

# LAYOUT STUDY FOR THE DIPOLE MAGNETS OF THE FUTURE CIRCULAR COLLIDER USING Nb-Ti AND Nb<sub>3</sub>Sn

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Introduction  
Input  
Results  
Conclusion



Work performed at CERN, Technology Department, Magnets, Superconductors and Cryostats group as part of the EuCARD-2 and FCC collaborations, within the framework of a PhD. At the University of Twente, Energy Materials and Systems group.



UNIVERSITY OF TWENTE.



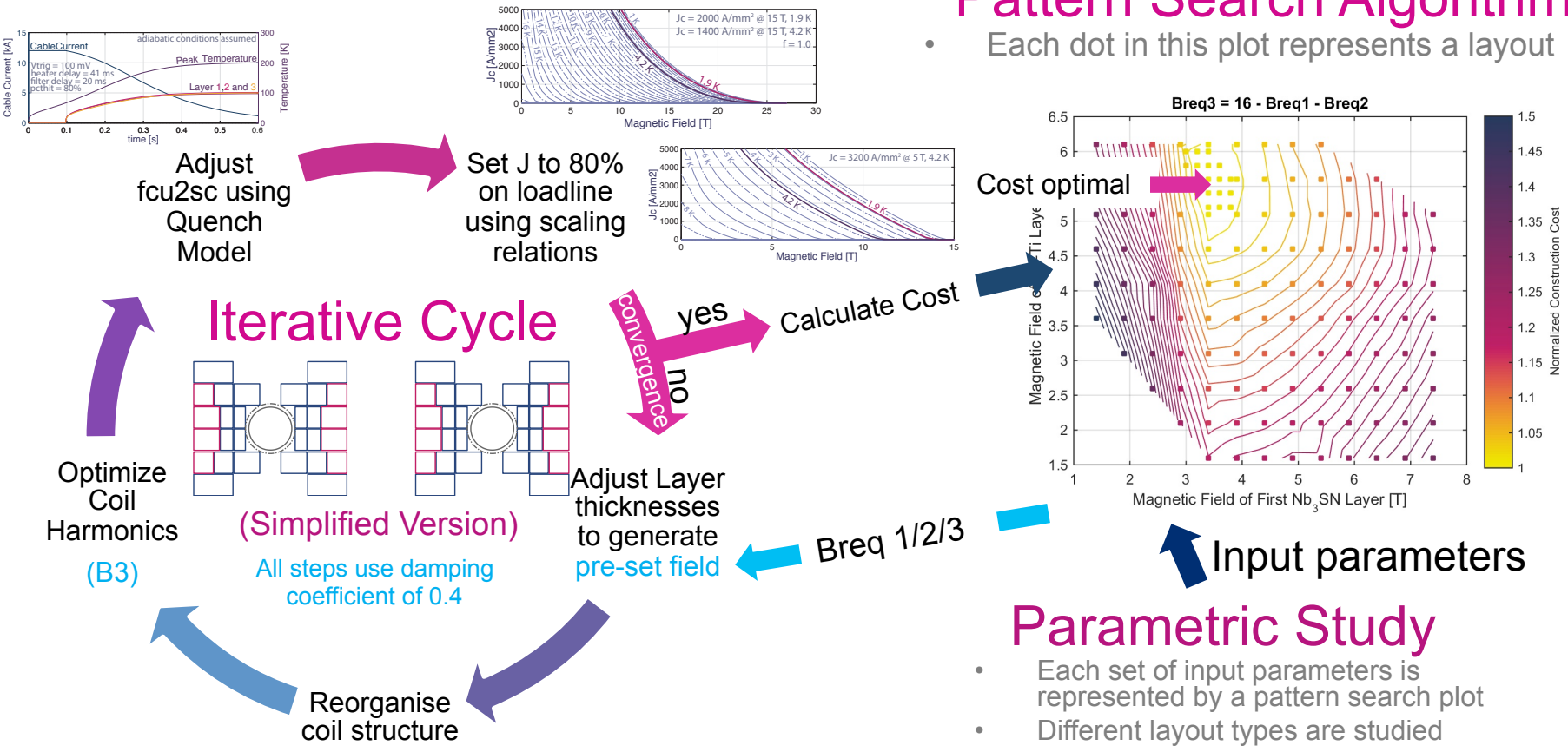
- Future Circular Collider (FCC) 100 TeV collision energy
  - The main bending dipole magnets have to operate at/near a magnetic field of 16 T
  - Providing a significant challenge for strand, cable and magnet R&D.
  - As a first step towards its realisation a cross section parametric layout study is performed



- Graded coil designs are necessary (as we will see later)
  - Iterative algorithm is needed to generate valid layout(s)
  - Pattern search algorithm is used to find optimal distribution of magnetic field contribution between layers
  - Outside a parametric study is performed

# Pattern Search Algorithm

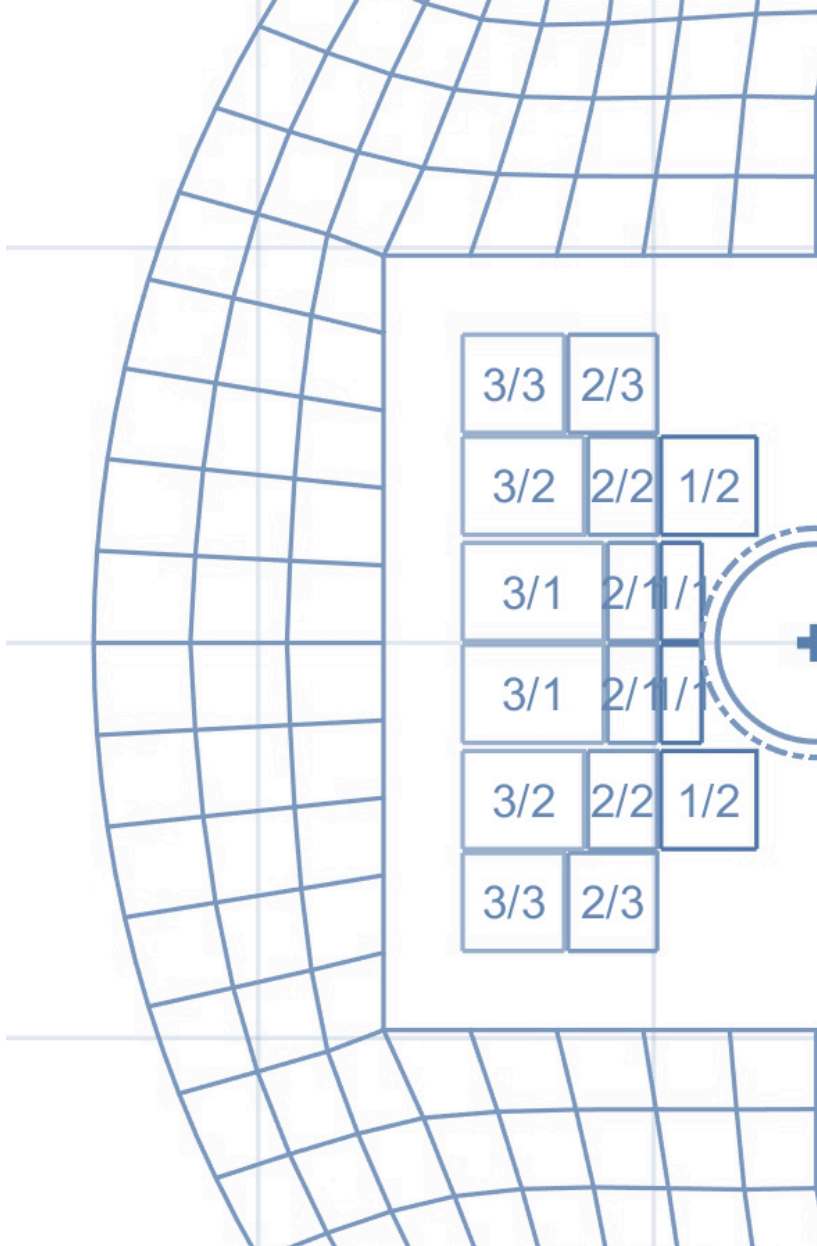
- Each dot in this plot represents a layout



Introduction

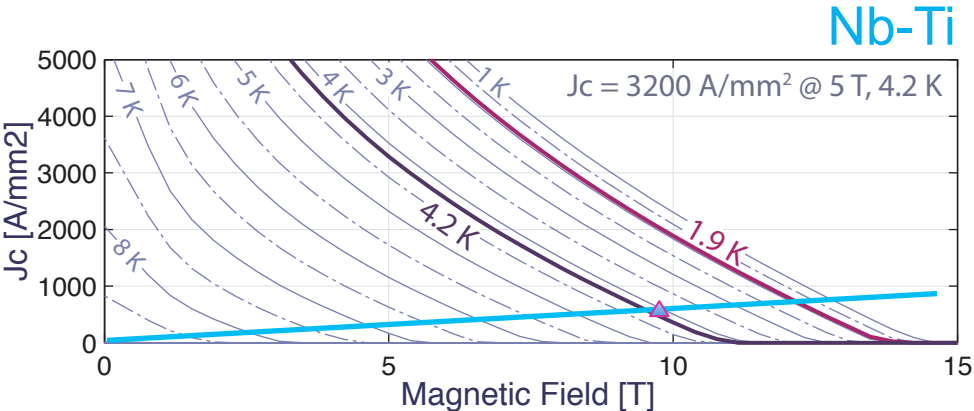
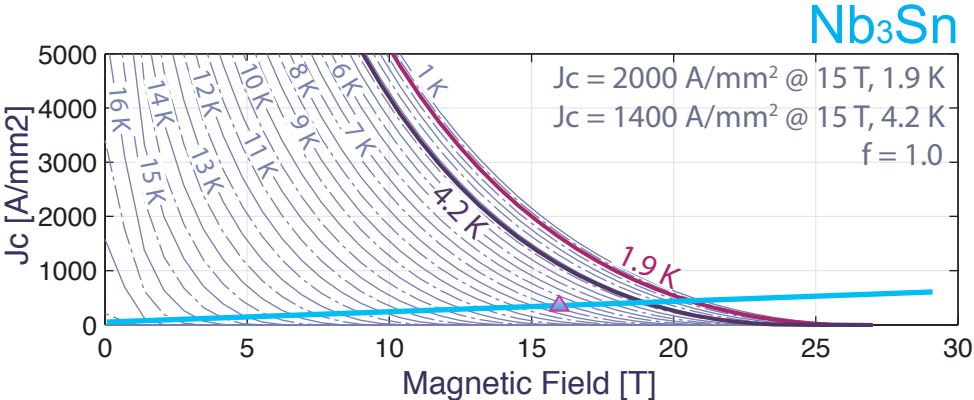
# INPUT

Results  
Conclusion



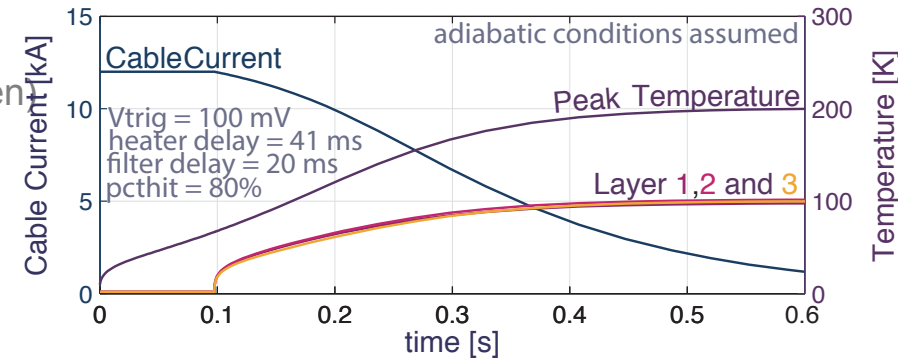


- Used scaling relations
  - Bottura scaling relation for Nb-Ti with LHC strand
  - Godeke scaling relation for Nb<sub>3</sub>Sn
- Cable parameters
  - Void fraction 0.14
  - Insulation fraction 0.06
  - Margin on loadline 20%
    - About 4K margin for Nb3SN
    - About 2K margin for Nb-Ti
- The Nb<sub>3</sub>Sn conductor is scaled using a factor  $f_{Nb3Sn}$ 
  - $J_{cscaled} = f_{Nb3Sn} \cdot J_c$



- Simple adiabatic model solving time dependent

- Current decay (all layers are connected in series)
- peak temperature for “quenching layer” (worst taken)
- average temperature for each layer



- Assumed circuit

- No dump resistor such that magnets can be chained
- Either Quench Heater or CLiQ (for now conservative LHC values for detection delay times assumed)

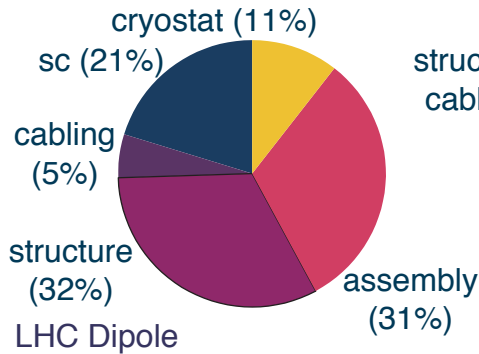
- Set Copper to Superconductor fraction in each layer such that

- Average Temperature Rise is equal between layers (spread out energy as equal as possible)
- Peak temperature for all designs is fixed at 200 K (conservative)
- Copper to Superconductor fraction has lower limit of 0.6

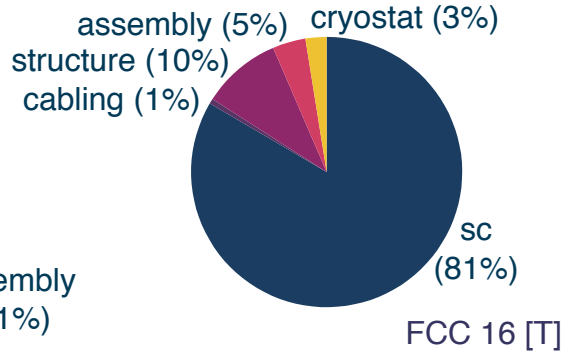
- Effect of the quench model on the magnet layouts

- Current density of outer layers is suppressed providing less advantage of grading
- Current density in inner part can be higher because we need less copper

## LHC



## FCC



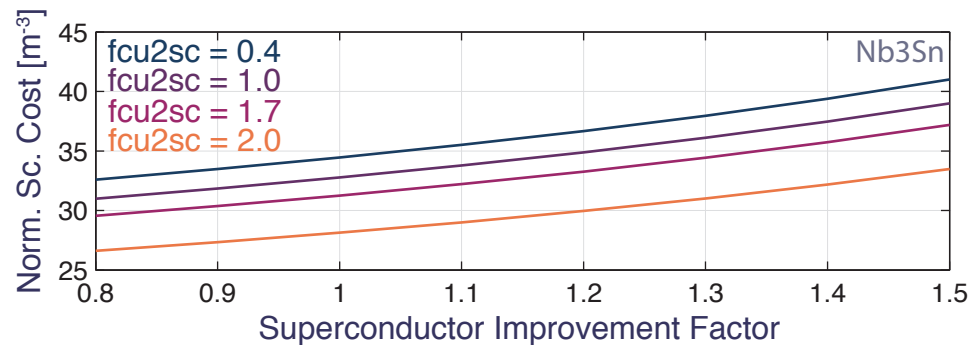
- Implemented cost model to compare different layouts. Included is:

- Cryostat
- Superconductor
- Cabling
- Structure
- Assembly

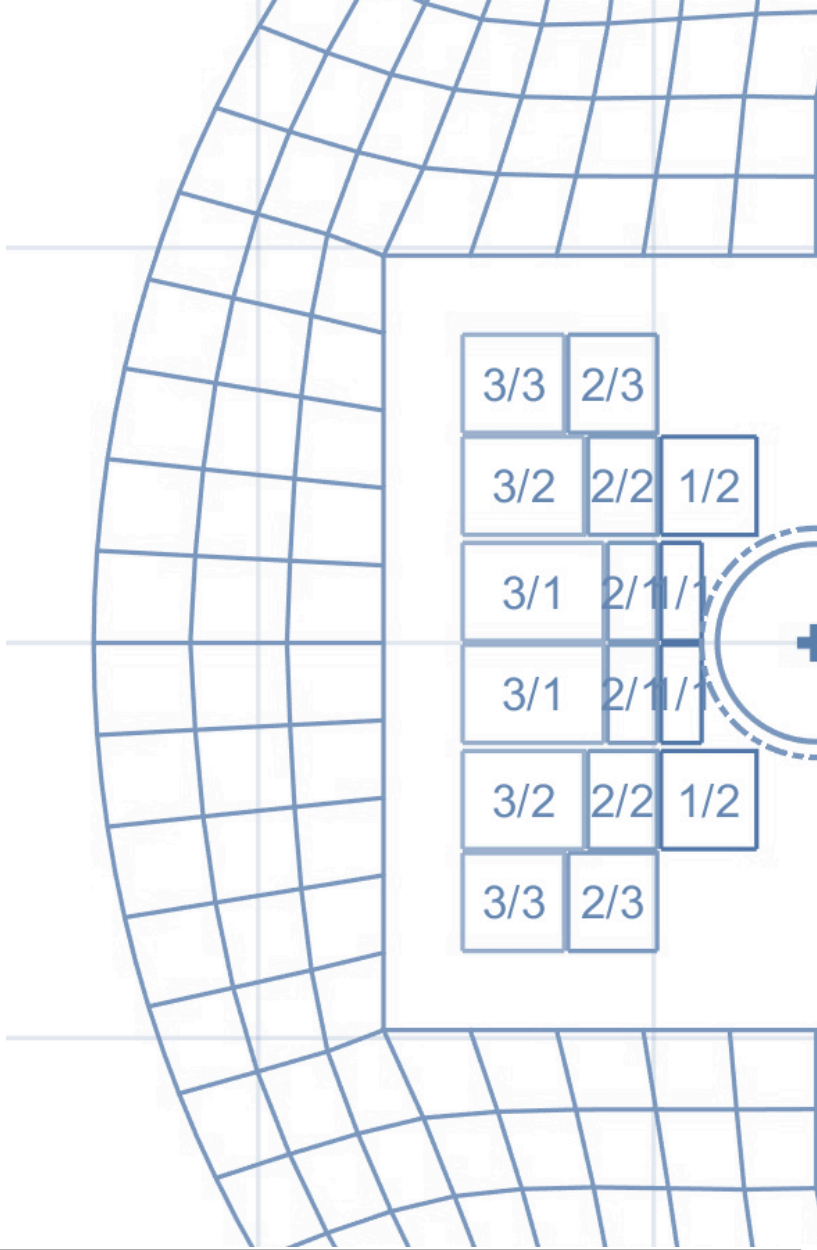
- Construction cost dominated by the superconductor cost

- Cost of Nb<sub>3</sub>SN depends on

- copper content
- improvement factor
- for  $f_{cu2sc} > 1.65$  the copper is no longer part of the strands and added separately to the cable

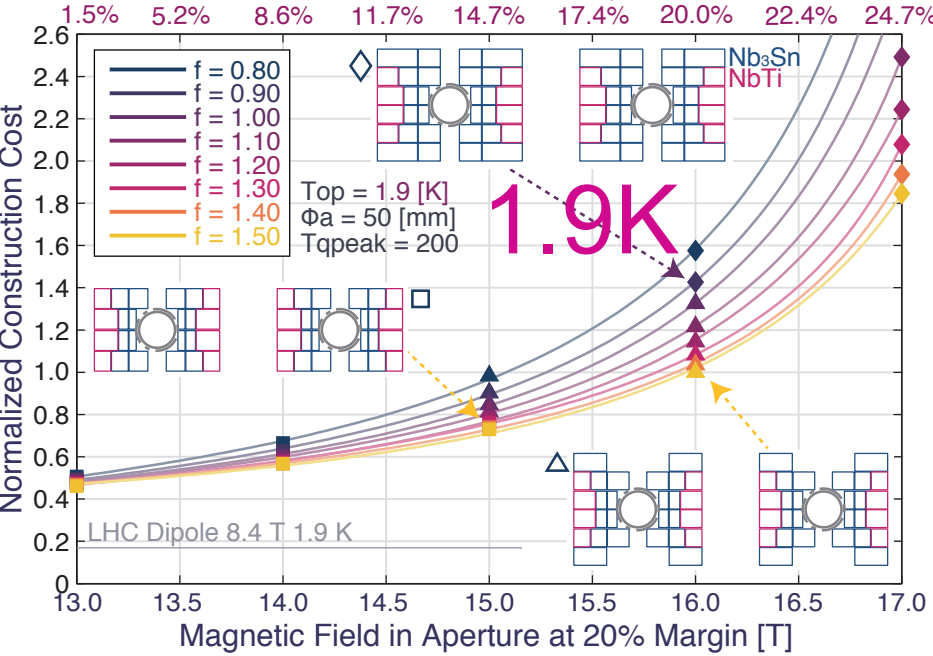


Introduction  
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**RESULTS**  
Conclusion

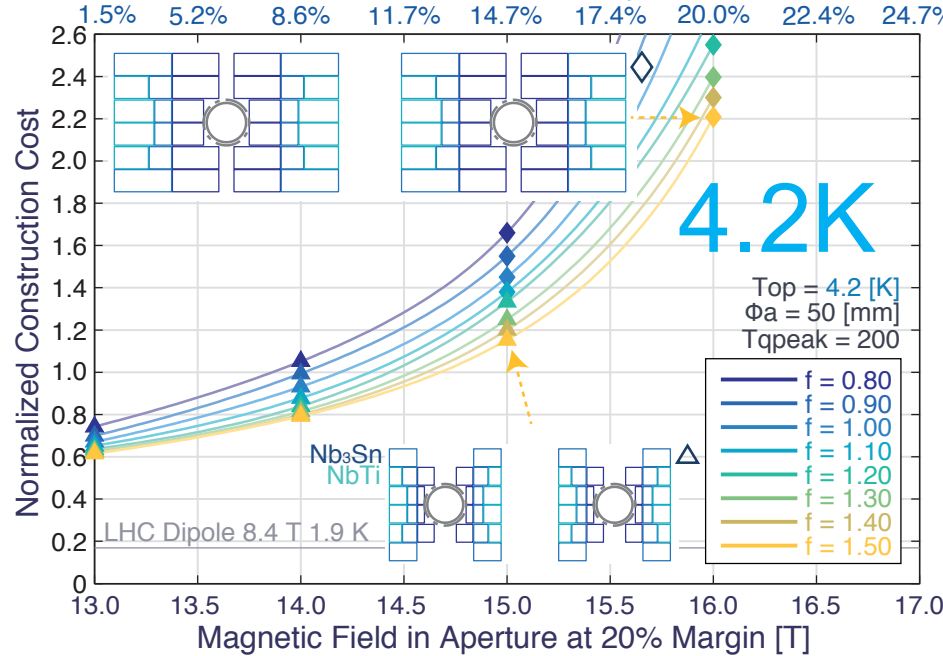




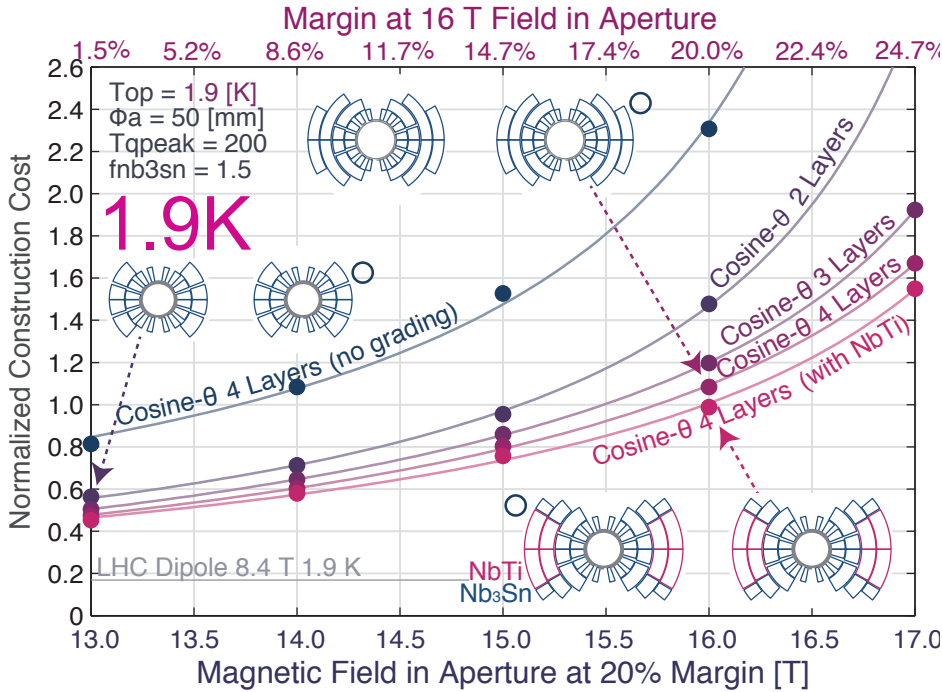
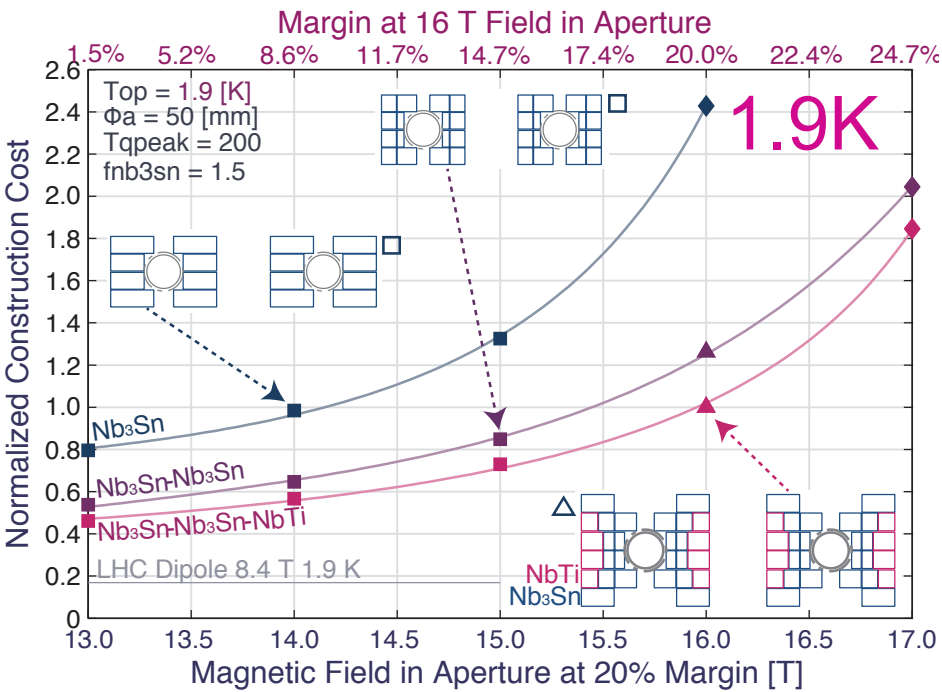
Margin at 16 T Field in Aperture



Margin at 16 T Field in Aperture

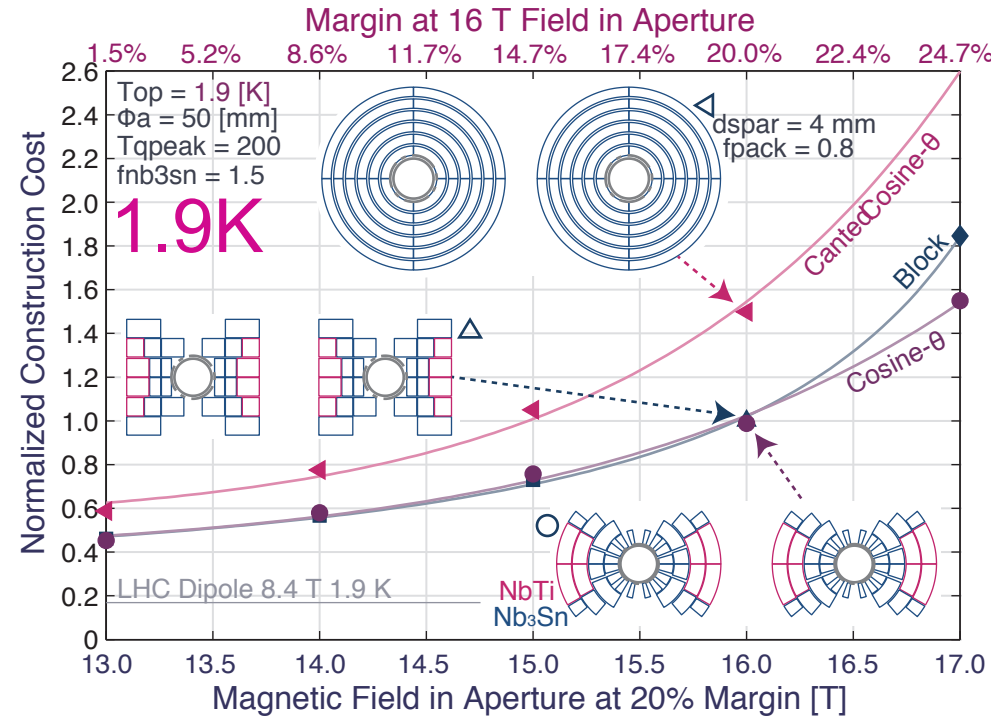


- No Iron is used in order to speed up calculations
- All layouts are normalized with respect to the  $\langle B=16T, f=1.5, T=1.9K, T_q=200K \rangle$  layout
- Different layout shapes are optimal at different fields and conductor improvement factors
- For reasonable 16T 20% margin layout we need:
  - 4.2 -> 1.9 K provides additional 1.2 T
  - fnb3sn 1.0 -> 1.5 provides additional 1 T
- Changing the margin is the same as changing the operating magnetic field
  - i.e. 16 T 14% margin = 15 T 20% margin
  - If training behaviour is improved the magnet cost is reduced significantly!

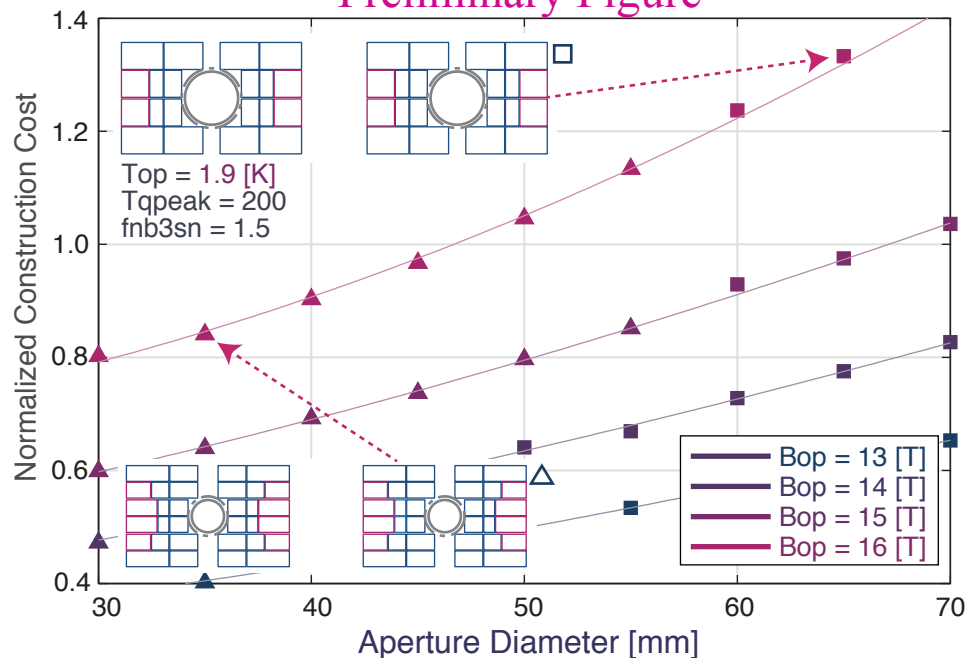


- Grading in the **Nb<sub>3</sub>Sn** gives a factor of **2** cost reduction and is a **MUST** have!
- Grading to **Nb-Ti** gives another factor of **1.1-1.2** cost reduction
  - Also it fills the high(er) stress region of the coil with Nb-Ti **which is nice (=**
- This means we need **R&D** on inter-layer joints (between Nb-Ti and Nb<sub>3</sub>Sn)
- Probably need to resin-impregnate the Nb-Ti layer?
- Also note that all decks need to have **flared coil ends** when grading is used

- Block and Cosine-Theta are very similar in terms of cost.
  - Similar shape and positioning of conductor (equal grading)
  - Extra mechanical structure in block balances out with wedges needed for cosine theta
  - Block favours wider (higher current) cables
- Canted Cosine Theta 1.4-1.5 times more expensive due to lower packing fraction -> less conductor close to aperture
- Depends on mechanical structure and assembly

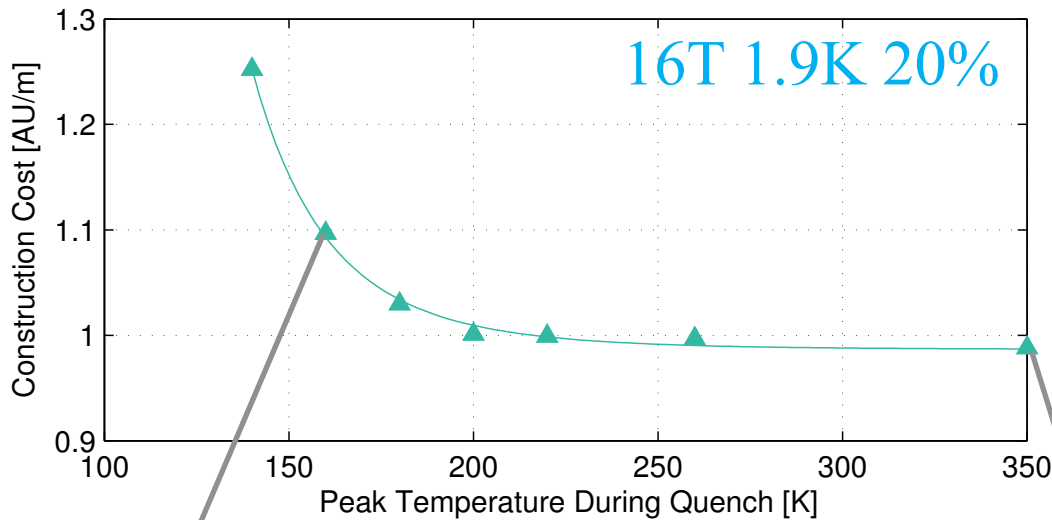


Preliminary Figure



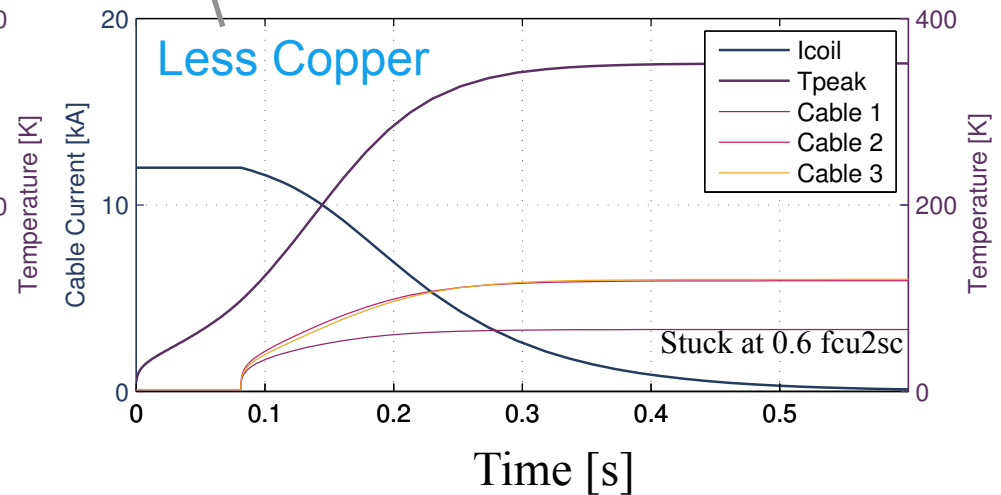
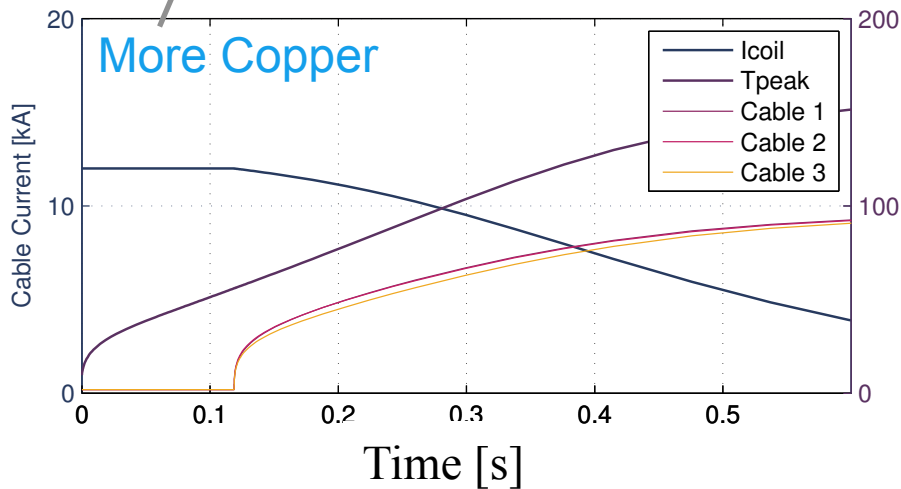
- Expected synchrotron radiation is **50 watt / m** (possibly need more space for cooling)
- More-or-less **linear** scaling with the aperture size (In agreement with analytical predictions)
- At high aperture size we get fresca-2 like configuration
- Larger aperture costs money!**

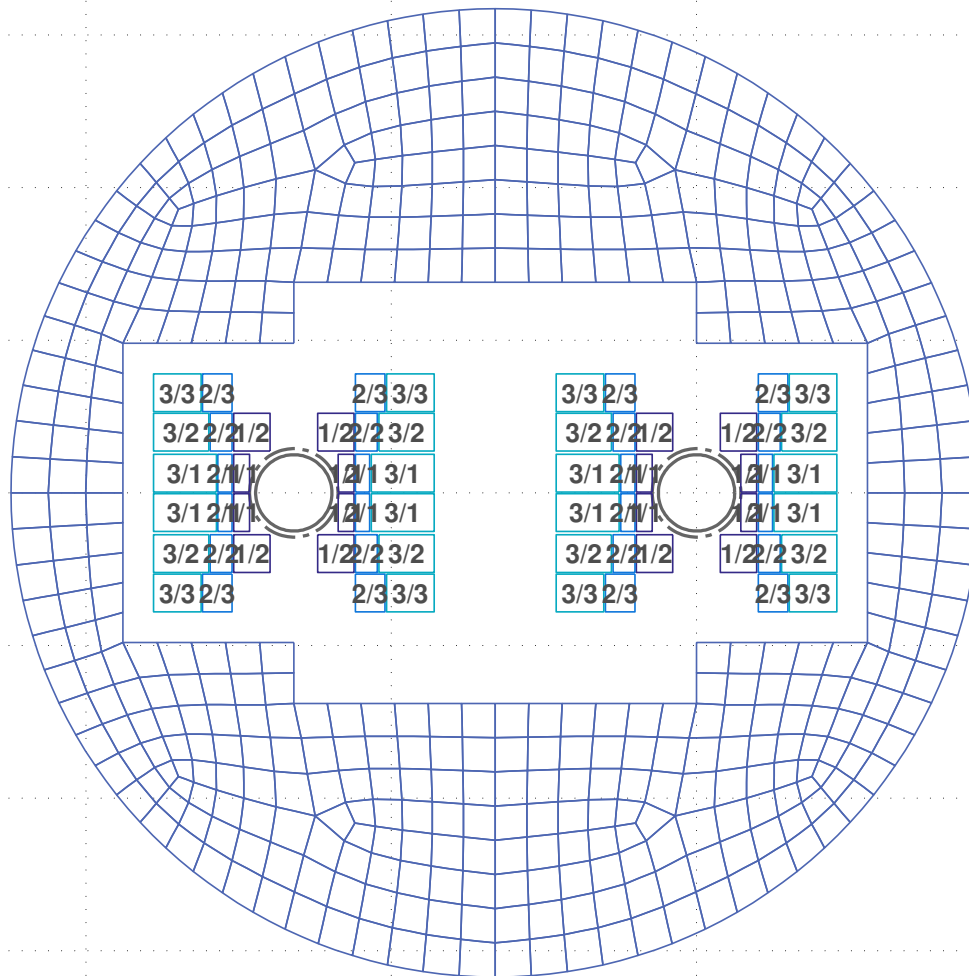




The influence of the peak temperature on the cost

- Default is a conservative **200 K**
- Lower peak temperatures push the cost up hitting a wall at **120 K**
- The **cost barely** reduces when the peak temperature is increased

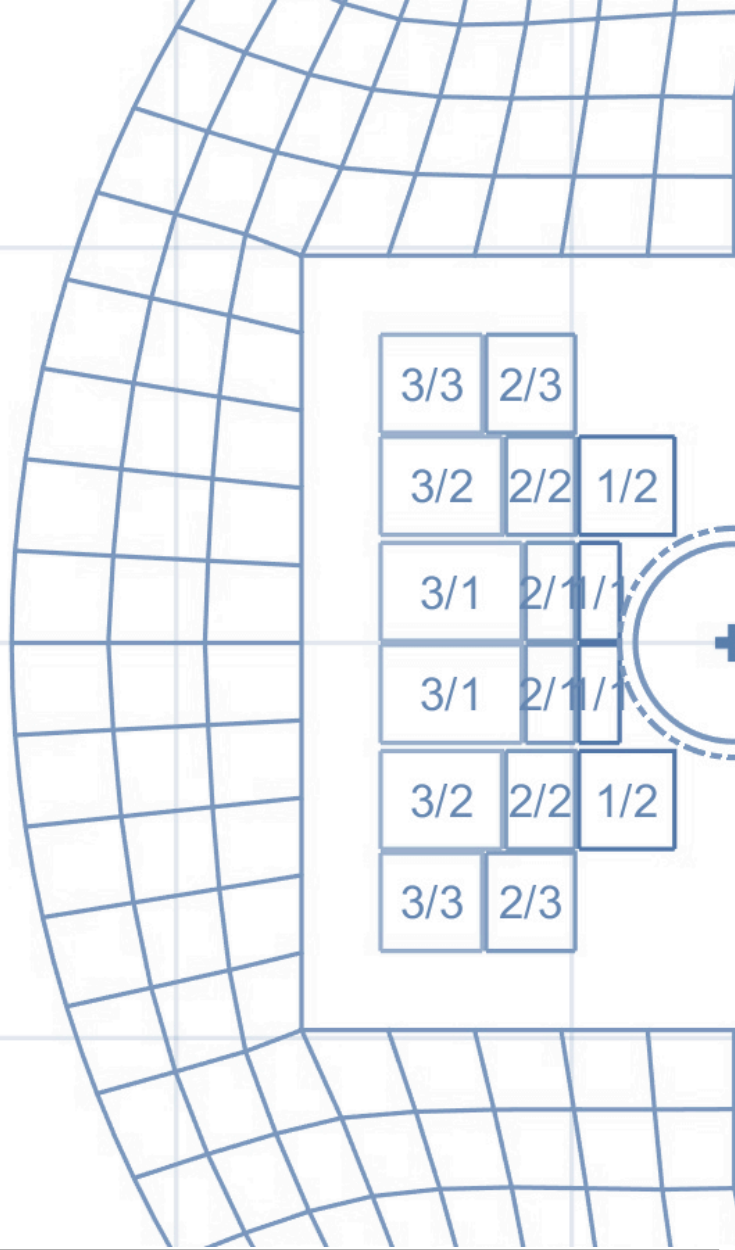




- After the parametric studies an **iron yoke** was added to the most optimal design
- Adding the yoke flips the block in the corner to **Nb-Ti**
  - The iron helps shape the field
  - Nb-Ti field contribution in aperture becomes **7.7 T** (was 5.5 T before)
- To avoid the yoke from becoming large
  - Either accept more stray field
  - Place **quadrupole active magnetic shield** coils on the outside of the yoke
- The yoke reduces the cost of the magnets by **17%** (due to the extra Nb-Ti block)

- For a 16 T magnet need both
  - Operating at 1.9 K provides an additional 1.2 T over 4.2 K
  - Improving the conductor by 50% is worth about 1 T
- Block and Cosine theta are the same in terms of cost Canted Cosine Theta is a bit more expensive
- In this field range grading is necessary to reduce conductor cost
  - Different current density
  - Different copper to superconductor fraction
- Mechanical studies are ongoing to determine structure that allows assembly of dual aperture

THANK YOU FOR  
YOUR ATTENTION





- We're building this really cool aligned block insert magnet!

4LPo2G-03: 153.



Applied Superconductivity Conference, Charlotte 2014

# STUDY OF A 5 T RESEARCH DIPOLE INSERT-MAGNET USING AN ANISOTROPIC REBCO ROEBEL CABLE

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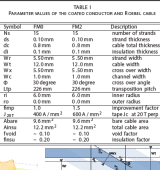
## I. INTRODUCTION

As part of the Future Circular Collider (FCC) hadron-hadron collider study, a new domain of high field dipole magnets is required. At present, there are two different target fields 16T and 20T. The first lies at the limit of the Nb<sub>3</sub>Sn conductor. The second will require the use of High Temperature Superconductors (HTS) at the inner, high field, part of the magnet. The first steps towards these HTS insert-magnets have already been made over the last years, within work-package 7 of the EuCARD-1 collaboration. These efforts will be continued in EuCARD-2, resulting in a useful synergy with the FCC study. Workpackage 10.3 of EuCARD-2 concerns the design and construction of a Five Tesla HTS Research (FeaTher) dipole insert-magnet.



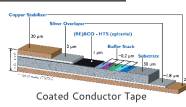
### III. REQUIREMENTS AND CABLE

This magnet is required to generate a 5 T standalone central operating field in a 40 mm aperture (with a reasonable field quality). By restricting the outer diameter of the magnet to 99 mm (this leaves 1 mm margin for adding extra insulation sheets) and by adding additional mechanical structure, it can be tested as an insert inside the Fresca-2 magnet. To achieve low magnet inductance and to allow, in future perspective, possible series operation with Nb-Ti/Nb<sub>3</sub>Sn coils, a 10 kA class cable is required. The designs are based Roebel cable because it is fully transposed and possesses sufficient current density to reach the target field.

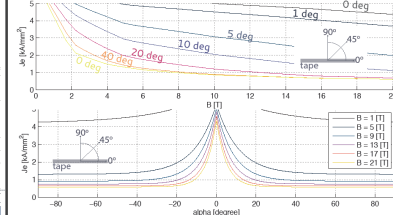


## II. REBCO COATED CONDUCTOR AND AN-ISOTROPY

The critical current of coated conductor tapes is highly an-isotropic, which means that it strongly depends on the incident angle of the magnetic field. This anisotropy becomes is more pronounced in high magnetic fields, at which the difference in critical current, between the good parallel and bad perpendicular applied magnetic field, can be as much as a factor 5. In the magnet design it is attempted to make use of this good parallel performance. In the magnet design ap-

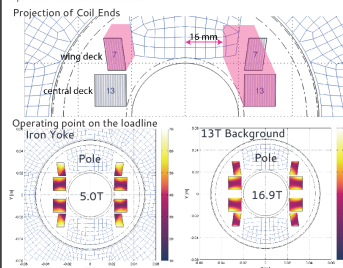


Engineering current density in tapes as function of field angle and magnitude

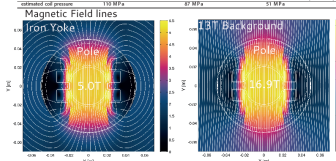
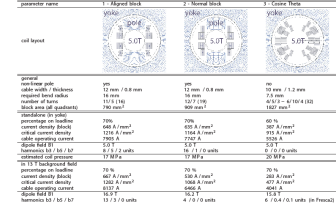


#### IV. CROSS SECTIONAL LAYOUT

The Feather-M2 magnet is designed to operate in two different scenarios, the first is standalone operation inside an iron yoke generating 5 T with reasonable field quality at the center of the aperture. The second is in a 13 T background field, generating as much magnetic field as possible, without imposing any field quality requirements. To maximize the magnetic field in the second scenario, the off-vertical angle of the blocks is adjusted to align the conductor orientation with the magnetic field lines inside the background field. At the same time the harmonics and the width of the coil blocks are optimized for the standalone case.

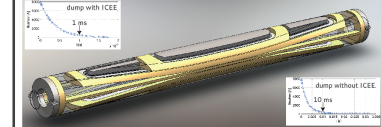


### Comparison with Other Layouts

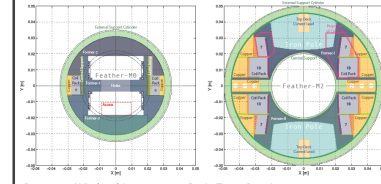


## V. MECHANICAL STRUCTURE AND ASSEMBLY

### Inductively Coupled Energy Extraction (ICEE) Rings



## Magnet Mechanical Structure



Compress-Wind and Impregnate - Resin Tests Ongoing



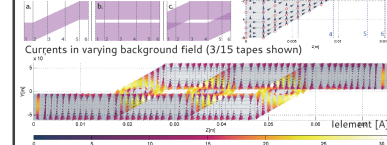
## VII. CRITICAL CURRENT CALCULATION AND NETWORK MODEL

The following three methods for calculating the critical current are proposed (values in Tables):

**Network Model Geometry**

1. Assume that no current sharing can occur (IcI).
2. Assume that current re-distribution can occur within the strand but not between the strands (IcII).
3. Assumes full current sharing in and between the tapes (IcIII).

### Cable Structure

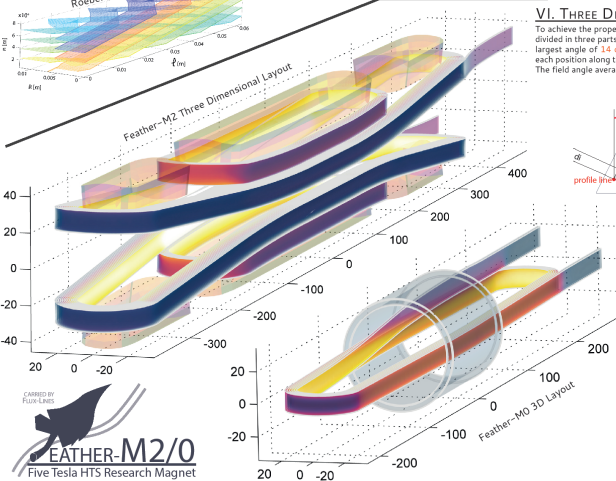


## VIII. CONCLUSION

- introduced a new layout, named aligned block coil, for ReBCO coated conductor coils. This layout takes advantage of the anisotropy of the conductor, by optimizing the alignment of the tapes with respect to the magnetic field lines.

- Using this concept a design for the HTS insert magnet for the EuCARD2 project using a Roebel cable has been developed. The design, although in its initial phase, addresses most issues related to the use of Roebel cable for a dipole magnet.

- Because current can flow freely in the tapes from side to side the calculation of the critical current is not straight forward. Different methods of the calculation of the critical current are introduced.



## VI. THREE DIMENSIONAL LAYOUT

To achieve the proper alignment in three dimensions is challenging. The coil can be divided in three parts: a straight section, a curved section and a sloped section. The largest angle of 14 degree is located at the edge of the cable in the coil ends. At each position along the cable there is a point where the magnetic field angle is zero. The field angle averaged over the width of the cable is always less than 4 degree.

