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NOTE

16T DIPOLE DESIGN OPTIONS: INPUT PARAMETERS AND EVALUATION CRITERIA

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Abstract:

This document summarizes the input parameters and the evaluation criteria to be considered for the exploration of the different design options of the 16T dipole.

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TABLE OF CONTENTS

1. INTRODUCTION

The aim of this document is to establish the input parameters and constraints for the electromagnetic and mechanical calculations to be performed to analyze the different coil layouts considered as candidates for a 16 T dipole in the framework of Eurocircol program.

2. INPUT PARAMETERS

Table I summarizes the main starting parameters for the 16T dipole design optimization.

TABLE I

COMMON STARTING PARAMETERS FOR THE MAGNET OPTIMIZATION

Dipole field at aperture	16	T
Aperture diameter	50	mm
Reference radius	33	mm
Beam-to-beam distance	250	mm
Iron outer diameter	700	mm
Cryostat outer diameter	1000	mm
Operating margin	≥10	%
Working temperature	4.5	K
Cable insulation thickness	0.2	mm per conductor face
Ground insulation thickness	2	mm
X-section multipoles (geometric)	A few 10^{-4}	units at reference radius
Overall coil length	14	m
Peak stress	150	MPa
Max coil deformation	<0.05?	mm (due to Lorentz forces)
Peak temperature	300	K (quench)
Peak voltage to ground	2000	V (quench)
Peak inter-turn voltage	100	V (quench)
Protection circuit delay	10-20-30	ms

2.1. CABLE PROPERTIES

Next paragraphs depict the cable properties as presently being used by CEA.

Mechanical parameters:

Table II

Material properties

<table>
<tr><th colspan="2">Young modulus [GPa]</th><th>ILTEC* [mm/m]</th><th>Material</th></tr>
<tr><td colspan="2">4</td><td>6.0</td><td>Epoxy**</td></tr>
<tr><td colspan="2">110</td><td>3.6</td><td>Copper</td></tr>
<tr><td>30@293K</td><td>42@4.2K</td><td>3.9</td><td>Nb_3Sn**</td></tr>
<tr><td colspan="2">210</td><td>2.9</td><td>Steel</td></tr>
</table>

*Integrated Linear Thermal Expansion Coefficient: 300 K to 4.2 K

**Measurements on impregnated Nb_3Sn [DUR1,DUR2]

[DUR1] M. Durante, “Essais de compression sur empilements droits de conducteurs isolés et autres échantillons”, internal note CEA : 5-2650N—2300 004 00, (oct. 2000)

[DUR2] M. Durante, “Mesure du rétreint thermique d’empilements droits de conducteurs isolés et autres échantillons”, internal note CEA : 5-2650N—2300 005 00, (oct. 2000)

Electrical parameters:

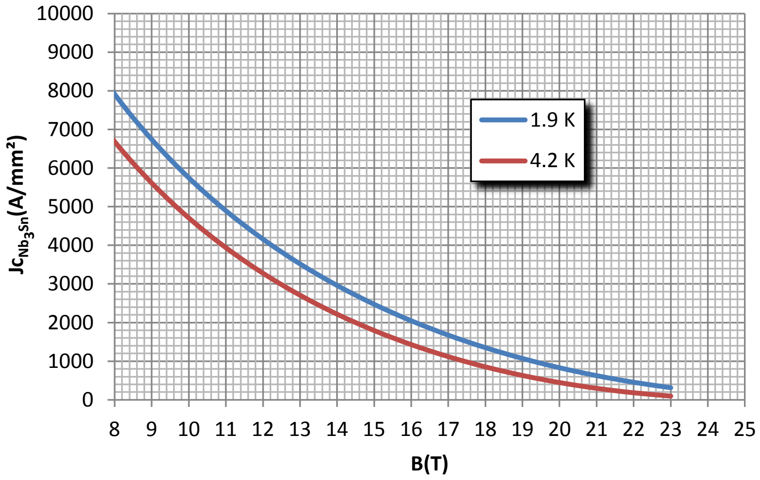
Fit function - Roxie [SUM1] (FCC target used for FCC quadrupole preliminary design [LOR1])

$$B_{c2}(T) = B_{c20}\left(1-\left(\frac{T}{T_{c0}}\right)^2\right)\left(1-0.31\left(\frac{T}{T_{c0}}\right)^2\left(1-1.77\ln\left(\frac{T}{T_{c0}}\right)\right)\right)$$

$$J_c(B,T) = \frac{C}{\sqrt{B}}\left(1-\frac{B}{B_{c2}(T)}\right)^2\left(1-\left(\frac{T}{T_{c0}}\right)^2\right)^2$$

with C = 4.4559e10 [$A.T^{0.5}m^{-2}$]   Bc20 = 29.08 T   Tc0 = 17.81 K

(*Remark: C ≈ 3.3313e10 [$A.T^{0.5}m^{-2}$] for High Lumi cables*)



Jc(12 T, 1.9 K) = 4159 A/mm²

Jc(16 T, 1.9 K) = 2046 A/mm²

Jc(12 T, 4.2 K) = 3277 A/mm²

Jc(16 T, 4.2 K) = 1794 A/mm²

[SUM1] L. Summers, M. Guinan, J. Miller, P. Hahn, “A model for the prediction of Nb3Sn critical current as a function of field temperature strain and radiation damage”, IEEE Trans. on Magnetics, vol 27, 2, (1991)

[LOR1] C. Lorin, “MQ for FCC”, FCC week, Washington, D.C., USA, 23-29 March 2015 (**data from M. Karppinen and L. Bottura**)

Cable design: Rule of thumb

cable width: $$w = \frac{\frac{Nd}{2\cos(\theta)} + ad}{1+c_w}$$

cable thickness: $$t = \frac{2d}{1+c_t}$$

cable compaction: $$c = (1+c_w)(1+c_t)$$

Table III

Cable design parameter description

Parameter	Description	Range*
w	cable width	
N	Nb of strand	
d	Strand diameter	0.5 – 1 mm
θ	Twist pitch angle	
a	*rule of thumb* coefficient	0.72 – 0.732
c_w	cable width compaction	-3% to 0%
t	cable thickness	-10% to -5%

c_t	cable thickness compaction	
c	total compaction	> 86 %
*Just to give an idea		

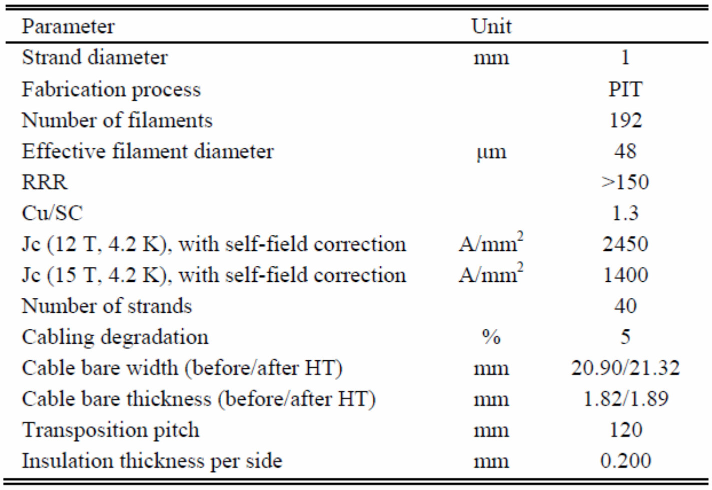
It is worth adding that the maximum keystoned angle is lower than for Nb-Ti cable (0.6° to 0.8°) [BOT1]. The critical current Ic degradation with the previous parameters should be of the order of 10%.

Most of the data are coming from [BOT2] and some from [DIE1][SCA1]

[BOT1] L. Bottura, Private communication, FCC week, Washington (March 2015)
[BOT2] L. Bottura. A. Godeke, "Supercoducting materials and conductors: fabrication and limiting parameters", Rev. Accel. Sci. Technol., vol 5, (2012)
[DIE1] D. Dietderich. A. Godeke, "Nb3Sn research and development in the USA – Wires and cables", Cryogenics, vol 48, (2008)
[SCA1] R. Scanlan, "The evolution of tooling, techniques, and quality control for accelerator dipole magnet cables", IEEE Trans. on Applied Superconductivity, vol 3, (1993)

Table IV depicts the cable parameters being used for FRESCA2 coils [FER1]:

Table IV
FRESCA2 cable parameters



Parameter	Unit	
Strand diameter	mm	1
Fabrication process		PIT
Number of filaments		192
Effective filament diameter	µm	48
RRR		>150
Cu/SC		1.3
Jc (12 T, 4.2 K), with self-field correction	A/mm^2	2450
Jc (15 T, 4.2 K), with self-field correction	A/mm^2	1400
Number of strands		40
Cabling degradation	%	5
Cable bare width (before/after HT)	mm	20.90/21.32
Cable bare thickness (before/after HT)	mm	1.82/1.89
Transposition pitch	mm	120
Insulation thickness per side	mm	0.200

[FER1] P. Ferracin et al., "Development of the EuCARD Nb3Sn Dipole Magnet FRESCA2", IEEE Transactions on Applied Superconductivity 23, 4002005 (June 2013).

3. EVALUATION CRITERIA

TABLE V
COMPARISON OF 16 T DIPOLE DESIGNS

Magnet type	Cos-θ	Common coil	Block	Units
Area of bare conductors/aperture				mm^2
Area of insulated conductors/aperture				mm^2
Number of strands per aperture				
Outer iron yoke radius				mm
Current				A
Margin on load line				%
Bore field				T
Peak field				T

Peak field /bore field	
Peak field for 0% on load line	T
Magnetic field quality	
b_3	10^{-4} units
b_5	10^{-4} units
b_7	10^{-4} units
b_9	10^{-4} units
b_{11}	10^{-4} units
Engineering current density	A/mm^2
Minimum bending radius	mm
Self inductance /aperture /unit length	mH/m
Stored energy /aperture / unit length	MJ/m
Stray magnetic field	
- at 50 mm of the outer iron radius	T
- at 1 m away from the magnet center	T
Lorentz forces	
- F_x per side of aperture	MN/m
- F_y per quadrant	MN/m
- Maximum accumulated membrane stress perpendicular to the broad side of the cable	MPa
- Maximum accumulated membrane stress parallel to the broad side of the cable	MPa