Susana Izquierdo Bermudez, Juan Carlos Perez, Etienne Rochepault

# Overview of grading considerations at CERN for a 16 T Dipole (Block type coil configuration)

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

# Content

# Content

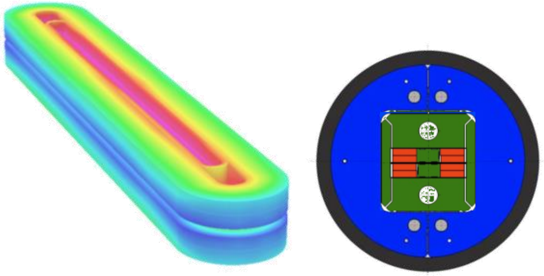
# 1. Introduction - CERN strategy

**ERMC**

Enhanced Racetrack Model Coil

16 T midplane field

- Demonstrate field on the conductor
- Coil technology development

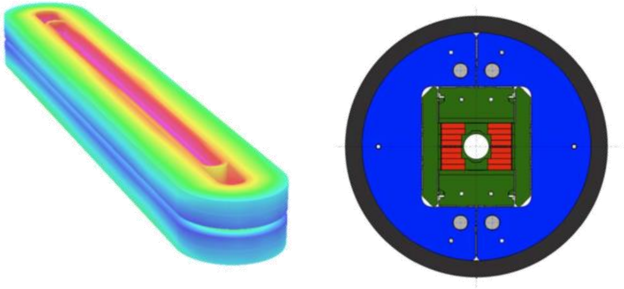


**RMM**

Racetrack Model Magnet

16 T in a 50 mm cavity

- Demonstrate field on the aperture
- Mechanics (including inner coil support)

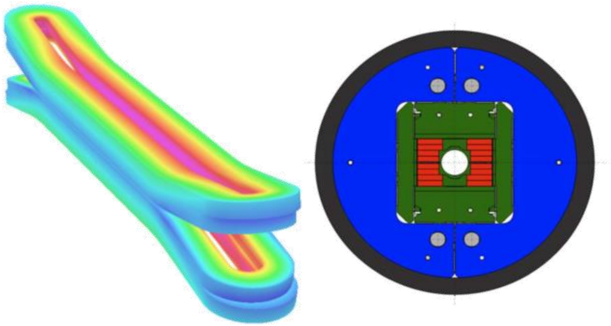


**DEMO**

Demonstrator Magnet

(blocks and cos-θ options under study)

- Accelerator quality magnet

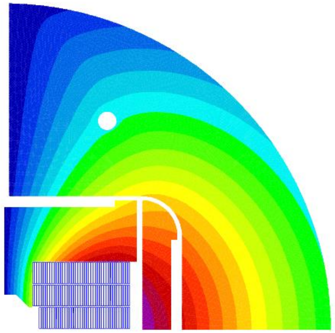


# 1. Introduction: ERMC/RMM

## ERMC/RMM : A two stages project

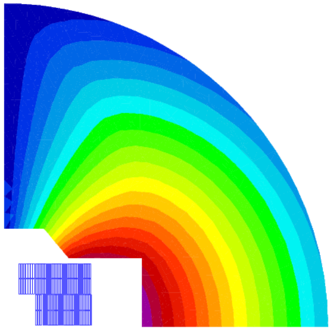
**Stage 1 priorities:**

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:**

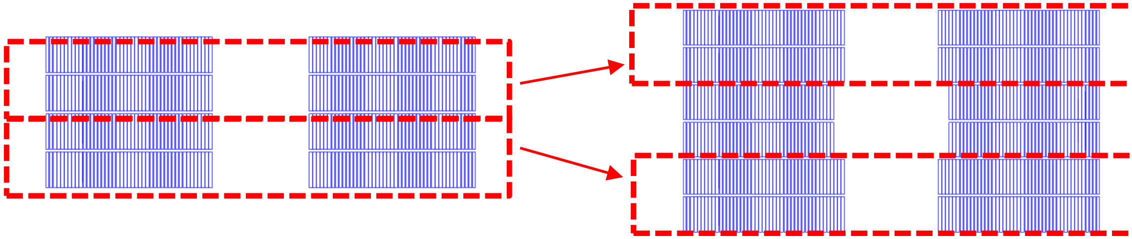
In order to optimise time and resources:

- 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.

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

**ERMC**

RMM



Remark: Possibility to test also a single coil configuration

# 1. Introduction

**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

**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

**OBJECTIVE TODAY: PROVIDE AN OVERVIEW OF POSSIBLE GRADED DESIGNS INCLUDING TECHNICAL CHALLENGES AND IDEAS TO OVERCOME THEM.**

# Content

1. Introduction
2. **Design constrains**
3. Electromagnetic designs overview
4. Technical challenges and "solutions"
5. Summary and next steps

# 2.1 Strand

- Strand diameter:
  - From **0.7** to **1.1 mm**
- Copper to superconductor **> 1**
  - **Time margin** for protection **≥ 50 ms**
- Strand critical current density:
  - **FCC Target:**

    $T_{c0}$ = 16 K, $B_{c20}$ = 29.38 T,
    $C_0$ = 267845 A/mm$^2$T,
    0 % cabling degradation

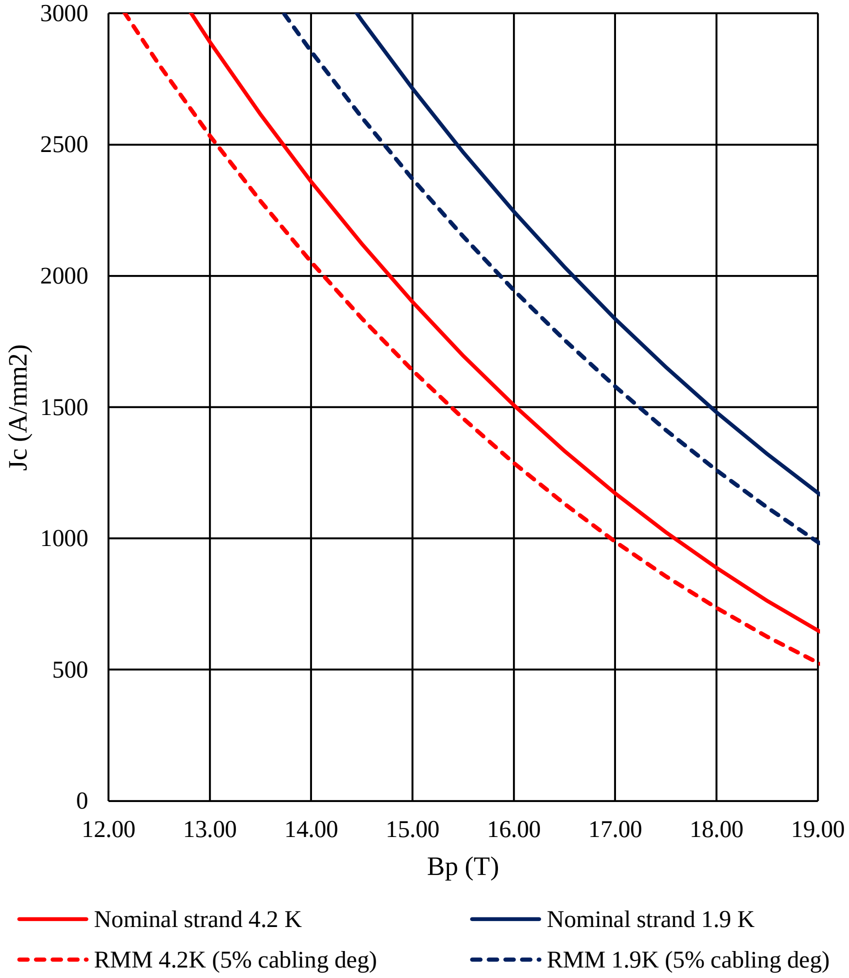
    **$J_c$(4.2K,16T) = 1507 A/mm$^2$**

    **$J_c$(4.2K,18T) = 887 A/mm$^2$**
  - ERMC/RMM:

    $T_{c0}$ = 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$^2$



# 2.2 Cable and Insulation

- Number of strands
  - **“Preferred solution”: less than 40 strands.**
  - **“Possible solution”: less than 50 strands.** Experience in Berkley with HD cable (51 strand, 0.8 mm diameter)
  - **“Risky solution”: less than 60 strands**. Mechanical stability of the cable can be a big issue

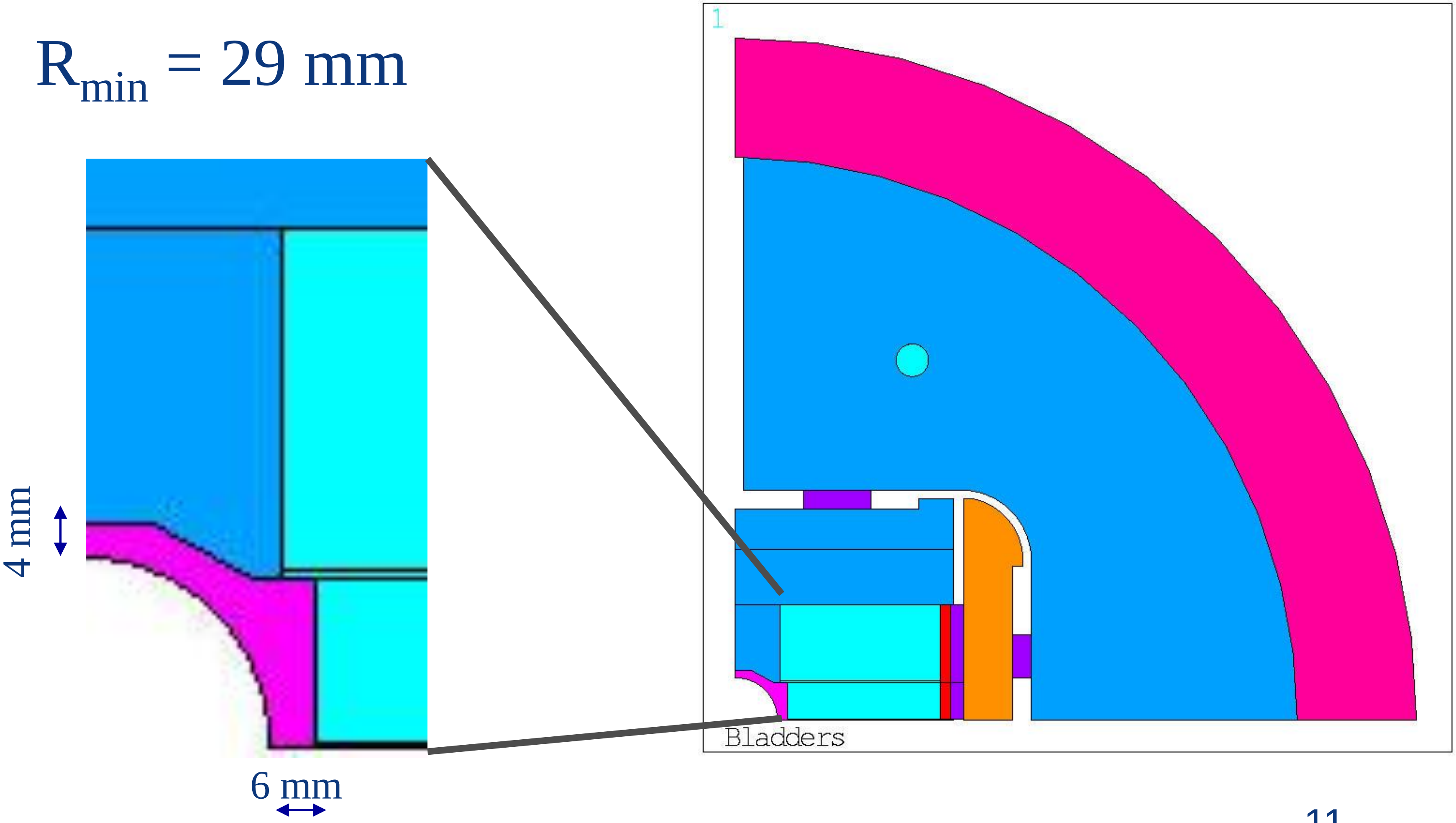
- Cable insulation thickness = **150 µm**
  - Can be either only S2-glass or **S2-glass/Mica**
  - Experience in 927 in terms of electrical robustness:
    - MQXF: 150 µm S2-glass
      - MQXFS_001 ~ 3.5kV
      - MQXFS_101 ~ 6.25kV
    - 11T: 150 µm S2-glass/Mica before HT, 100 µm S2-glass/Mica after HT
      - 11T#110: > 7kV (limit of the capacitor discharge generator)

http://indico.cern.ch/event/395351/

# 2.3 Size of the inner support structure

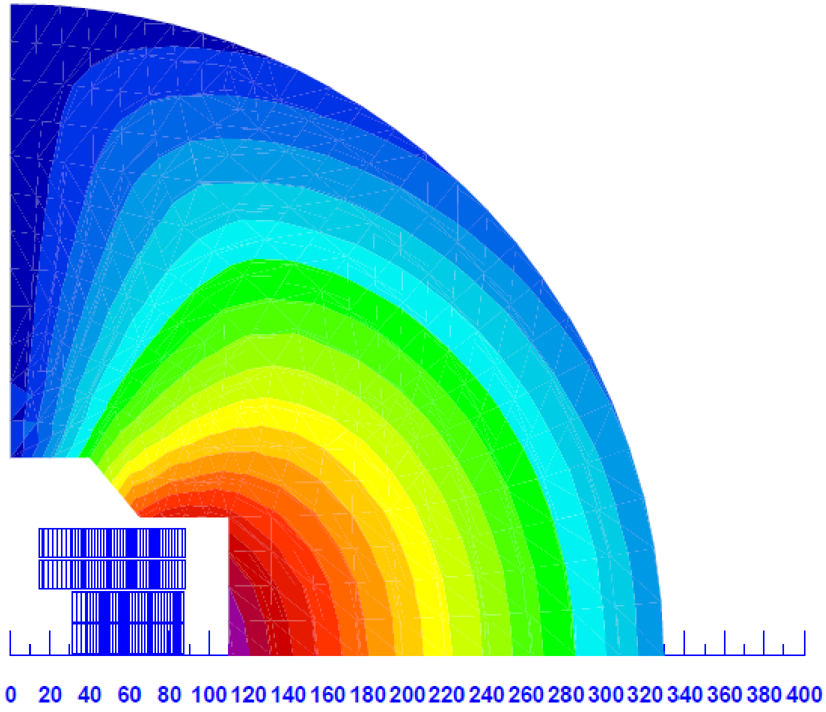
Based on RMM ANSYS analysis:

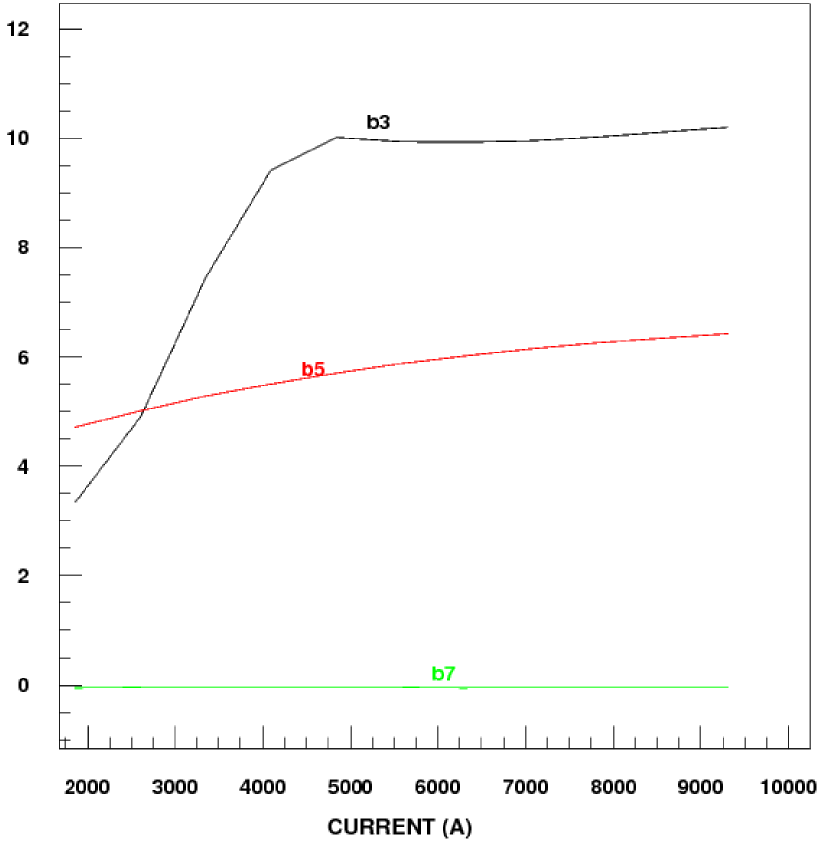
- Wall thickness = 6 mm
- $R_{min}$ = 29 mm



# 2.4 Overall magnet size

- Shell thickness = 70 mm
- Outer magnet diameter = 800 mm
- Iron optimized to have small of saturation on field quality





# Content

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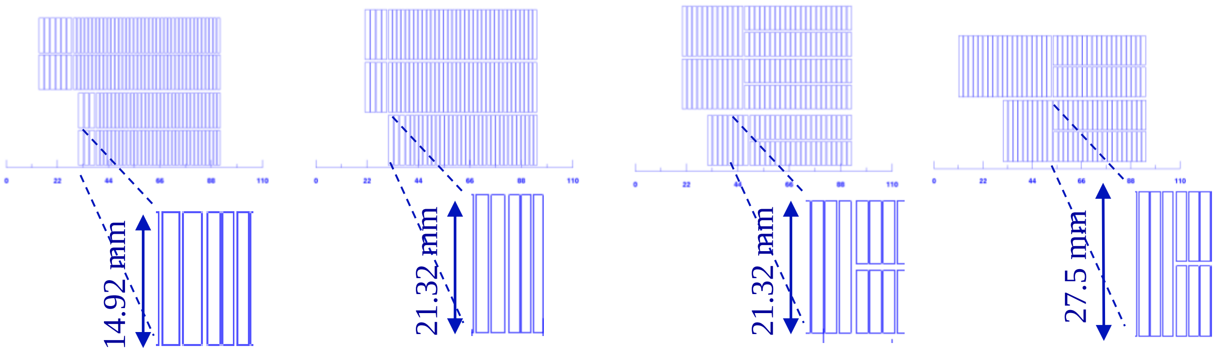
# 3. Electromagnetic designs overview



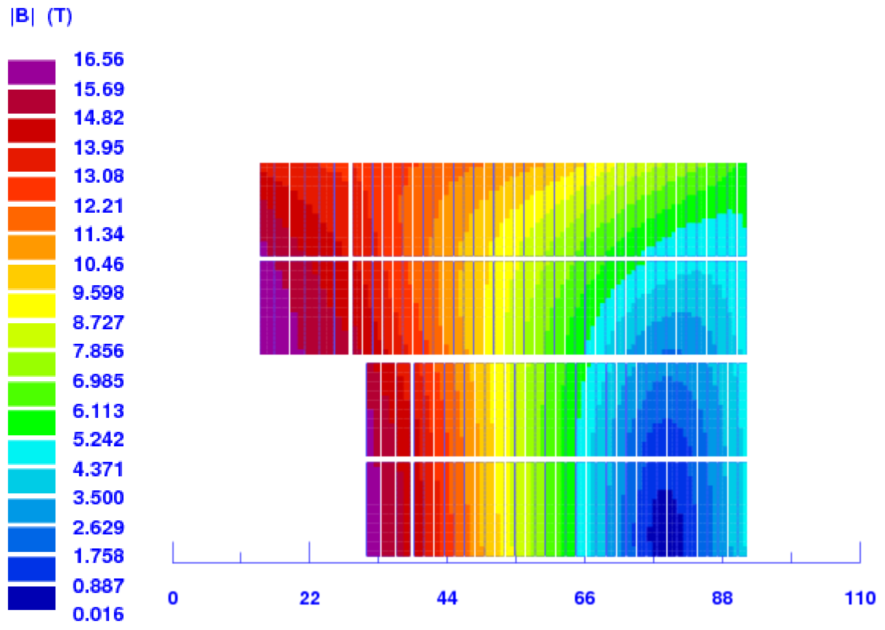
| | Design A | | Design B | | Design C | | Design D | |
|---|---|---|---|---|---|---|---|---|
| | **HF** | **LF** | **HF** | **LF** | **HF** | **LF** | **HF** | **LF** |
| Strand Diameter, mm | 1.1 | 0.7 | 1.1 | 0.8 | 1 | 1 | 1 | 1 |
| Number of strands | 26 | 40 | 36 | 50 | 40 | 19 | 51 | 51 |
| Non-insulated cable width, mm | 14.92 | 14.92 | 21.32 | 21.32 | 21.32 | 10.13 | 27.5 | 27.5 |
| Non-insulated cable thickness, mm | 2.08 | 1.32 | 2.08 | 1.52 | 1.89 | 1.89 | 1.89 | 1.89 |
| Copper to Superconductor Ration | 1 | 1:2 | 1 | 1:2 | 1 | 1:2 | 1 | 1:2 |
| $A_{LF}/A_{FH}$ | 1.58 | | 1.37 | | 2.10 | | 1.00 | |

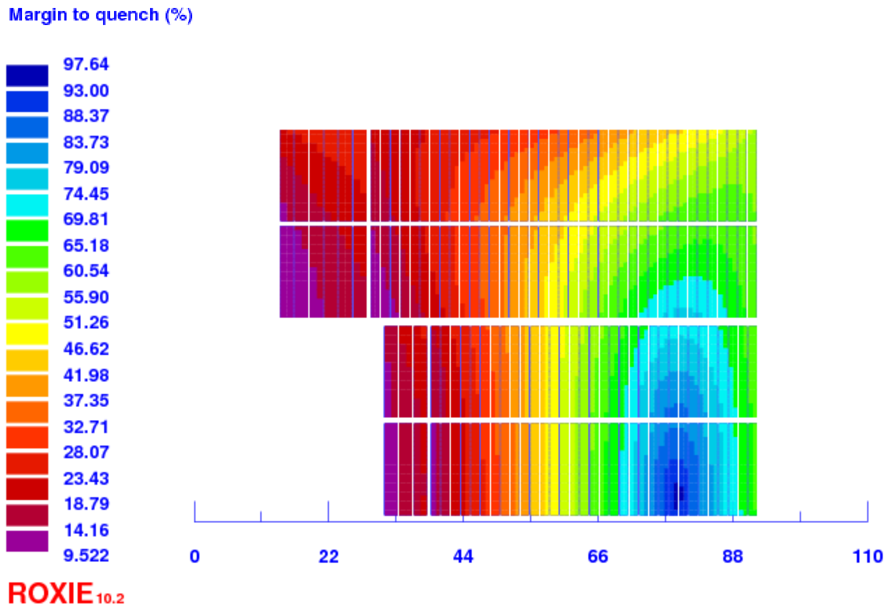
**Some remarks:**

- Designs C&D challenging coil fabrication (details will be addressed later)
- Designs B&D challenging cable (>40 strands)

# 3. Design A

| | | Design A | |
|---|---|---|---|
| | | HF | LF |
| **Strand & Cable** | | | |
| Strand diameter | **mm** | 1.1 | 0.7 |
| Cu2SC ratio | | 1 | 1.15 |
| # of strands in cable | | **26** | **40** |
| **Coil dimensions** | | | |
| number of conductors | | **20** | **130** |
| coil area (per aperture), including insulation | mm2 | 2898 | 12821 |
| coil area (per coil) ,including insulation | mm2 | 1449 | 6411 |
| conductor area per coil | mm2 | 4991 | |
| r | mm | 25 | |
| w/r | w_eq | 2.6 | |
| Equivalent coil width | mm | 65.2 | |
| **Operation parameters (16T)** | | | |
| **Inom** | **A** | **9310** | **9310** |
| **Jsc** | **A/mm2** | **754** | **1300** |
| **Jcu** | **A/mm2** | **754** | **1131** |
| **Jeng** | **A/mm2** | **377** | **605** |
| **Joverall** | **A/mm2** | **257** | **378** |
| **Ratio LF/JF Joverall** | | **1.47** | |
| Bore field at Inom | T | 16.00 | |
| Conductor peak field at Inom | T | 16.58 | 14.71 |
| **Short sample limits** | | | |
| Short sample current Iss at 4.2 K | A | 10378 | 10382 |
| Coil peak field at 4.2 K Iss | T | 18.20 | 16.20 |
| Margin on the load line at 4.2 K | % | 10 | 10 |
| Short sample current Iss at 1.9 K | A | 11465 | 11456 |
| Coil peak field at 1.9 Iss | T | 19.90 | 17.70 |
| Margin on the load line at 1.9 K | % | 19 | 19 |



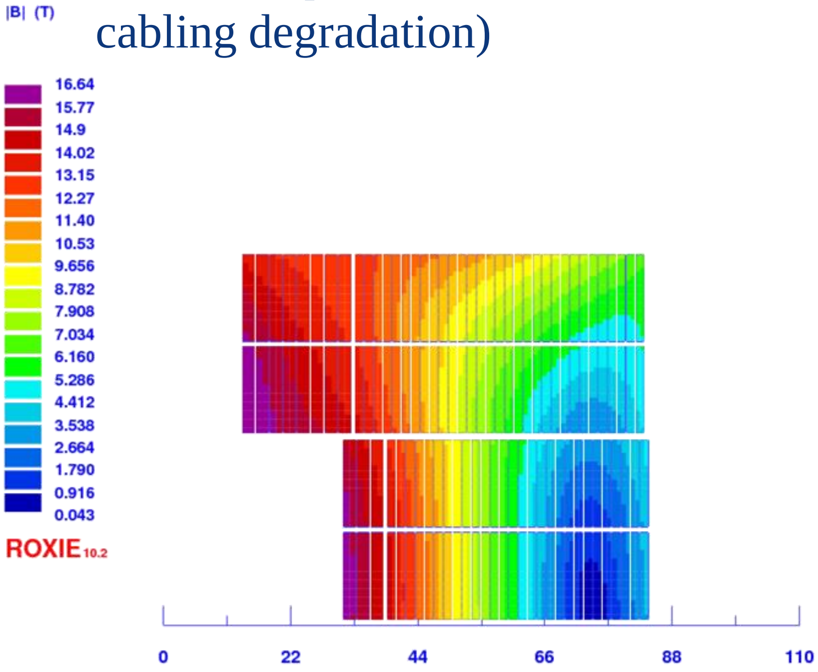


v37 (11710 tons of $Nb_3Sn$)

# 3. Design A - Enhanced

| | | Design A | | Design A - Enhanced | |
|---|---|---|---|---|---|
| | | **HF** | **LF** | **HF** | **LF** |
| **Strand & Cable** | | | | | |
| Strand diameter | **mm** | 1.1 | 0.7 | 1.1 | 0.7 |
| Cu2SC ratio | | **1** | **1.15** | **0.8** | **1.3** |
| # of strands in cable | | **26** | **40** | **26** | **40** |
| **coil dimensions** | | | | | |
| number of conductors | | **20** | **130** | **22** | **118** |
| coil area (per aperture), including insulation | mm2 | 2898 | 12821 | 3188 | 11638 |
| coil area (per coil) ,including insulation | mm2 | 1449 | 6411 | 1594 | 5819 |
| conductor area per coil | mm2 | 4991 | | 4720 | |
| r | mm | 25 | | 25 | |
| w/r | w_eq | 2.6 | | 2.5 | |
| Equivalent coil width | mm | **65.2** | | **62.8** | |
| **Operation parameters (16T)** | | | | | |
| **Inom** | **A** | **9310** | **9310** | **9800** | **9800** |
| **Jsc** | **A/mm2** | **754** | **1300** | **714** | **1464** |
| **Jcu** | **A/mm2** | **754** | **1131** | **892** | **1126** |
| **Jeng** | **A/mm2** | **377** | **605** | **397** | **637** |
| **Joverall** | **A/mm2** | **257** | **378** | **271** | **397** |
| **Ratio LF/JF Joverall** | | **1.47** | | **1.47** | |
| Bore field at Inom | T | 16.00 | | 16.00 | |
| Conductor peak field at Inom | T | 16.58 | 14.71 | 16.65 | 14.24 |
| **Short sample limits** | | | | | |
| Short sample current Iss at 4.2 K | A | 10378 | 10382 | 10982 | 10943 |
| Coil peak field at 4.2 K Iss | T | 18.20 | 16.20 | 18.35 | 15.70 |
| Margin on the load line at 4.2 K | % | **10** | **10** | **11** | **10** |
| Short sample current Iss at 1.9 K | A | 11465 | 11456 | 12148 | 12114 |
| Coil peak field at 1.9 Iss | T | 19.90 | 17.70 | 20.10 | 17.10 |
| Margin on the load line at 1.9 K | % | **19** | **19** | **19** | **19** |

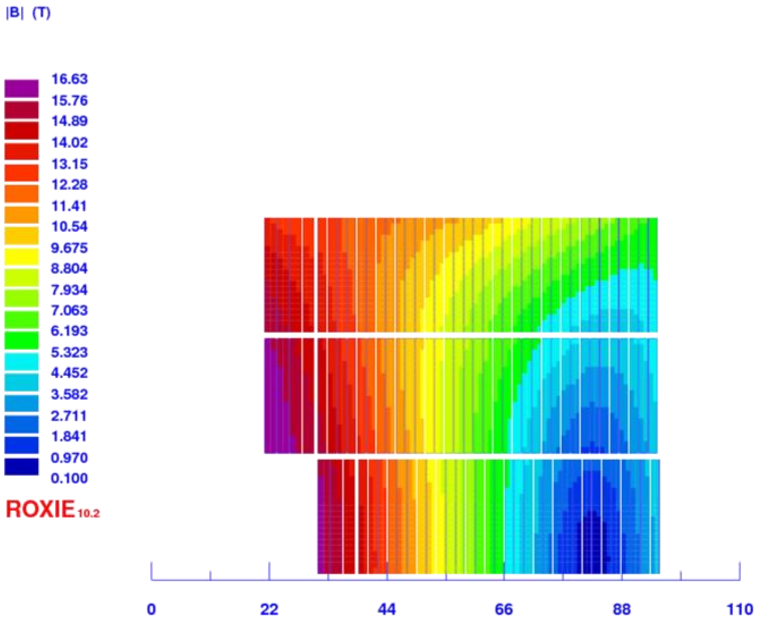
- Coil size can be reduced by 3.5 % when reducing the copper to superconductor ration from 1 to 0.8 in the high field region.
- As a drawback, copper to superconductor ratios lower than 1 require R&D effort (difficult to achieve requirements with small cabling degradation)

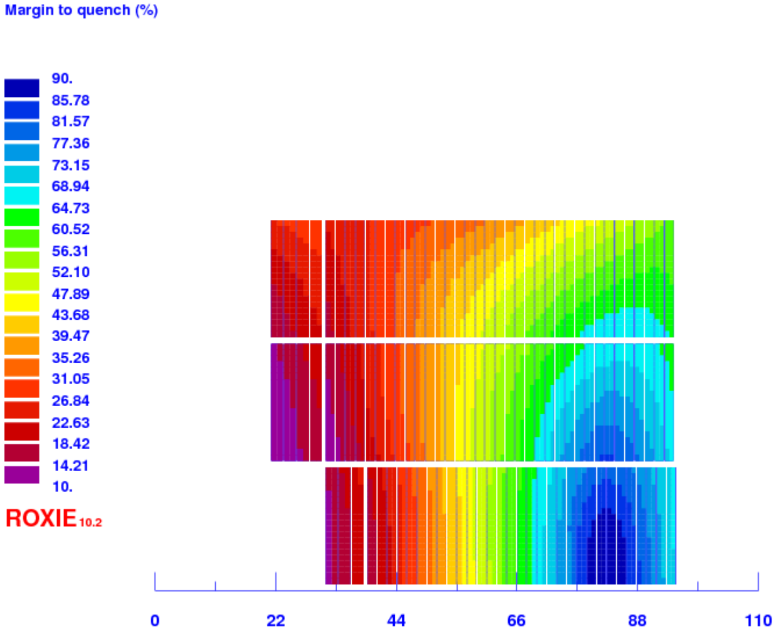


v36 (11075 tons of $Nb_3Sn$)

# 3. Design B

| | | Design B | |
|---|---|---|---|
| | | **HF** | **LF** |
| **Strand & Cable** | | | |
| Strand diameter | mm | 1.1 | 0.8 |
| Cu2SC ratio | | 1 | 1 |
| # of strands in cable | | **36** | **50** |
| **coil dimensions** | | | |
| number of conductors | | **11** | **101** |
| coil area (per aperture), including insulation | mm2 | 2264 | 15897 |
| coil area (per coil) ,including insulation | mm2 | 1132 | 7948 |
| conductor area per coil | mm2 | 5829 | |
| r | mm | 25 | |
| w/r | w_eq | 2.9 | |
| Equivalent coil width | mm | 71.4 | |
| **operation parameters (16T)** | | | |
| **Inom** | **A** | **12790** | **12790** |
| **Jsc** | **A/mm2** | **748** | **1018** |
| **Jcu** | **A/mm2** | **748** | **1018** |
| **Jeng** | **A/mm2** | **374** | **509** |
| **Joverall** | **A/mm2** | **249** | **325** |
| **Ratio LF/JF Joverall** | | **1.31** | |
| Bore field at Inom | T | 16.00 | |
| Conductor peak field at Inom | T | 16.63 | 15.29 |
| **short sample** | | | |
| Short sample current Iss at 4.2 K | A | 14198 | 14502 |
| Coil peak field at 4.2 K Iss | T | 18.25 | 17.07 |
| Margin on the load line at 4.2 K | % | 10 | 12 |
| Short sample current Iss at 1.9 K | A | 15703 | 16035 |
| Coil peak field at 1.9 Iss | T | 19.97 | 18.66 |
| Margin on the load line at 1.9 K | % | 19 | 20 |



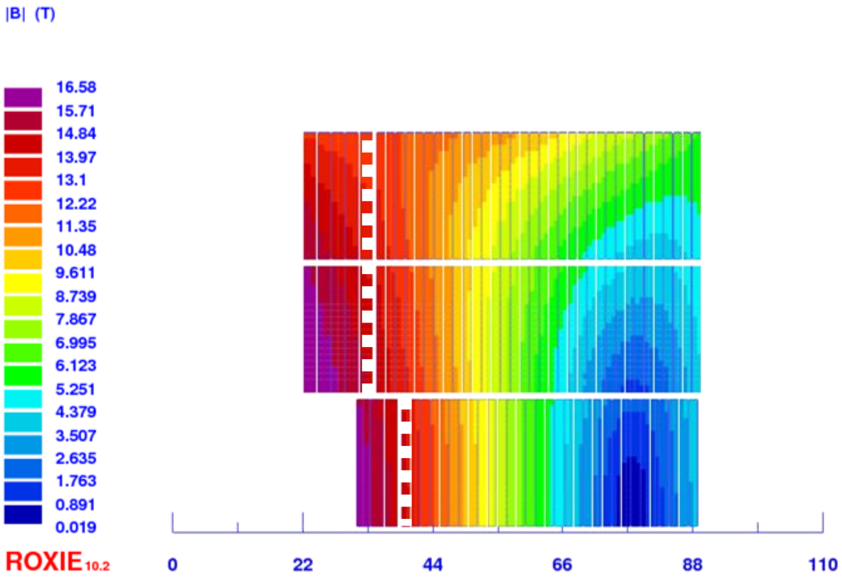


v29 (13678 tons of $Nb_3Sn$)

# 3. Design B - Enhanced

| | | **Design B** | | **Option B - Enhanced** | |
|---|---|---|---|---|---|
| | | **HF** | **LF** | **HF** | **LF** |
| **Strand & Cable** | | | | | |
| Strand diameter | mm | 1.1 | 0.8 | 1.1 | 0.7 |
| Cu2SC ratio | | 1 | 1 | 1 | 1.2 |
| # of strands in cable | | **36** | **50** | **36** | **57** |
| **coil dimensions** | | | | | |
| number of conductors | | **11** | **101** | **13** | **99** |
| coil area (per aperture), including insulation | mm2 | 2264 | 15897 | 2676 | 13870 |
| coil area (per coil) ,including insulation | mm2 | 1132 | 7948 | 1338 | 6935 |
| conductor area per coil | mm2 | 5829 | | 5233 | |
| r | mm | 25 | | 25 | |
| w/r | w_eq | 2.9 | | 2.7 | |
| Equivalent coil width | mm | **71.4** | | **67.3** | |
| **operation parameters (16T)** | | | | | |
| **Inom** | **A** | **12790** | **12790** | **12548** | **12548** |
| **Jsc** | **A/mm2** | **748** | **1018** | **734** | **1258** |
| **Jcu** | **A/mm2** | **748** | **1018** | **734** | **1049** |
| **Jeng** | **A/mm2** | **374** | **509** | **367** | **572** |
| **Joverall** | **A/mm2** | **249** | **325** | **244** | **358** |
| **Ratio LF/JF Joverall** | | **1.31** | | **1.47** | |
| Bore field at Inom | T | 16.00 | | 16.00 | |
| Conductor peak field at Inom | T | 16.72 | 15.33 | 16.72 | 14.79 |
| **short sample** | | | | | |
| Short sample current Iss at 4.2 K | A | 14198 | 14502 | 13993 | 14009 |
| Coil peak field at 4.2 K Iss | T | 18.25 | 17.07 | 18.20 | 17.00 |
| Margin on the load line at 4.2 K | % | 10 | 12 | 10 | 10 |
| Short sample current Iss at 1.9 K | A | 15703 | 16035 | 15498 | 15505 |
| Coil peak field at 1.9 Iss | T | 19.97 | 18.66 | 19.90 | 18.60 |
| Margin on the load line at 1.9 K | % | 19 | 20 | 19 | 19 |

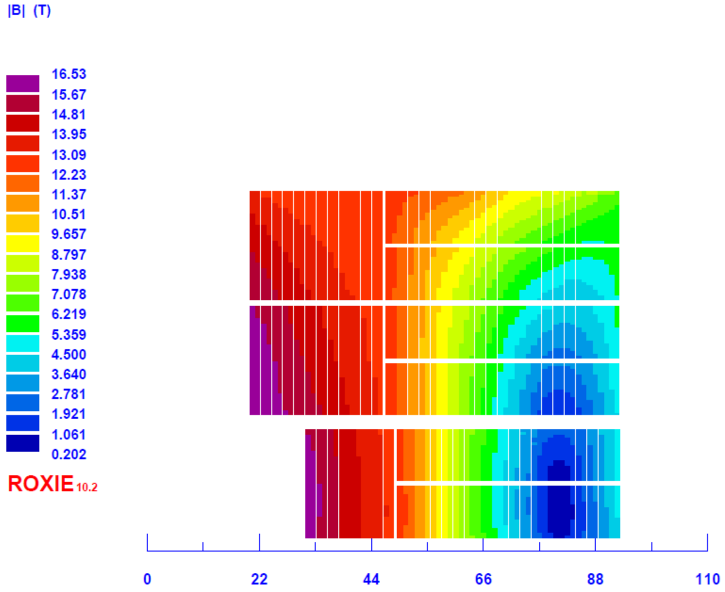
- Coil size can be reduced by 6 % when increasing the grading ratio from 1.3 to 1.5
- As a drawback, the number of strands of the low field cable is 57 → risk in terms of mechanical stability
- Even for the enhance version, coil size is 3 % bigger than for the Design option A

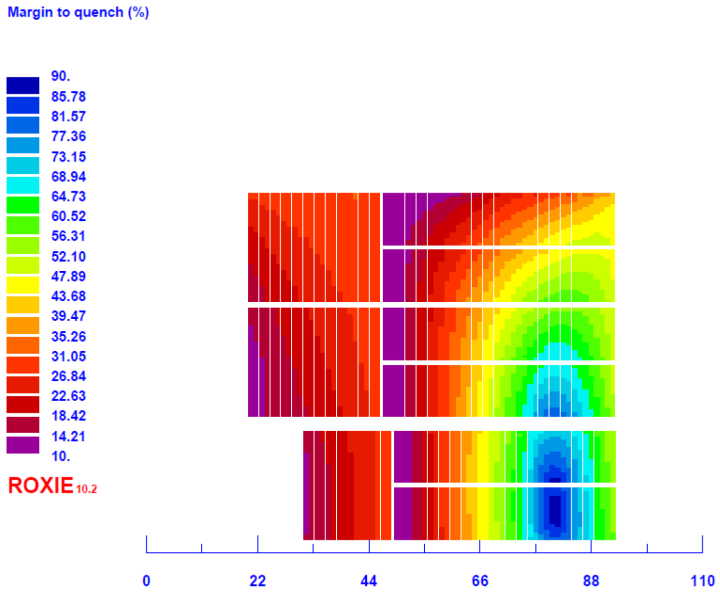


v41 (12278 tons of $Nb_3Sn$)

# 3. Design C

| | | Design C | |
|---|---|---|---|
| | | **HF** | **LF** |
| **Strand & Cable** | | | |
| Strand diameter | **mm** | 1 | 1 |
| Cu2SC ratio | | 1 | 2 |
| # of strands in cable | | **40** | **19** |
| **coil dimensions** | | | |
| number of conductors | | **32** | **124** |
| coil area (per aperture), including insulation | mm2 | 6061 | 11329 |
| coil area (per coil) ,including insulation | mm2 | 3030 | 5665 |
| conductor area per coil | mm2 | 5711 | |
| r | mm | 25 | |
| w/r | w_eq | 2.8 | |
| Equivalent coil width | mm | 69.5 | |
| **operation parameters (16T)** | | | |
| **Inom** | **A** | **9800** | **9800** |
| **Jsc** | **A/mm2** | **624** | **1970** |
| **Jcu** | **A/mm2** | **624** | **985** |
| **Jeng** | **A/mm2** | **312** | **657** |
| **Joverall** | **A/mm2** | **207** | **429** |
| **Ratio LF/JF Joverall** | | **2.07** | |
| Bore field at Inom | T | 16.00 | |
| Conductor peak field at Inom | T | 16.53 | 12.99 |
| **short sample limits** | | | |
| Short sample current Iss at 4.2 K | A | 11263 | 10973 |
| Coil peak field at 4.2 K Iss | T | 18.80 | 14.30 |
| Margin on the load line at 4.2 K | % | 13 | 11 |
| Short sample current Iss at 1.9 K | A | 12456 | 12087 |
| Coil peak field at 1.9 Iss | T | 20.50 | 15.60 |
| Margin on the load line at 1.9 K | % | 21 | 19 |





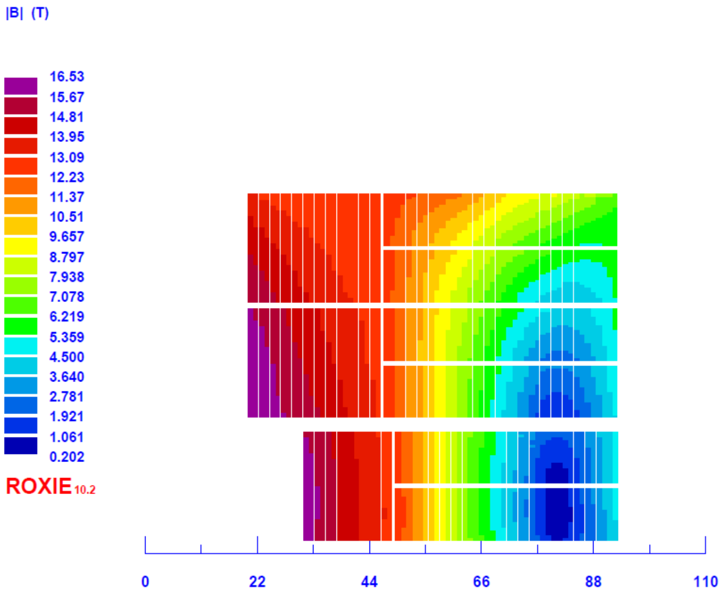
v26 (13400 tons of $Nb_3Sn$)

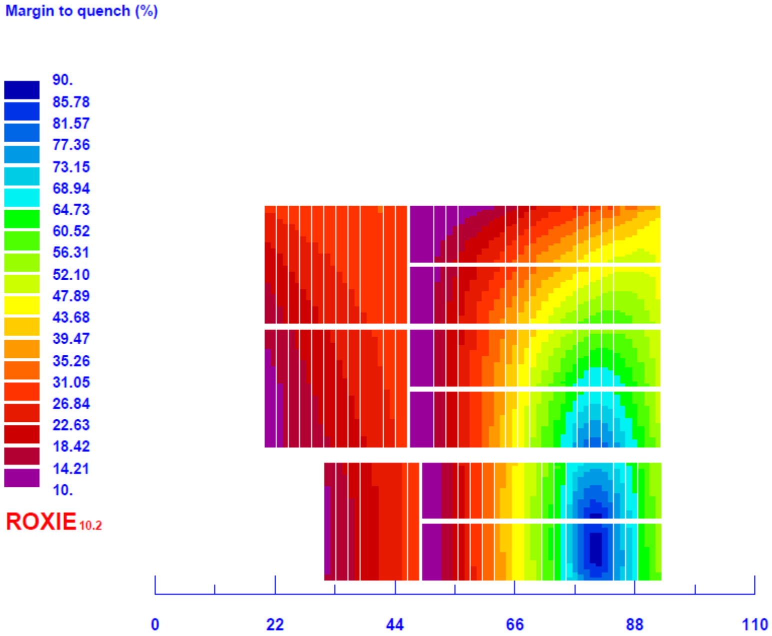
# 3. Design C

**Design limited by the high current density in the low field.**

In order to be able to protect (time margin > 45 ms), we need a copper to superconductor ≥ 2.

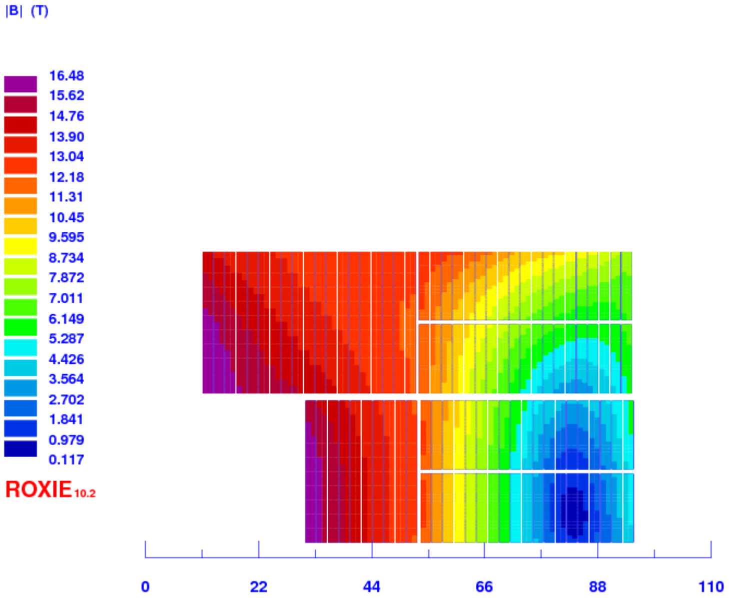
- An increase of the copper to superconductor from 2 to 2.5 increases the time margin by ~ 5 ms.
- An increase on the operation current of ~ 1 kA implies 16 ms decrease on the time margin (assuming inductance does not change).

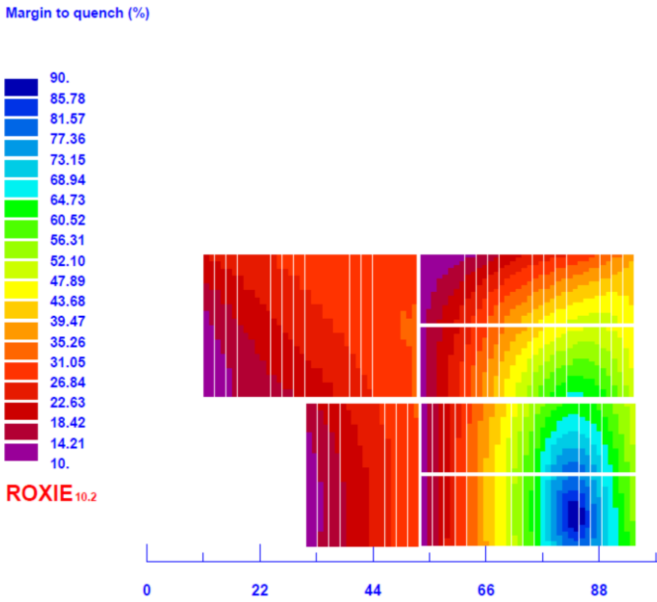




# 3. Design D

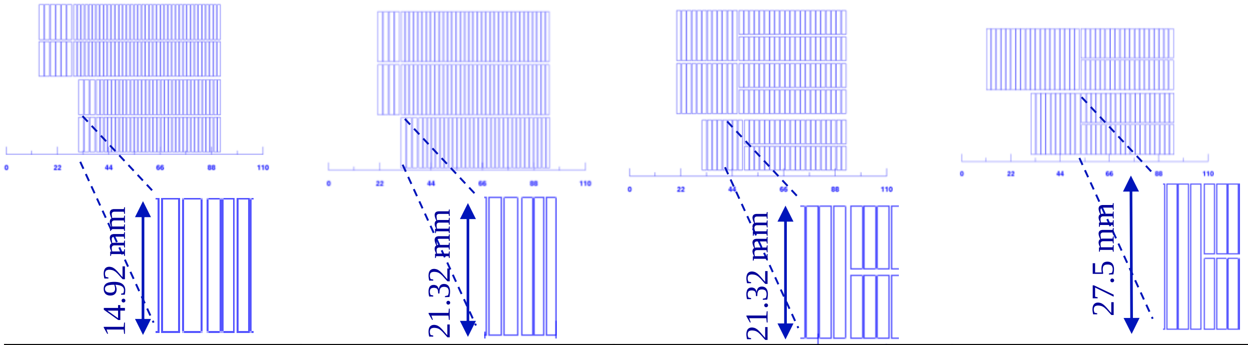
|  |  | Design D |  |
|---|---|---|---|
|  |  | HF | HF |
| **Strand & Cable** |  |  |  |
| Strand diameter | **mm** | 1 | 1 |
| Cu2SC ratio |  | 1 | 2 |
| # of strands in cable |  | **51** | **25** |
| **coil dimensions** |  |  |  |
| number of conductors |  | **28** | **78** |
| coil area (per aperture), including insulation | mm2 | 6819 | 9258 |
| coil area (per coil) ,including insulation | mm2 | 3409 | 4629 |
| conductor area per coil | mm2 | 5306 |  |
| r | mm | 25 |  |
| w/r | w_eq | 2.6 |  |
| Equivalent coil width | mm | 66.1 |  |
| **operation parameters (16T)** |  |  |  |
| **Inom** | **A** | **13633** | **13633** |
| **Jsc** | **A/mm2** | **681** | **2083** |
| **Jcu** | **A/mm2** | **681** | **1041** |
| **Jeng** | **A/mm2** | **340** | **694** |
| **Joverall** | **A/mm2** | **224** | **459** |
| **Ratio LF/JF Joverall** |  | **2.05** |  |
| Bore field at Inom | T | 16.00 |  |
| Conductor peak field at Inom | T | 16.48 | 12.72 |
| **short sample limits** |  |  |  |
| Short sample current Iss at 4.2 K | A | 15521 | 15111 |
| Coil peak field at 4.2 K Iss | T | 18.46 | 13.91 |
| Margin on the load line at 4.2 K | % | 12 | 10 |
| Short sample current Iss at 1.9 K | A | 17124 | 16650 |
| Coil peak field at 1.9 Iss | T | 20.15 | 16.65 |
| Margin on the load line at 1.9 K | % | 20 | 18 |





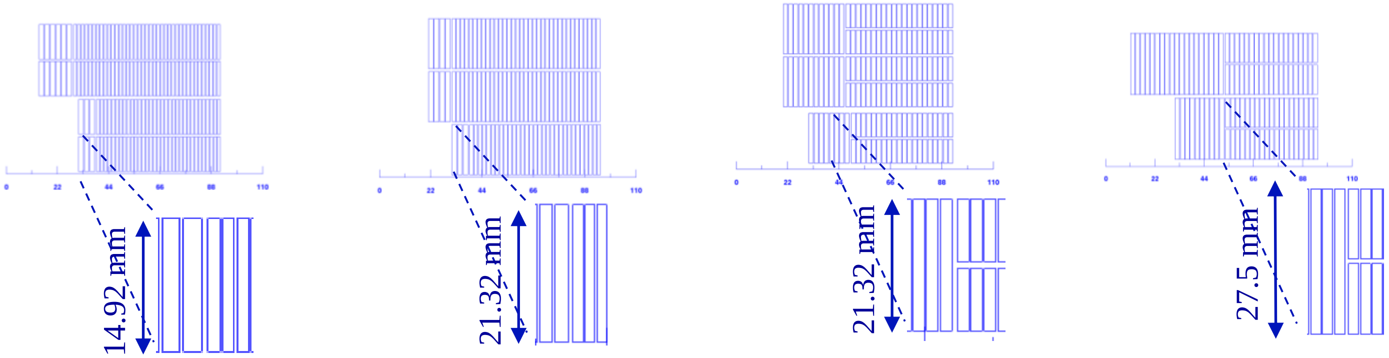
v34 (12450 tons of $Nb_3Sn$)

# 3. Designs Comparison: Coil size

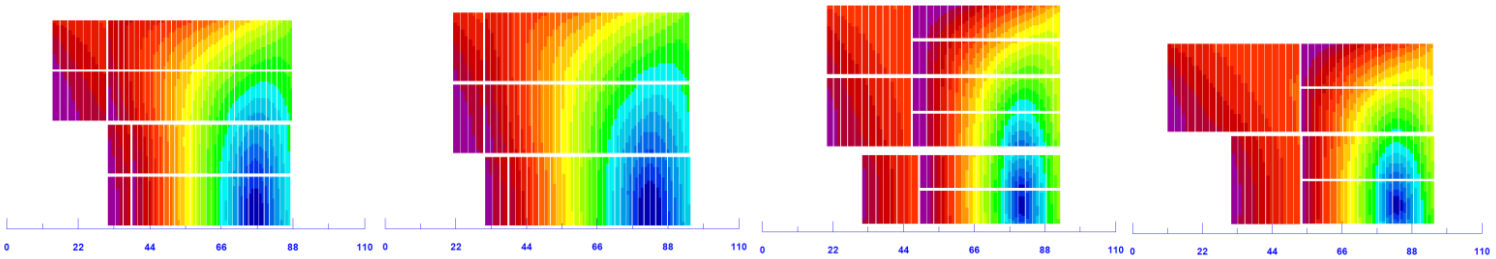


| | | **Design A** | | **Design B** | | **Design C** | | **Design D** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **HF** | **LF** | **HF** | **LF** | **HF** | **LF** | **HF** | **HF** |
| Strand diameter | **mm** | 1.1 | 0.7 | 1.1 | 0.8 | 1 | 1 | 1 | 1 |
| Cu2SC ratio | | 1 | 1.15 | 1 | 1 | 1 | 2 | 1 | 2 |
| # of strands in cable | | **26** | **40** | **36** | **50** | **40** | **19** | **51** | **25** |
| number of conductors | | **20** | **130** | **11** | **101** | **32** | **124** | **28** | **78** |
| conductor area per coil | mm2 | 4991 | | 5829 | | 5711 | | 5306 | |
| w/r | w_eq | 2.6 | | 2.9 | | 2.8 | | 2.6 | |
| Equivalent coil width | mm | 65.2 | | 71.4 | | 69.5 | | 66.1 | |
| **Operation Parameters (16T)** | | | | | | | | | |
| **Inom** | **A** | **9310** | **9310** | **12790** | **12790** | **9800** | **9800** | **13633** | **13633** |
| **Jsc** | **A/mm2** | **754** | **1300** | **748** | **1018** | **624** | **1970** | **681** | **2083** |
| **Jcu** | **A/mm2** | **754** | **1131** | **748** | **1018** | **624** | **985** | **681** | **1041** |
| **Jeng** | **A/mm2** | **377** | **605** | **374** | **509** | **312** | **657** | **340** | **694** |
| **Joverall** | **A/mm2** | **257** | **378** | **249** | **325** | **207** | **429** | **224** | **459** |
| **Ratio LF/JF Joverall** | | **1.47** | | **1.31** | | **2.07** | | **2.05** | |
| Bore field at Inom | T | 16.00 | | 16.00 | | 16.00 | | 16.00 | |
| Conductor peak field at Inom | T | 16.58 | 14.71 | 16.63 | 15.29 | 16.53 | 12.99 | 16.48 | 12.72 |
| **Short sample limit** | | | | | | | | | |
| Short sample current Iss at 4.2 K | A | 10378 | 10382 | 14198 | 14502 | 11263 | 10973 | 15521 | 15111 |
| Coil peak field at 4.2 K Iss | T | 18.20 | 16.20 | 18.25 | 17.07 | 18.80 | 14.30 | 18.46 | 13.91 |
| Margin on the load line at 4.2 K | % | **10** | **10** | **10** | **12** | **13** | **11** | **12** | **10** |
| Short sample current Iss at 1.9 K | A | 11465 | 11456 | 15703 | 16035 | 12456 | 12087 | 17124 | 16650 |
| Coil peak field at 1.9 Iss | T | 19.90 | 17.70 | 19.97 | 18.66 | 20.50 | 15.60 | 20.15 | 16.65 |
| Margin on the load line at 1.9 K | % | **19** | **19** | **19** | **20** | **21** | **19** | **20** | **18** |

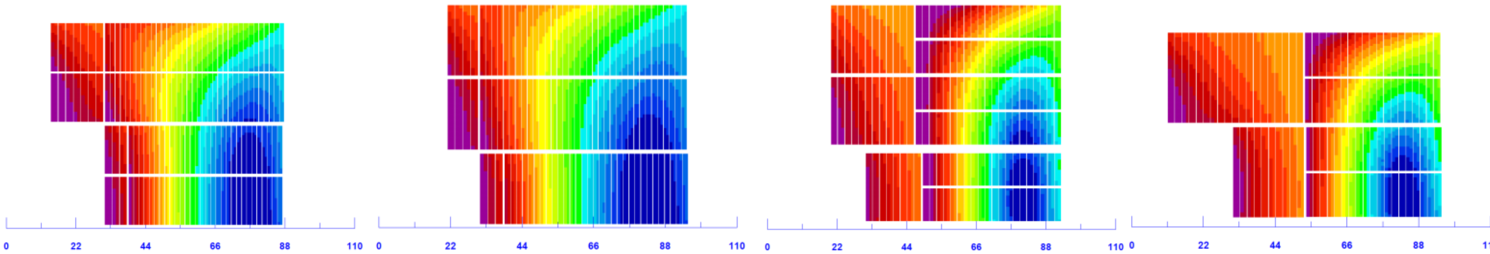
# 3. Designs comparison: Margin



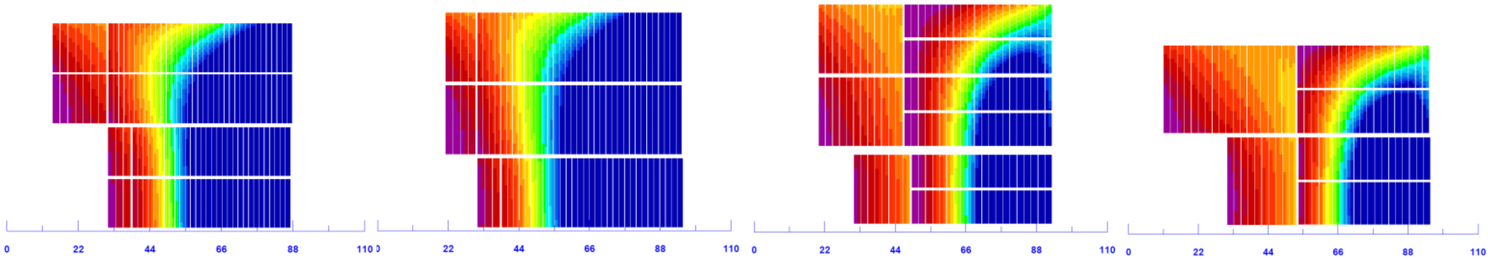
Load line
margin
[10,90]%



Temperature
margin
[2,10] K



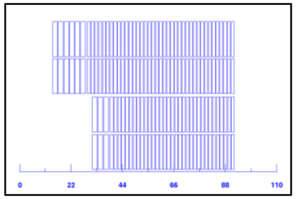
Engineering current
density margin
[200, 2000] A/mm$^2$



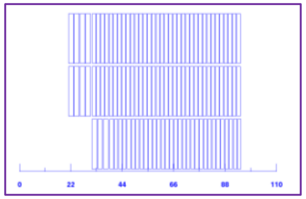
Design A Design B Design C Design D

# 3. Designs comparison: load lines

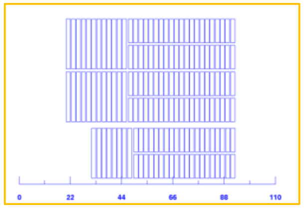
Design A



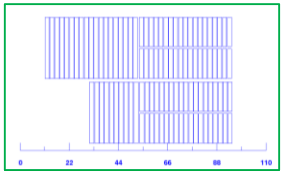
Design B

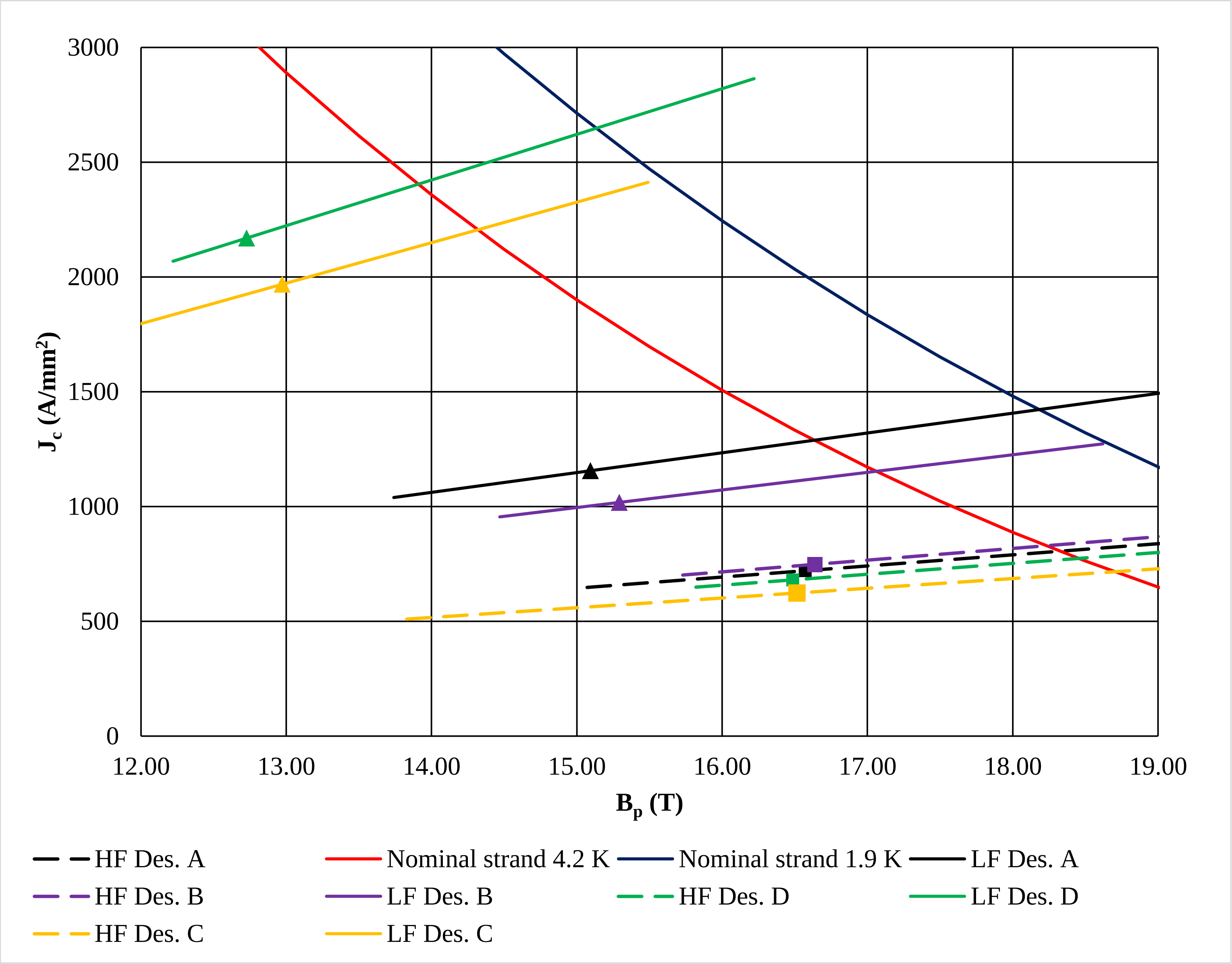


Design C

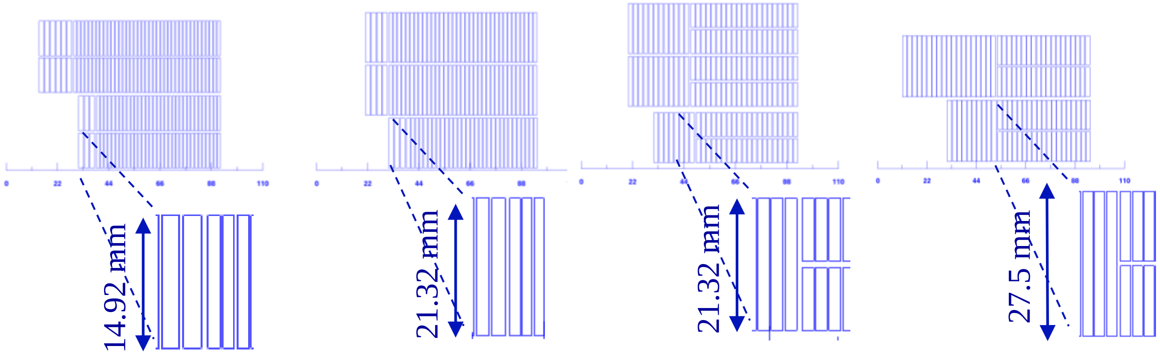


Design D



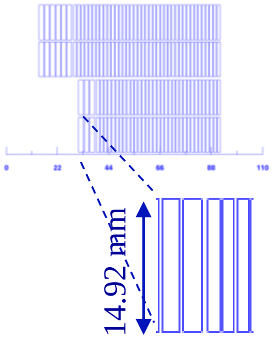


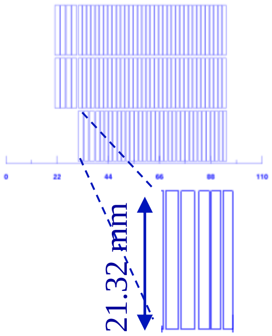
# 3. Designs Comparison: Protection

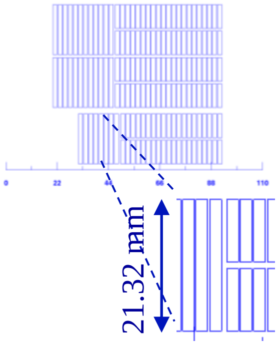


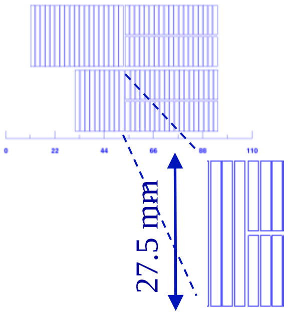
| | | Design A | | Design B | | Design C | | Design D | |
|---|---|---|---|---|---|---|---|---|---|
| | | **HF** | **LF** | **HF** | **LF** | **HF** | **LF** | **HF** | **HF** |
| **Copper to superconductor ratio** | | 1 | 1.15 | 1 | 1 | 1 | 2 | 1 | 2 |
| **Equivalent coil width** | | 65.2 | | 71.4 | | 69.5 | | 66.1 | |
| **Nominal Current** | **A** | **9310** | **9310** | **12790** | **12790** | **9800** | **9800** | **13633** | **13633** |
| **Jsc** | **A/mm2** | **754** | **1300** | **748** | **1018** | **624** | **1970** | **681** | **2083** |
| **Jcu** | **A/mm2** | **754** | **1131** | **748** | **1018** | **624** | **985** | **681** | **1041** |
| **Jeng** | **A/mm2** | **377** | **605** | **374** | **509** | **312** | **657** | **340** | **694** |
| **Joverall** | **A/mm2** | **257** | **378** | **249** | **325** | **207** | **429** | **224** | **459** |
| **Protection with Quench Heaters** | | | | | | | | | |
| MIITs to reach 300 K (conductor+insulation)@ LF | MA2s | | 14.12 | | 34.59 | | 17.59 | | 30.27 |
| MIITs to reach 300 K (conductor+insulation) @HF | MA2s | 32.30 | | 62.66 | | 53.17 | | 86.21 | |
| Stored energy in straight sect. at Inom (per aperture) | kJ/m | 1743.30 | | 1891.40 | | 2136.60 | | 2001.50 | |
| Stored energy density | MJ/m3 | **111** | | **104** | | **123** | | **124** | |
| Differential inductance at Inom (per aperture) | mH/m | 37.19 | | 20.99 | | 41.92 | | 20.07 | |
| MIITs consumed during decay | MA2s | 10.33 | 10.25 | 23.33 | 23.33 | 13.36 | 13.36 | 23.83 | 23.83 |
| time margin | ms | **253** | **45** | **240** | **69** | **415** | **44** | **336** | **35** |

# 3. Designs Comparison: Force & Stress







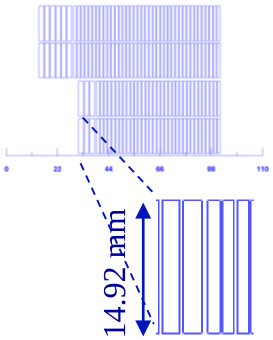


| | | **Design A** | | **Design B** | | **Design C** | | **Design D** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **HF** | **LF** | **HF** | **LF** | **HF** | **LF** | **HF** | **HF** |
| Equivalent coil width | mm | 65.2 | | 71.4 | | 69.5 | | 66.1 | |
| **Joverall** | **A/mm2** | **257** | **378** | **249** | **325** | **207** | **429** | **224** | **459** |
| coil width | mm | 56.30 | | 64.00 | | 61.82 | | 64.00 | |
| coil height | mm | 63.28 | | 66.89 | | 68.33 | | 59.60 | |
| Fx (per quadrant) at 16 T | kN/m | 9069 | | 8989 | | 9468 | | 9191 | |
| Fy (per quadrant) at 16 T | kN/m | -4016 | | -4109 | | -4329 | | -4579 | |
| Fx/CoilHeight at 16 T | MPa | **143** | | **134** | | **139** | | **154** | |
| Fy/CoilWidth at 16 T | MPa | -71 | | -64 | | -70 | | -72 | |
| Fx (per quadrant) at 18 T | kN/m | 11400 | | 11340 | | 11010 | | 11530 | |
| Fy (per quadrant) at 18 T | kN/m | -5271 | | -5430 | | -5354 | | -6009 | |
| Fx/CoilHeight at 18 T | MPa | **180** | | **170** | | **178** | | **180** | |
| Fy/CoilWidth at 18 T | MPa | -94 | | -85 | | -78 | | -101 | |

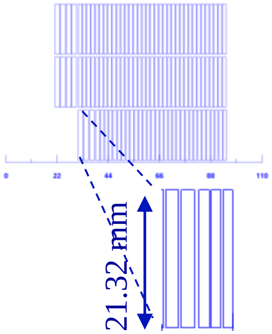
# 3. General remarks and conclusions

- The most compact, and “easiest” to build is Design A.

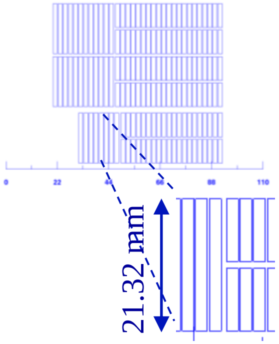
Design A



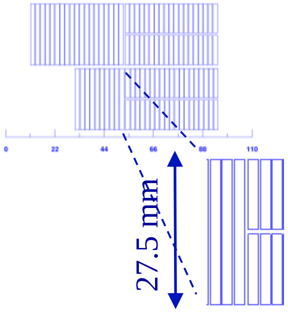
Design B



Design C



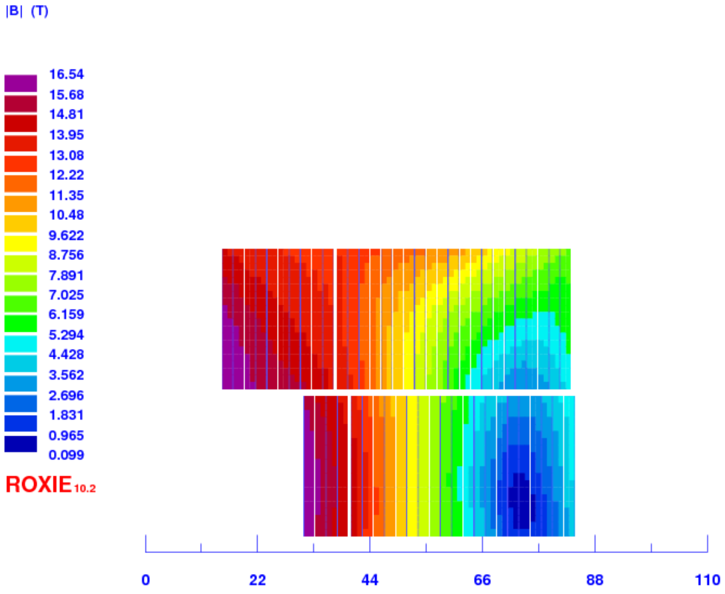
Design D

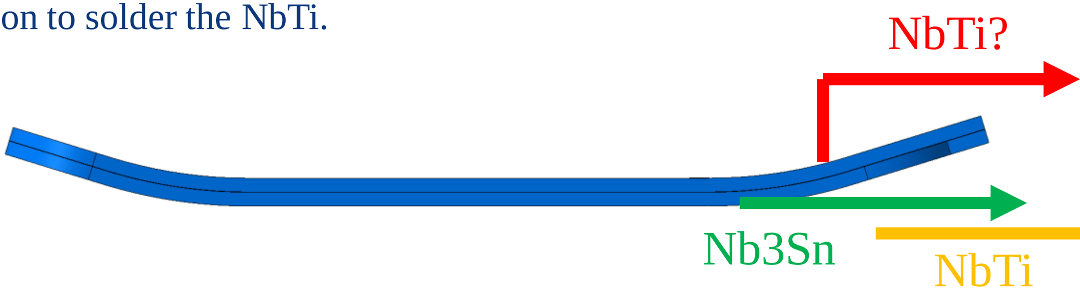


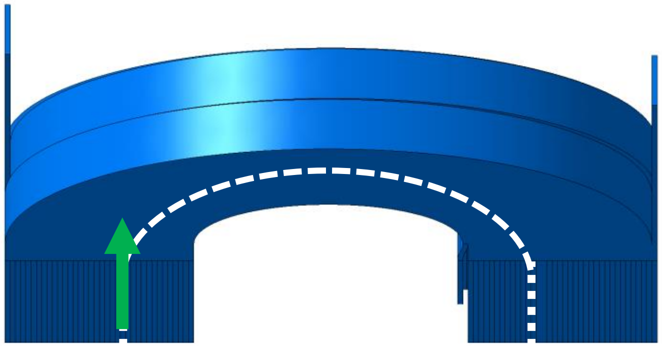
- Coil size is comparable to the achievable coil size for a cos-theta configuration.
- To further reduce the coil size, the option of two independently powered layers can be studied.

# 3. General remarks and conclusions

- Two power converters and a 50 x 1mm strands cable would lead to the most compact solution.
- We will not be able to build this in a flat coil configuration, but it might be possible with flared ends:
  - The lead of **the high field lower coil** can go out of the coil straight → $Nb_3Sn$-NbTi standard splice
  - The lead of the **high field upper coil** cannot go out of the coil straight!
    - If the field is low enough, we could solder a NbTi cable to bring out.
    - If the field is too high for NbTi, it will be difficult to set up a robust configuration to bring the lead from the coil to the low field region to solder the NbTi.



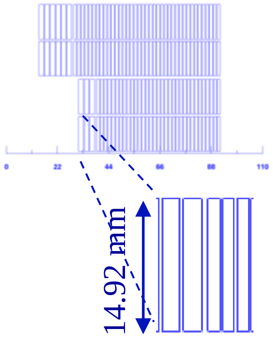




# Content

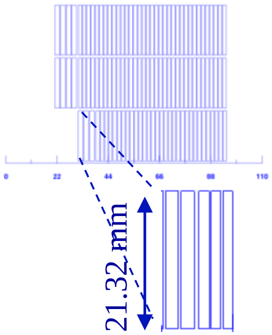
# 4. Technical challenges

## Design A



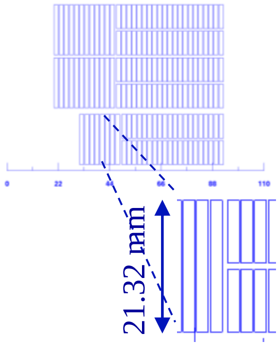
- High inductance
- $Nb_3Sn$ internal splice
- Min. conductor bending radius

## Design B



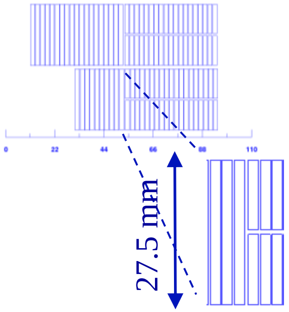
- $Nb_3Sn$ internal splice
- Cable geometry (50 strands)

## Design C



- High inductance
- $Nb_3Sn$ internal splice
- Complex coil geometry

## Design D



- $Nb_3Sn$ internal splice
- Complex coil geometry
- Min. conductor bending radius
- Cable geometry (50 strands)

# Design A: Minimum bending radius

In **block coils**:

- Typically:

$R_{min}$ = 8-10 x Cable Mid Thickness

- The lowest found in literature: HD1

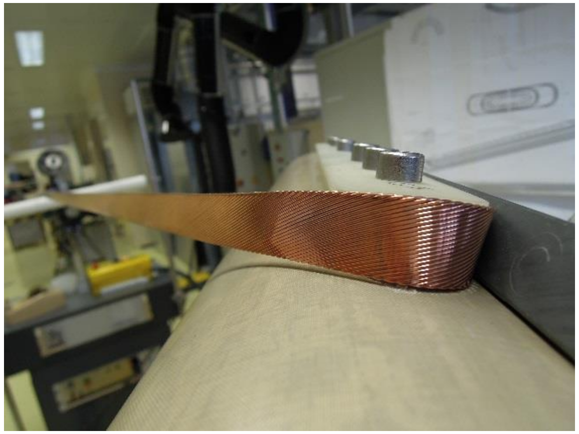
$R_{min}$ = 6.5 x Cable Mid Thickness

- In this specific design

$R_{min}$ = 7 x Cable Mid Thickness

***Remark:*** for the DS-11T dipole, this ratio is ~ 5.5 for the thin edge of the conductor

**Proposal:** winding test using SMC 11 T, RMC MQXF and FRESCA 2 in order to determine the minimum bending radius of each conductor.



We did similar tests for MQXF. For this specific test we will:

- Use RMC winding table
- Produce simple pole parts by 3 D printing with different radius (10,15 and 20 mm)

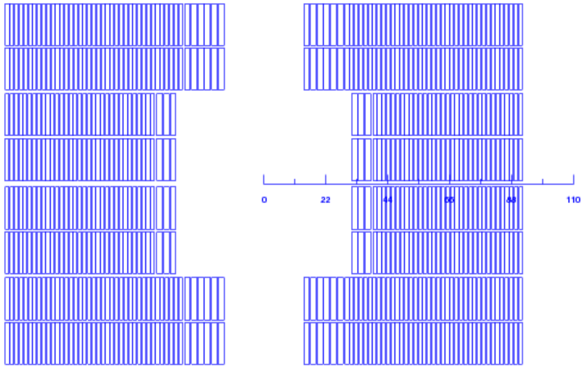
Fast and simple test

# Designs A&C: Electrical insulation

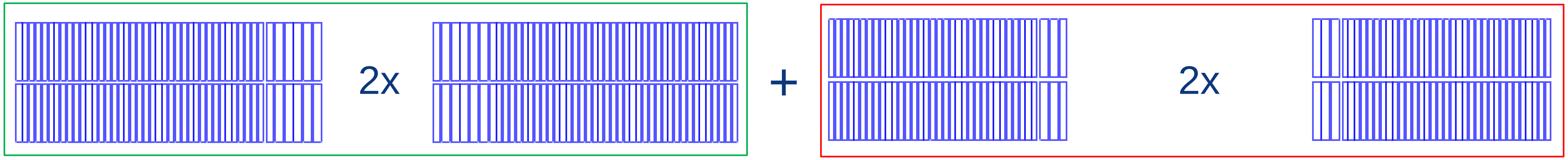
- **High inductance** ( ~ 45 mH/m)
  - High inductive voltage in case of a quench → robust electrical insulation needed.

- **Mica-Glass insulation** successfully implemented on the 11 T project.
  - Potential to improve the electrical robustness, but more R&D needed (Developments stopped within the 11 T project for a question of budget and time.)

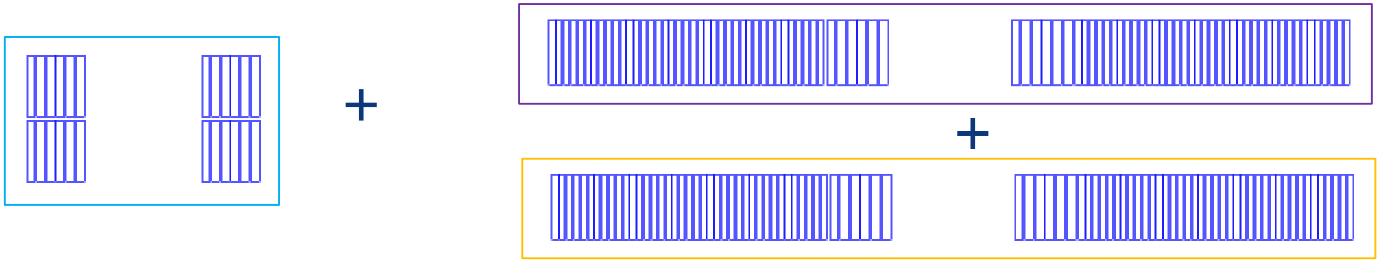
# $Nb_3Sn$ High Field Splice



- 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

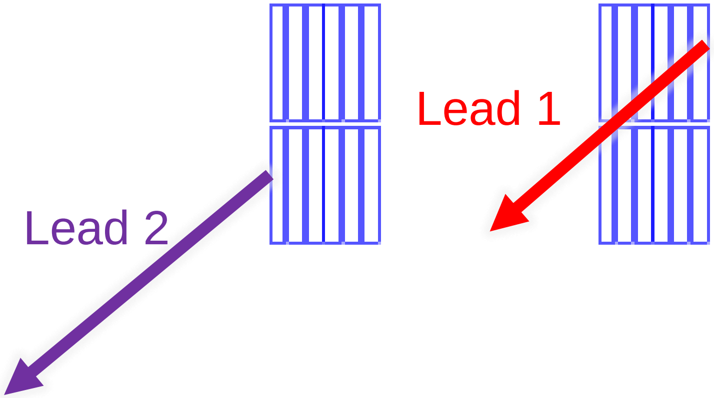
- **Two possible options:**
  - Winding + Reaction + Splicing + Impregnation
    - High field and low field are wound together and spliced after reaction
  - Winding + Reaction + Impregnation + Splicing
    - High field and low field are wound, reacted and impregnated independently, and they are spliced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

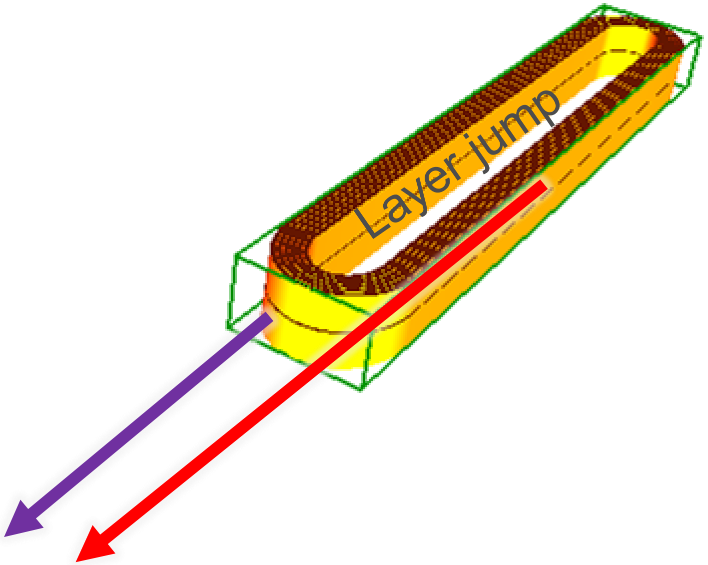
# $Nb_3Sn$ High Field Splice

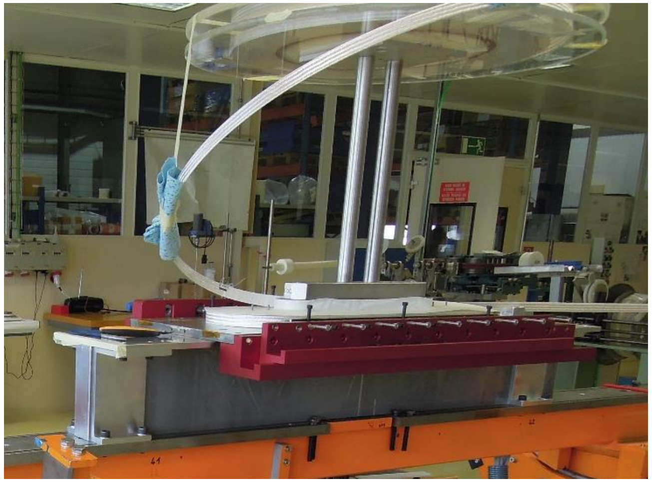
- Two possible options:
  - **Winding + Reaction + Splicing + Impregnation**
    - **High field and low field are wound together and spliced after reaction**
  - Winding + Reaction + Impregnation + Splicing
    - High field and low field are wound, reacted and impregnated independently, and they are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

# $Nb_3Sn$ High Field Splice

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

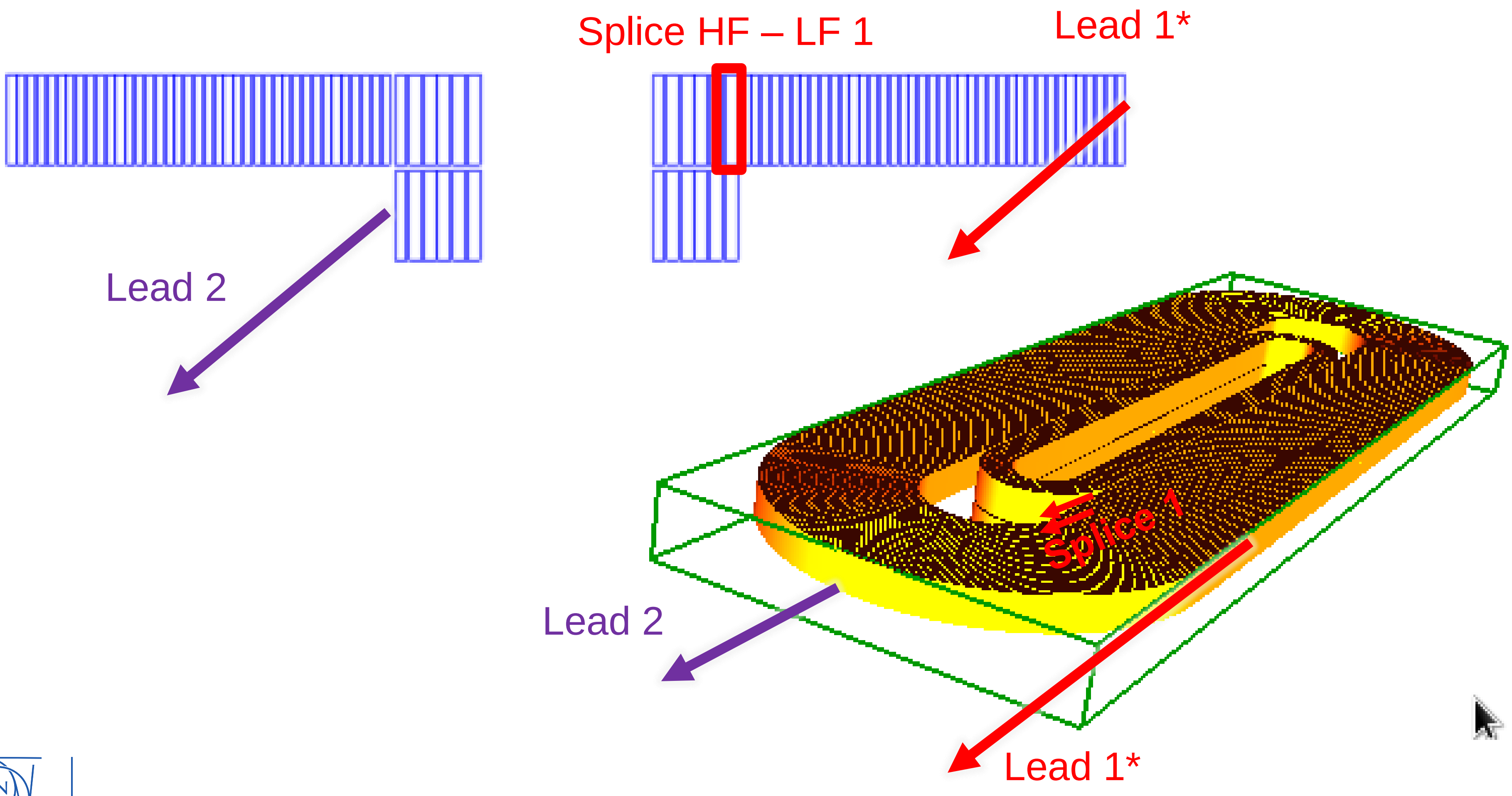






# $Nb_3Sn$ High Field Splice

## 1.2. Winding of the upper low field layer



Splice HF – LF 1

Lead 1*

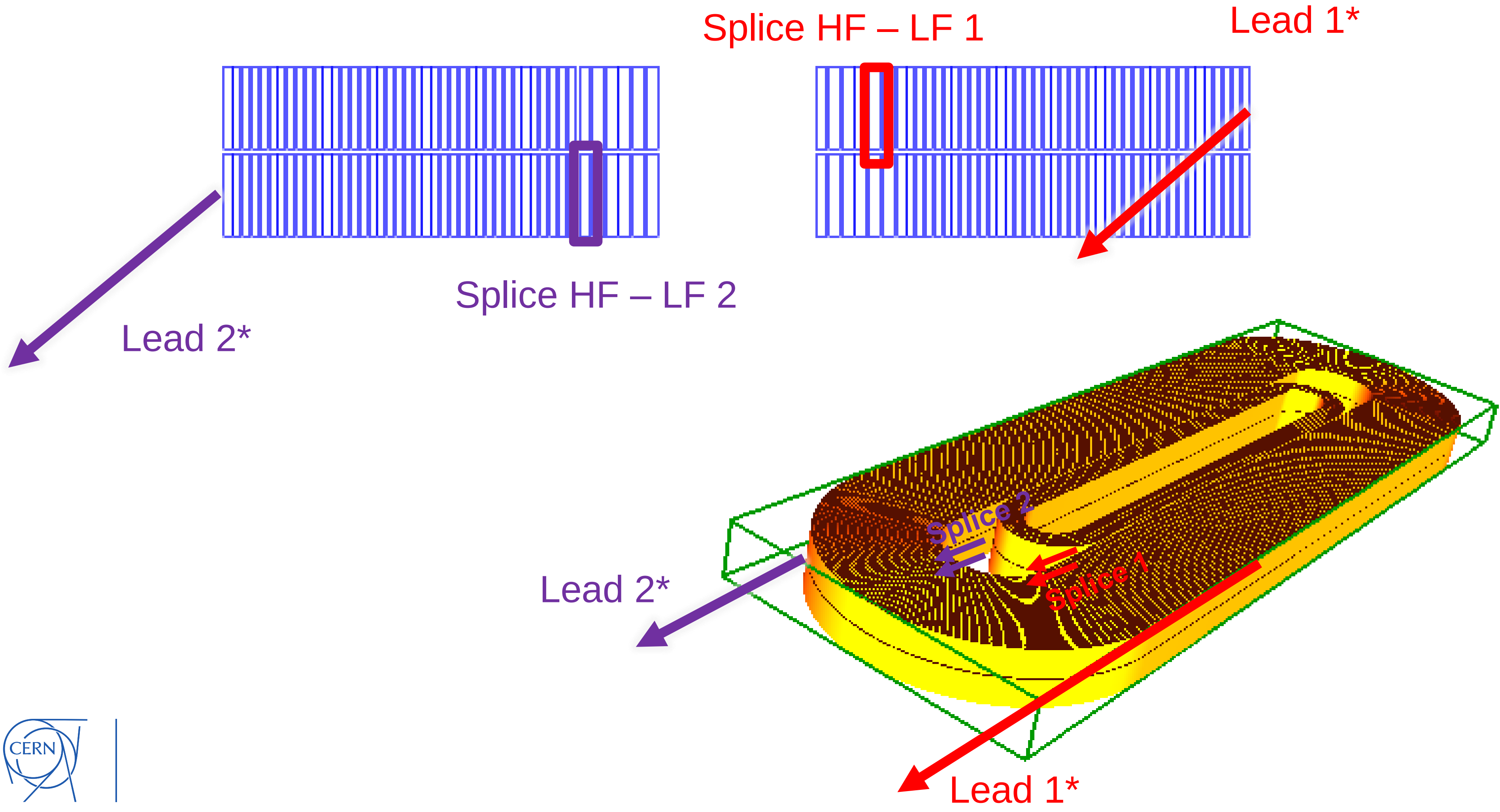
Lead 2

Lead 2

Lead 1*

# Nb$_3$Sn High Field Splice

## 1.3. Winding of the lower field block



Splice HF – LF 1

Lead 1*

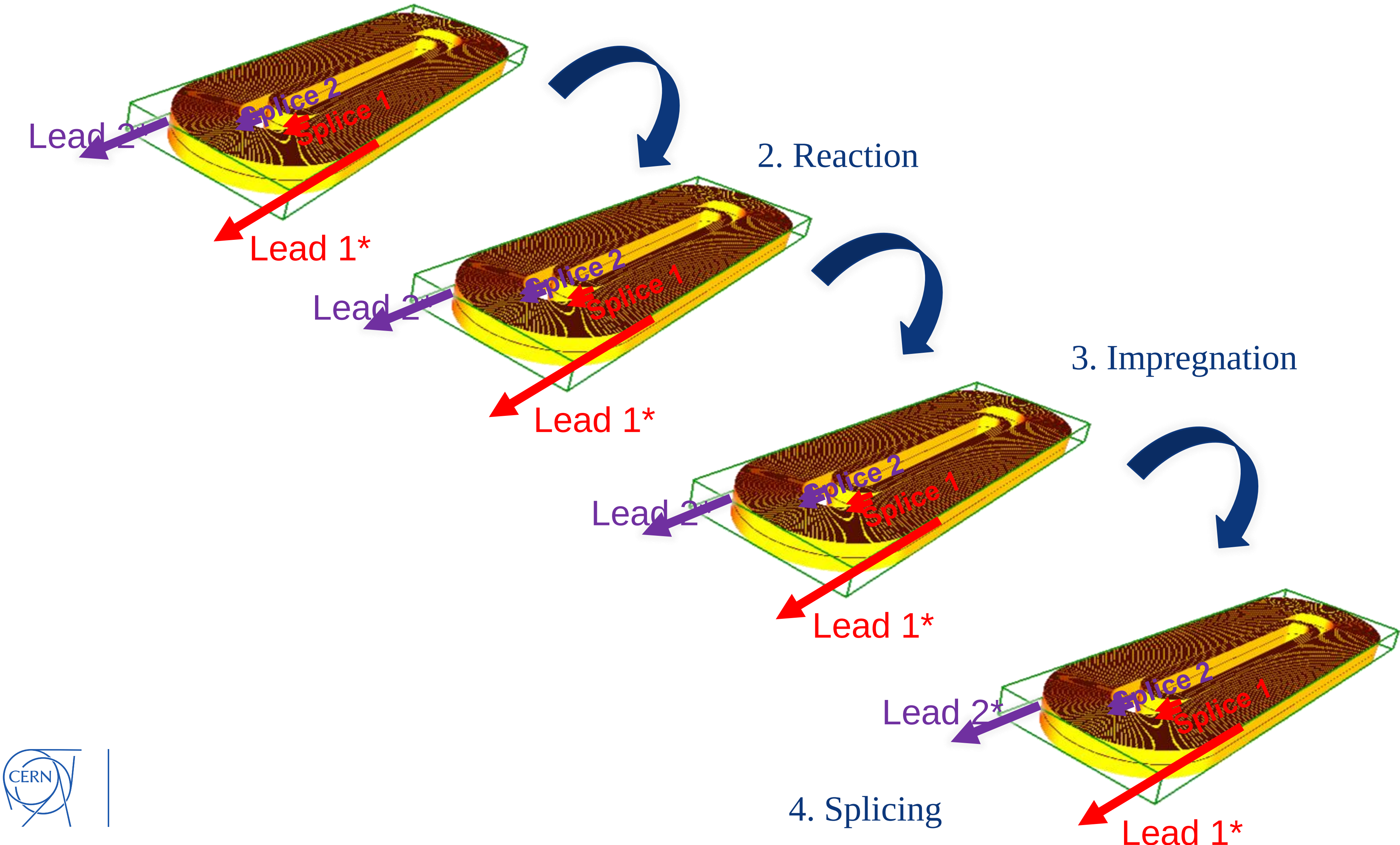
Splice HF – LF 2

Lead 2*

Lead 2*

Lead 1*

# Nb$_3$Sn High Field Splice



1. Winding

2. Reaction

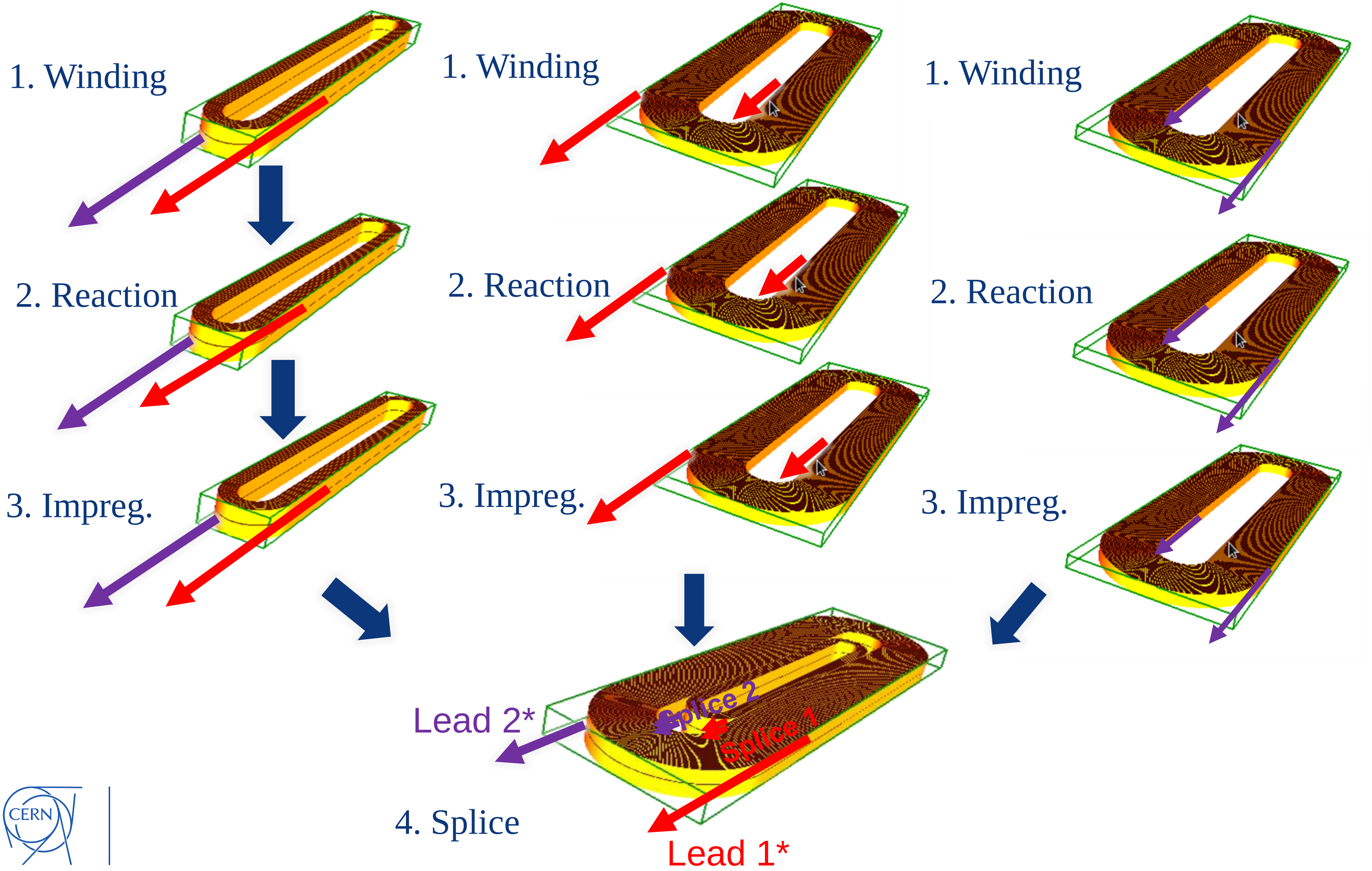
3. Impregnation

4. Splicing

# $Nb_3Sn$ 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$_3$Sn High Field Splice



1. Winding

2. Reaction

3. Impreg.

1. Winding

2. Reaction

3. Impreg.

1. Winding

2. Reaction

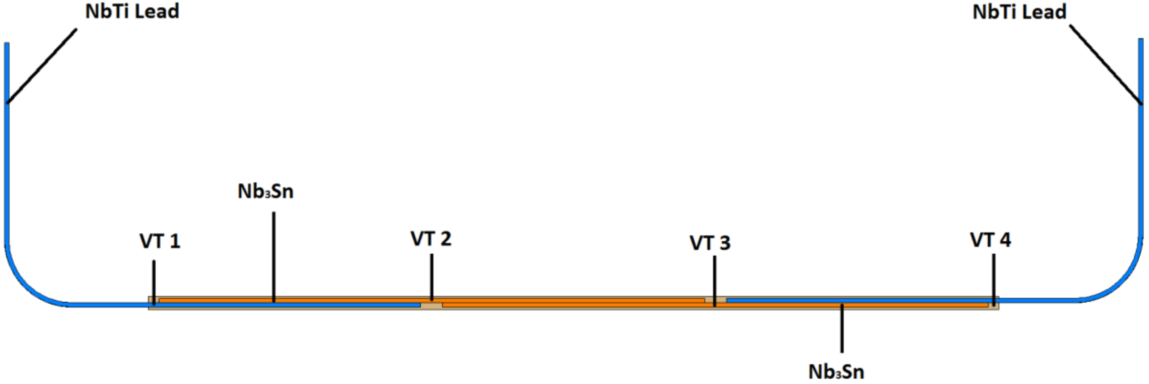
3. Impreg.

4. Splice

# $Nb_3Sn$ High Field Splice

- Questions we need to answer:
  - Can we reach a good quality splice using the same technology as in the NbTi-Nb3Sn low field splice? (i.e. $Sn_{96}Ag_4$ and halogen free flux)
  - Are there solders more suitable than $Sn_{96}Ag_4$ or $Sn_{60}Pb_{40}$?
    - We don't have the same limit in terms of melting temperature than in the case of NbTi splices.
  - Can we splice two $Nb_3Sn$ reacted (oxidized) cables without cleaning?
  - Is there a way to clean the cable without mechanical contact?

- Many of these questions can already be answered with a simple set up, measuring the contact resistance in the Diode Cryostat in SM18:

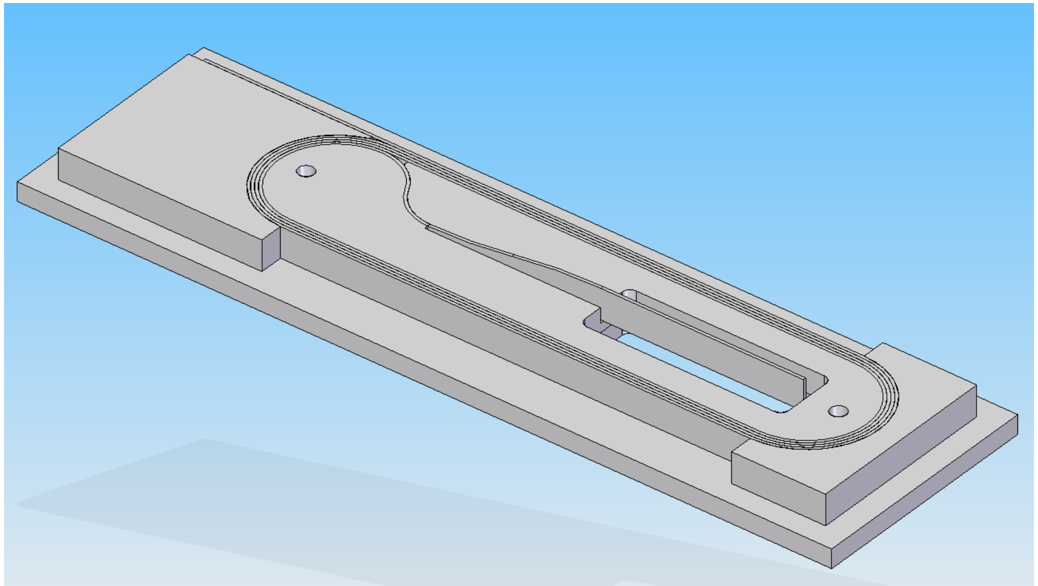


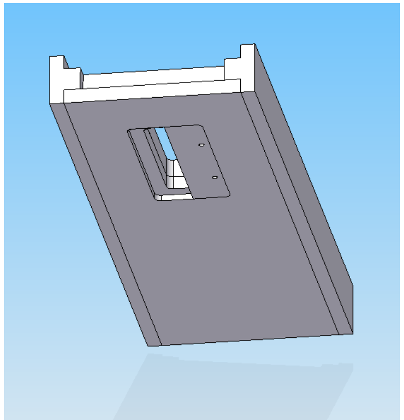
- But…this will tell us what is **a bad splice**. To know if we have a **good splice**, we need a **background field**.
  - →"Wound Conductors Test Facilities" [F. Lackner], will provide a full electrical characterization of the splice (long term development)

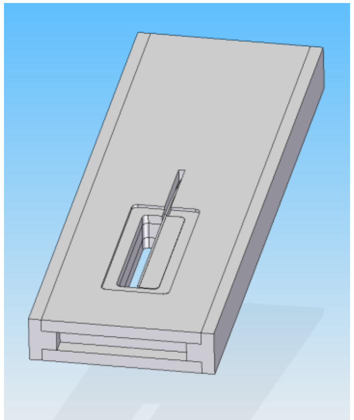
# Designs A&B: Nb$_3$Sn High Field Splice

**Our need:** Nb$_3$Sn/Nb$_3$Sn interlayer splice in **coil relevant conditions**

- On-going activity within a collaboration with STFC (UK) to develop an internal splice using RMC-ILS configuration.

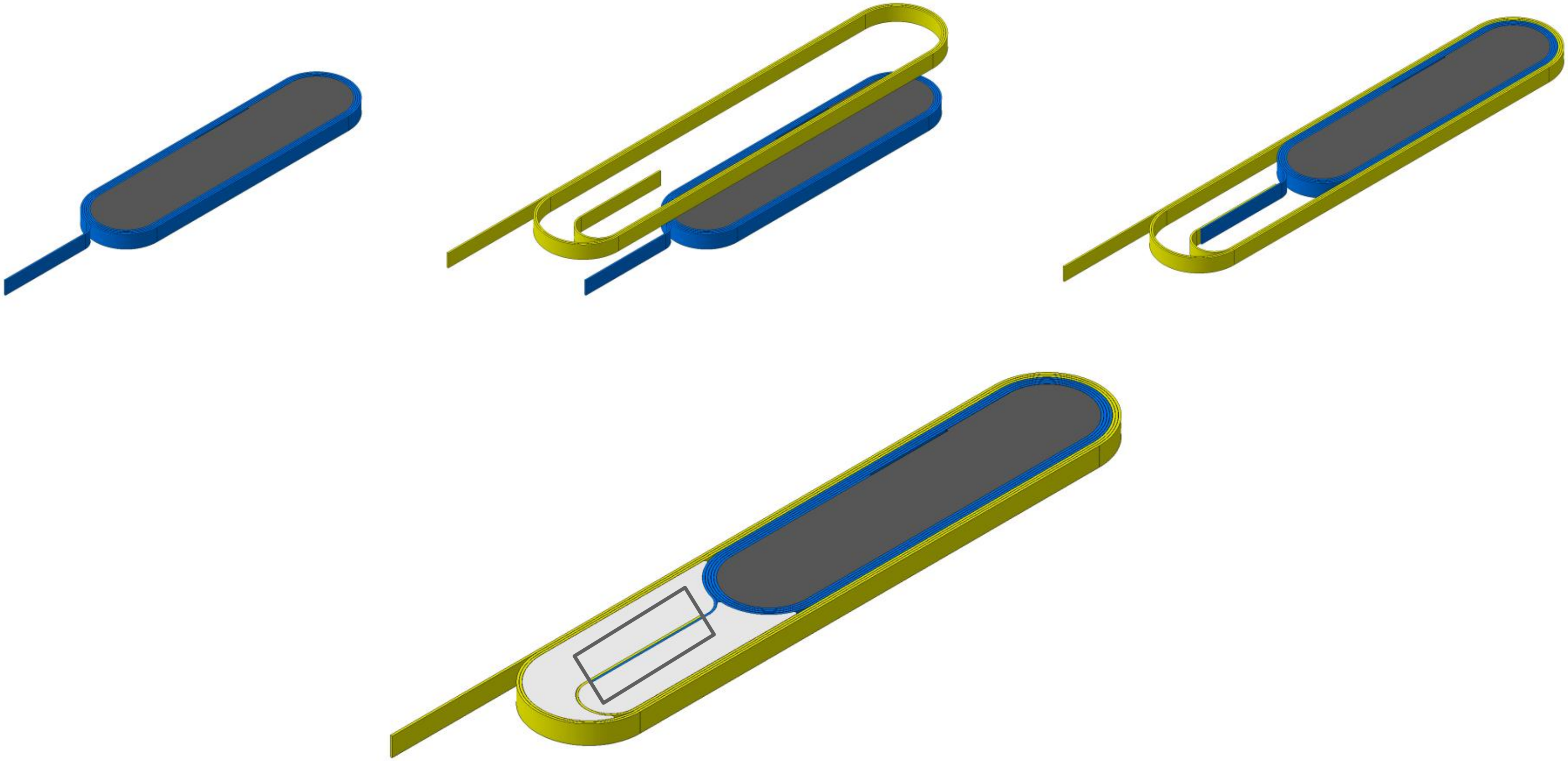






# Nb$_3$Sn High Field Splice

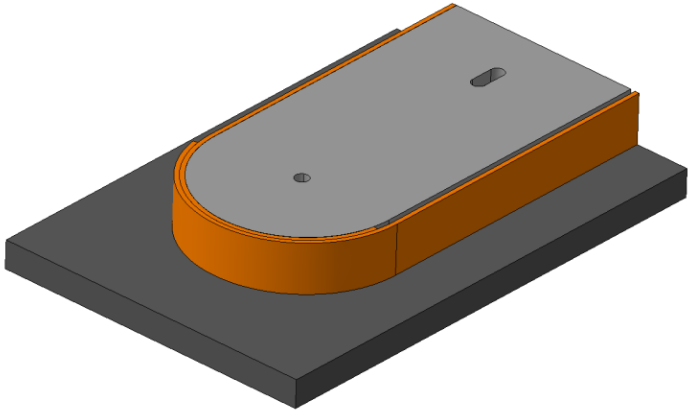
- The same concept is applicable for our case, if we perform the splice in the end region.



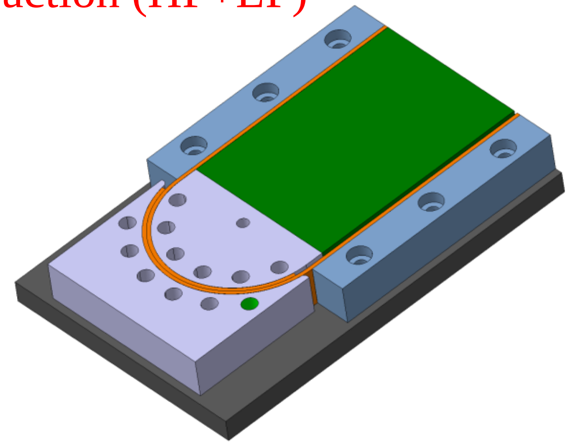
# Nb$_3$Sn High Field Splice

- But this is taken some precious longitudinal space, so there might be better ways to do it!
- We could save this room if we make the splice at the level of the coil end spacers

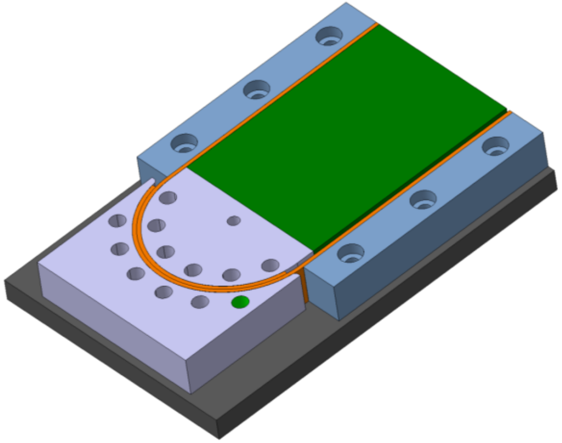
1. Winding (HF+LF)



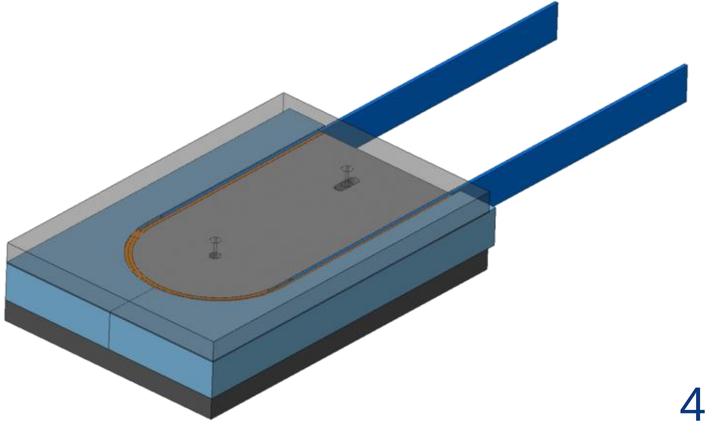
2. Reaction (HF+LF)



3. Splicing

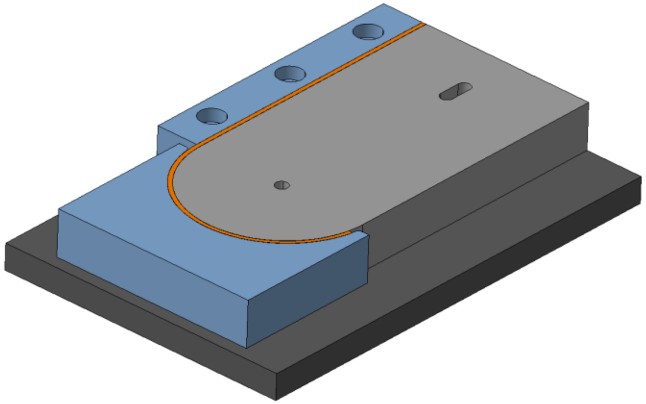


4. Impregnation

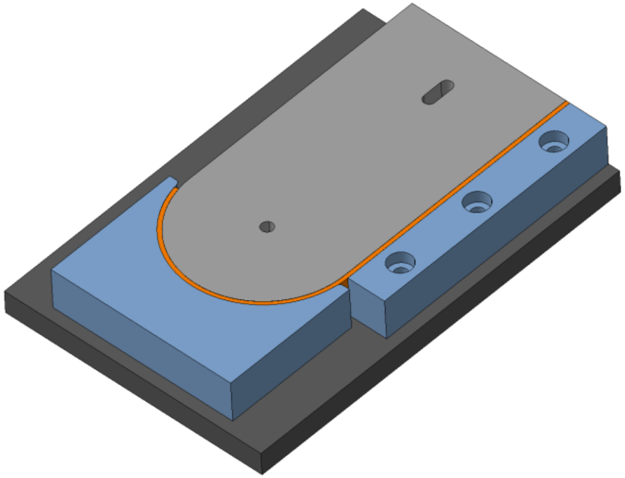


# $Nb_3Sn$ High Field Splice

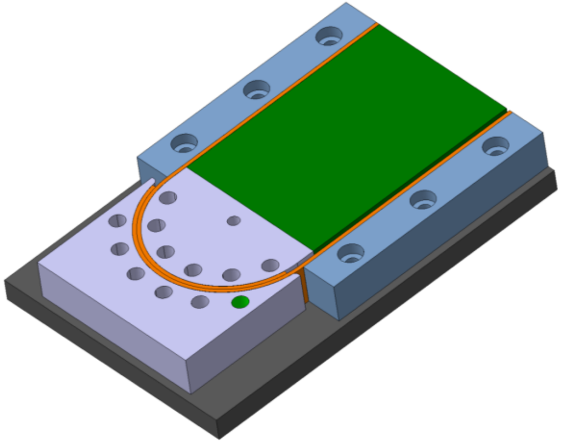
1. Winding (HF) + Reaction (HF) + Impregnation (HF)



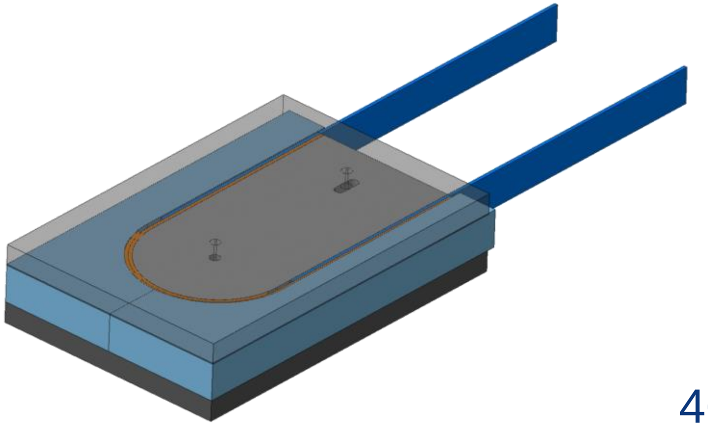
2. Winding (LF) + Reaction (LF) + Impregnation (LF)



3. Splicing

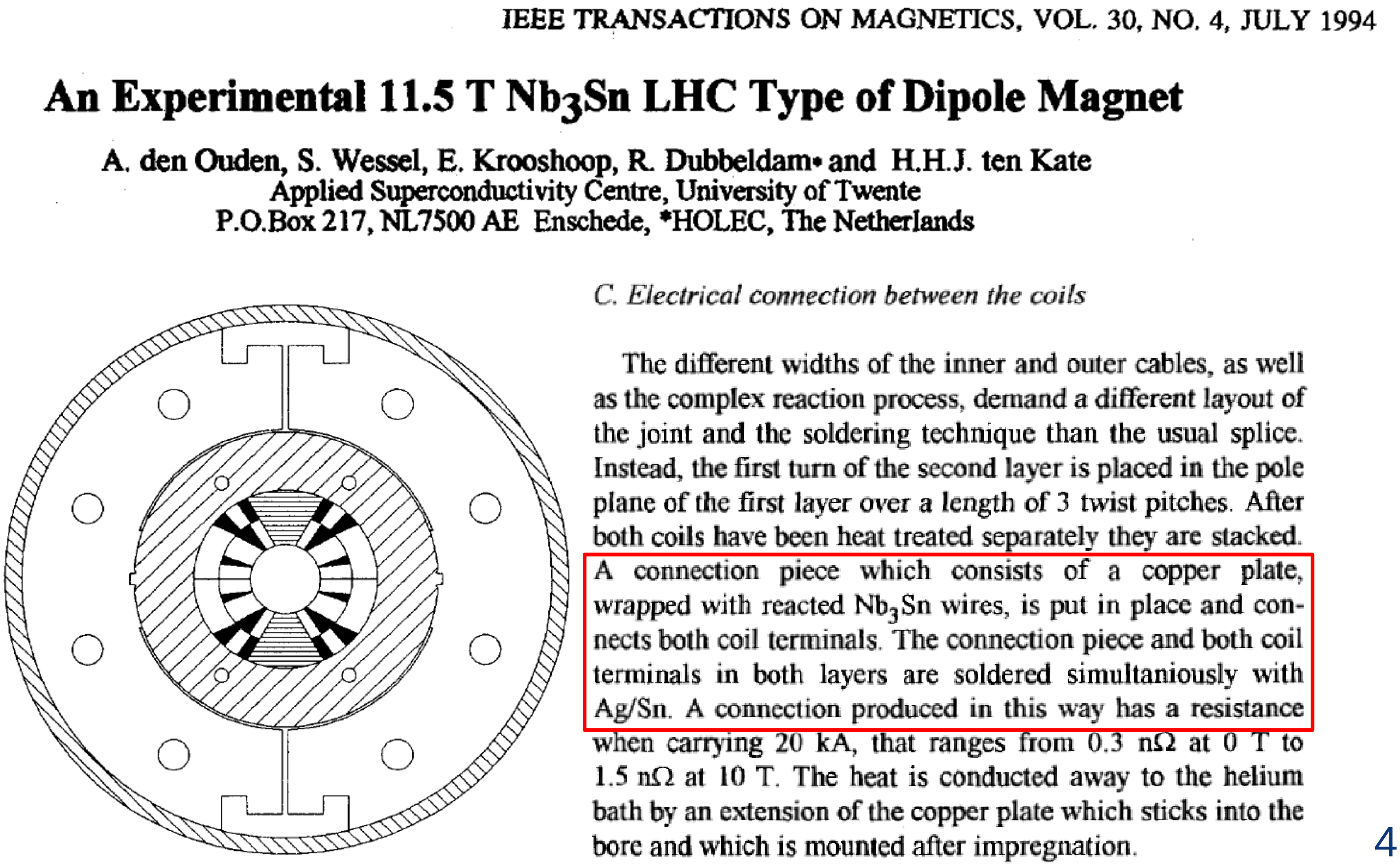


4. Impregnation



# $Nb_3Sn$ High Field Splice

- There is some room for creativity here, and we should also take a look to what was done in the past…



IEEE TRANSACTIONS ON MAGNETICS, VOL. 30, NO. 4, JULY 1994

## An Experimental 11.5 T $Nb_3Sn$ LHC Type of Dipole Magnet

A. den Ouden, S. Wessel, E. Krooshoop, R. Dubbeldam* and H.H.J. ten Kate
Applied Superconductivity Centre, University of Twente
P.O.Box 217, NL7500 AE Enschede, *HOLEC, The Netherlands

*C. Electrical connection between the coils*

The different widths of the inner and outer cables, as well as the complex reaction process, demand a different layout of the joint and the soldering technique than the usual splice. Instead, the first turn of the second layer is placed in the pole plane of the first layer over a length of 3 twist pitches. After both coils have been heat treated separately they are stacked. A connection piece which consists of a copper plate, wrapped with reacted $Nb_3Sn$ wires, is put in place and connects both coil terminals. The connection piece and both coil terminals in both layers are soldered simultaniously with Ag/Sn. A connection produced in this way has a resistance when carrying 20 kA, that ranges from 0.3 nΩ at 0 T to 1.5 nΩ at 10 T. The heat is conducted away to the helium bath by an extension of the copper plate which sticks into the bore and which is mounted after impregnation.

# Content

1. Introduction
2. Design constrains
3. Electromagnetic designs overview
4. Technical challenges and “solutions”
5. **Summary and next steps**

# Summary and next steps

- A series of solutions to grade a block coil have been discussed, with a coil equivalent width ranging from 65 to 70 mm (compared to ~85 mm for non-graded solutions).

- The most compact solution that can be build with the present constraints is “Design A”.

- Conservative design criteria for quench protection (time margin ~45 ms), which is the limiting factor for designs C and D.

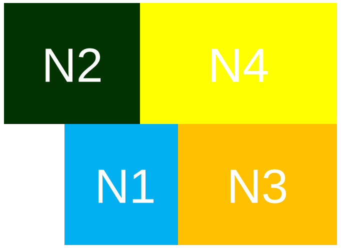
- If low operating current and high inductance is a showstopper for a magnet operating in the machine, a compact solution with wide cable (50 strands x 1 mm) and two power supplies can be a good option.

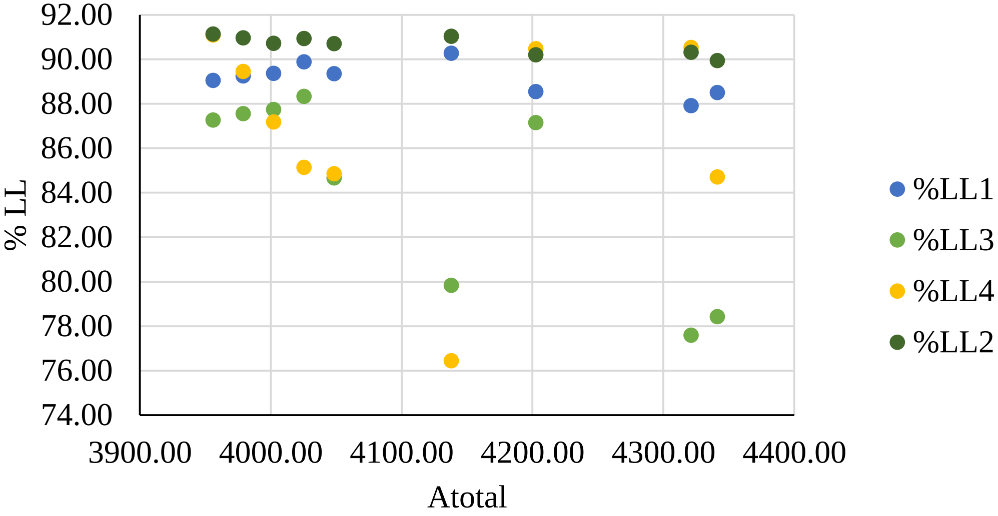
- In all the cases, the **main challenge is the development of the high field $Nb_3Sn$ splice**.

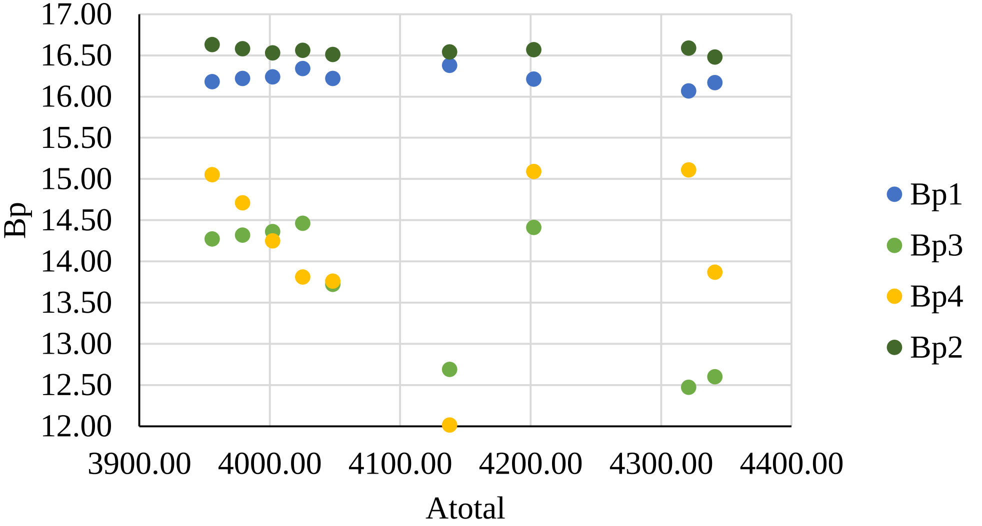
# Additional slides

# Parametric

- In general, the smallest coil is achieved when the load line margin is 10 % both in the high field and in the low field.
- But solutions can be found where the increase of coil size is not very big when the margin in the low field is increase by a factor 2:
  - The operating current can be slightly higher for the same peak field, so at the end the “lost” due to having less coil with high current density is balanced by the slightly higher current density

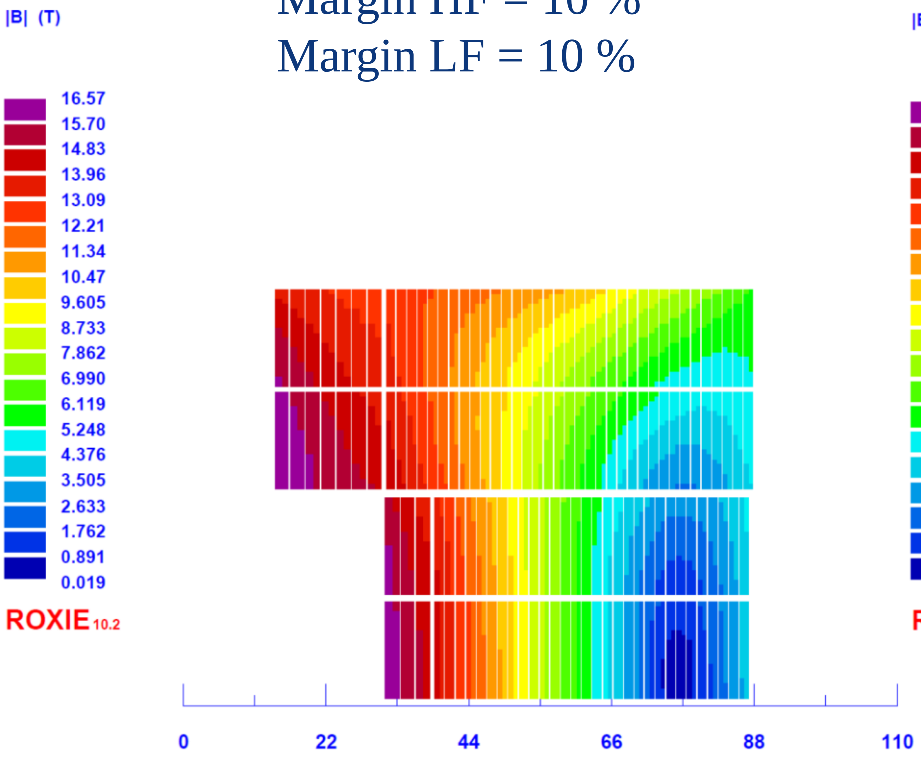






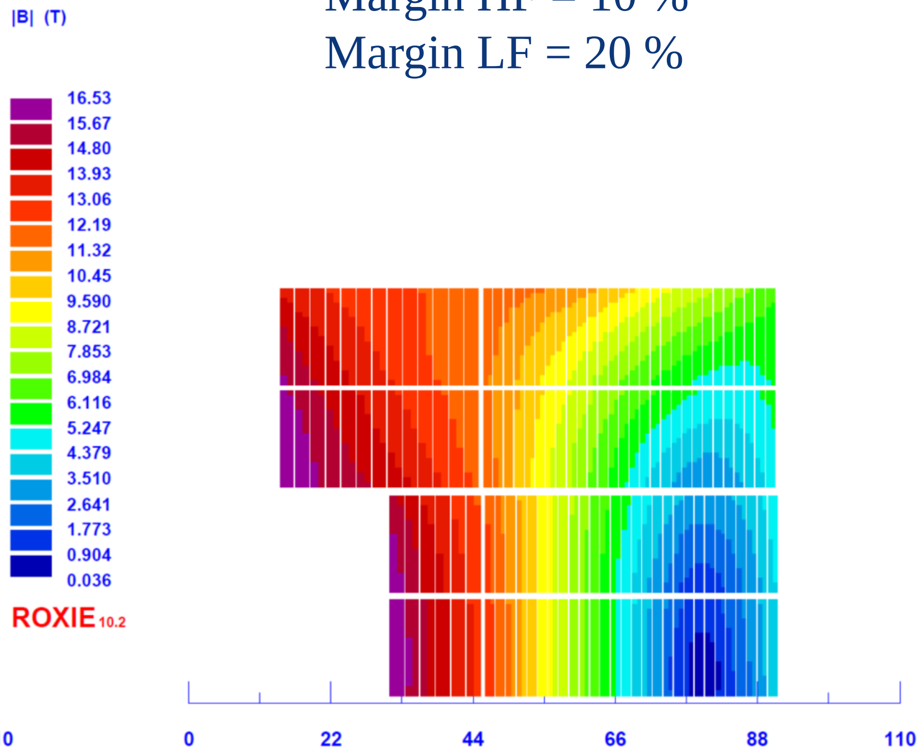
# What if in Design A, we want 20 % margin in the low field?

Margin HF = 10 %
Margin LF = 10 %



Equivalent coil width: 65.2 MM
$Nb_3Sn$ for FCC: 11710 tons

Margin HF = 10 %
Margin LF = 20 %



Equivalent coil width: 66.6 MM
$Nb_3Sn$ for FCC: 12265 tons

# Strand - RMM

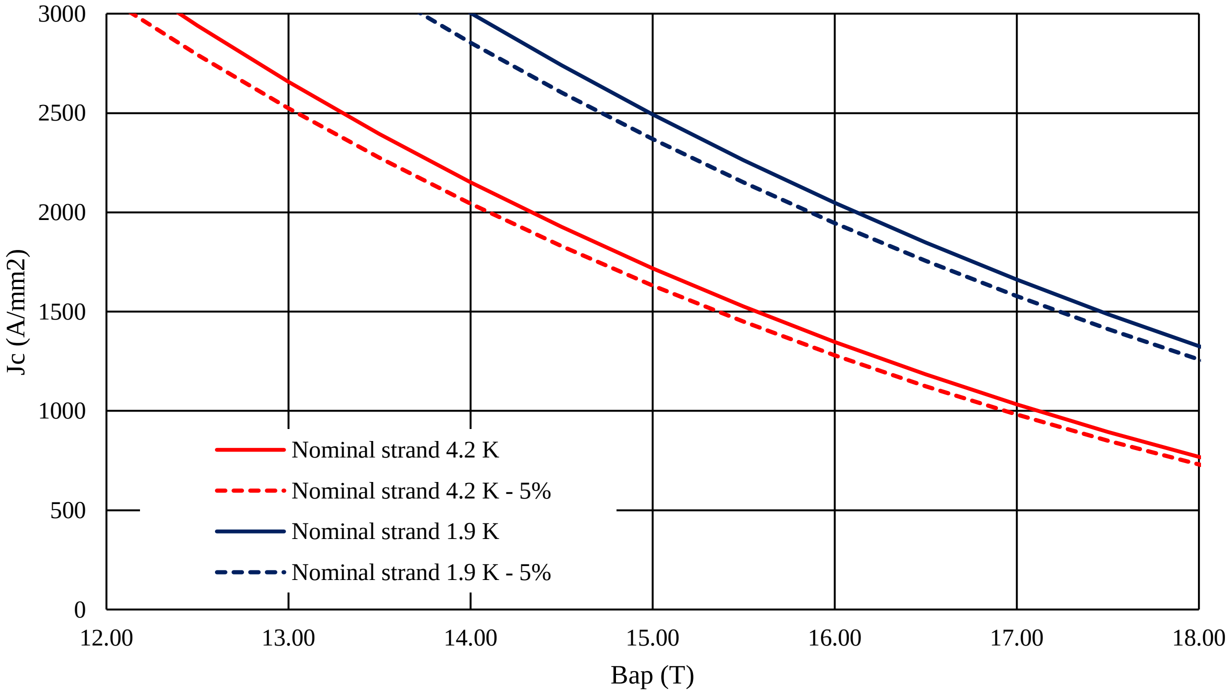
- Strand diameter: **1 mm**
- Critical surface parametrization from EuroCircol, without self-field correction
- Cu2SC ratio = 1.0
- Critical current degradation due to cabling = 5 %

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

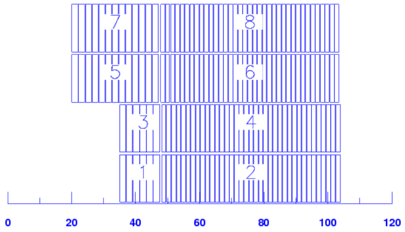
$$J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1 - b)^2$$

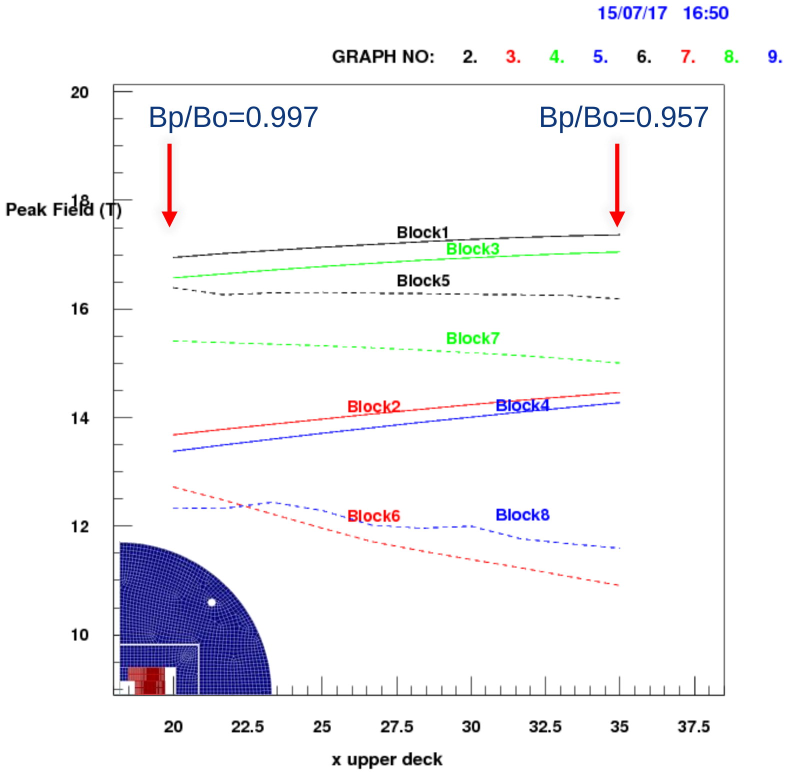
$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$

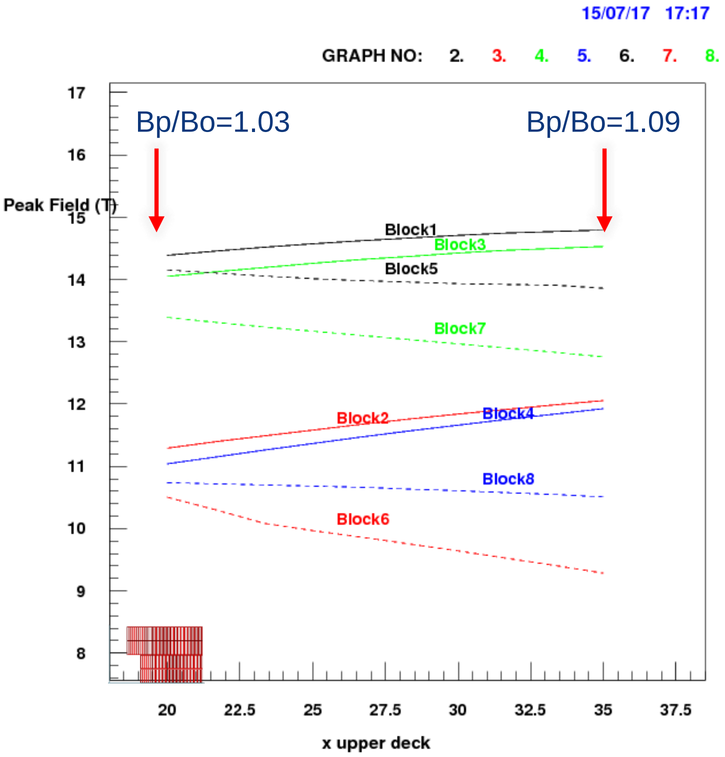
$T_{c0} = 16\ K,\ B_{c20} = 28.8\ T,\ \alpha = 0.96,\ C_0 = 255230\ A/mm^2\ T$



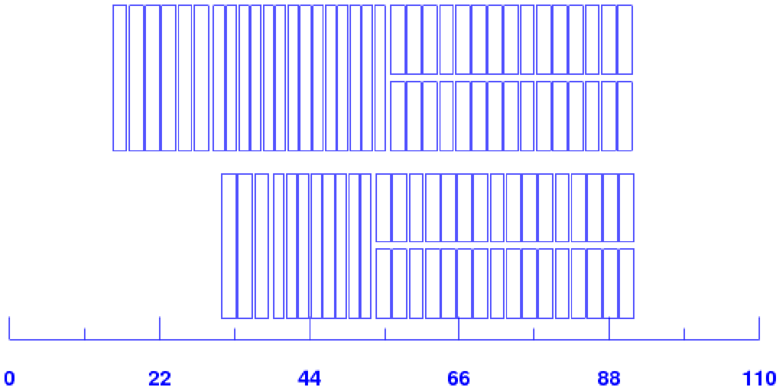
# Sensitivity to the longitudinal block position

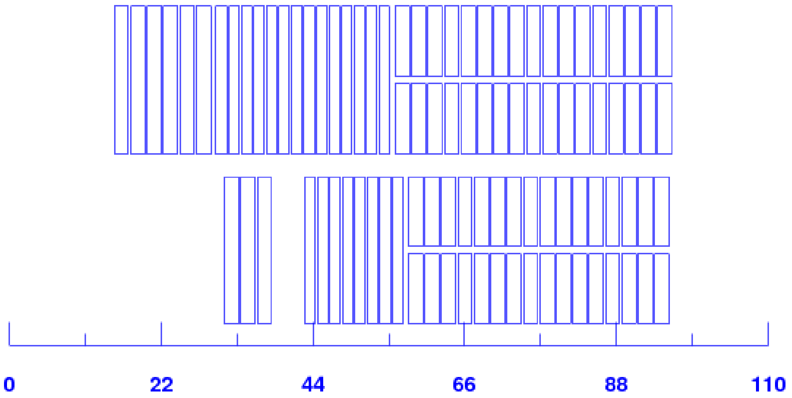






# Other lay-outs we looked at





# Design from G.S

Sabbi, EUCAS-15_2A-LS-P-02.06

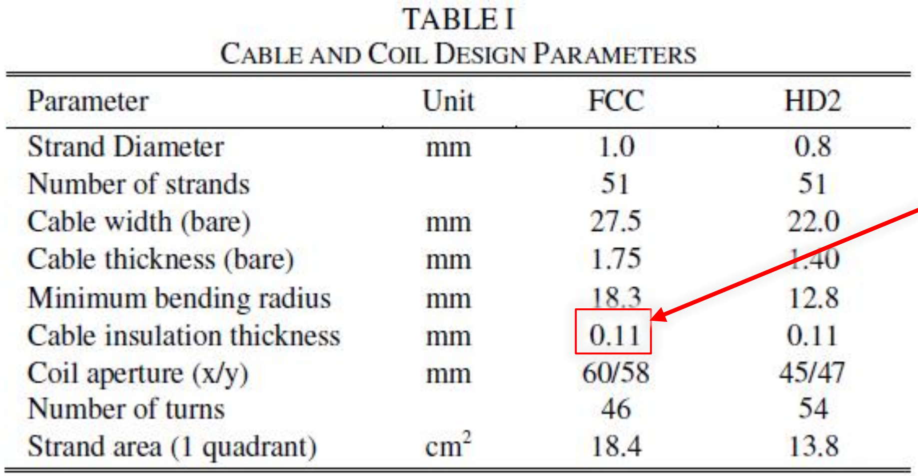


TABLE I
CABLE AND COIL DESIGN PARAMETERS

| Parameter | Unit | FCC | HD2 |
|---|---|---|---|
| Strand Diameter | mm | 1.0 | 0.8 |
| Number of strands | | 51 | 51 |
| Cable width (bare) | mm | 27.5 | 22.0 |
| Cable thickness (bare) | mm | 1.75 | 1.40 |
| Minimum bending radius | mm | 18.3 | 12.8 |
| Cable insulation thickness | mm | 0.11 | 0.11 |
| Coil aperture (x/y) | mm | 60/58 | 45/47 |
| Number of turns | | 46 | 54 |
| Strand area (1 quadrant) | $cm^2$ | 18.4 | 13.8 |

0.15 mm

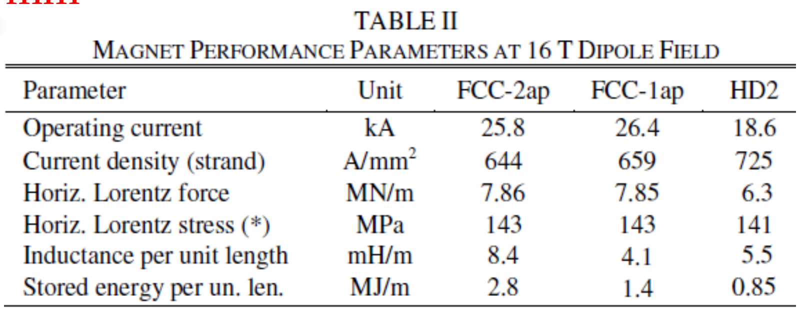


TABLE II
MAGNET PERFORMANCE PARAMETERS AT 16 T DIPOLE FIELD

| Parameter | Unit | FCC-2ap | FCC-1ap | HD2 |
|---|---|---|---|---|
| Operating current | kA | 25.8 | 26.4 | 18.6 |
| Current density (strand) | $A/mm^2$ | 644 | 659 | 725 |
| Horiz. Lorentz force | MN/m | 7.86 | 7.85 | 6.3 |
| Horiz. Lorentz stress (*) | MPa | 143 | 143 | 141 |
| Inductance per unit length | mH/m | 8.4 | 4.1 | 5.5 |
| Stored energy per un. len. | MJ/m | 2.8 | 1.4 | 0.85 |

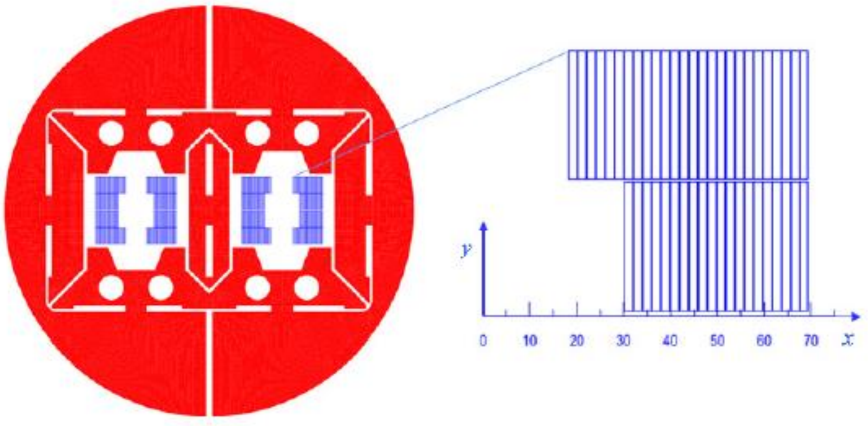


Fig. 1. Left: reference twin-aperture design for FCC with symmetric coils and a central iron insert for magnetic decoupling. The iron yoke radius is 700 mm. Right: detail of the cross-section for one coil quadrant.

1.5 $kA/mm^2$

<0.5

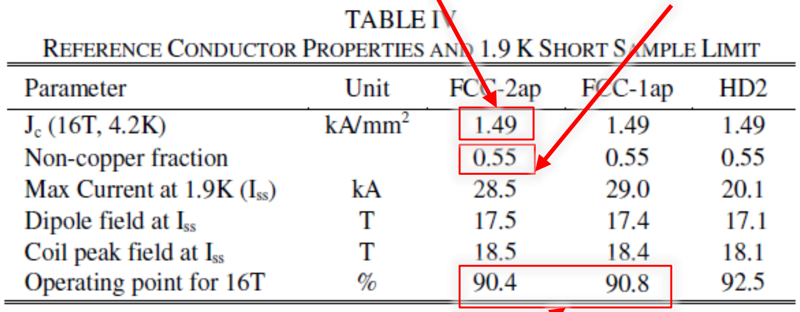


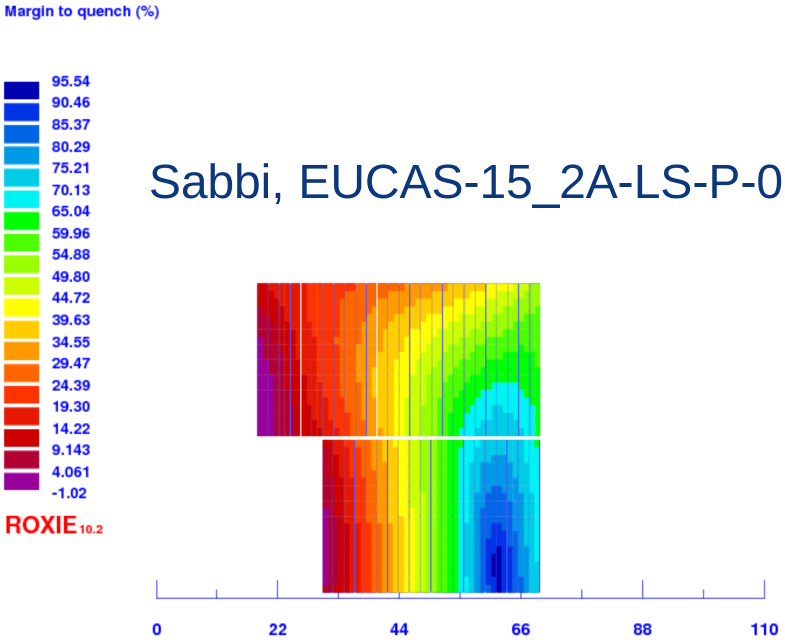
TABLE IV
REFERENCE CONDUCTOR PROPERTIES AND 1.9 K SHORT SAMPLE LIMIT

| Parameter | Unit | FCC-2ap | FCC-1ap | HD2 |
|---|---|---|---|---|
| $J_c$ (16T, 4.2K) | $kA/mm^2$ | 1.49 | 1.49 | 1.49 |
| Non-copper fraction | | 0.55 | 0.55 | 0.55 |
| Max Current at 1.9K ($I_{ss}$) | kA | 28.5 | 29.0 | 20.1 |
| Dipole field at $I_{ss}$ | T | 17.5 | 17.4 | 17.1 |
| Coil peak field at $I_{ss}$ | T | 18.5 | 18.4 | 18.1 |
| Operating point for 16T | % | 90.4 | 90.8 | 92.5 |

80 %

# G.S design translated to FCC criteria

| | Sabbi | FCC criteria |
|---|---|---|
| I @ 16 T, kA | 25800 | 17400 |
| Insulation thickness, mm | 0.11 | 0.15 |
| Copper to non-copper ratio | 0.82 | 1 |
| Operation point at 4.2K, assuming FCC target Jc | -1 % | 5 %<br>! Should be >10% |
| Strand area per quadrant, $cm^2$ | 18.4 | 32 |


Sabbi, EUCAS-15_2A-LS-P-02.06