Magnet cost model and targets

D. Schoerling, CERN

Maria Durante, Clement Lorin, CEA

Teresa Martinez, Fernando Toral, CIEMAT

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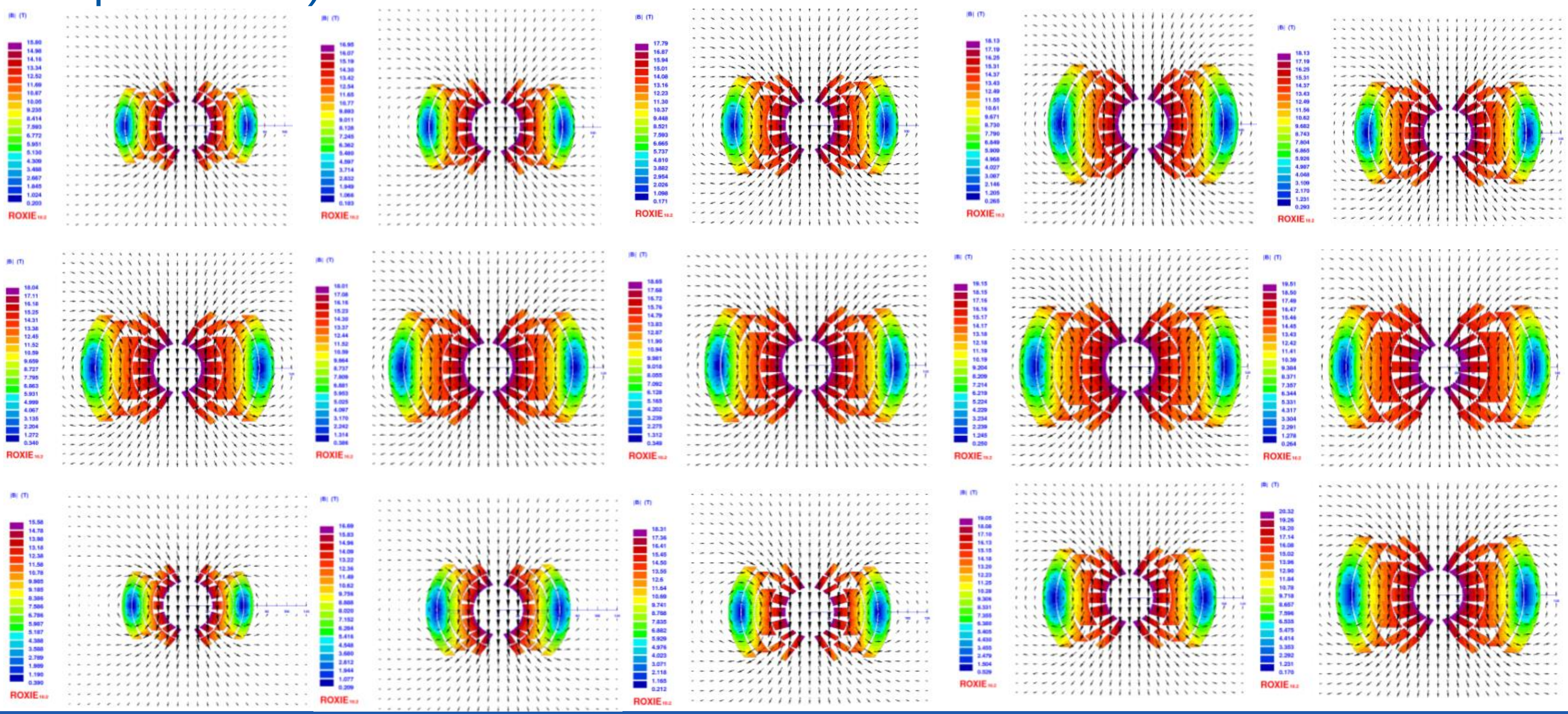
Status

- Goal: Provide preliminary estimates of the cost of the dipole magnets as a function of field and temperature based on cross-sections scaled from the EuroCirCol 16 T dipole design and from LHC magnet cost
- Reference parameters: 50 mm aperture, 4578 magnets, 14.3 m long, 16 T
- $J_{cu} \leq 1200$ A/mm^2 (magnet protection at short sample) and Cu/Non-Cu ≥ 1:1(optimized strand production)



Target cost of magnet

- Cost of LHC dipole magnet taken as reference and target
- LHC dipole cost was around 1 MCHF/dipole, 2000 (around 660 kEUR/dipole, 2000)
- The conductor cost was around 200 kEUR/dipole, 2000
- Assuming 2% inflation over 16 years for the dipoles one finds 900 kEUR/dipole, 2015
- The cost of the LHC dipole without conductor is 630 kEUR/dipole, 2015
- Manufacturing process involves more steps due to heat treatment, different insulation technique, etc., but number of units is larger (detailed study started with CEA & CIEMAT).

Analytical model (CIEMAT)

Coils
Conductor (Nb3Sn)
Conductor insulation (material+braiding)
End Spacers
raw material
machining
insulation
Wedges
raw material
machining
insulation
Interlayer insulation
Ground insulation (polyimide)
Winding
Procedure
Tooling
Winding poles
Winding Mandrel
Clampings
Infrastructure*
Winding machine
Curing
Material (binder agent)
Procedure
Tooling
Curing shell
Infrastructure*
Curing Press
Curing Furnace

Coils
Reaction
Material (Ar)
Procedure
Tooling
Reaction mould
Infrastructure*
Reaction furnace
Splicing procedure (current leads soldering)
Special tooling for transfer from reaction tooling to impregnation tooling
Impregnation
Material
Procedure
Tooling
Impregnation mould
Infrastructure*
Impregnation tank
Quench heaters (in case of using them)
Acceptance Tests
Electrical integrity to ground (spacers and poles)
Metrology of the finished coil (main dimensions)
Checking & Finishing
**** Infrastructure will not be considered for the cost estimation***

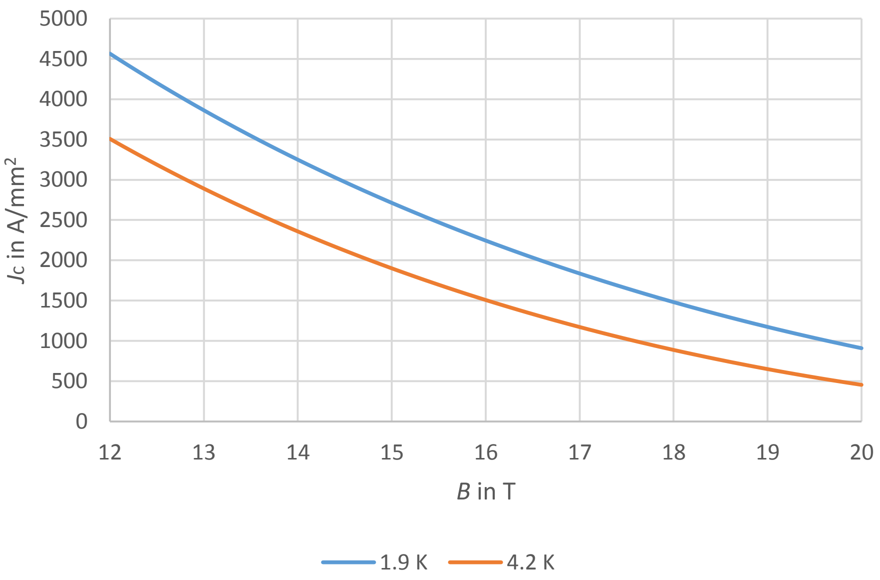
Structure support
Collar
Bladders
Aligment keys
Load Keys
Iron Pad
Masters
Yoke
raw material
machining
Shell
End plates
Axial rods

Cold Mass
He Vessel
Cryogenic lines
Bus Bars

Conductor J_c-fit

Fit for the target value of $J_c(4.2\text{ K}, 16\text{ T}) = 1500\text{ A/mm}^2$

$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$
$$J_c = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1-b)^2$$
$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$



Where: $t = \frac{T}{T_{c0}}$; $b = \frac{B_p}{B_{c2}(t)}$

with B_p peak field on the conductor

T_{c0} = 16 K, B_{c20} =29.4 T, α = 0.96, C_0 = 270 kA/mm^2 T.

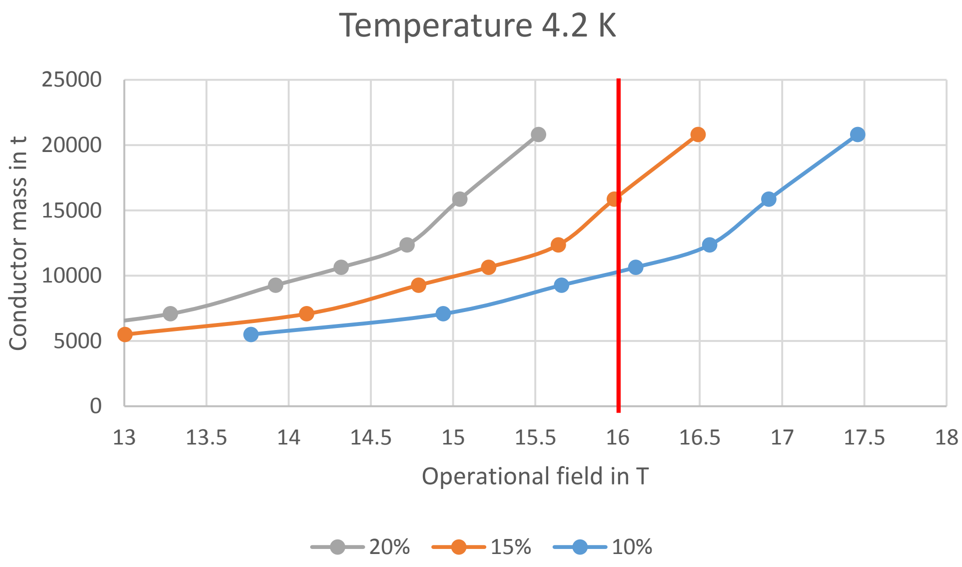
Cable degradation: 0%.

Conductor amount vs field @ 4.2 K

- Conductor amount is **very** sensitive to the operational field and margin!

Conductor mass in kt

kt	15 T	16 T
10%	7	10
15%	10	16
20%	17	>25

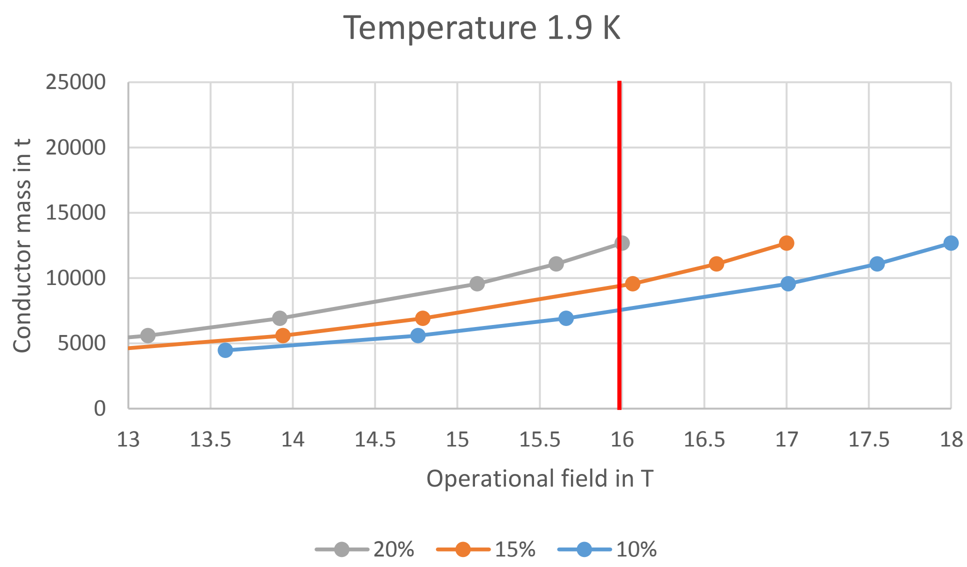


Conductor amount vs field @ 1.9 K

- Conductor amount is sensitive to the operational field and margin!

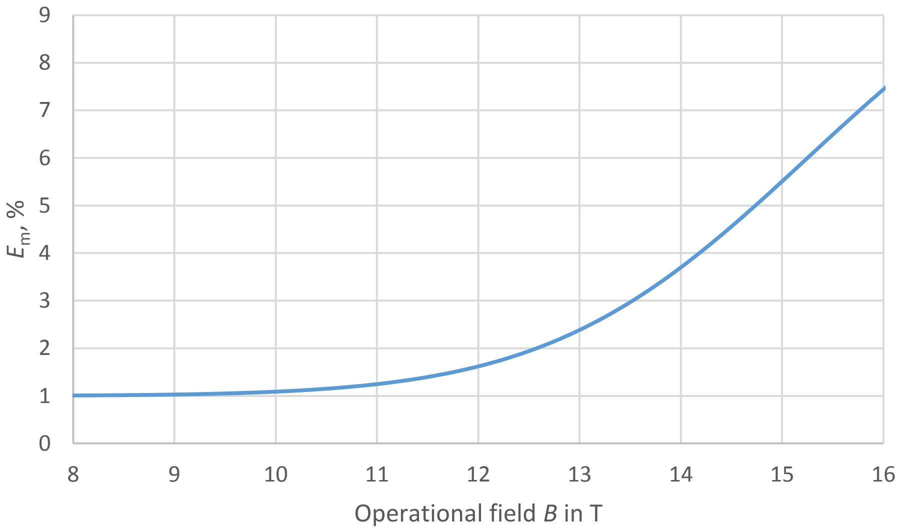
Conductor mass in kt

kt	15 T	16 T
10%	6	7
15%	8	9
20%	10	12



Elasticity of conductor mass (CEA)

- We can define a field elasticity as $E_{\mathrm{m}} = \frac{B}{m}\frac{dm}{dB}$
- An operational field of 14 T requires ~50% of the conductor required for 16 T



1% more field at 14 T cost 3.5% more mass of conductor,

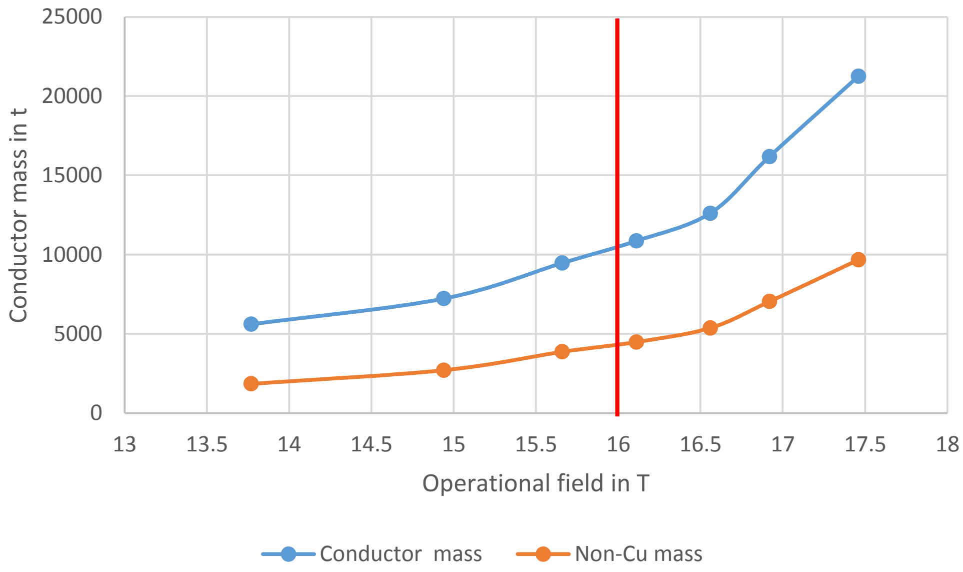
1% more field at 16 T cost 7.5% more mass of conductor

Conductor composition

- 10% margin at 4.2 K and ~18% margin at 1.9 K are equivalent

Non-Cu and conductor mass in kt

kt	15 T	16 T
Non-Cu	3	4
Total	7	10



Target cost of conductor

- Discussion between mass and performance based cost is on-going
- Target performance is set to J_c(4.2 K, 16 T) = 1500 A/mm^2
- Outer layers require larger Cu/non-Cu ratios than inner layers

Performance based cost c_p	**Mass based cost c_m**
c_{pt} = 5 EUR/kA.m at 4.2 K and 16 T	c_{mt} = 430 EUR/kg
c_{pp} = 10 EUR/kA.m at 4.2 K and 16 T	c_{mp} = 860 EUR/kg
$C_p = c_p \times J_c \times A_{SC} \times N \times L = c_m \times 2m_{SC}$	$C_m = c_m (A_{SC} + A_{Cu}) \times \rho \times N \times L = c_m (m_{SC} + m_{Cu})$

J_c (4.2 K, 16 T) =1500 A/mm^2
A_{SC} & A_{Cu} : Total area of SC and Cu in conductor
m_{SC} & m_{Cu}: Total mass of SC and Cu
N = 4578 units
L = 14.3 m : Length of per magnet unit
ρ = 8.7 kg/dm^3

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Conductor cost for FCC-hh dipoles

Total cost of conductor	15 T [MEUR]	16 T [MEUR]
C_{mt} with 430 EUR/kg	3,200	4,400
C_{mp} with 860 EUR/kg	6,300	8,800
C_{pt} with 5 EUR/kA.m	2,500	3,700
C_{pp} with 10 EUR/kA.m	4,700	7,400

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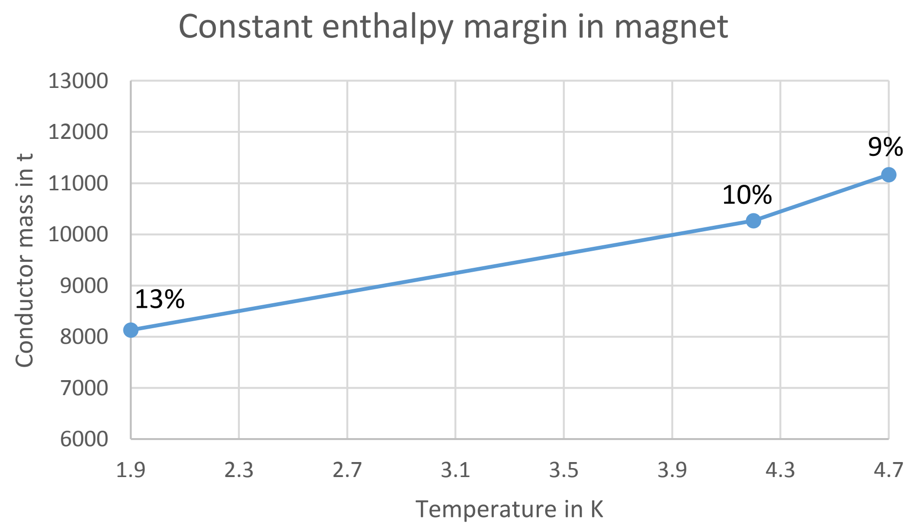
Conductor amount vs operating temperature

- In the EuroCirCol baseline design we set a baseline margin of 10% at 4.2 K , which is equivalent to a margin of ~18% at 1.9 K
- If we assume the enthalpy margin is meaningful to compare the margin to quench:
  - We could re-design the magnet for 1.9 K, such that the margin is limited to 13%
  - This, at this stage, appears nevertheless too aggressive.



Conductor amount vs aperture

- Increasing the aperture from 50 to 60 mm would increase the required conductor amount by ~13%
- This estimate coincides well with the approximate estimate:

$$A = (k^2 + 2kr_i)\phi^*,\ k = \frac{B_1 \pi}{2\mu_0 J_{\mathrm{eng}} \sin\phi},$$

with $r_i \approx$ 50-60 mm (aperture); $J_{eng} \approx$ 880 A/mm^2 (equivalent average engineering current density), B_1 = 16 T, ϕ = 60°

- In terms of magnet cost this would represent a cost increase of approximately ~10%, i.e., the magnet cost increase is of the order of half of the aperture increase:

$$\Delta\mathrm{Cost}, \% \approx \frac{1}{2}\Delta r_i, \%$$ at around 50 mm and 16 T

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Total cost of FCC-hh dipoles

- FCC with LHC magnet cost without conductor: 630 kEUR/unit x 4578 unit= 2900 MEUR
- Magnets at 4.2 K at 10% margin and at 1.9 K at ~18% margin have a similar cost
- The cost for 15 T magnets is given for 4883 units (constant integrated field)

Total cost	15 T [MEUR]	16 T [MEUR]
C_{mt} with 430 EUR/kg	6,100	7,300
C_{mp} with 860 EUR/kg	9,200	11,700
C_{pt} with 5 EUR/kA.m	5,400	6,600
C_{pp} with 10 EUR/kA.m	7,600	10,300

Conclusion

- The difference in cost for the magnets between 1.9 K or 4.7 K is ~1 GEUR
- Operating at 15 T instead of 16 T represents a cost reduction of >1 GEUR
- Margin is very expensive especially at 4.2 K
  - 5% (10%->15%) margin at 4.2 K => 40% more conductor cost (~ 3 GEUR)
  - 5% (15%->20%) margin at 1.9 K => 25% more conductor cost (~ 1.5 GEUR)
- The conductor cost represents more than half of the magnet cost: any effort shall be pursued to minimize this cost

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