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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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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. This document summarizes the discussions held at the kick-off meeting and first periodical meetings of WP5.

This comparison will be performed for double aperture magnet models, which is the final aim of FCC study. However, the detailed analysis (tasks 5.4 and 5.7) will be done for a single aperture magnet, if cos-theta or block layouts are the preferred configuration, because in that case, the prototype will have a single aperture.

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	17	mm
Beam-to-beam distance	250	mm
Outer diameter	750	mm
Cryostat outer diameter	1000	mm
Operating margin (current)	≥10	%
Working temperature	4.5	K
Cable insulation thickness	0.2	mm per conductor face
Inter-layer insulation thickness	0.5	mm
Ground insulation thickness	2	mm
X-section multipoles (geometric)	A few 10^{-4}	units at reference radius
Overall coil length	14	m
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

Some remarks should be made on those initial assumptions:

- Considering the given target cost of Nb_3Sn for FCC program, in the exploration of the design options we will not consider grading with NbTi unless an evident advantage in terms of complexity can be justified for a specific design. However, grading may be done by changing the copper to superconductor ratio or using the different cable sizes proposed in paragraph 2.1.
- Aperture diameter provides the radial position of the insulated cables of the inner layer.
- Reference radius is established using the classical criterion taking 2/3 of the aperture. This value is a bit high, since the physical aperture for the maximum particle excursion is 14 mm off-center.
- Working temperature is 4.5 K, which is more advantageous from the cryogenics point of view, but implies some challenges for the beam pipe design. If final decision is 1.9 K, the impact on the magnet design will be moderate: operating margin will increase, but stability issues will be more significant.

- Only field multipoles created by the coil geometry and the iron saturation will be considered at this design stage. The allowable values with geometric origin are the following:
  - $b_{3geo} < 3$ units (means demonstrating that we can keep it under control and that we can very likely introduce, at the level of conceptual study, a possible compensation)
  - $b_{5geo} < 5$ units (it scales rapidly with the radius, and can be compensated with correctors)
  - $b_{7geo} < 3$ units (it scales even more rapidly, but we do not want b7 correctors)
- Concerning saturation effects, set a "soft target" in the range of $b_{3sat} < 10$ units.

2.1. CABLE PROPERTIES

Next paragraphs depict the cable properties to be used for the analysis of the magnet design options. The maximum number of strands is kept as 40, according the existing cabling experience.

Critical surface

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

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

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

Where $t = \frac{T}{T_{c0}}$; $b = \frac{B_p}{B_{c2}(t)}$: with B_p as peak field on the conductor.

T_{c0}, B_{c20}, α, C_0 are fitting parameters computed from the analysis of measurements on the conductor.

For a reasonable estimate of the critical current density of a round wire, magnet designers can assume the following parameters: $T_{c0} = 16$ K, $B_{c20} = 28.8$ T, $\alpha = 0.96$, $C_0 = 255230$ A/mm^2 T. For the cable degradation we assume 5%.

Reference conductor

The magnet will be wound with two different types of Nb_3Sn Rutherford cable: a "high-field" one and a "low field" one. Both types will be based on high J_c wires; the Cu-to-non-Cu ratio is expected to be around 1 for the "high field" cable and larger than 1.5 for the other one.

We consider here three baseline cables:

1) a "high-field" cable constituted of 40 wires that have a relatively large diameter (1-1.1 mm); the precise dimensions of the wire and consequently of the cable are left as a free parameter for the magnet designers (in the case of a 1 mm wire the following reference cable dimensions can be taken: 1.82 mm for the mid-thickness; 21.0 mm for the width);
2) a "low field" cable constituted of 20 wires that have the same diameter as the wire used for the "high-field" cable (this cable will have approximately the same thickness of the high-field cable and half of its width);

3) a "low field" cable constituted of 40 wires that have relatively small diameter (0.7 mm); the following reference dimensions can be taken: 1.25 mm for the mid-thickness; 14.7 mm for the width.

We assume that the cable can be produced either in rectangular shape or with a keystone angle. The keystone angle have to be sufficiently small to prevent a compaction *c* of the cable thin-edge larger than 0.14 ($c = 1-h/2d$; where *h* is the cable thin edge thickness and *d* the wire diameter). As a reference, the keystone angle should not exceed 0.5°.

The specific characteristics of these cables and wires (in particular the Cu to non Cu ratio) can be later trimmed depending on the advancement and requirements of the study of the different design options.

2.2. STRUCTURAL DATA

We assume that all materials are limited by the yield strength, or by the material degradation (coil).

Concerning the ferromagnetic material (low carbon steel), a limit of tensile stress of $\sigma_l < 200$ MPa shall be considered at cold. This limit has to be considered as a prudent design threshold: it may change considerably depending on the exact steel composition and on its treatment.

The stress on the coil can vary considerably depending on the coil spot, in particular the interface conditions between coil and surrounding structure. We assume that the "reference coil pre-stress" in the 2D section is the one at the middle of the cable. The coil is modelled as a sector, with smeared-out mechanical properties as shown in Table II.

Concerning this last point, we set a baseline design such that the coil is loaded until the nominal magnetic field in the aperture of 16T. This will leave the opportunity, in a model magnet, to explore different configurations of pre-stress, including the ones unloading the coil at a lower field than the nominal one (for example setting an unloading target at 15T).

At the stage of exploring and comparing design options, we will consider that the pole tip is glued to the coil. If finite-element modelling is easier, pole and coil can be considered as independent parts, but not losing contact between them. At a later stage a decision about separate or glued coil will have to be taken: an independent coil can possibly allow the exploration of low pre-stress conditions.

The same criterion is followed for friction, which will be neglected at the level of the exploration of design options. At a later stage the use of a friction coefficient of 0.2 for most surfaces may be considered, but its need in a magnet which will certainly perform some "settling quenches" is still controversial.

Table II: Material Data for the exploration of 16T dipole design options

Material	Stress limit (MPa)		E (GPa)		ν	α
	293 K	4.2 K	293 K	4.2 K*	293 K /4.2 K	293 K→4.2 K
Coil	150	200	EX=52 EY=44 GXY=21	EX=52 EY=44 GXY=21	0.3	X=3.1E-3 Y=3.4E-3
Austenitic steel 316LN	350	1050	193	210	0.28	2.8E-3
Al 7075	480	690	70	79	0.3	4.2E-3

Ferromagnetic iron	180	720	213	224	0.28	2.0E-3
Pole (Ti6Al4V)	800	1650	130	130	0.3	1.7E-3

**In accordance to the experience of the LARP program, we use the same coil elastic modulus at warm and at cold. This may evolve when performing the final design if new data will be available.*

X cable side direction (radial in cos-theta), Y cable face direction (azimutal in cos-theta).

3. EVALUATION CRITERIA

TABLE III
CRITERIA FOR 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 turns per aperture				
Outer iron yoke radius				mm
Current				A
Margin on load line (current)				%
Bore field				T
Peak field				T
Peak field /bore field				
Peak field for 0% on load line				T
Field transfer function nonlinearity (between 1% and nominal current)				%
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
Insulated cable energy density				J/mm^3
Estimated time margin for magnet protection in case of quench [1]				ms
Minimum bending radius				mm
Self inductance per unit length				mH/m
Stored energy per unit length				MJ/m
Weight per unit length				kg
Stray magnetic field				
- at 50 mm of the outer iron radius				T
- at 1 m away from the magnet center				T
Lorentz forces				
- *Fx* per side of aperture				MN/m
- *Fy* per quadrant				MN/m
- Coil peak stress (warm, cold, cold & nominal current)				MPa
- Support structure peak stress (warm, cold, cold & nominal current)				MPa

4. REFERENCES

[1] E. Todesco, L. Bottura, G. De Rijk, L. Rossi, "*Dipoles for High Energy LHC*", IEEE Trans. Appl. Supercond. 24, (2014) 4004306.