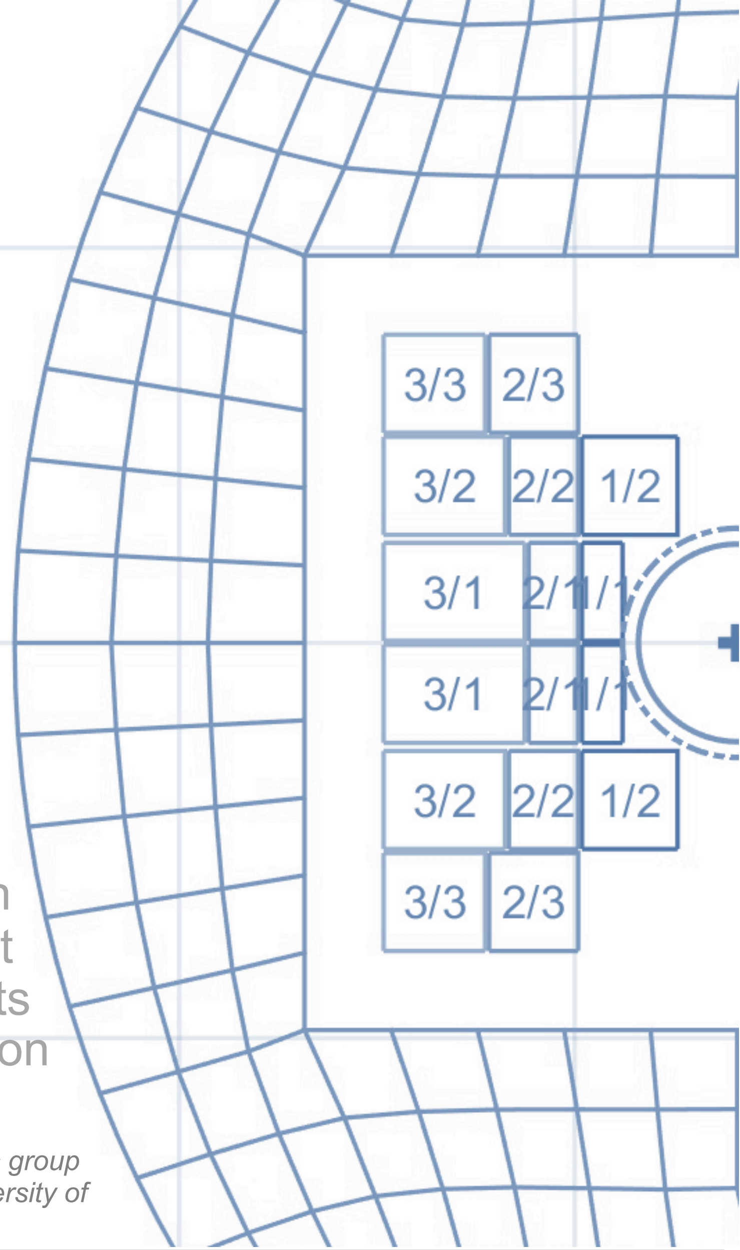
Layout Study for the Dipole Magnets of the Future Circular Collider using Nb-Ti and Nb_3Sn

FUTURE CIRCULAR COLLIDER WEEK, WASHINGTON, MARCH 2015

J. VAN NUGTEREN, D. SCHOERLING, G.A. KIRBY, G. DE RIJK, L. ROSSI, L. BOTTURA, H.H.J. TEN KATE AND J.S. MURTOMAKI



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.

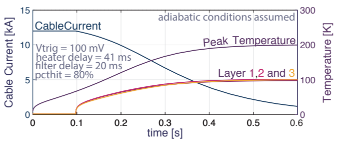
CERN
UNIVERSITY OF TWENTE.

INTRODUCTION

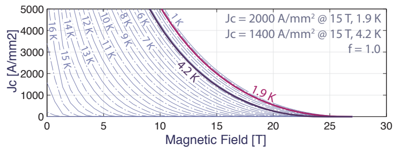
- Future Circular Collider (FCC) 100 TeV collision energy
  - The main bending dipole magnets have to operate at/near a magnetic field of 16 T
  - Providing a significant challenge for strand, cable and magnet R&D.
  - As a first step towards its realisation a cross section parametric layout study is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

OPTIMIZATION ALGORITHM

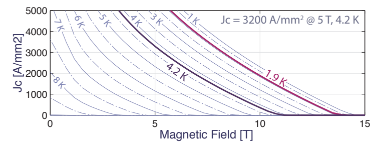
- Graded coil designs are necessary (as we will see later)
  - Iterative algorithm is needed to generate valid layout(s)
  - Pattern search algorithm is used to find optimal distribution of magnetic field contribution between layers
  - Outside a parametric study is performed



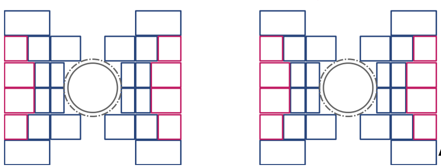
Adjust fcu2sc using Quench Model



Set J to 80% on loadline using scaling relations



Iterative Cycle



(Simplified Version)

All steps use damping coefficient of 0.4

convergence — yes → Calculate Cost; no → Adjust Layer thicknesses to generate pre-set field

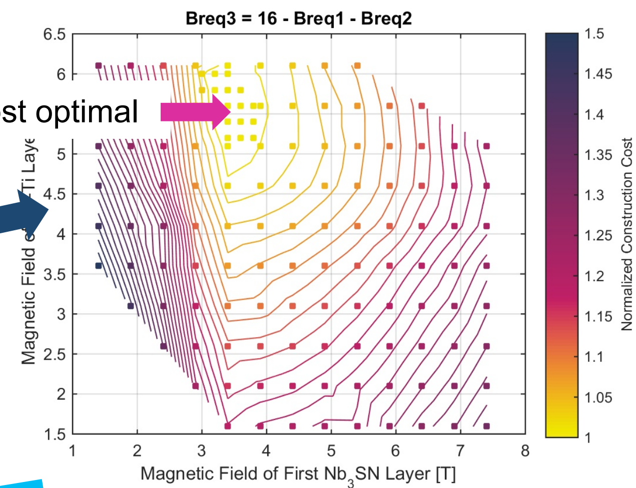
Reorganise coil structure

Optimize Coil Harmonics (B3)

Breq 1/2/3

Pattern Search Algorithm

- Each dot in this plot represents a layout



Input parameters

Parametric Study

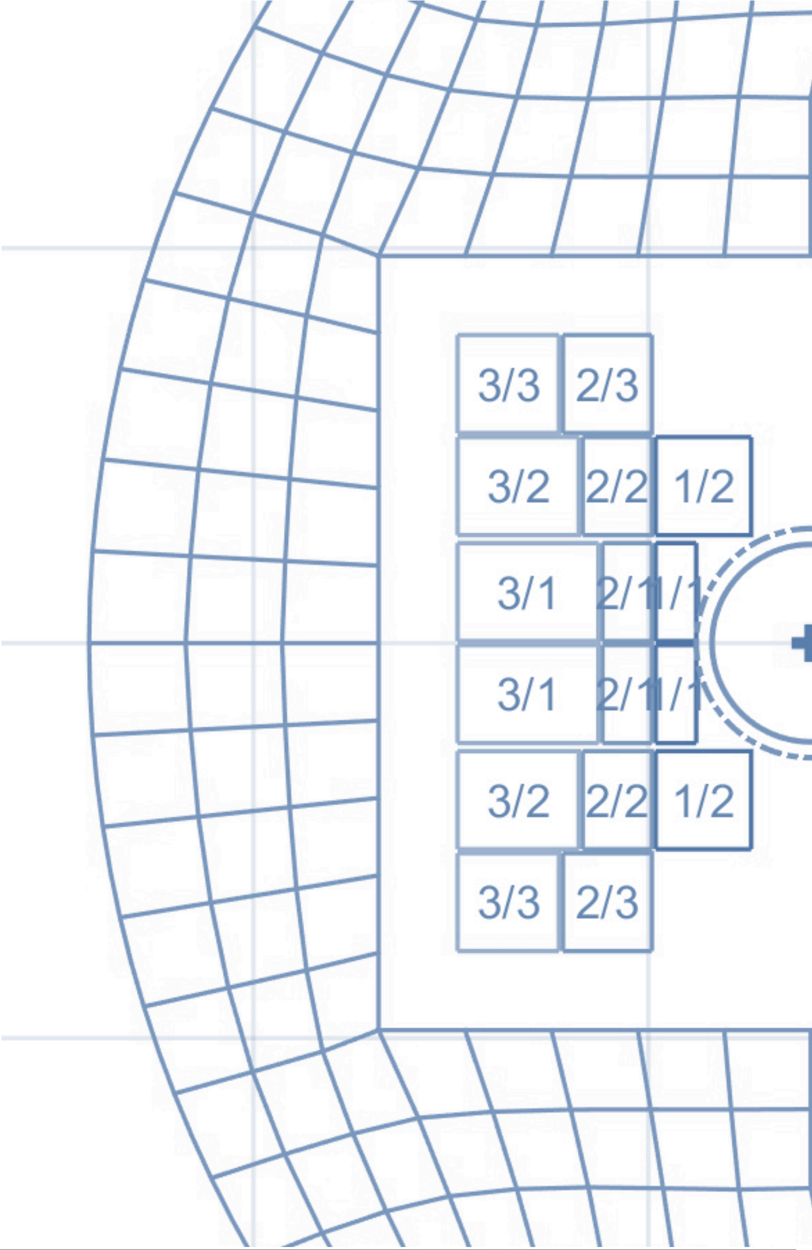
- Each set of input parameters is represented by a pattern search plot
- Different layout types are studied

Introduction

INPUT

Results

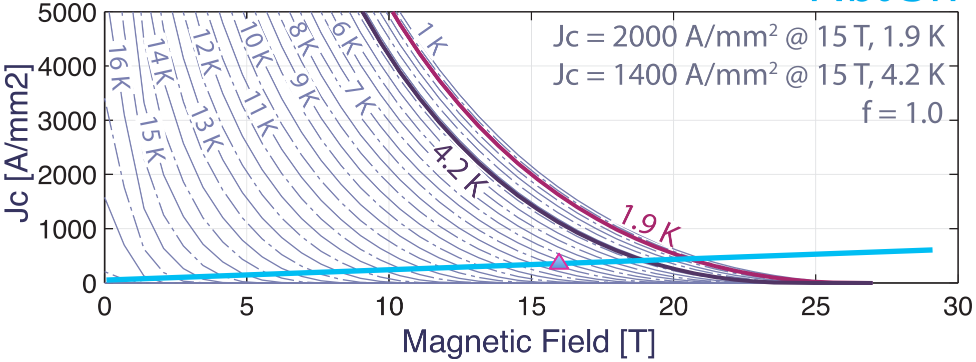
Conclusion



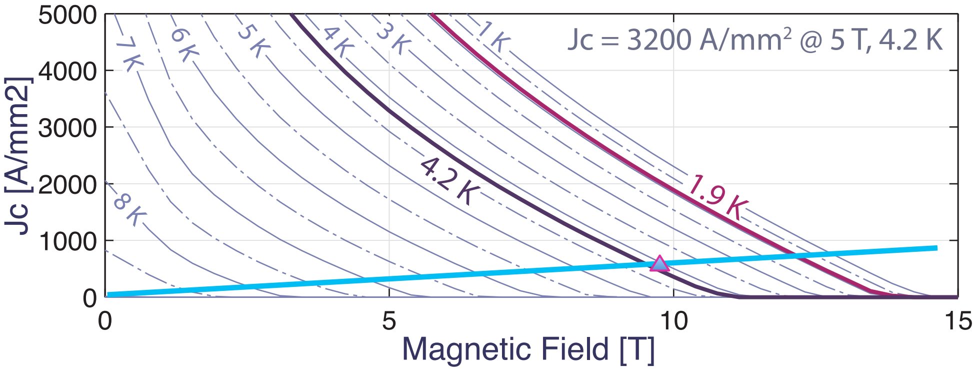
CONDUCTOR PERFORMANCE

- Used scaling relations
  - Bottura scaling relation for Nb-Ti with LHC strand
  - Godeke scaling relation for Nb_3Sn
- 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_3Sn conductor is scaled using a factor f_{Nb3Sn}
  - $J_{cscaled} = f_{Nb_3Sn} \cdot J_c$

Nb_3Sn

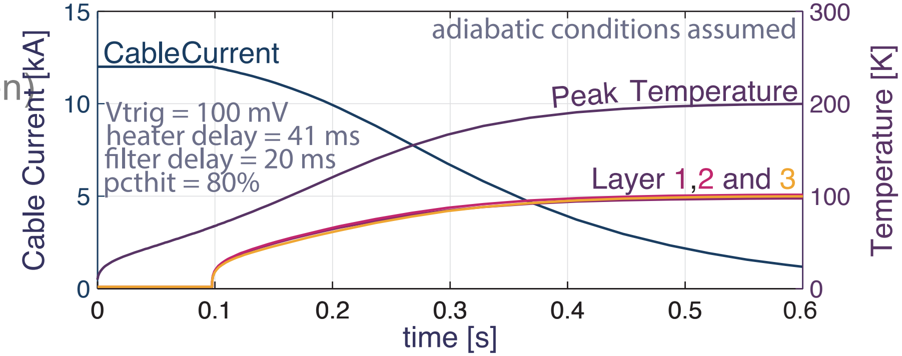


Nb-Ti



QUENCH MODEL

- 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

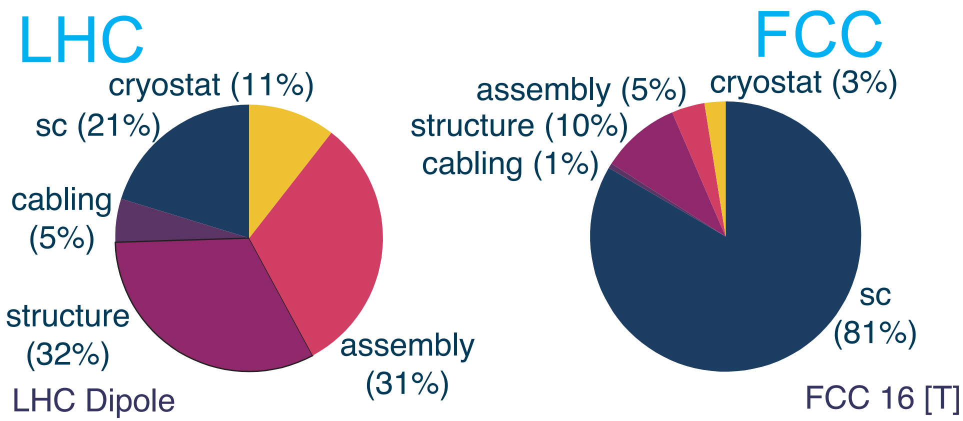


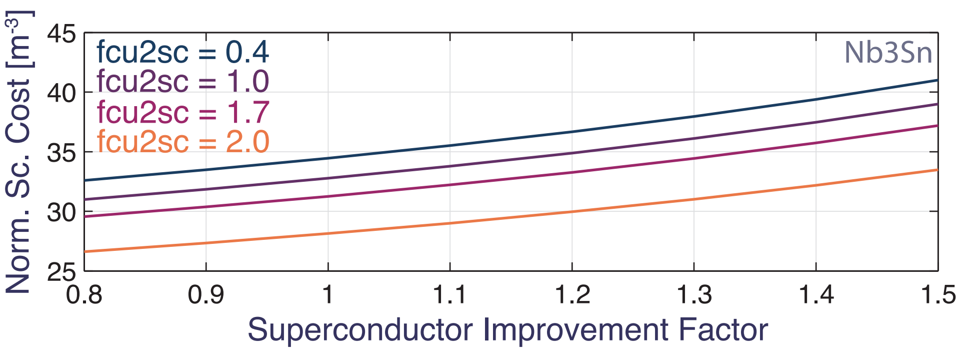
- Assumed circuit
  - No dump resistor such that magnets can be chained
  - Either Quench Heater or CLiQ (for now conservative LHC values for detection delay times assumed)

- 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

COST MODEL





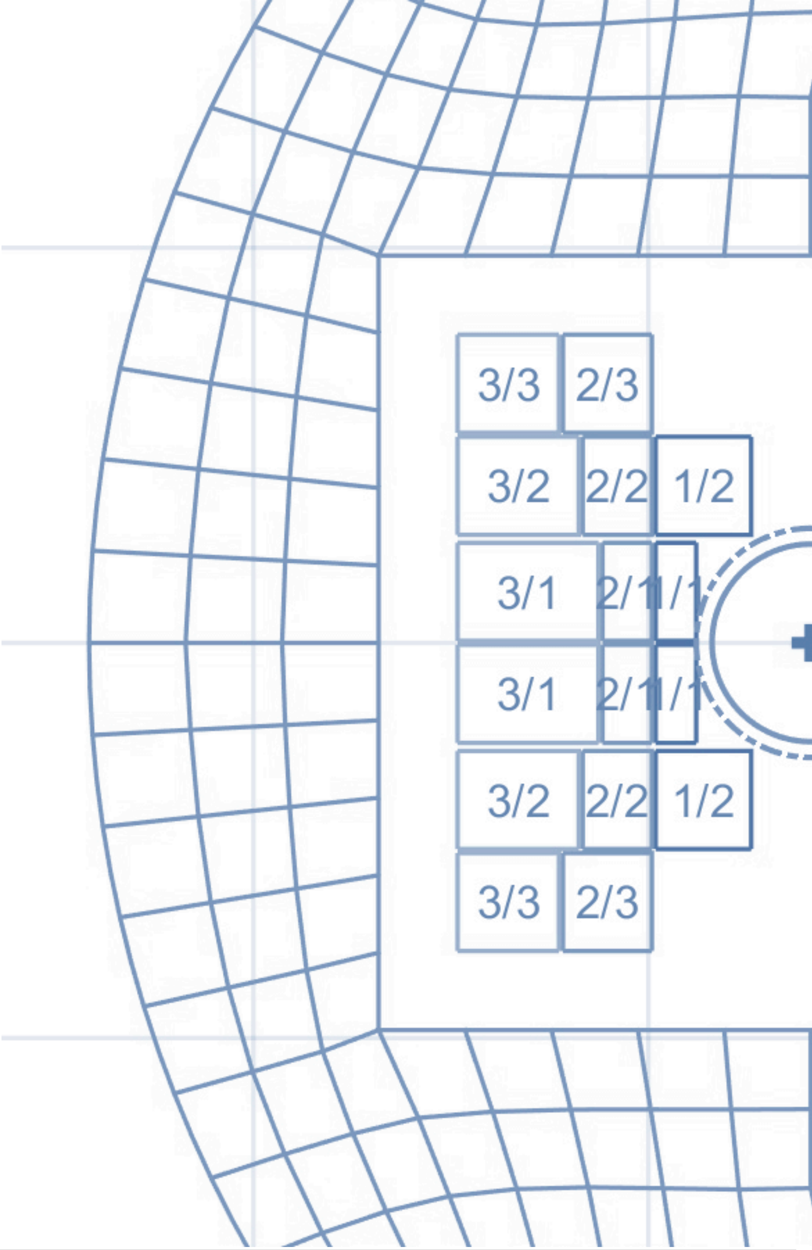
- Implemented cost model to compare different layouts. Included is:
  - Cryostat
  - Superconductor
  - Cabling
  - Structure
  - Assembly
- Construction cost dominated by the superconductor cost
- Cost of Nb_3SN depends on
  - copper content
  - improvement factor
  - for fcu2sc > 1.65 the copper is no longer part of the strands and added separately to the cable

Introduction

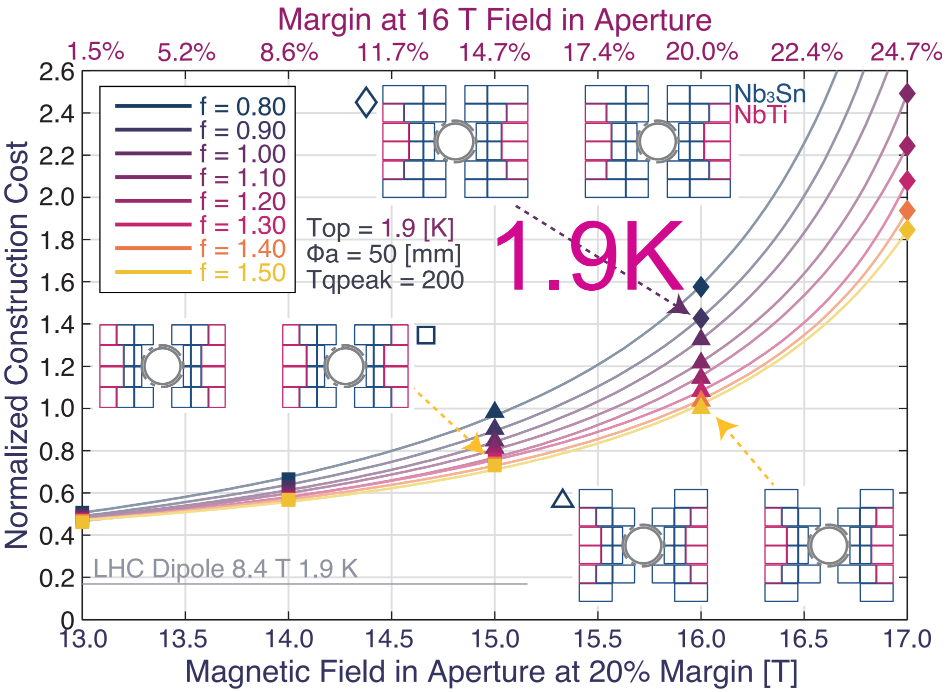
Input

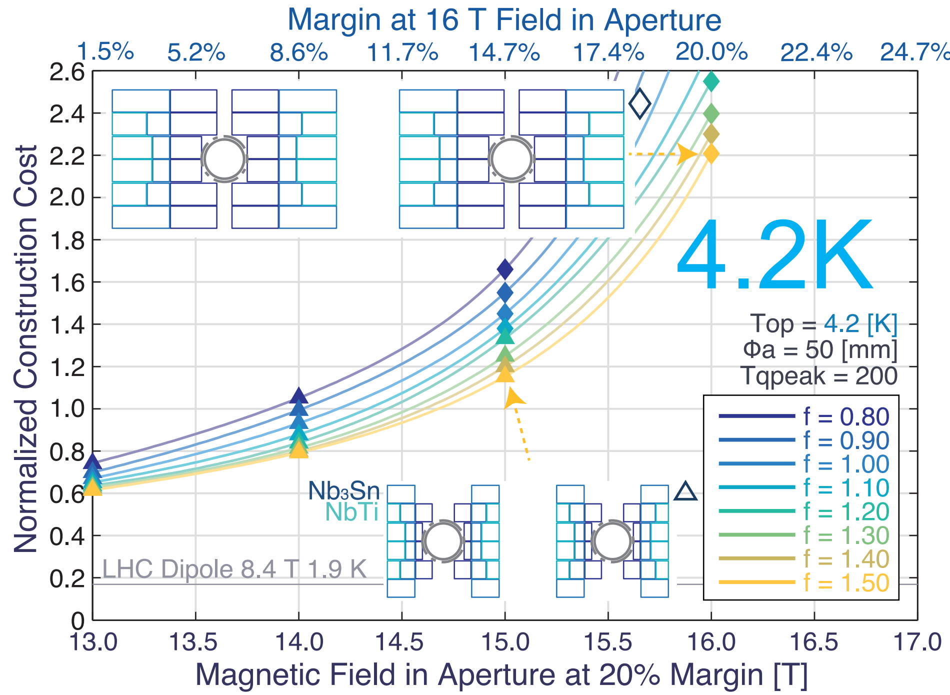
RESULTS

Conclusion



OPERATING TEMPERATURE AND IMPROVEMENT FACTOR

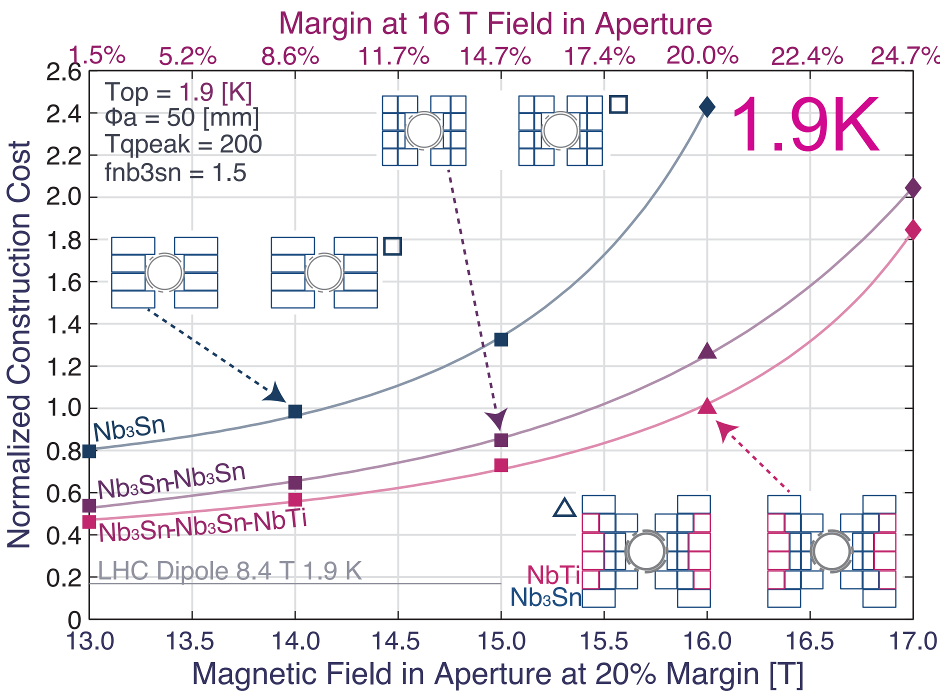


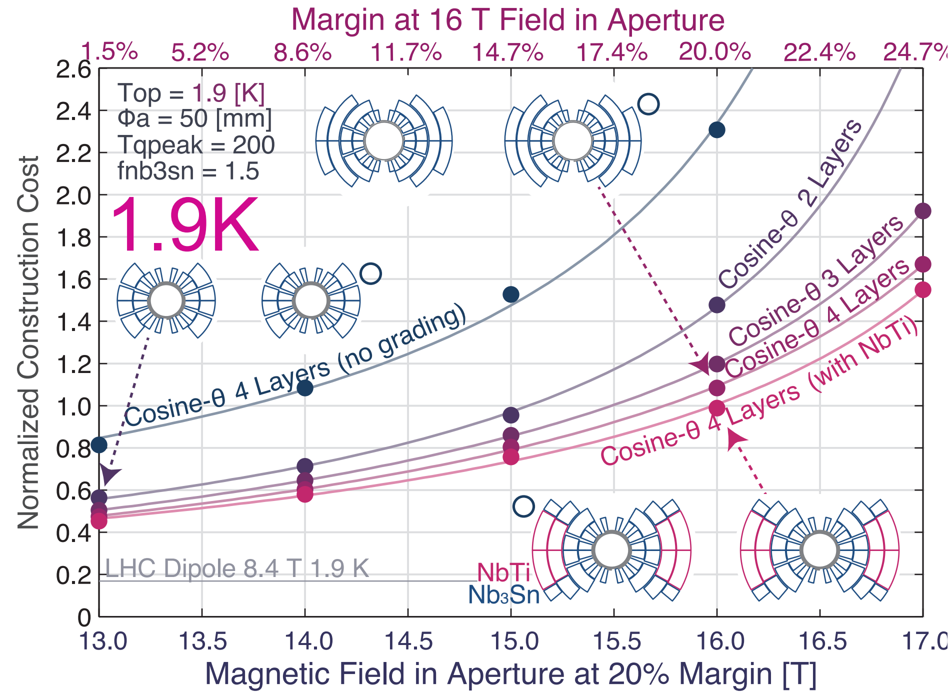


- No Iron is used in order to speed up calculations
- All layouts are normalized with respect to the <B=16T, f=1.5, T=1.9K, Tq=200K> layout
- Different layout shapes are optimal at different fields and conductor improvement factors
- For reasonable 16T 20% margin layout we need:
  - 4.2 -> 1.9 K provides 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 AND LAYOUT TYPE





- Grading in the Nb_3Sn 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 (=

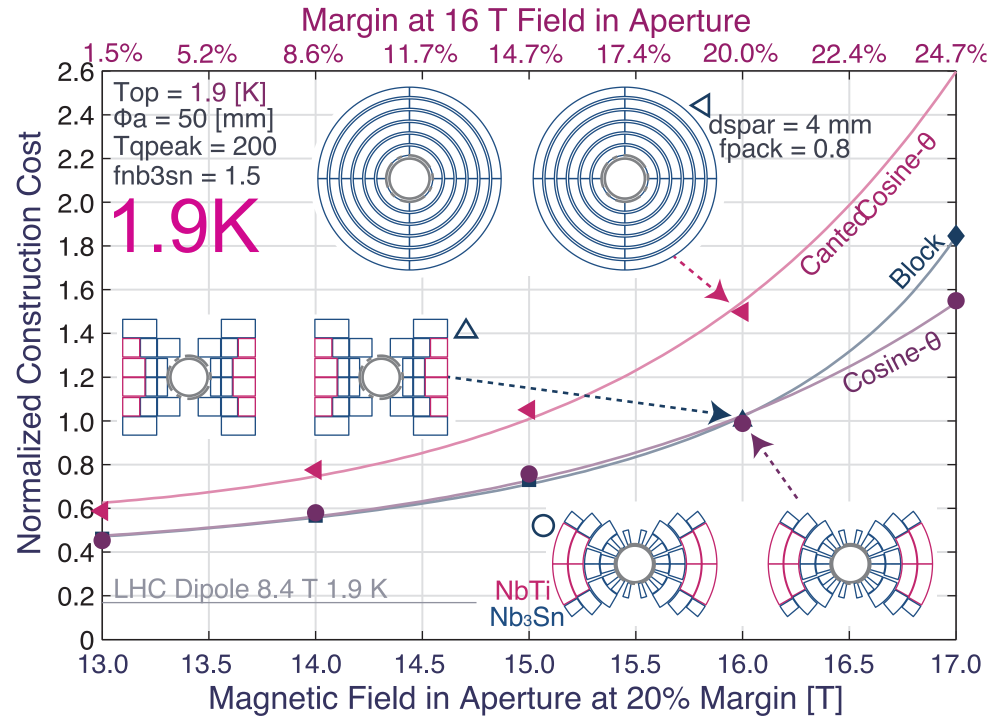
- This means we need R&D on inter-layer joints (between Nb-Ti and Nb_3Sn)
- Probably need to resin-impregnate the Nb-Ti layer?
- Also note that all decks need to have flared coil ends when grading is used

GRADING AND LAYOUT TYPE

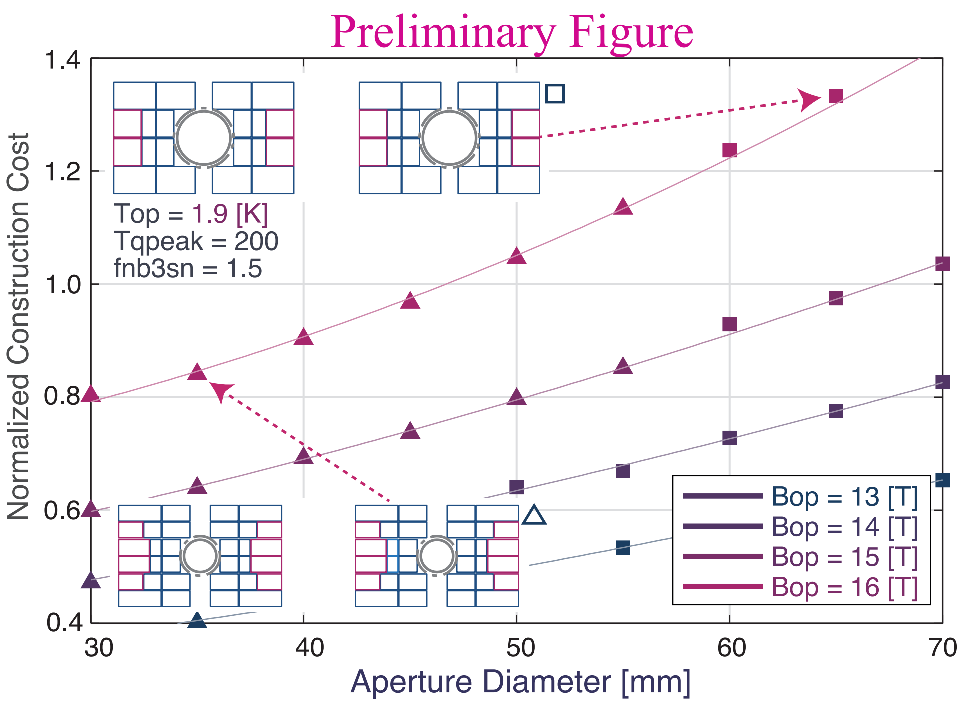
- Block and Cosine-Theta are very similar in terms of cost.
  - Similar shape and positioning of conductor (equal grading)
  - Extra mechanical structure in block balances out with wedges needed for cosine theta
  - Block favours wider (higher current) cables

- 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

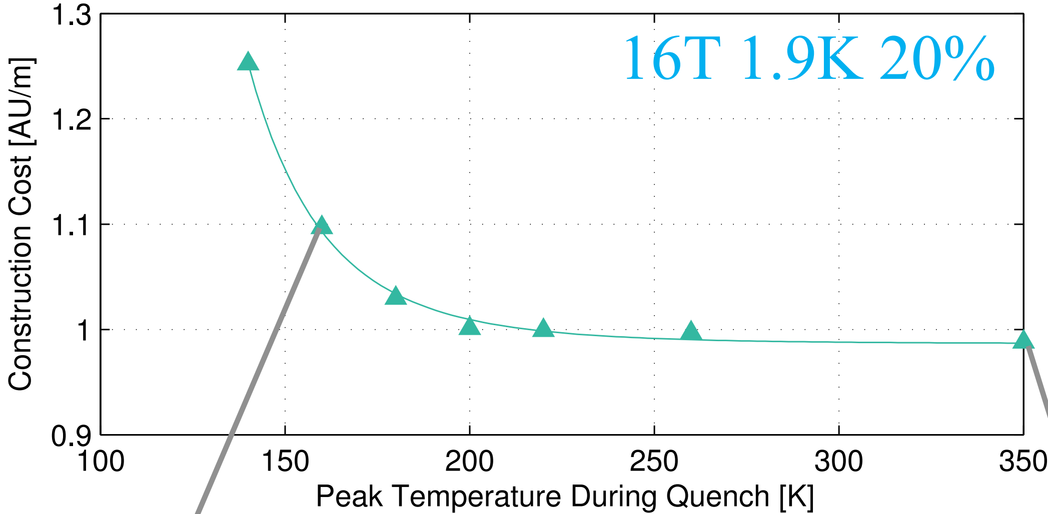


APERTURE SIZE

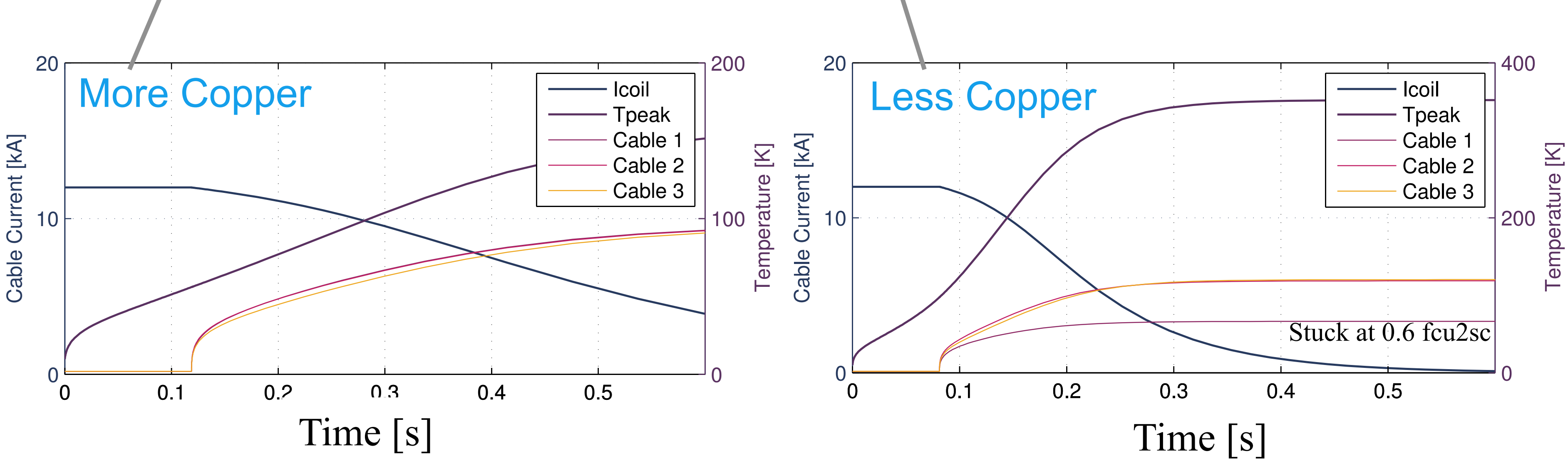


- Expected synchrotron radiation is 50 watt / m (possibly need more space for cooling)
- More-or-less linear scaling with the aperture size (In agreement with analytical predictions)
- At high aperture size we get fresca-2 like configuration
- Larger aperture costs money!

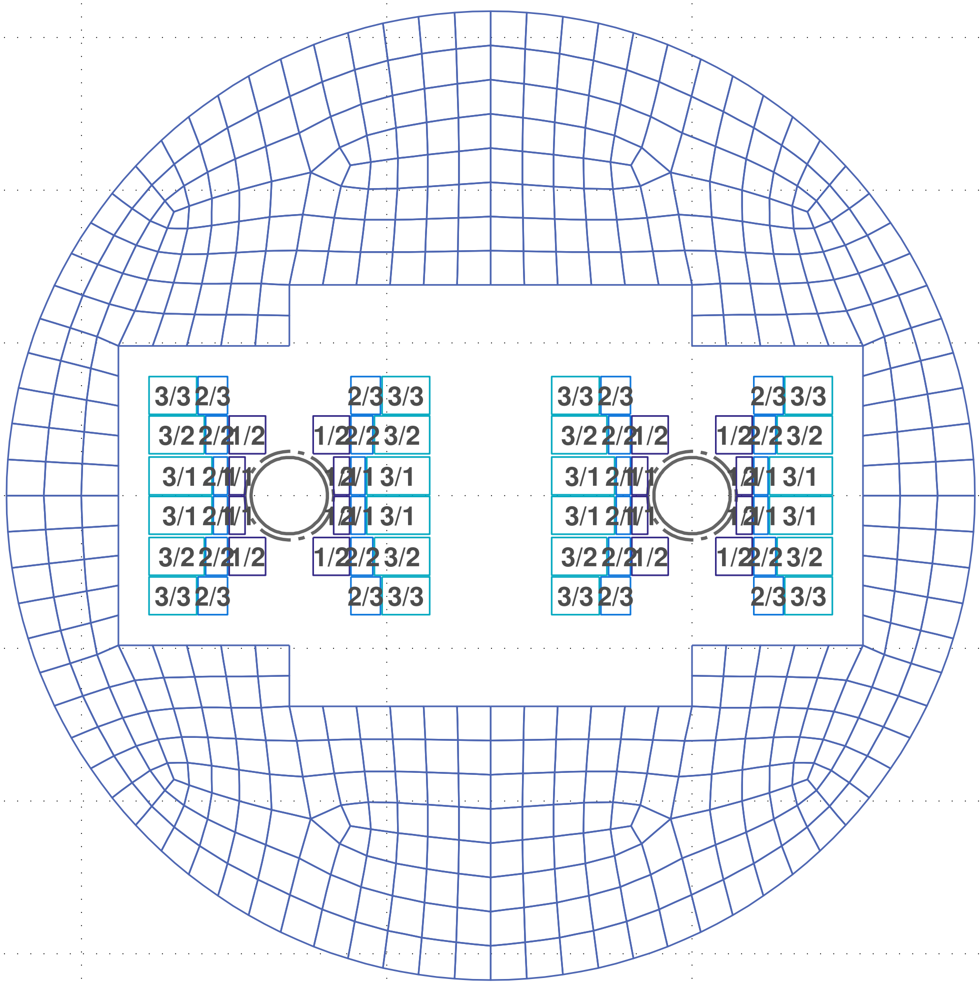
ALLOWABLE PEAK TEMPERATURE



- 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



ACTIVE SHIELDING AND//OR IRON YOKE



- 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)

CONCLUSION

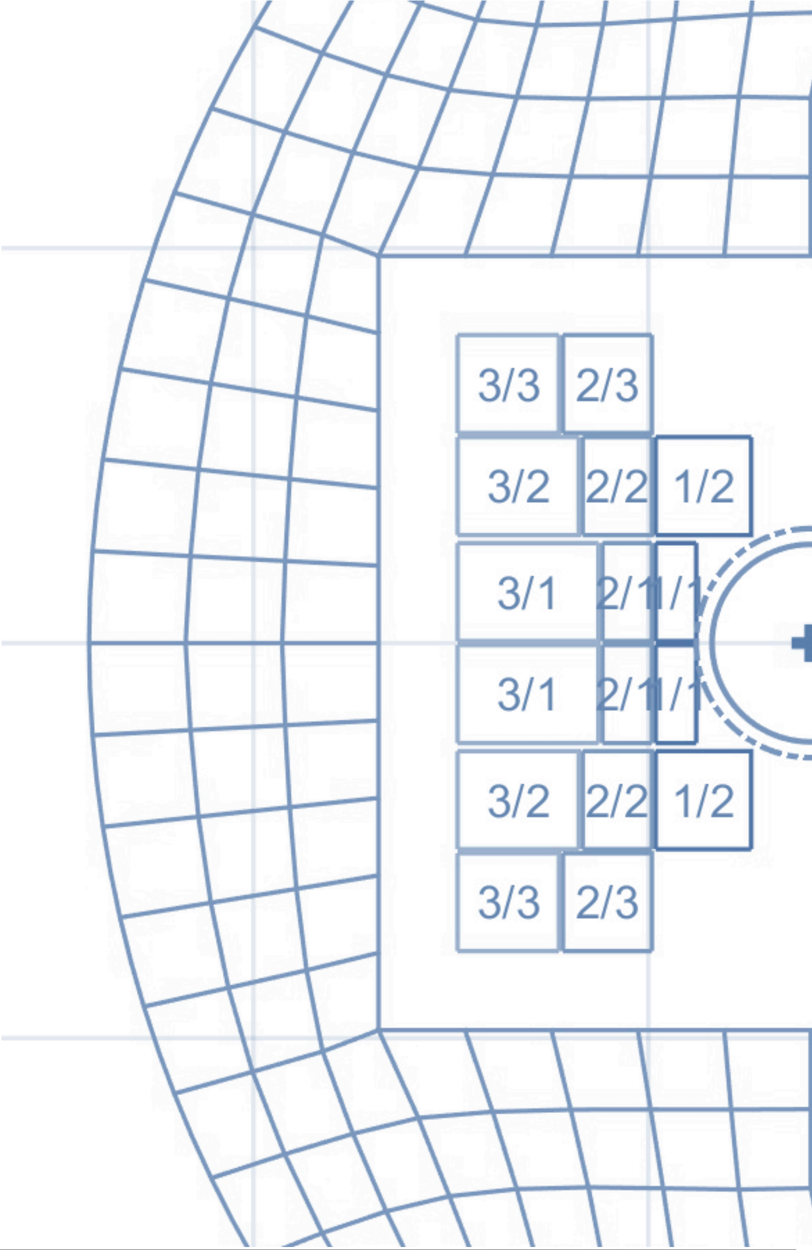
- For a 16 T magnet need both
  - Operating at 1.9 K provides an additional 1.2 T over 4.2 K
  - Improving the conductor by 50% is worth about 1 T

- 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

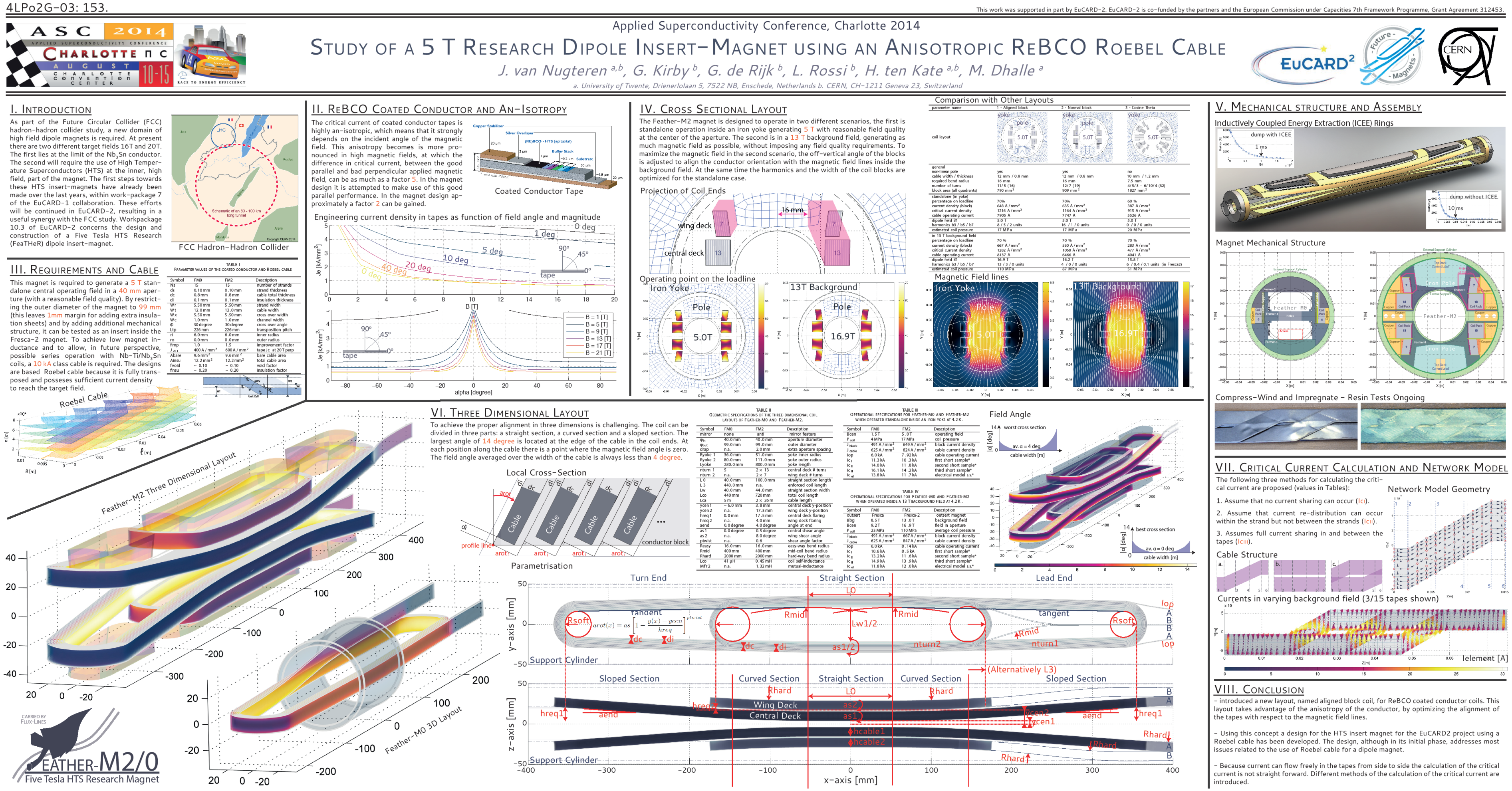
- Mechanical studies are ongoing to determine structure that allows assembly of dual aperture

THANK YOU FOR YOUR ATTENTION



LETS NOT FORGET ABOUT HTS

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



UNIVERSITY OF TWENTE.