2K,18T) = 735 A/mm^2
  - **ERMC/RMM graded design: (FCC Target)**

    T_{c0} = 16 K, B_{c20} = 29.38 T,
    C_0 = 267845 A/mm^{2}T,
    0 % cabling degradation
    J_c(4.2K,16T) = 1507 A/mm^2
    J_c(4.2K,18T) = 887 A/mm^2

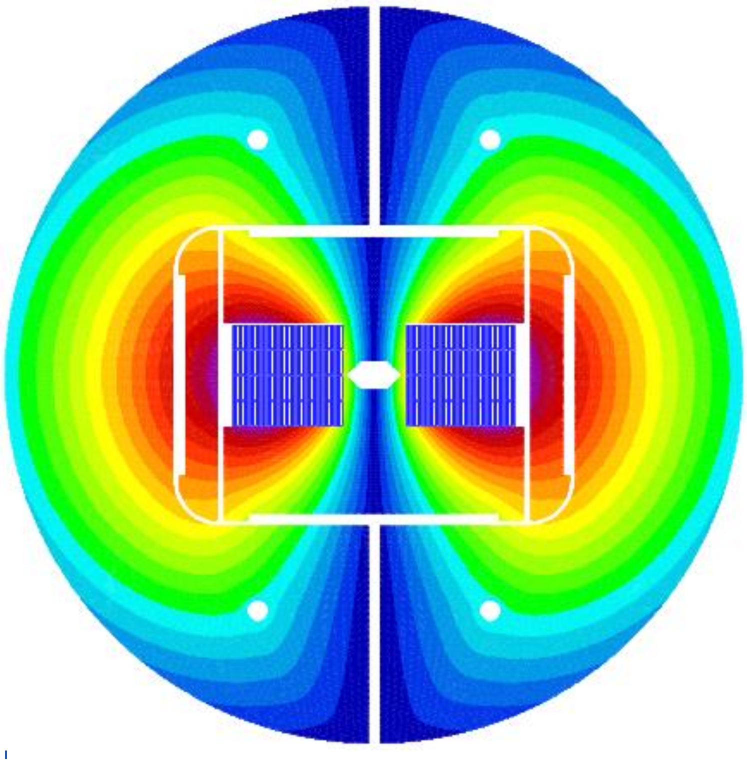


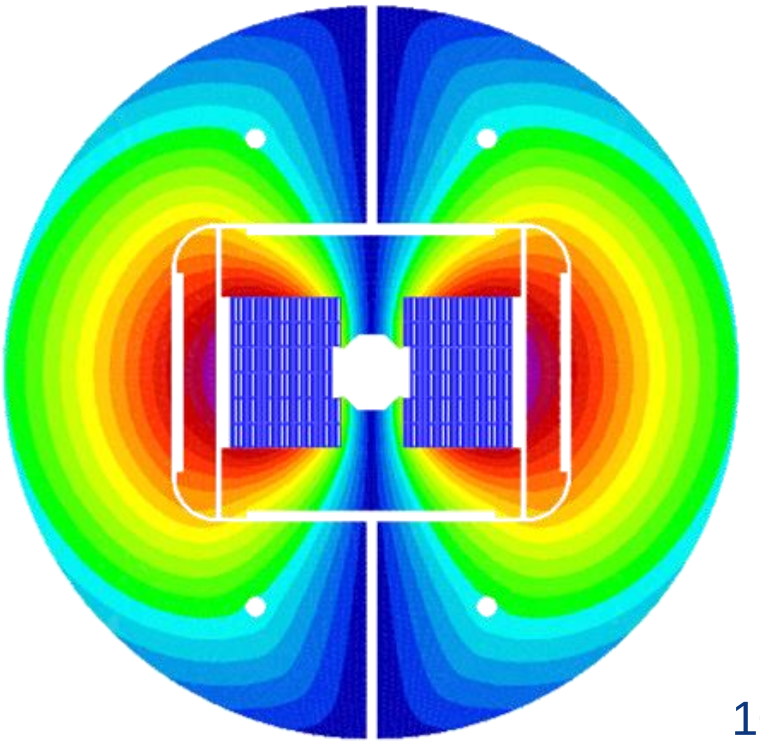
Cable and Insulation

- Non-graded design
  - 1 mm strand x **40 strands** per cable **(FRESCA2)**
- Graded solutions
  - Many options have been explored, decision on what to build has not been taken yet → Align with EuroCirCol guidelines to accompany conductor developments needs.
- Cable insulation thickness = **150 µm**
  - **S2-glass/Mica** using 11 T development.
  - Parallel material development program to explore and identify enhanced solutions.

Magnet Cross Section

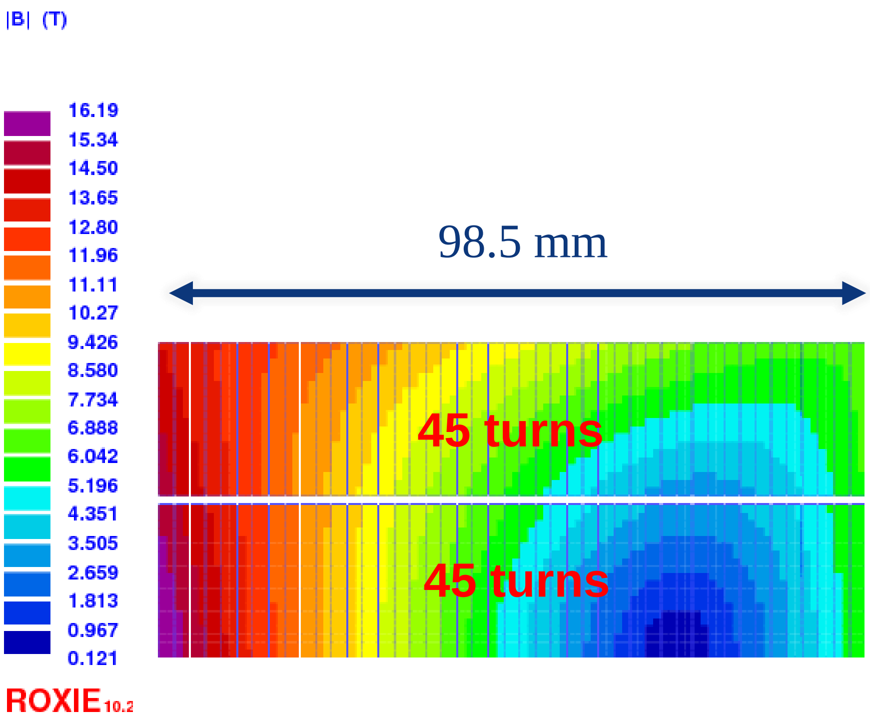
- Outer diameter of the iron yoke = 660 mm
- Same structure for ERMC and RMM
- Aperture
  - ERMC ~ 8 mm
  - RMM = 50 mm



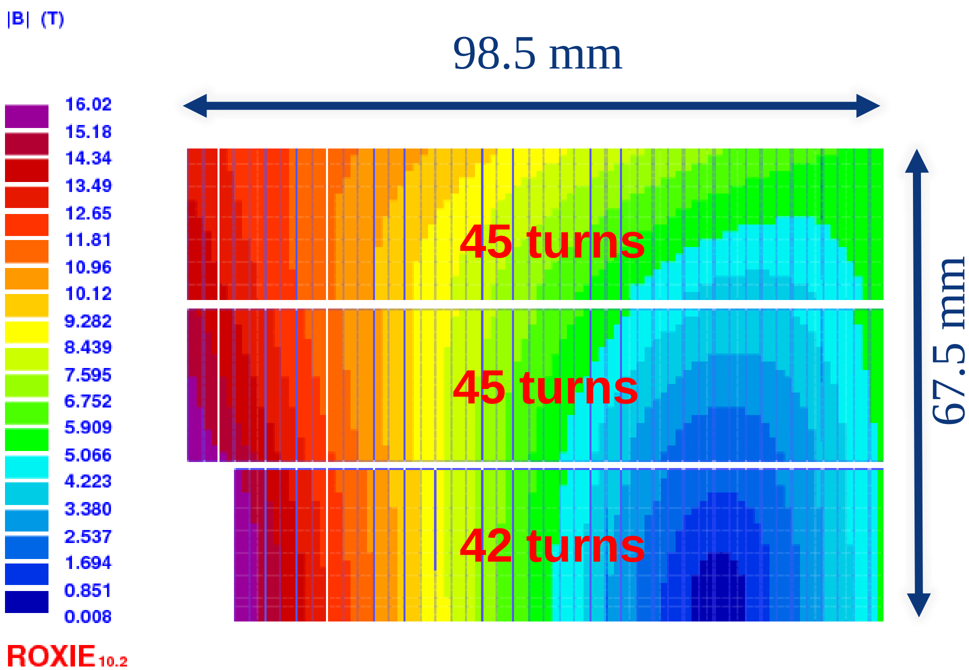


Coil Field at B_0 = 16 T

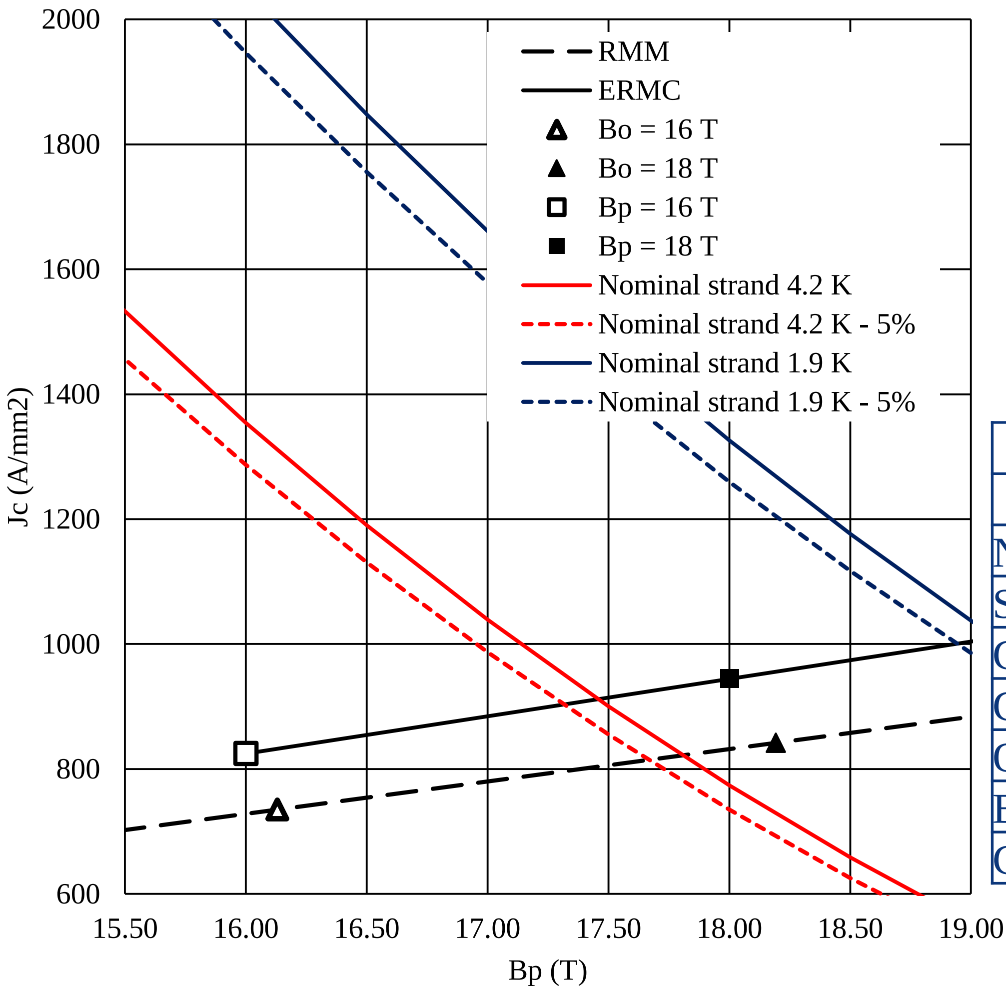
- ERMC
  - $B_p/B_o = 1.097$



- RMM
  - $B_p/B_o = 1.002$



Electromagnetic design – Non Graded



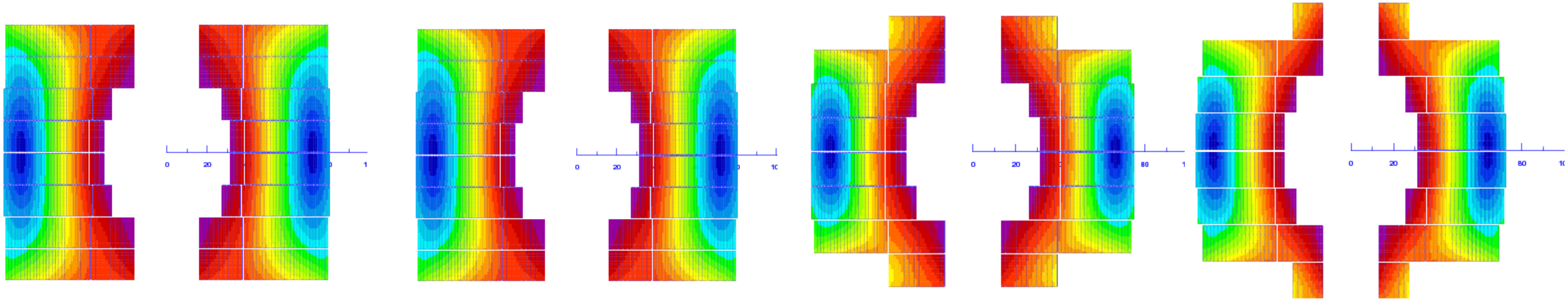
Margin on the load line

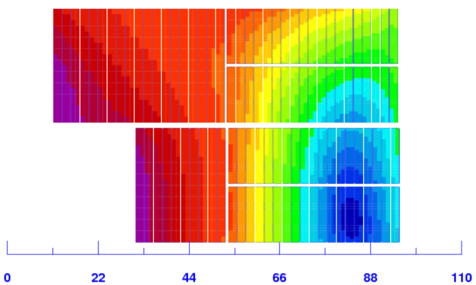
- ERMC : 8 % for a coil peak field of 16 T at 4.2 K (17 % at 1.9 K)
- RMM : 10 % for a bore field of 16 T at 4.2 K (19 % at 1.9 K)

Operation Parameters

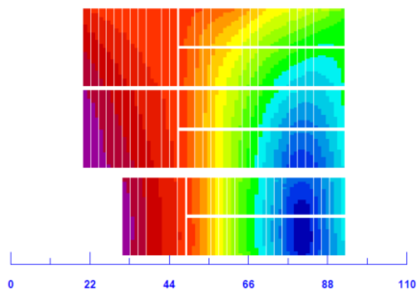
		RMM	ERMC
Nominal current, I_{nom}	A	11546	12953
SC current density, J_{sc}	A/mm²	735	825
Cu current density, J_{cu}	A/mm²	735	825
Cu + SC current density, J_{eng}	A/mm²	368	412
Overall current density, $J_{overall}$	A/mm²	248	278
Bore field at I_{nom}	T	16.00	15.73
Conductor peak field at I_{nom}	T	16.13	16.00

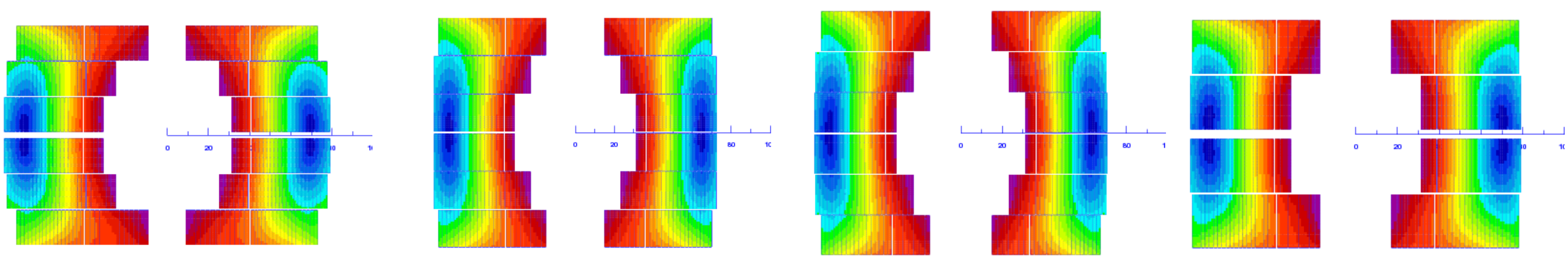
Electromagnetic design – Graded





MANY SOLUTIONS EXPLORED, BUT WE NEED TO THINK WHAT WE ACTUALLY WANT TO BUILD!

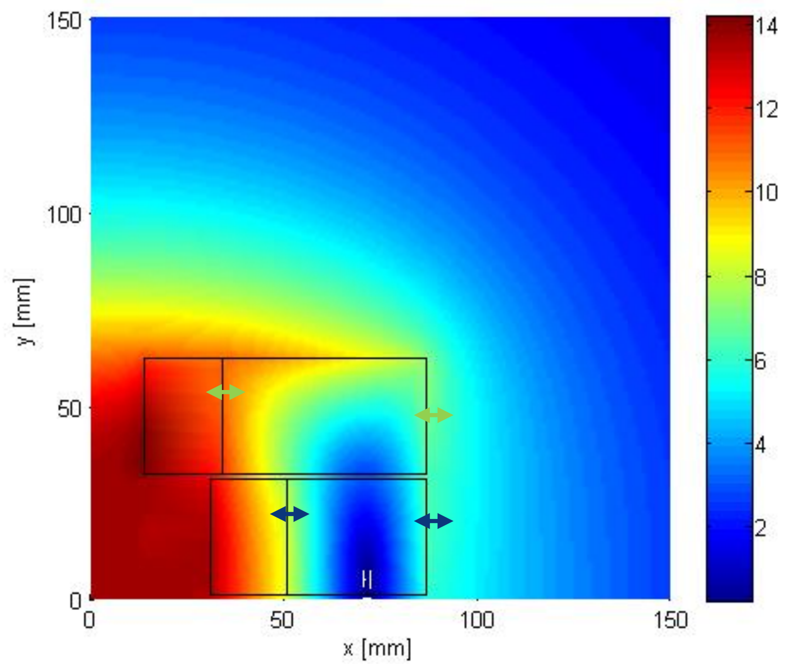


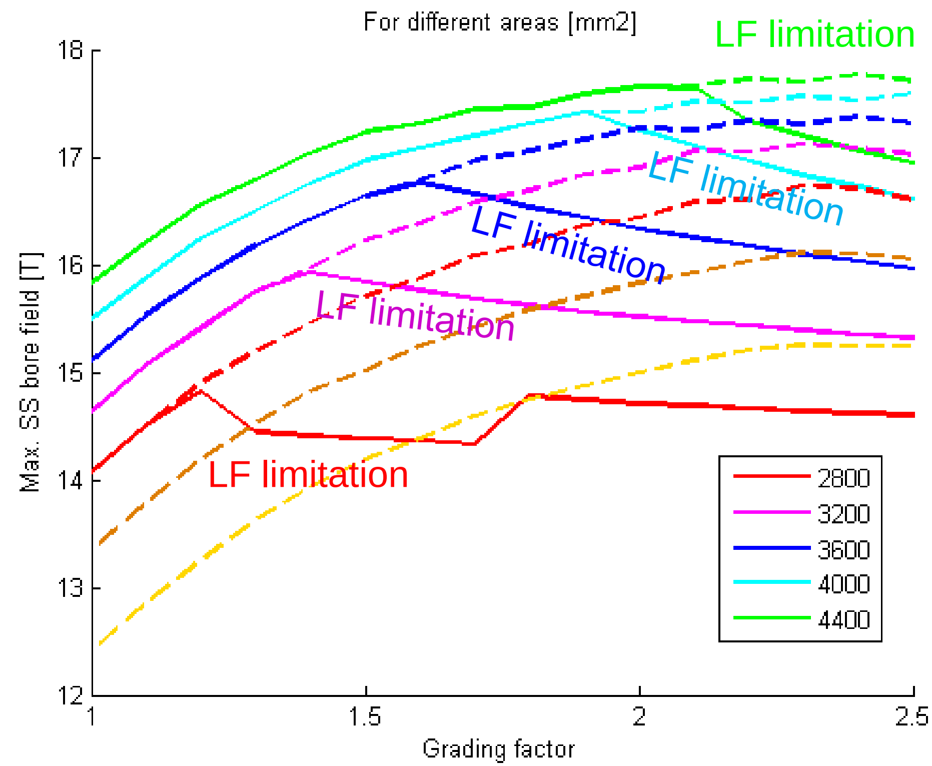


Electromagnetic design - Graded

E. Rochepault

- In addition…parametric scan of the different parameters using analytical formulas to complement ROXIE optimization.



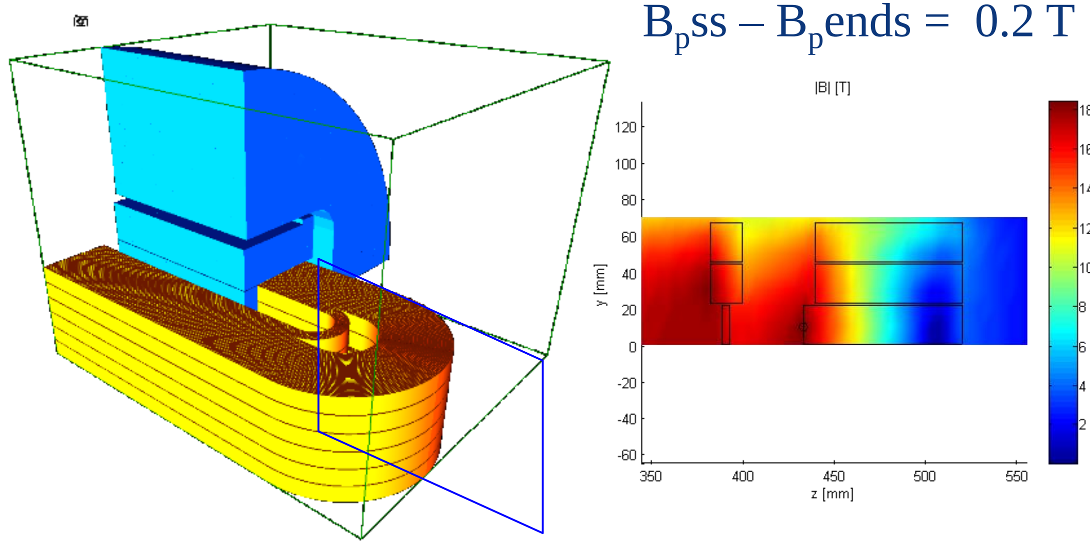


3D Magnetic Design

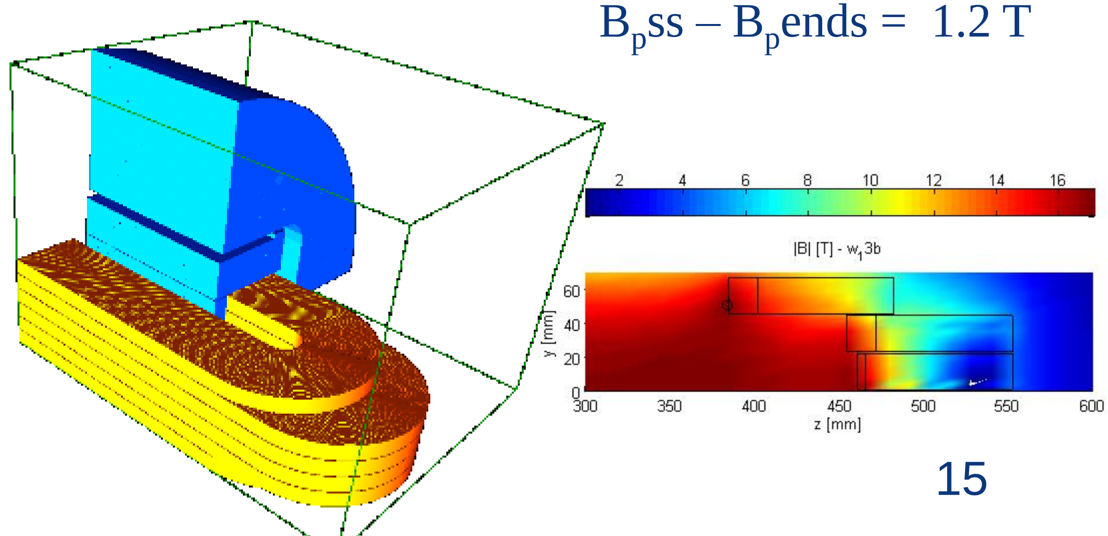
E. Rochepault

- Design guideline: peak field in the coil ends 1 T lower than in the straight section.
- Magnetic optimization to define:
  - Number of blocks in the coil ends.
  - Relative position of the coil blocks.
- Outcome of the study:
  - It is more efficient to increase the relative distance in between layers than introduce spacers within the same layer
  - With this approach we are able to avoid the use of coil end spacers

$B_p ss - B_p ends = 0.2$ T



$B_p ss - B_p ends = 1.2$ T



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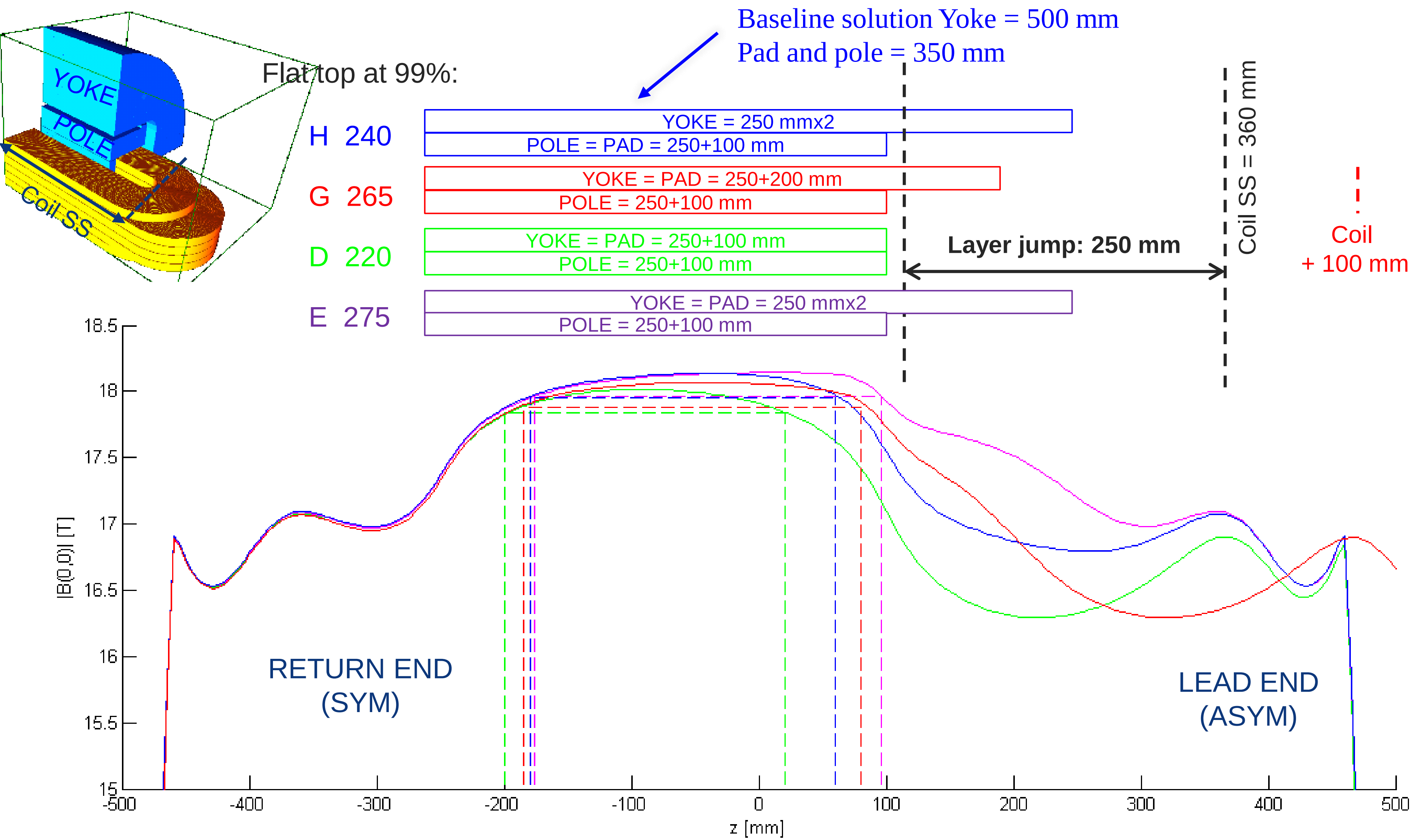
Optimization on the magnetic structural components



Conductor unit length/coil = 220 m

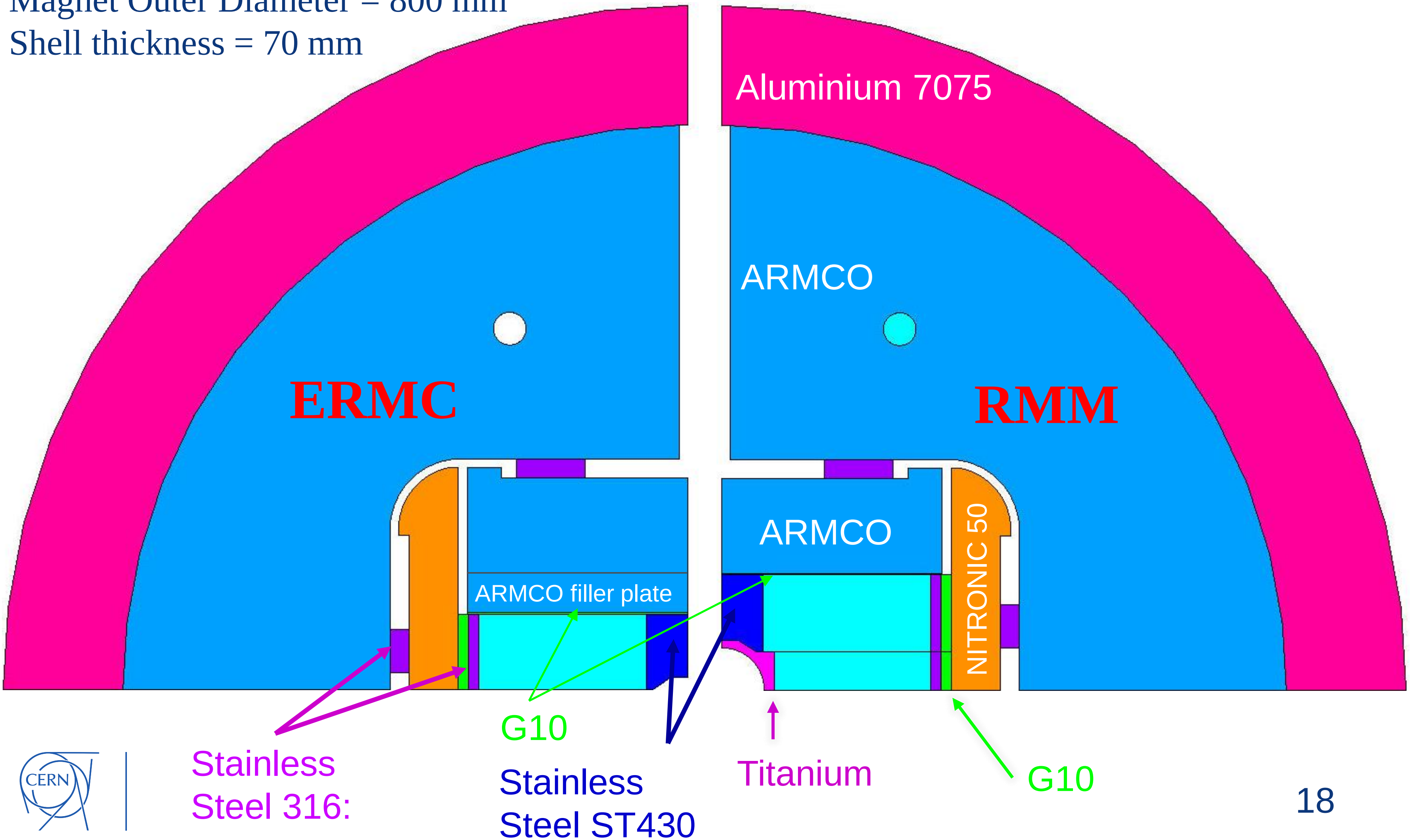
Content

1. Introduction
2. Electromagnetic design
3. **Mechanical design**
4. Engineering design
5. Main technical developments needed
6. Summary and next steps

Mechanical design – Structural components

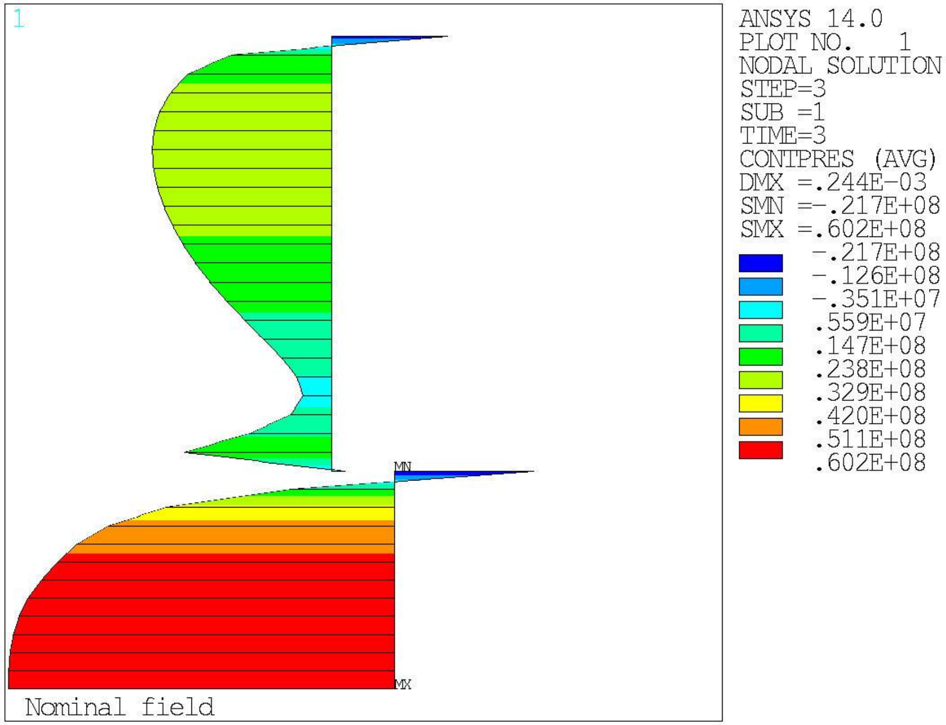
Aim: Have an unique support structure for ERMC and RMM.

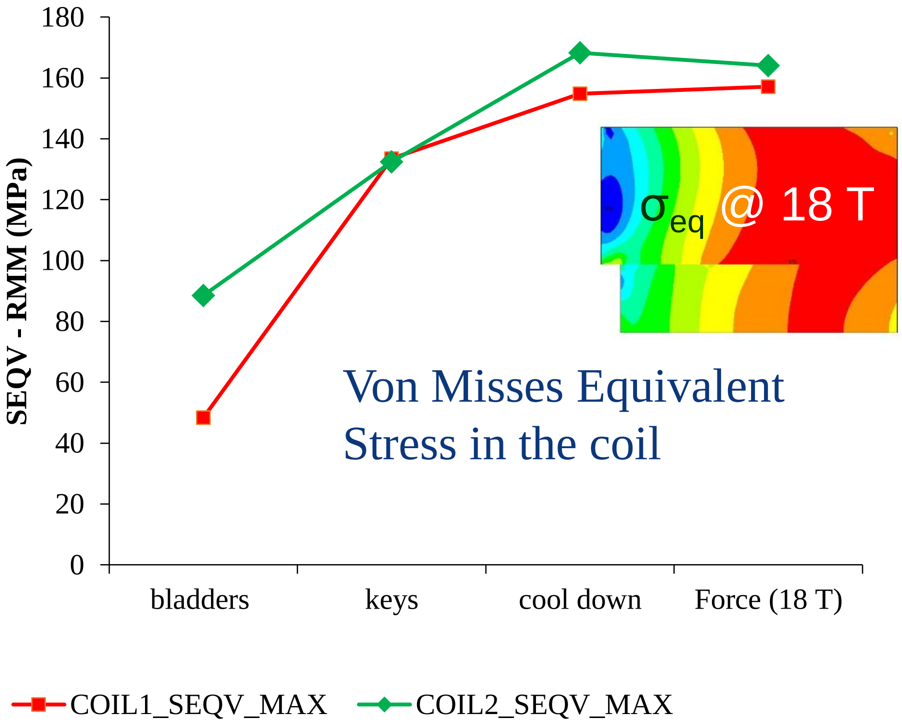
Magnet Outer Diameter = 800 mm
Shell thickness = 70 mm



RMM non-graded – Loading Case 18 T

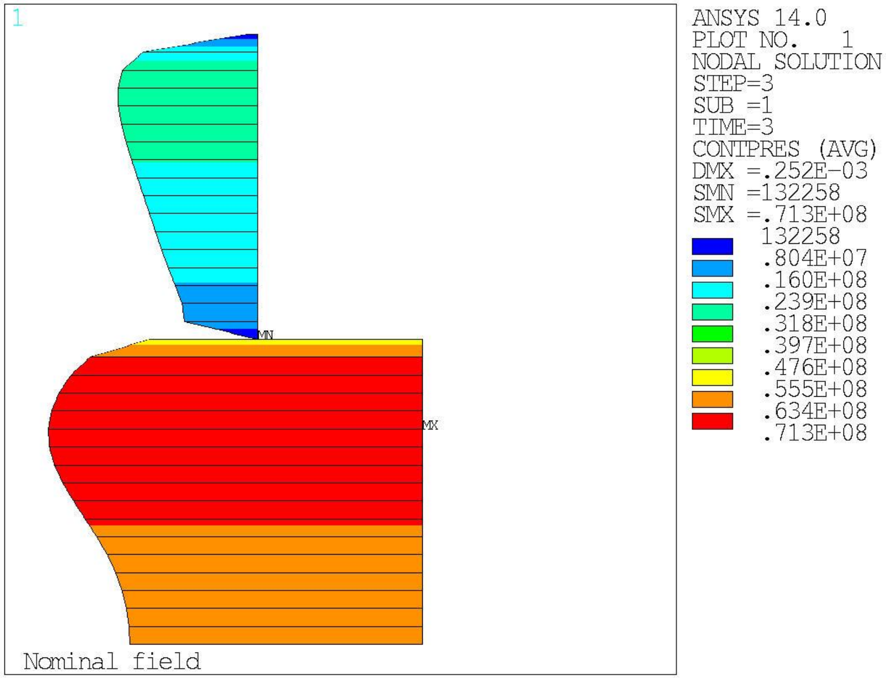
TARGET: To have a pressure on the pole > 2 MPa at 18 T central field

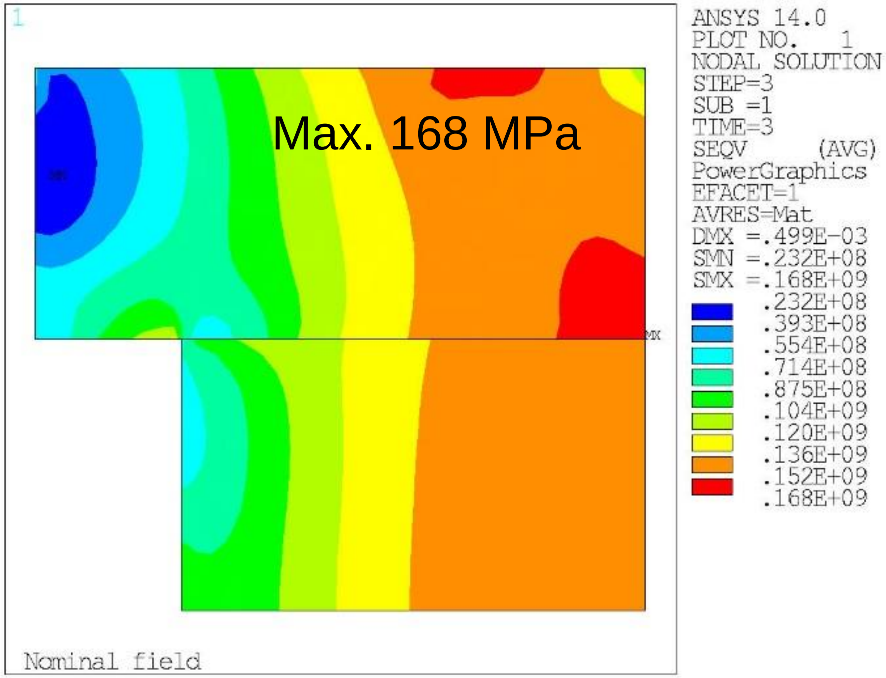




RMM - Graded

TARGET: To have a pressure on the pole > 2 MPa at 16 T central field





Peak stress during cool down 200 MPa

Remark: Max. SEQ non-graded version at 18 T is about the same that the maximum SEQ of the graded version at 16 T

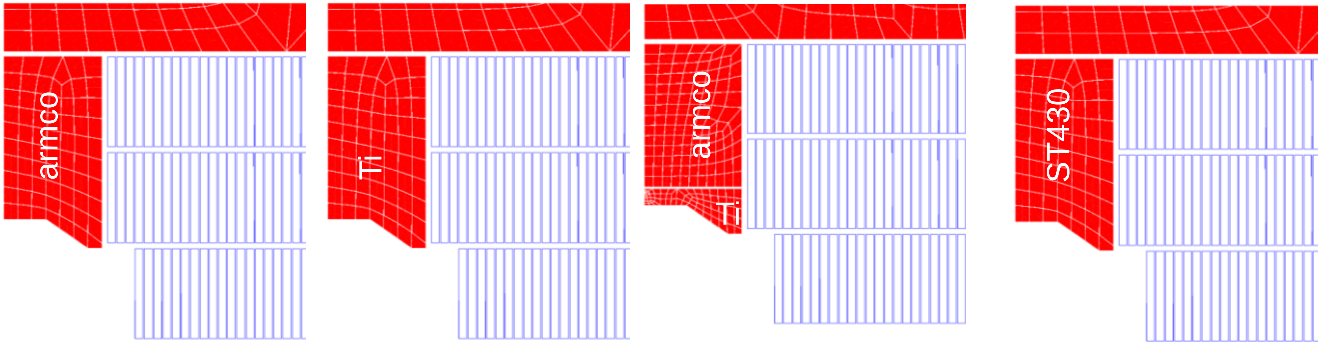
Structural integrity

- **Criteria**: All the components should stay below yield limit up to a field of 20 T

The hardest task: stress in the pole at RT

↓

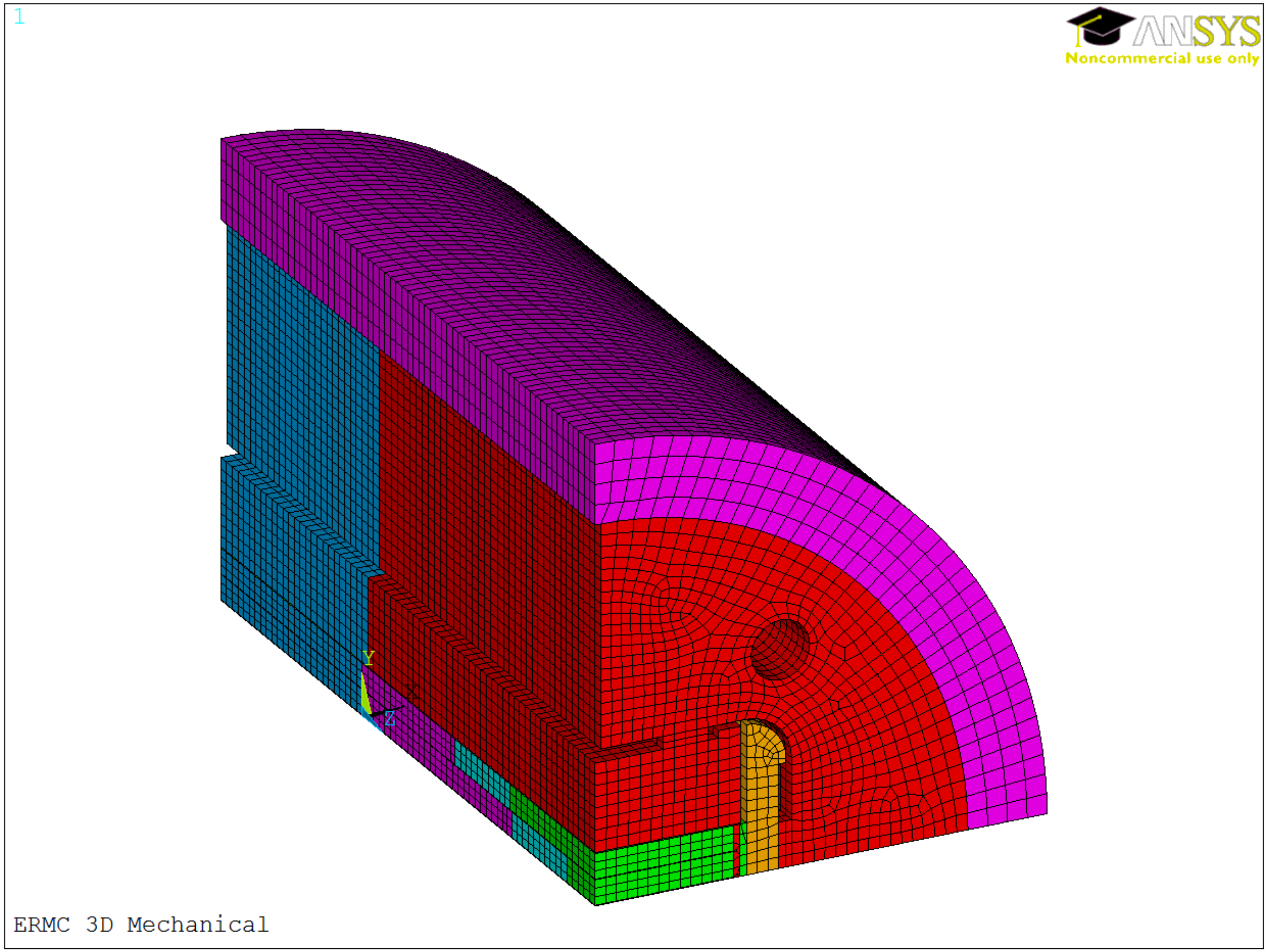
Approach: go for a compromise in between magnetic and mechanical performance



	ARMCO	Titanium	Ti-ARMCO	ST430
0.2 % YS RT (MPa)	180	827	--	310
Saturation (T)	2.15	--	--	1.47
$(L_{4.3K}-L_{293K})/L_{293K}$	1.97e-3	1.74e-3	--	1.74e-3
I @ 16 T(kA)	11.450	11.886	11.550	11.617
Bp @ 16 T	16.00	16.47	16.23	16.12
Margin in the load line (%) $(1-I_{nom}/I_{ss})*100$	10.67	7.50	9.33	9.76

3D Mechanical Design

- We just started!



Content

1. Introduction
2. Electromagnetic design
3. Mechanical design
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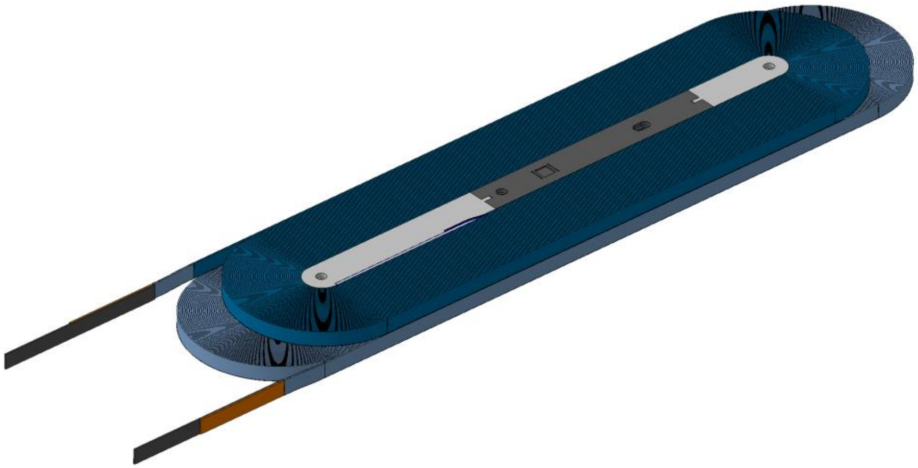
5. Main technical developments needed
6. Summary and next steps

Coil CAD model

- **Aim:** start winding in January 2017 (Cold test end 2017)

- Detailed CAD model from ERMC coil type configuration is available.

- Next steps
  - CAD preliminary design for RMM coil type
  - Detailed design of the RMM-ERMC pole geometry:
    - Integration of instrumentation in the central coil (closed cavity) will be a nice challenge to overcome.
    - A good design in this region is critical.



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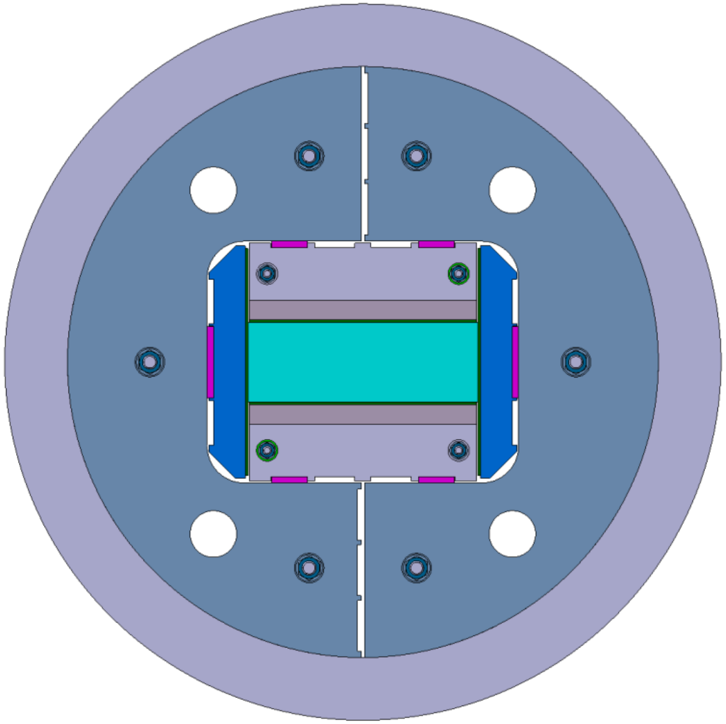
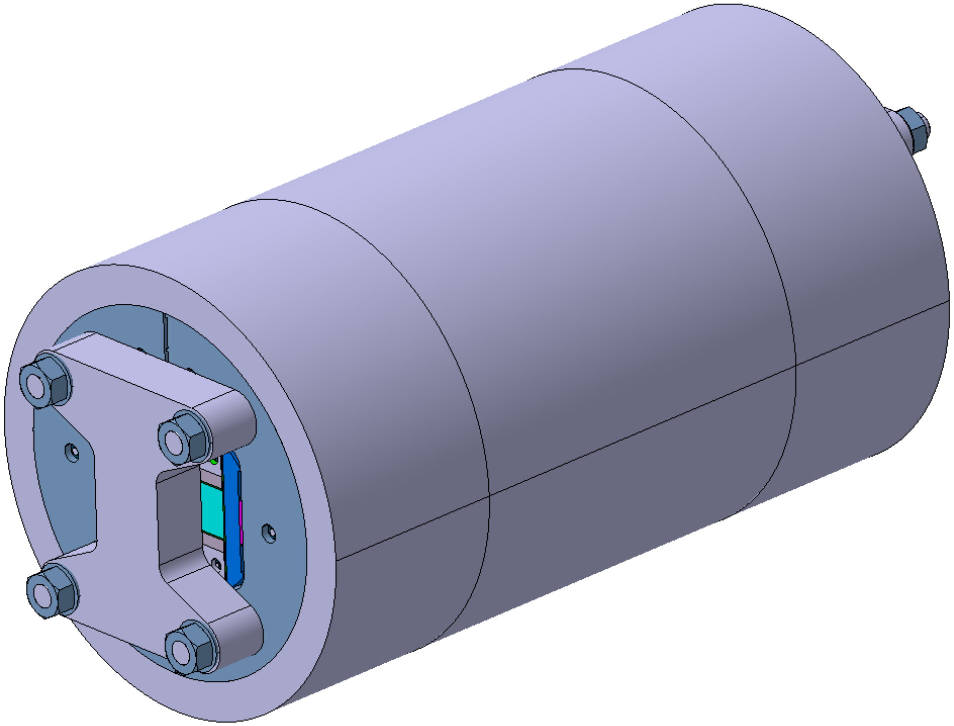
Structure CAD model

- We have a "conceptual" CAD model of the structure
- Iteration on the bladder slots size and position on-going to optimize the assembly.
- Still…a lot of details to go through

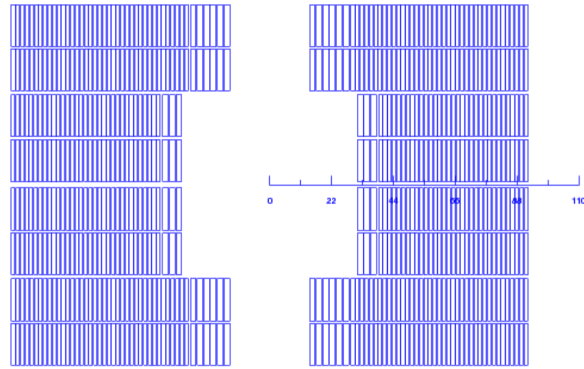




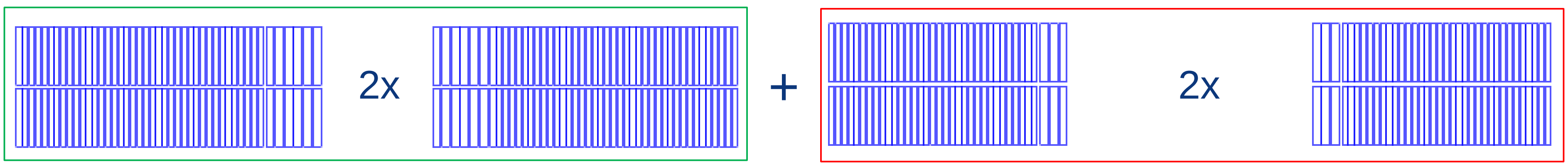
Content

1. Introduction
2. Electromagnetic design
3. Mechanical design
4. Engineering design
5. **Main technical developments needed**
6. Summary and next steps

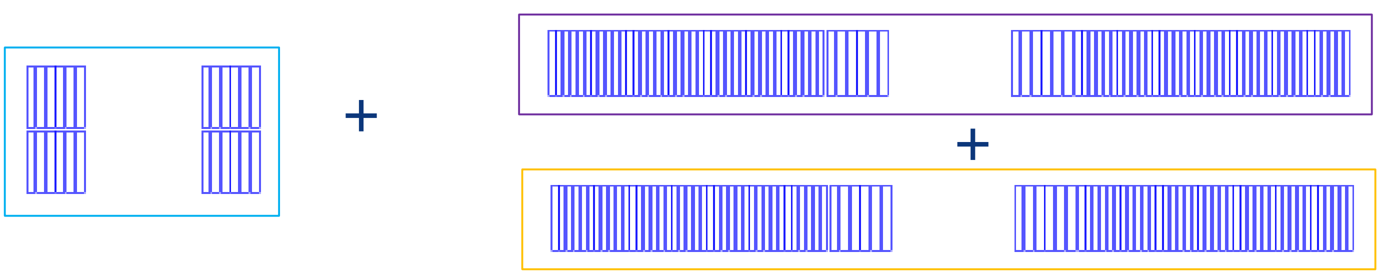
Nb_3Sn High Field Splice



- Each aperture is made out of 4 double pancakes



- Each pancake can be built with a double pancake for the high field region + 2 single pancakes for the low field

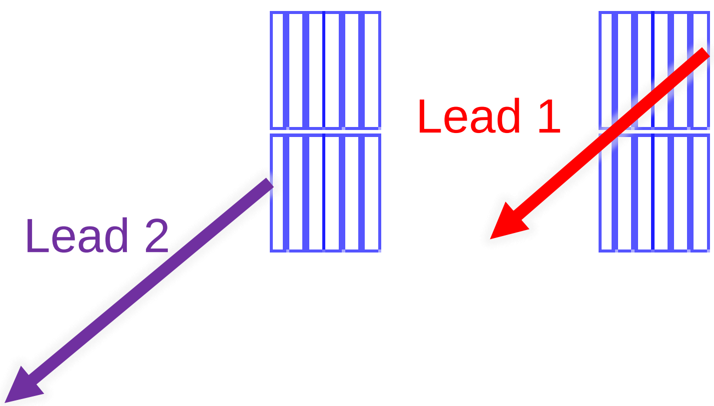


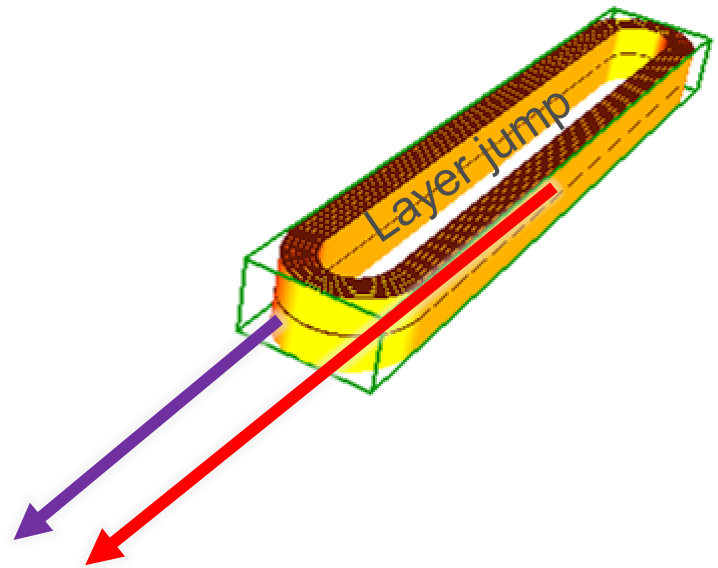
Nb_3Sn High Field Splice

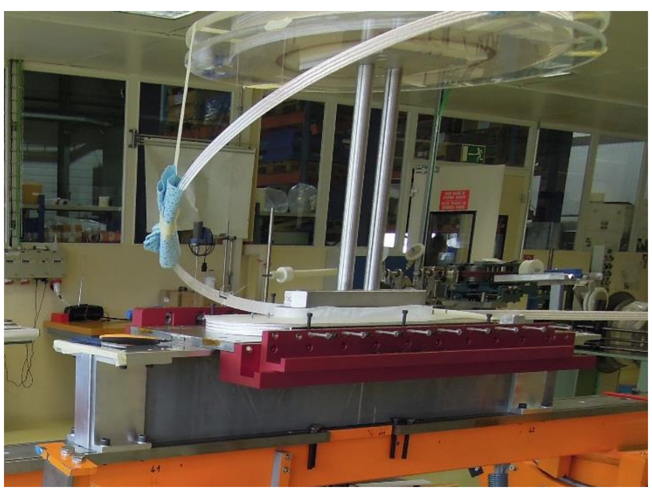
- **Two possible options:**
  - Winding + Reaction + Splicing + Impregnation
    - High field and low field are wound together and spliced after reaction
  - Winding + Reaction + Impregnation + Splicing
    - High field and low field are wound, reacted and impregnated independently, and they are spliced after impregnation

Nb_3Sn High Field Splice

Winding of the high field double pancake (standard winding as in RMC&SMC)

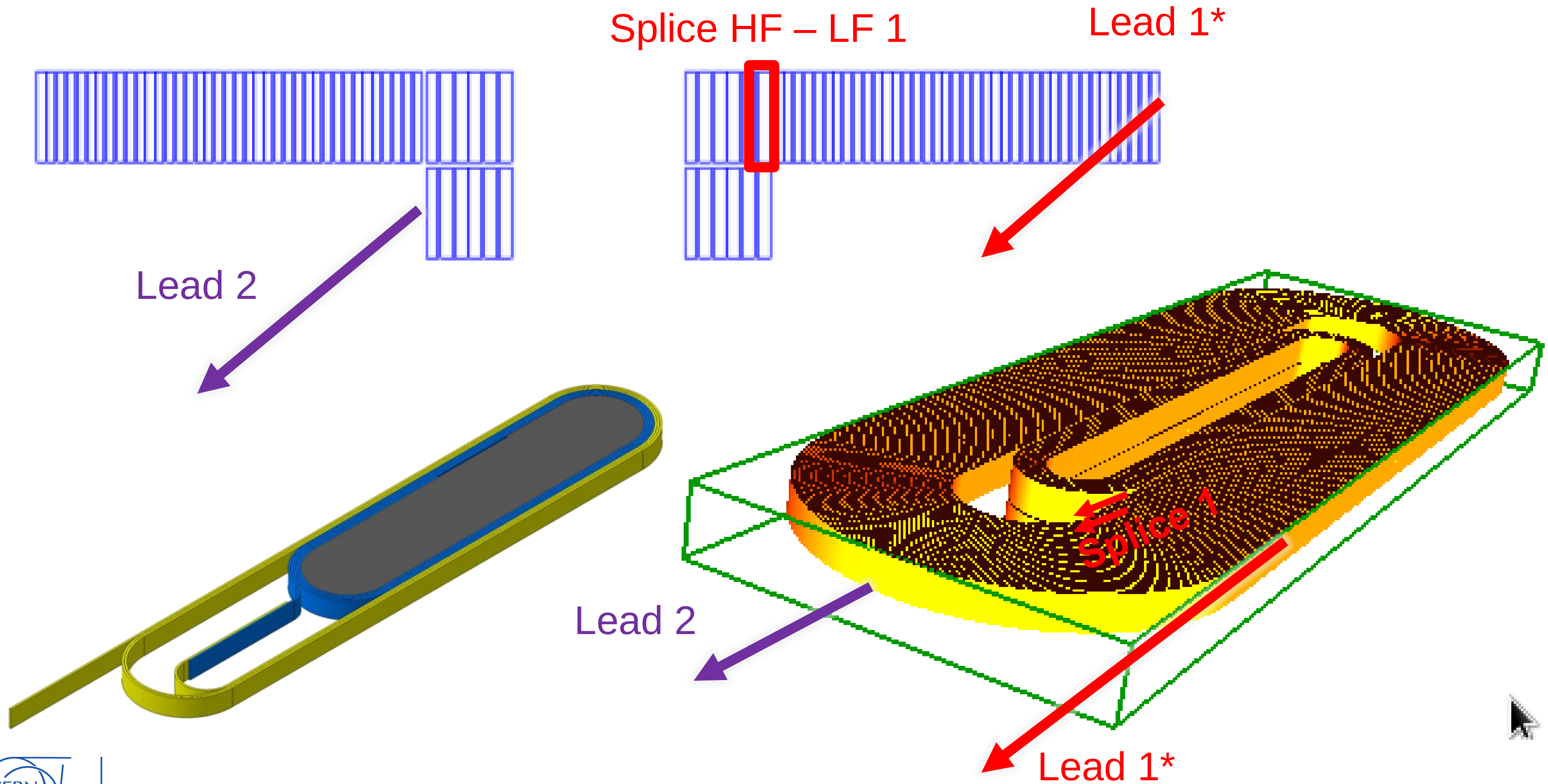






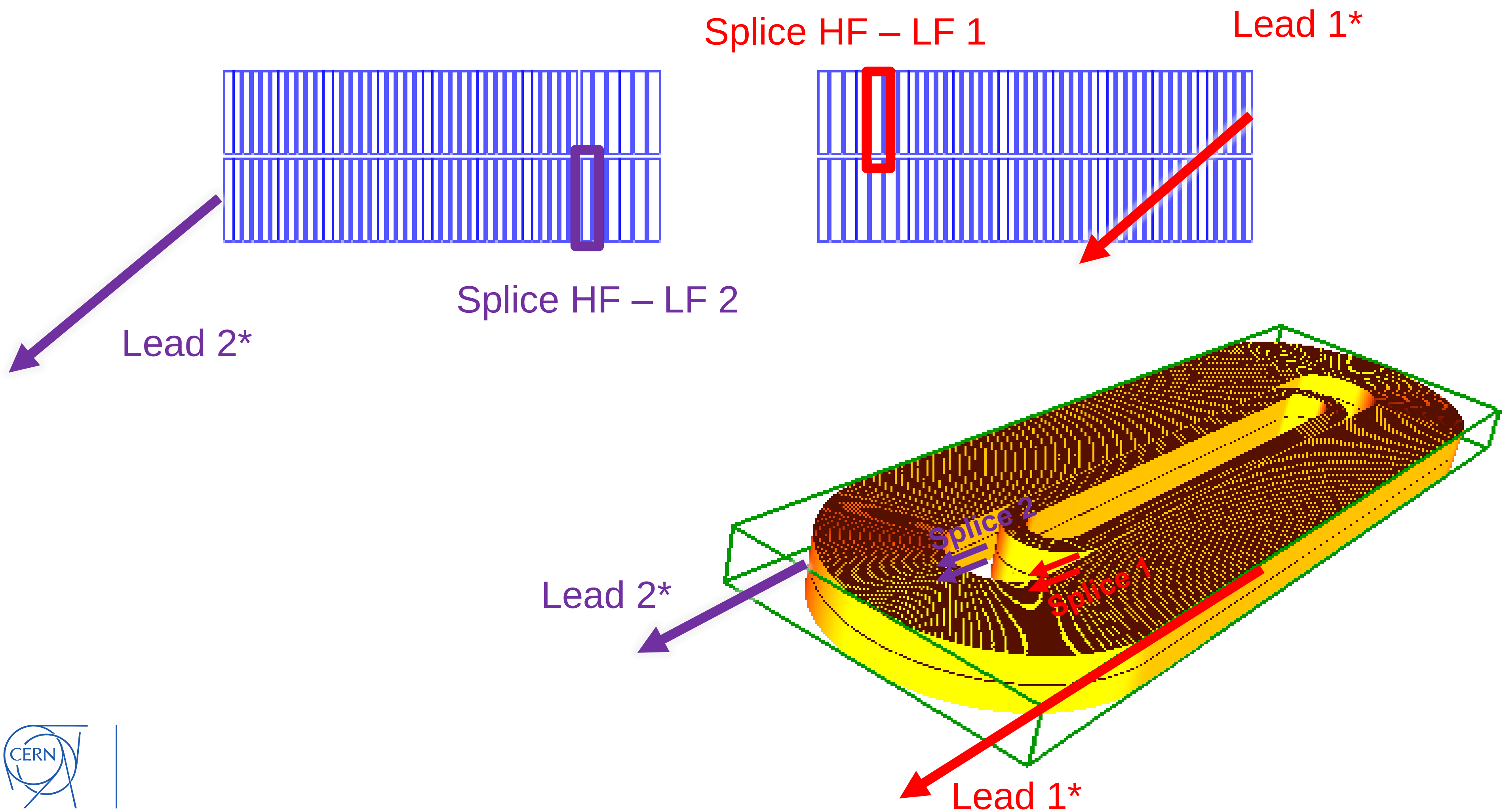
Nb$_3$Sn High Field Splice

1.2. Winding of the upper low field layer



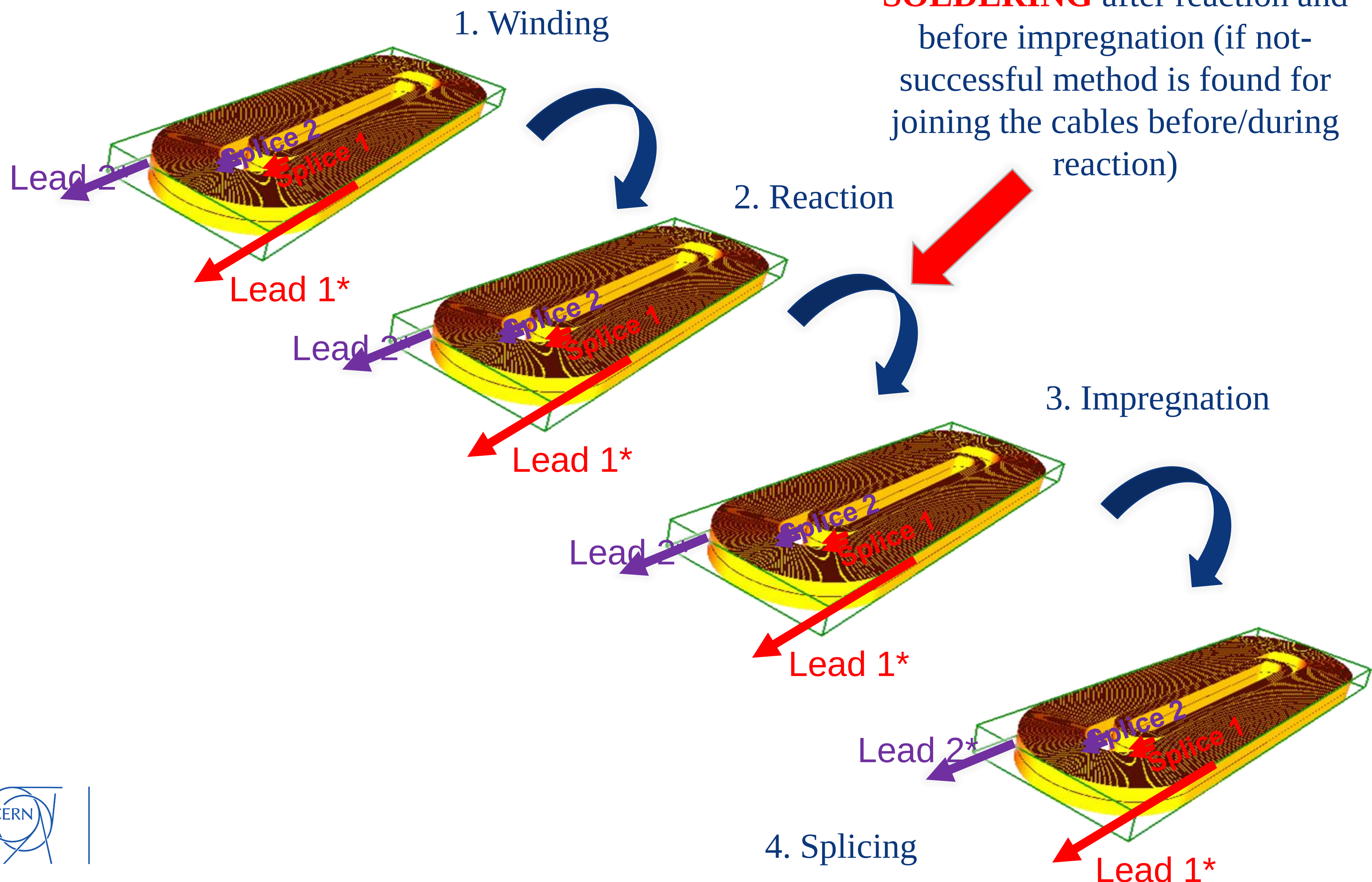
Nb_3Sn High Field Splice

1.3. Winding of the lower field block



Nb_3Sn High Field Splice

SOLDERING after reaction and before impregnation (if not-successful method is found for joining the cables before/during reaction)



Other technical challenges

- Winding
  - Based on the 11 T winding experience (0.7 mm x 40 strands cable, 60 mm aperture), wind-ability in cos-theta configuration for larger cables and smaller aperture should not be underestimated.
  - Coil ends in HD/FRESCA2 were not optimized in terms of field quality. A coil end optimization including the field quality variable might bring additional complexity that we will need to handle.
- Insulation
  - 11 T cable insulation development pushed forward the electrical integrity of the coil pack, but there is room for optimization.
- Impregnation
  - Parallel R&D to understand what are the best materials to put in our coils.

ERMC will allow to test the most promising ideas from the parallel R&D programs with a fast turn around time and enough flexibility.

Content

1. Introduction
2. Electromagnetic design
3. Mechanical design
4. Engineering design
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6. **Summary and next steps**

Summary and next steps

- We have a stablished program to accompany the 16 T R&D needs in terms of magnet technology development.

- First step: Non graded design
  - 2D design and 3D magnetic design is done. 3D mechanical analysis just started.
  - Engineering design is on-going, with the aim of start winding by beginning 2017 (cold test of first ERMC end of 2017).

- The same structure can be used for a graded coil design with minor modifications. The main challenge is the development of the high field Nb_3Sn splice.

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Additional Slides

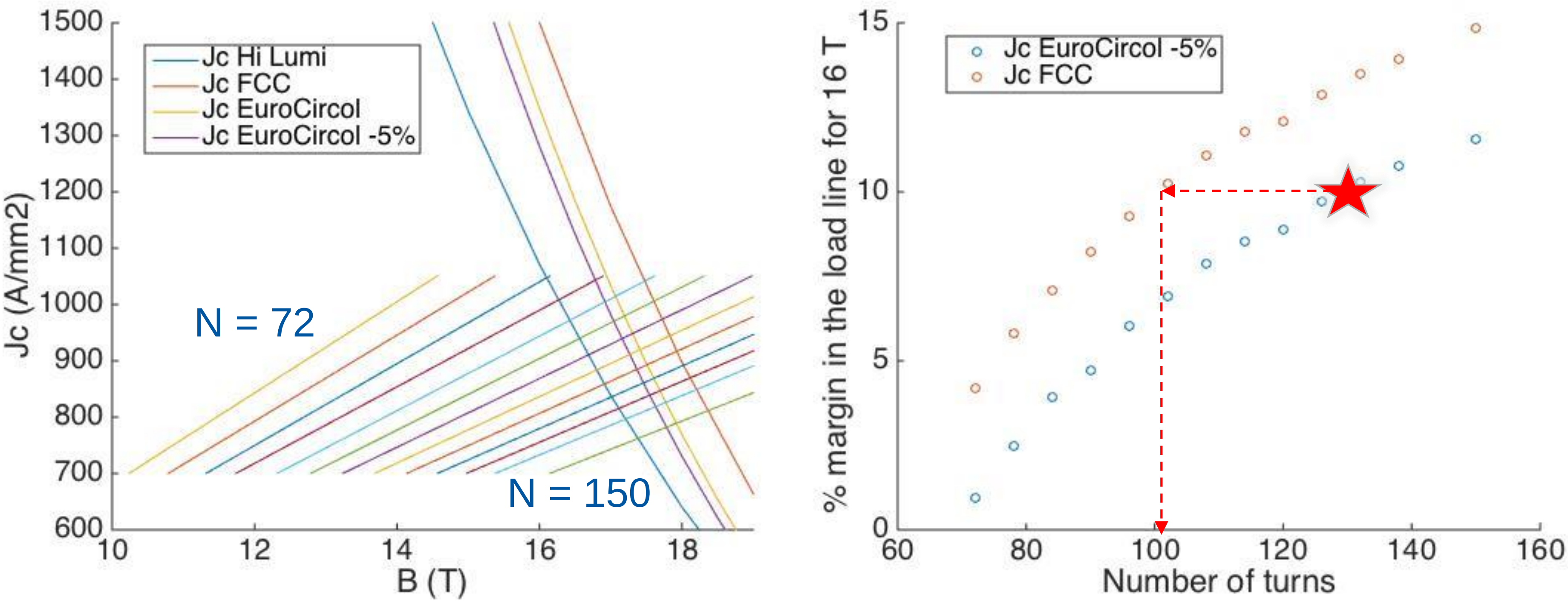
Contents

Parametric study non-graded design

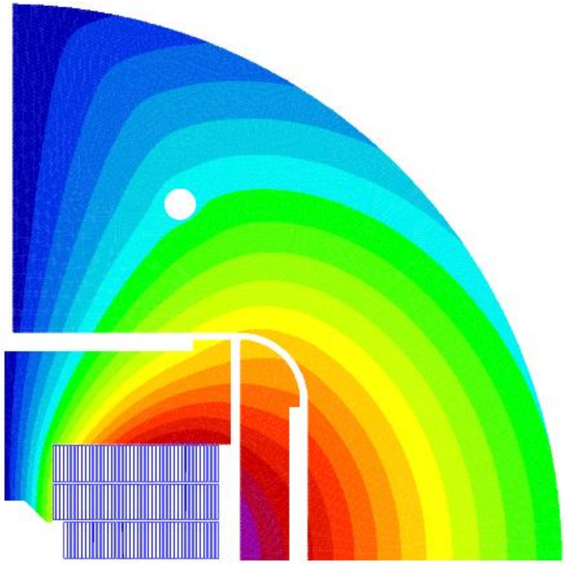
1. Margin on the load line
2. Copper to superconductor ratio
3. Strand diameter
4. Insulation thickness
5. Iron pole

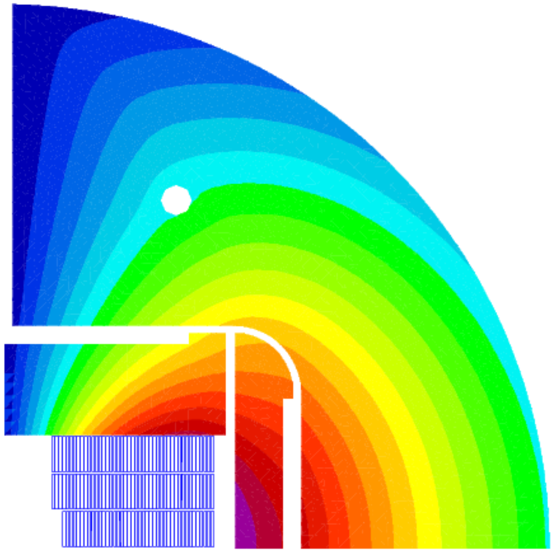
Margin on the load line

- Number of turns need to reach 16 T @ 4.2 K with 10 % margin:
  - 132 turns assuming EuroCircol Critical Current Density and 5 % cabling degradation
  - 100 turns assuming minimum required for FCC



Iron pole



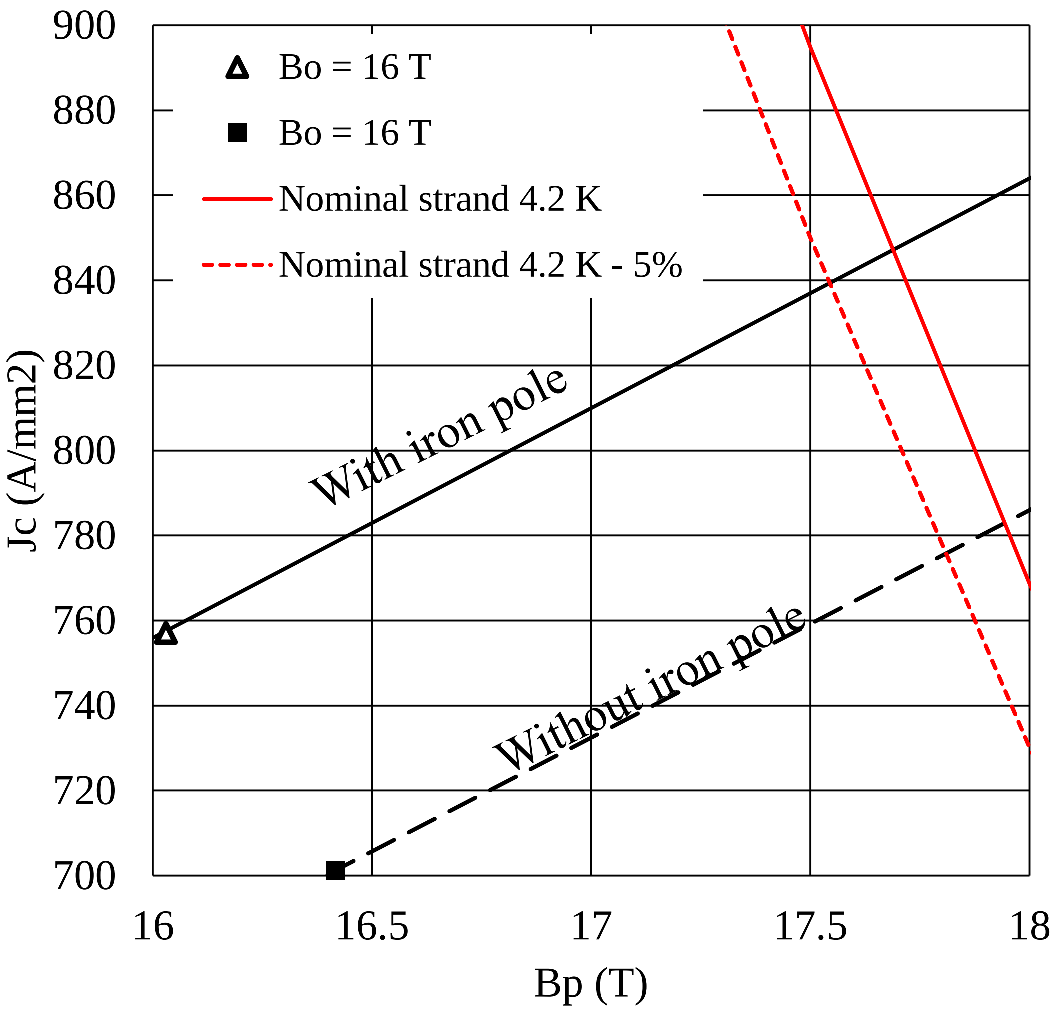


- I_{nom} = 11862 A
- B_o = 16.00 T
- B_p = 16.03 T

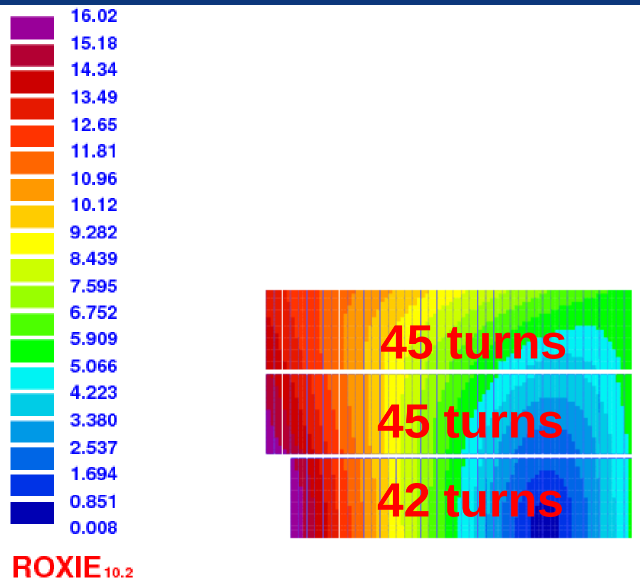
For more efficient graded coils, the additional field given by the iron pole will be less critical

- I = 11862 A
- B_o = 15.55 T
- B_p = 15.99 T
- To reach B_o = 16 T with 10 % margin at 4.2 K
  - Additional number of turns = 24
  - I_{nom} = 11016 A
  - B_o = 15.55 T
  - B_p = 15.99 T

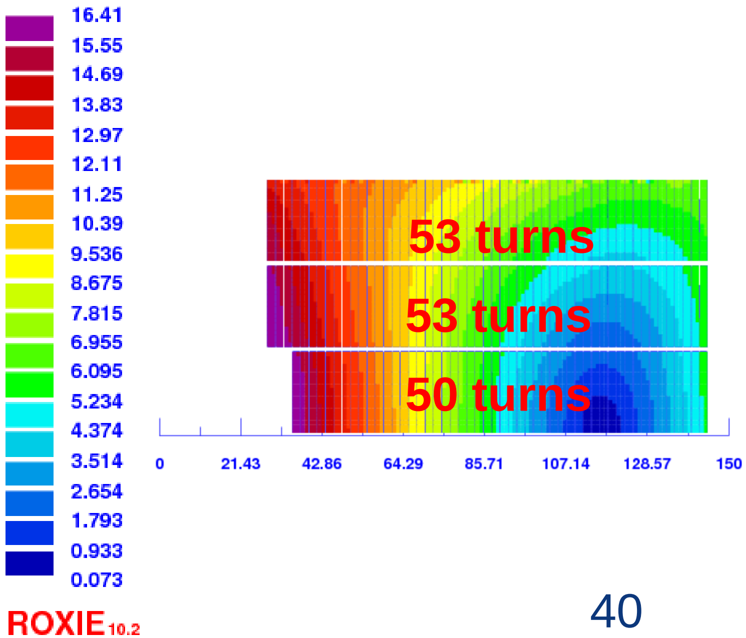
Iron Pole



900
880
860
840
820
800
780
760
740
720
700
Jc (A/mm2)
16
16.5
17
17.5
18
Bp (T)
Bo = 16 T
Bo = 16 T
Nominal strand 4.2 K
Nominal strand 4.2 K - 5%
With iron pole
Without iron pole



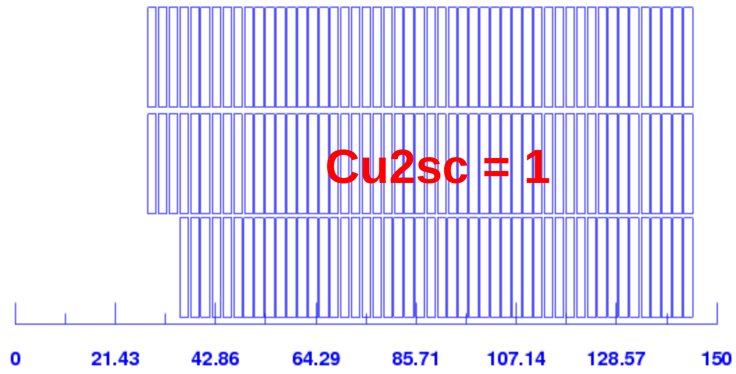
16.02
15.18
14.34
13.49
12.65
11.81
10.96
10.12
9.282
8.439
7.595
6.752
5.909
5.066
4.223
3.380
2.537
1.694
0.851
0.008
ROXIE10.2
45 turns
45 turns
42 turns

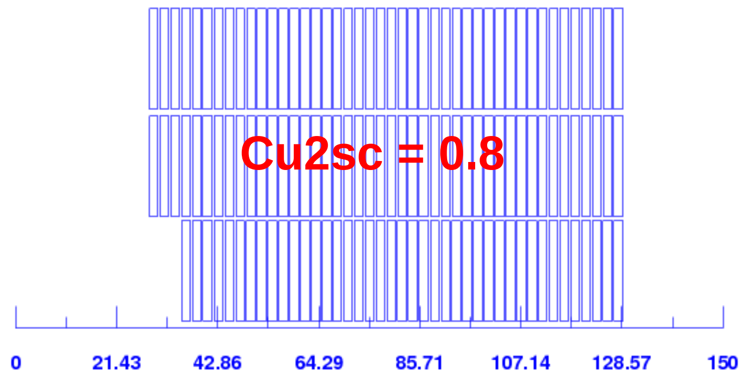


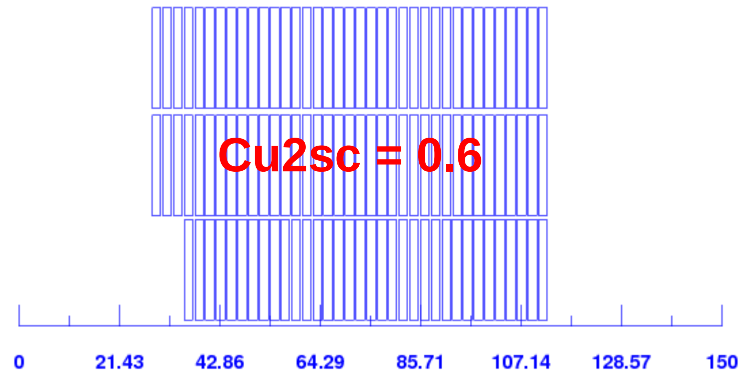
16.41
15.55
14.69
13.83
12.97
12.11
11.25
10.39
9.536
8.675
7.815
6.955
6.095
5.234
4.374
3.514
2.654
1.793
0.933
0.073
ROXIE10.2
53 turns
53 turns
50 turns
0
21.43
42.86
64.29
85.71
107.14
128.57
150

Copper to superconductor ratio

Copper to Supercondutor		1	0.8	0.6
number of conductors	--	150	129	108
coil area (per aperture)	mm^2	29843	25665	21487
coil area (per coil)	mm^2	14922	12833	10744
w_{eq}	mm	96.96	88.49	79.33
operation parameters				
I_{nom}	A	11000	12200	13800
J_{sc}	A/mm^2	700	699	703
J_{cu}	A/mm^2	700	874	1171
J_{eng}	A/mm^2	350	388	439
$J_{overall}$	A/mm^2	221	245	277
Stored energy density	MJ/mm^3	90.44	94.40	99.59
Differential inductance at Inom (per aperture)	mH/m	42.07	30.67	21.14







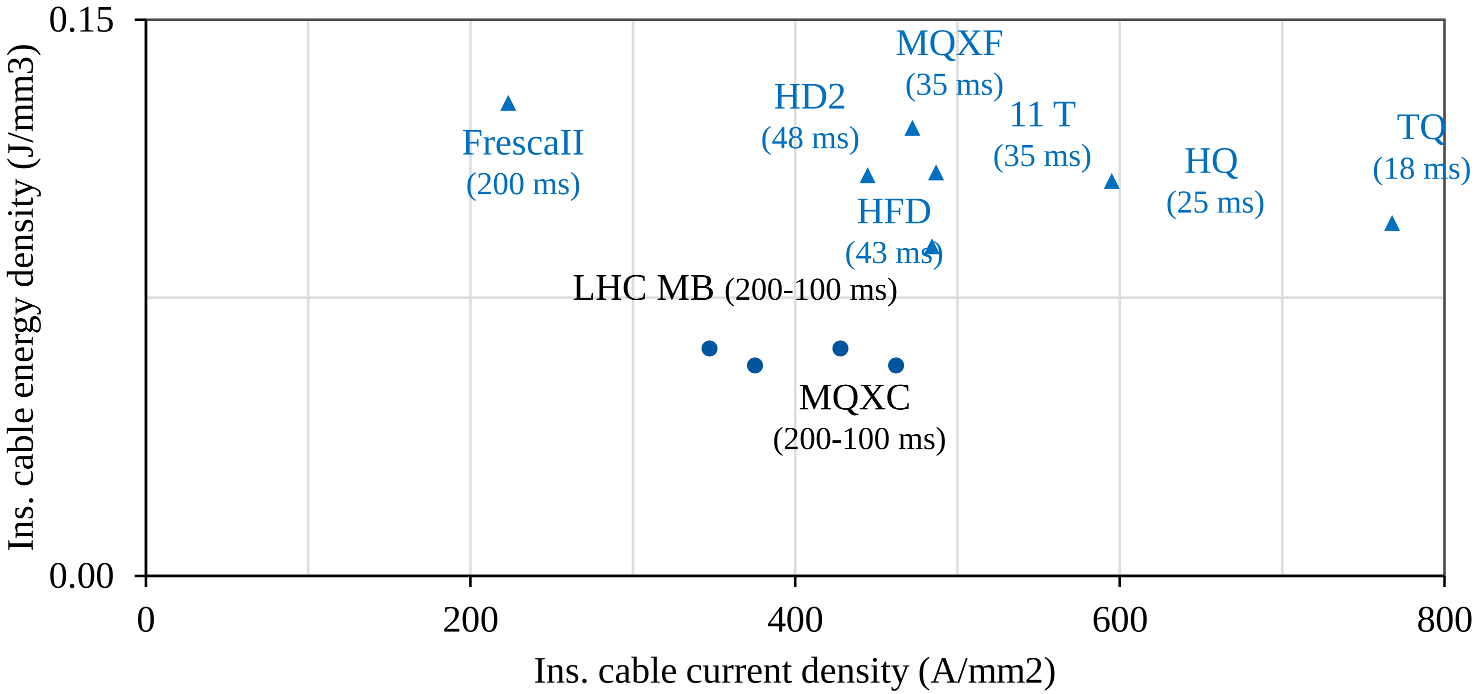
Remark:

The case cu2sc = 1 does not correspond to the "reference case". Differences:

- Conductor insulation thickness = 200 μm
- Different critical surface

Copper to superconductor ratio

		cu2sc = 1	cu2sc = 0.8	cu2sc = 0.6
Insulated cable energy density	(J/mm^3)	**0.0904**	**0.0944**	**0.0996**
Insulated cable current density	(A/mm^2)	**221**	**245**	**277**
MIITS available	(MA^2s)	**53.62**	**46.93**	**38.82**
MIITS consumed decay	(MA^2s)	**32.47**	**49.21**	**28.56**
Time left to quench	(ms)	**175**	**119**	**54**



Strand diameter

- **Pros:** In a block coil the magnet aperture and coil geometry are closely linked. Wider cable goes in the good direction for an efficient coil geometry, but it does not provide a significant improvement
- **Cons:** Wind-ability and Stability
  - FRESCA2 step back from 1.25 mm strand to 1 mm because the cable was declared "un-windable"

cu2sc = 1
t_{ins} = 0.2 mm

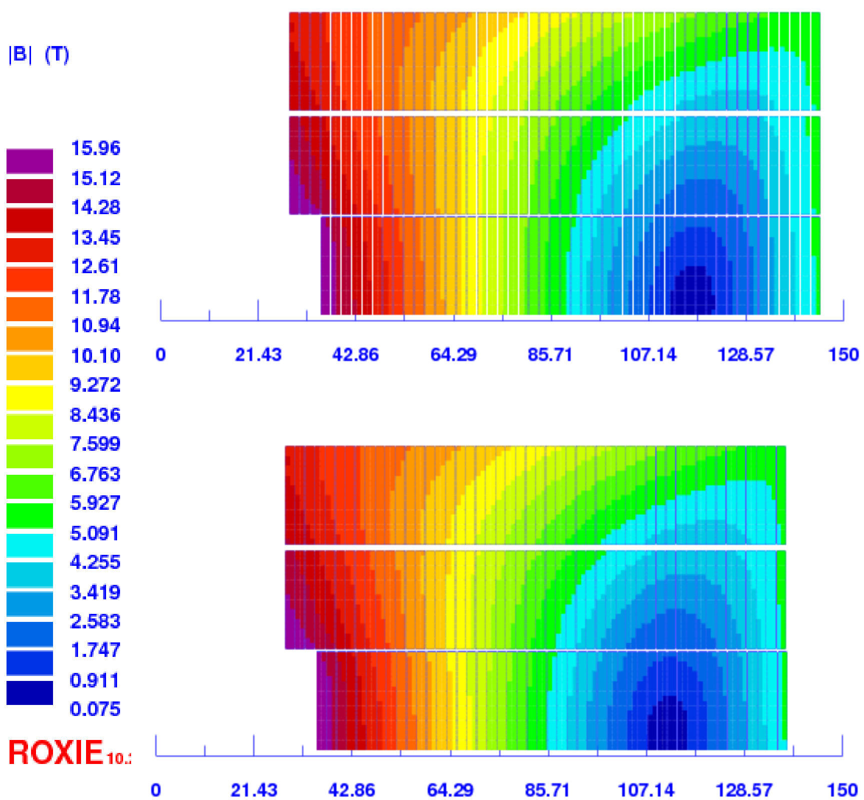
		d=1.1 mm	d=1 mm
coil dimensions			
number of conductors		125	150
coil area (per aperture)	mm^2	29565	29843
coil area (per coil)	mm^2	14782	14922
w_{eq}	mm	96.41	96.96
operation parameters			
Inom	A	13310	11000
Jsc	A/mm^2	700	700
Jcu	A/mm^2	700	700
Jeng	A/mm^2	350	350
Joverall	A/mm^2	225	221

No significant gain in terms of coil size

Insulation thickness

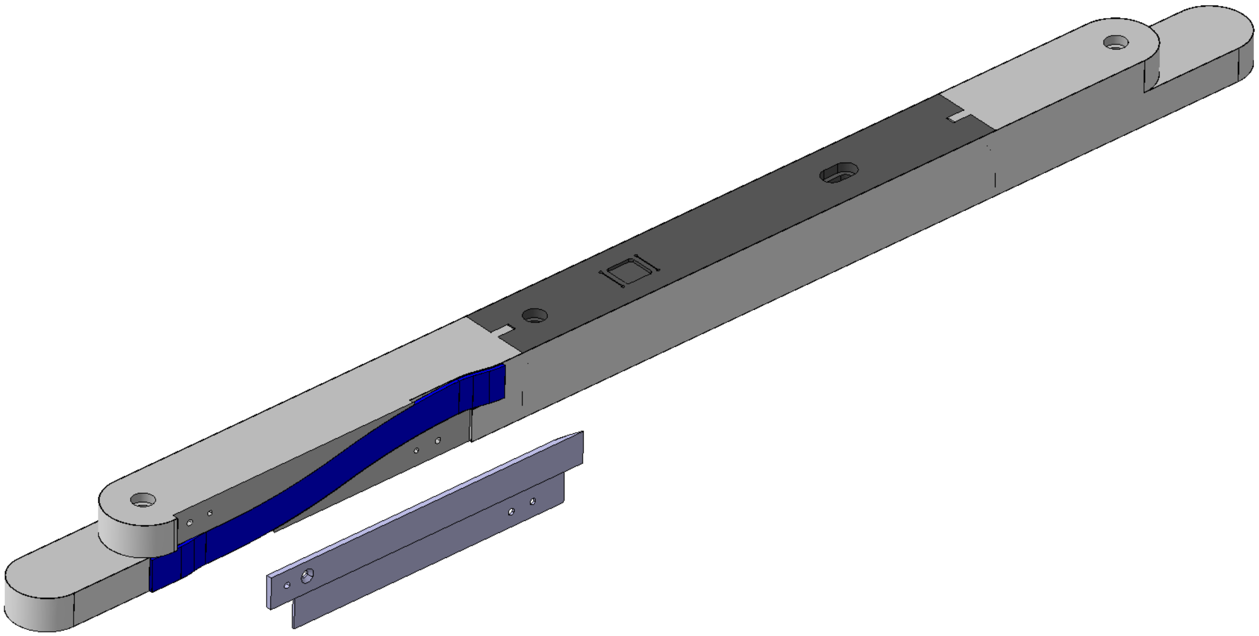
cu2sc = 1

d_{strand} = 1 mm

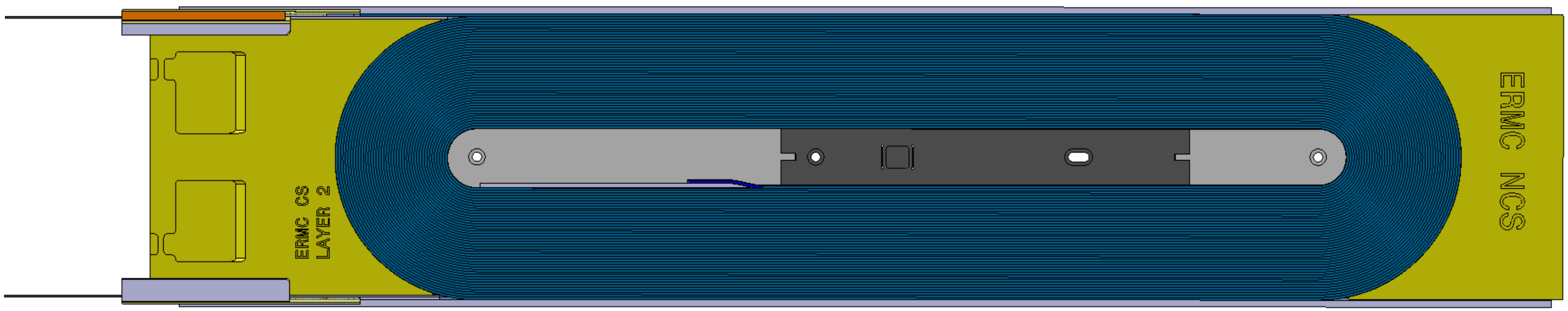


		t=0.15 mm	t=0.2 mm
Coil dimensions			
number of conductors		147	150
coil area (per aperture)	mm^2	27841	29843
coil area (per coil)	mm^2	13920	14922
w_{eq}	mm	92.97	96.96
Current density			
I	A	11000	11000
Jsc	A/mm^2	700	700
Jcu	A/mm^2	700	700
Jeng	A/mm^2	350	350
Joverall	A/mm^2	232	221

Interesting gain in terms of coil size



CERN


ERMC CS
LAYER 2
ERMC NCS