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Study of a 5 T Research Dipole Insert-Magnet using an Anisotropic ReBCO Roebel Cable

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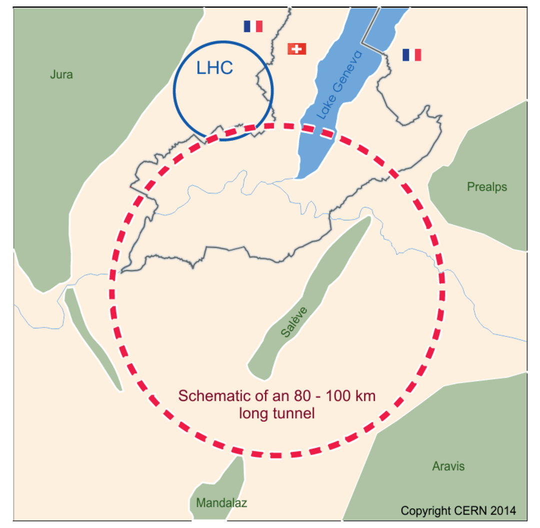
I. Introduction

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_3Sn conductor. The second will require the use of High Temperature Superconductors (HTS) at the inner, high field, part of the magnet. 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.



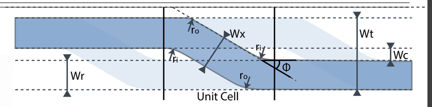
FCC Hadron-Hadron Collider

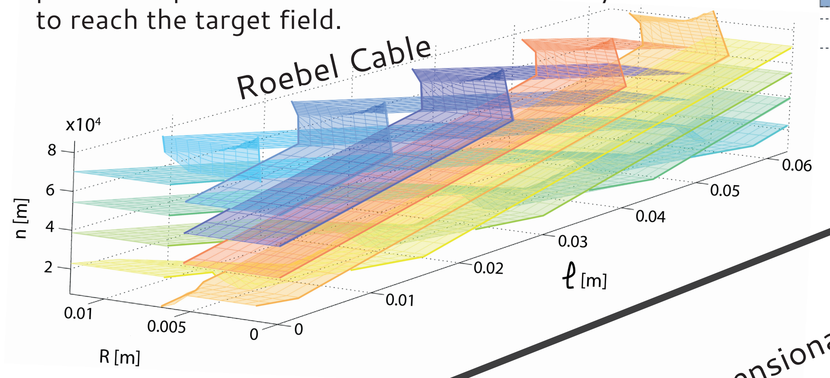
III. Requirements and Cable

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 1mm 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_3Sn coils, a 10 kA class cable is required. The designs are based Roebel cable because it is fully transposed and posseses sufficient current density to reach the target field.

TABLE I
Parameter values of the coated conductor and Roebel cable

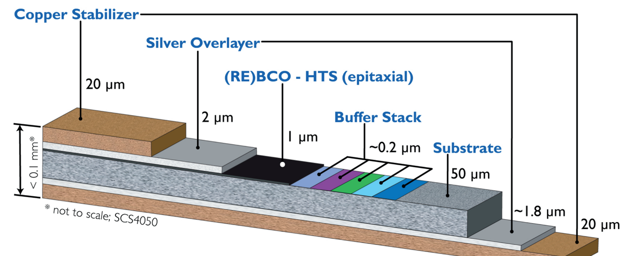
Symbol	FM0	FM2	Description
Ns	15	15	number of strands
ds	0.10 mm	0.10 mm	strand thickness
dc	0.8 mm	0.8 mm	cable total thickness
di	0.1 mm	0.1 mm	insulation thickness
Wr	5.50 mm	5.50 mm	strand width
Wt	12.0 mm	12.0 mm	cable width
Wx	5.50 mm	5.50 mm	cross over width
Wc	1.0 mm	1.0 mm	channel width
Φ	30 degree	30 degree	cross over angle
Ltp	226 mm	226 mm	transposition pitch
ri	6.0 mm	6.0 mm	inner radius
ro	0.0 mm	0.0 mm	outer radius
fimp	1.0	1.5	improvement factor
J_{20T}	400 A / mm^2	600 A / mm^2	tape Jc at 20 T perp
Abare	9.6 mm^2	9.6 mm^2	bare cable area
Ainsu	12.2 mm^2	12.2 mm^2	total cable area
fvoid	~ 0.10	~ 0.10	void factor
finsu	~ 0.20	~ 0.20	insulation factor





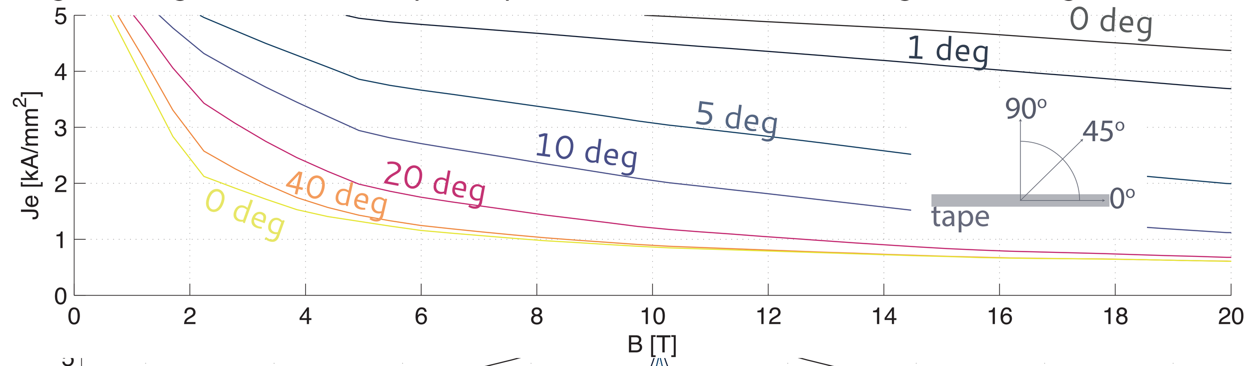
II. ReBCO Coated Conductor and An-Isotropy

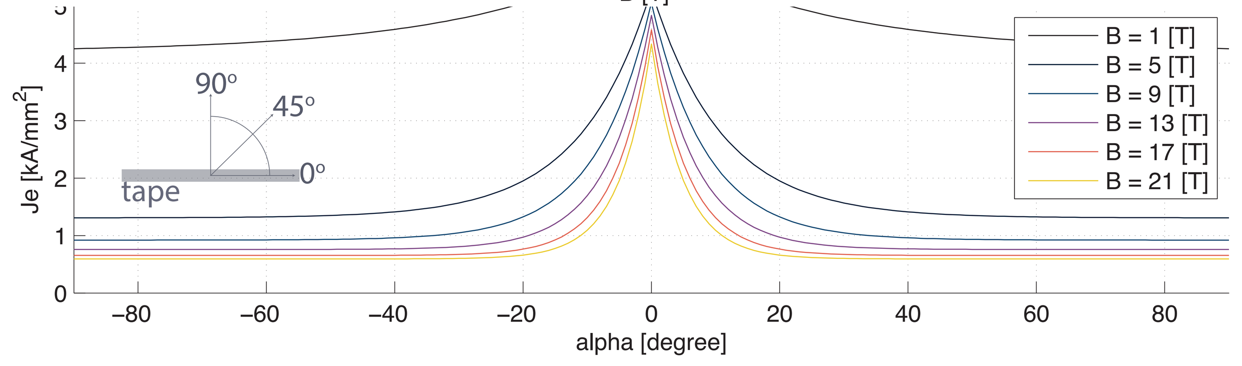
The critical current of coated conductor tapes is highly an-isotropic, which means that it strongly depends on the incident angle of the magnetic field. This anisotropy becomes is more pronounced in high magnetic fields, at which the difference in critical current, between the good parallel and bad perpendicular 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 approximately a factor 2 can be gained.



Coated Conductor Tape

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

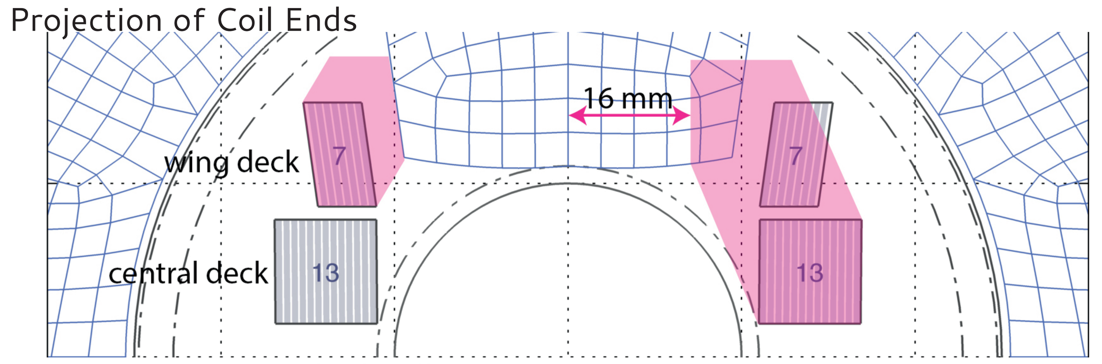




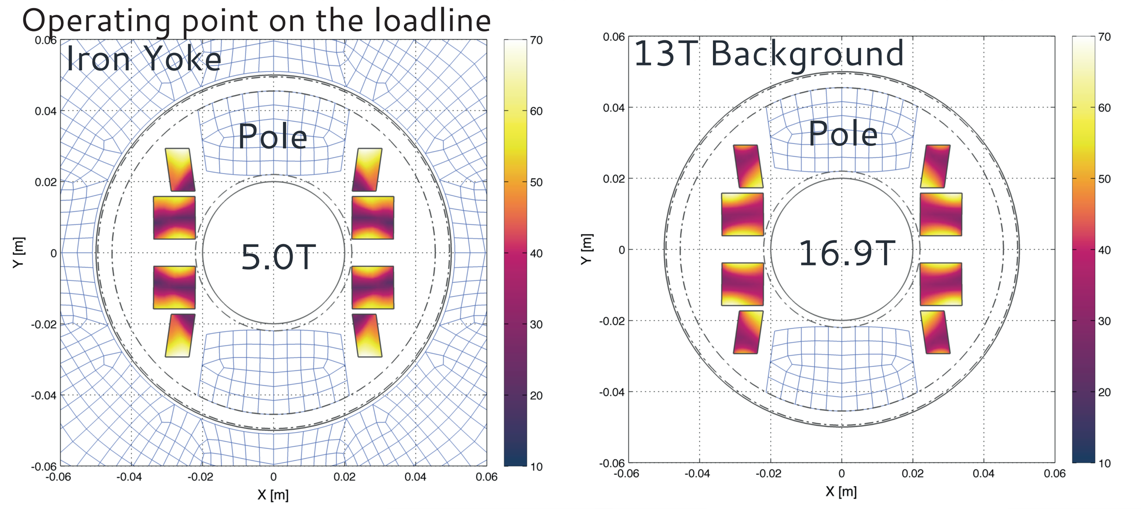
IV. Cross Sectional Layout

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.

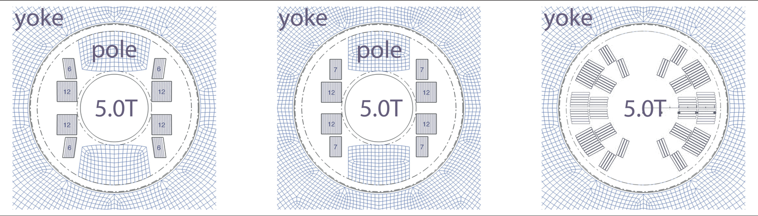
Projection of Coil Ends



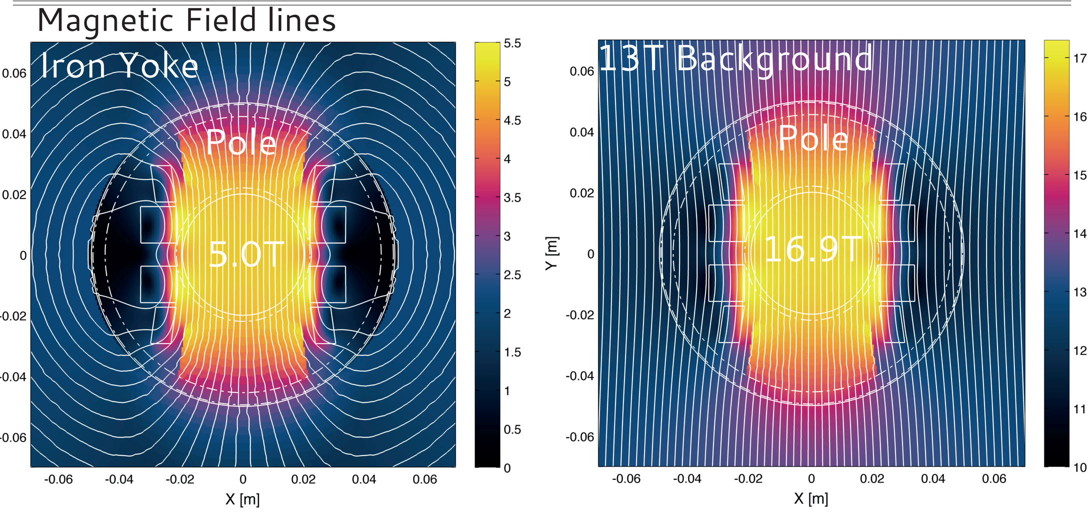
Operating point on the loadline



Comparison with Other Layouts

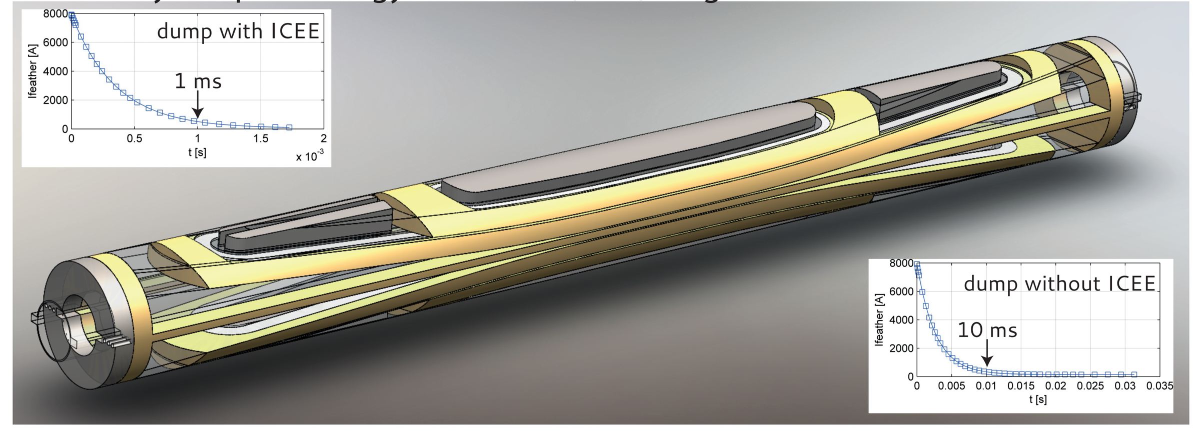
parameter name	1 - Aligned block	2 - Normal block	3 - Cosine Theta
coil layout			
general			
non-linear pole	yes	yes	no
cable width / thickness	12 mm / 0.8 mm	12 mm / 0.8 mm	10 mm / 1.2 mm
required bend radius	16 mm	16 mm	7.5 mm
number of turns	11/5 (16)	12/7 (19)	4/5/3 – 6/10/4 (32)
block area (all quadrants)	790 mm^2	909 mm^2	1827 mm^2
standalone (in yoke)			
percentage on loadline	70%	70%	60 %
current density (block)	648 A / mm^2	635 A / mm^2	387 A / mm^2
critical current density	1216 A / mm^2	1164 A / mm^2	915 A / mm^2
cable operating current	7905 A	7747 A	5526 A
dipole field B1	5.0 T	5.0 T	5.0 T
harmonics b3 / b5 / b7	8 / 5 / 2 units	16 / 1 / 0 units	0 / 0 / 0 units
estimated coil pressure	17 MPa	17 MPa	20 MPa
in 13 T background field			
percentage on loadline	70 %	70 %	70 %
current density (block)	667 A / mm^2	530 A / mm^2	283 A / mm^2
critical current density	1282 A / mm^2	1068 A / mm^2	477 A / mm^2
cable operating current	8137 A	6466 A	4041 A
dipole field B1	16.9 T	16.2 T	15.8 T
harmonics b3 / b5 / b7	13 / 3 / 0 units	4 / 0 / 0 units	6 / 0.4 / 0.1 units (in Fresca2)
estimated coil pressure	110 MPa	87 MPa	51 MPa

Magnetic Field lines

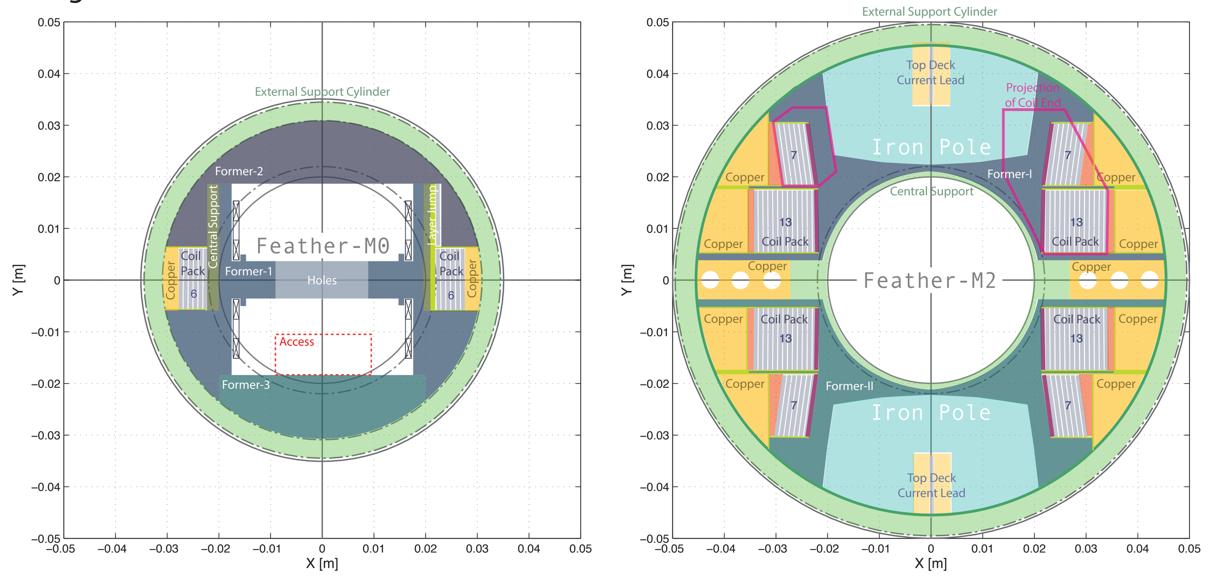


V. Mechanical Structure and Assembly

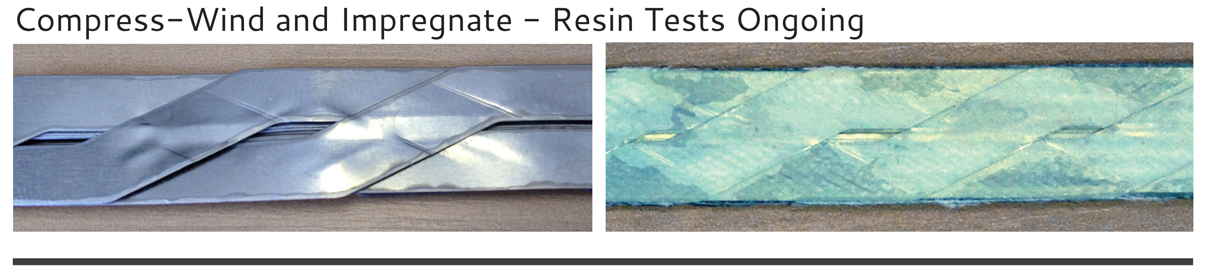
Inductively Coupled Energy Extraction (ICEE) Rings



Magnet Mechanical Structure

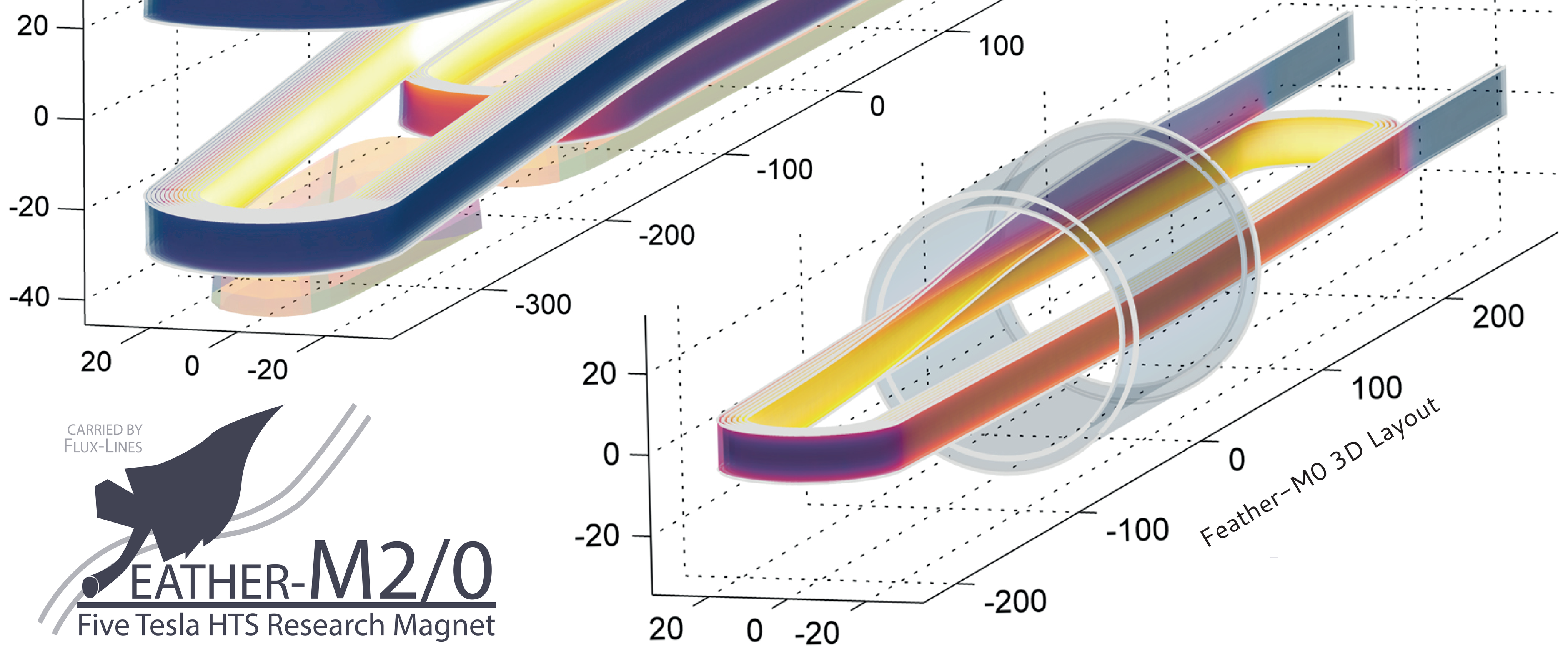


Compress-Wind and Impregnate - Resin Tests Ongoing

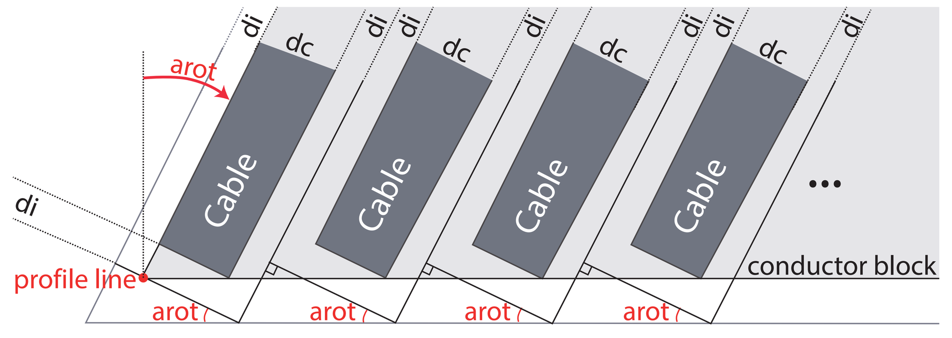


VI. Three Dimensional Layout

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.



Local Cross-Section



Parametrisation

TABLE II
Geometric specifications of the three-dimensional coil layouts of Feather-M0 and Feather-M2.

Symbol	FM0	FM2	Description
mirror	none	anti	mirror feature
φ_{in}	40.0 mm	40.0 mm	aperture diameter
φ_{out}	99.0 mm	99.0 mm	outer diameter
drap	n.a.	2.0 mm	extra aperture spacing
Ryoke 1	36.0 mm	51.0 mm	yoke inner radius
Ryoke 2	80.0 mm	111.0 mm	yoke outer radius
Lyoke	280.0 mm	800.0 mm	yoke length
nturn 1	5	2 × 13	central deck # turns
nturn 2	n.a.	2 × 7	wing deck # turns
L 0	40.0 mm	100.0 mm	straight section length
L 3	440.0 mm	n.a.	enforced coil length
Lw	40.0 mm	44.0 mm	straight section width
Lco	440 mm	720 mm	total coil length
Lca	5 m	2 × 26 m	cable length
ycen 1	– 6.0 mm	3.8 mm	central deck y-position
ycen 2	n.a.	17.3 mm	wing deck y-position
hreq 1	0.0 mm	17.5 mm	central deck flaring
hreq 2	n.a.	4.0 mm	wing deck flaring
aend	0.0 degree	4.0 degree	angle at end
as 1	0.0 degree	0.5 degree	central shear angle
as 2	n.a.	8.0 degree	wing shear angle
ptwist	n.a.	0.6	shear angle factor
Reasy	16.0 mm	16.0 mm	easy-way bend radius
Rmid	400 mm	400 mm	mid-coil bend radius
Rhard	2000 mm	2000 mm	hard-way bend radius
Lco	41 µH	0.45 mH	coil self-inductance
Mfr2	n.a.	1.32 mH	mutual-inductance

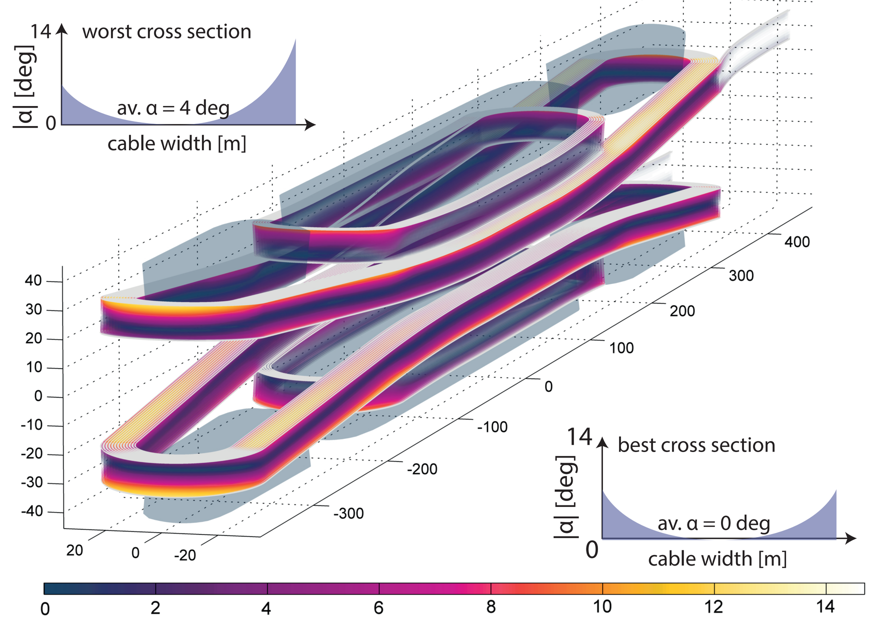
TABLE III
Operational specifications for Feather-M0 and Feather-M2 when operated standalone inside an iron yoke at 4.2 K.

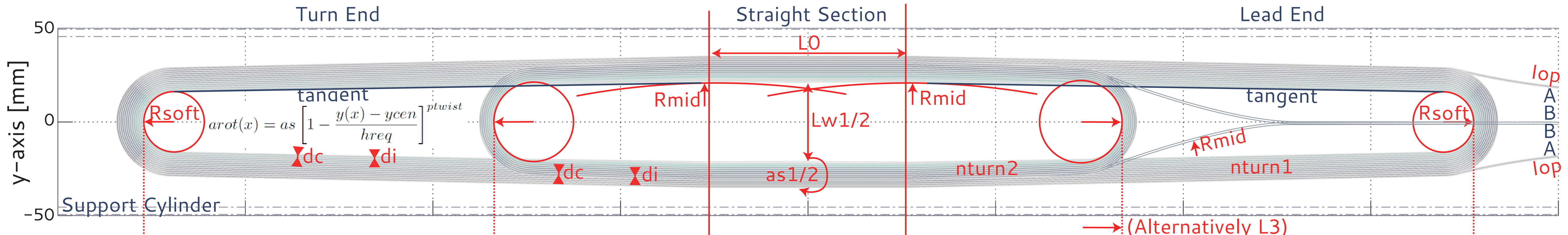
Symbol	FM0	FM2	Description
Bcen	1.5 T	5.0 T	operating field
P_{coil}	4 MPa	17 MPa	coil pressure
J_{block}	491 A / mm^2	649 A / mm^2	block current density
J_{cable}	625 A / mm^2	824 A / mm^2	cable current density
Iop	6.0 kA	7.92 kA	cable operating current
Ic_{I}	11.3 kA	10.3 kA	first short sample*
Ic_{II}	14.0 kA	11.8 kA	second short sample*
Ic_{III}	16.1 kA	14.2 kA	third short sample*
Ic_{el}	13.8 kA	11.7 kA	electrical model s.s.*

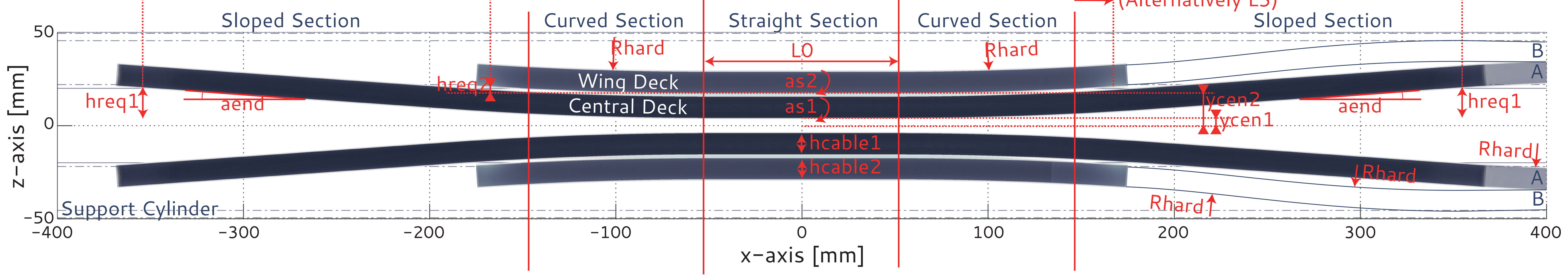
TABLE IV
Operational specifications for Feather-M0 and Feather-M2 when operated inside a 13 T background field at 4.2 K.

Symbol	FM0	FM2	Description
outsert	Fresca	Fresca-2	outsert magnet
Bbg	8.5 T	13.0 T	background field
Bcen	9.2 T	16.9 T	field in aperture
P_{coil}	23 MPa	110 MPa	average coil pressure
J_{block}	491 A / mm^2	667 A / mm^2	block current density
J_{cable}	625 A / mm^2	847 A / mm^2	cable current density
Iop	6.0 kA	8.14 kA	cable operating current
Ic_{I}	10.6 kA	8.5 kA	first short sample*
Ic_{II}	13.2 kA	11.6 kA	second short sample*
Ic_{III}	14.9 kA	13.9 kA	third short sample*
Ic_{el}	11.8 kA	12.0 kA	electrical model s.s.*

Field Angle







VII. Critical Current Calculation and Network Model

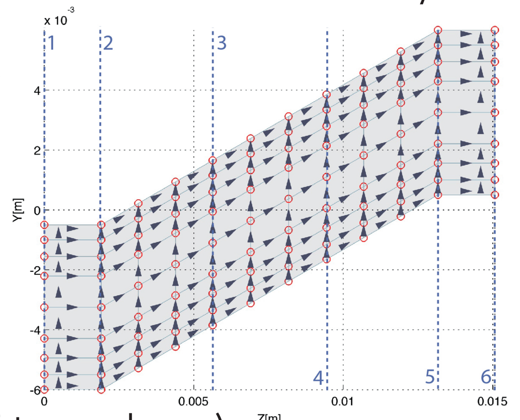
The following three methods for calculating the critical current are proposed (values in Tables):

1. Assume that no current sharing can occur (Ic_{I}).

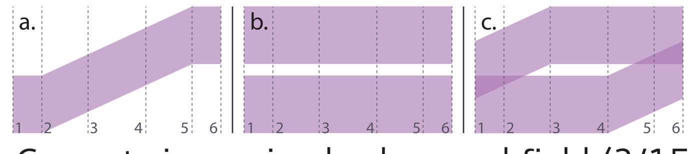
2. Assume that current re-distribution can occur within the strand but not between the strands (Ic_{II}).

3. Assumes full current sharing in and between the tapes (Ic_{III}).

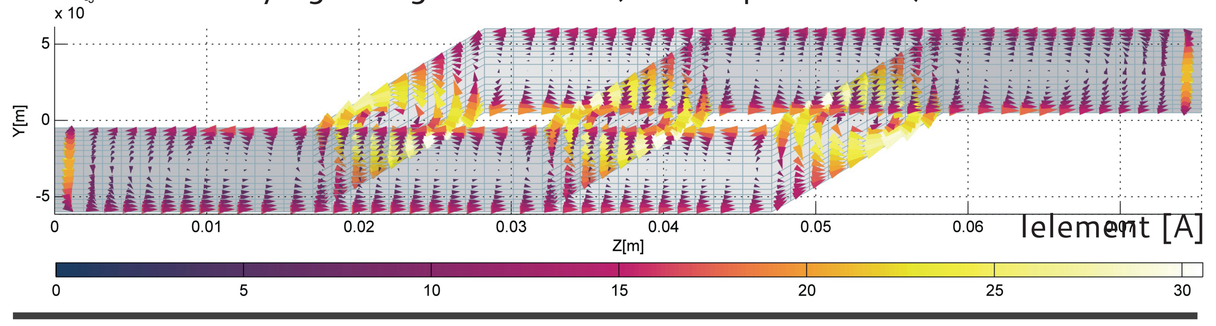
Network Model Geometry



Cable Structure



Currents in varying background field (3/15 tapes shown)



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.