Plan and status of the cost model

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Introduction cost model

- The cost model shall provide in the initial design phase (completed, see ASC paper) input for:
  - the technological choice of superconducting material and its cost
  - the target performance of Nb_3Sn superconductor
  - the choice of operating temperature
  - the relevant design margins and their importance for cost
  - the nature and extent of grading
  - the aperture's influence on cost.
- in the advanced design phase it helps to:
  - identify the cost drivers and feed-back this information to the respective magnet designers to make their design as cost effective as possible
  - compare the optimized design options to each other and make possibly a down-selection of one or two designs.

Cost model task: Structure

- CERN: Coordination
- CIEMAT: Cost of parts
- CEA: Cost of assembly

TUT: Magnet protection equipment

INFN: Consultancy for cos-theta

Updated mandate

A well-calibrated cost model is an important ingredient to magnet design since it serves as a performance indicator (input for task 5.2) and determines the financial envelope of the collider design. The model, associated to D-5.3, will explore and possibly combine analytical approaches (based on materials and production features) and extrapolation of available data of past projects, in particular the LHC. The major cost drivers will be identified and specifically discussed. Initially, based on the experience of the LHC dipoles, CERN will set-up a simplified analytical model to be used for providing feedback for the evaluation of the design options. CEA will work on an advanced model of the assembly costs; while CIEMAT will work on an advanced model of the production costs for the different parts of the magnets. Initially, the study will be focussed on the cos-θ design option, but will be later extended to the other design options.

Timeline: 01/03/2017-01/09/2018

Conductor choices and targets

- Nb_3Sn is currently only realistic conductor material
- Target cost including testing and waste **5 EUR/kA.m at 16 T and 4.2 K** (= 3.5 EUR/kA.m at 16 T and 1.9 K), corresponding to 450 EUR/kg for a Cu/Non-Cu ratio of 1/1 and the target performance
- Target critical current performance of **J_c= 1500 A/mm^2 at 16 T and 4.2 K** (J_c= 2250 A/mm^2 at 16 T and 1.9 K (50% above HL-LHC specification)
- Cu/Non-Cu down to 0.8 to increase the overall current density in the high-field part

Operating temperature

Capital extra cost 4.5 K → 1.9 K

Cryoplant extra cost	~ 100-180 MCHF
Cold compression extra cost	~ 70 MCHF

Operational cost 4.5 K → 1.9 K

Power to refrigerator	500 W/m for 4.5 K, 1200 W/m for 1.9K
Energy cost over 10 years	150 MCHF for 4.5 K, 350 MCHF for 1.9 K

Total difference 4.5 K → 1.9 K

~ 400 MCHF

Courtesy Laurent Tavian

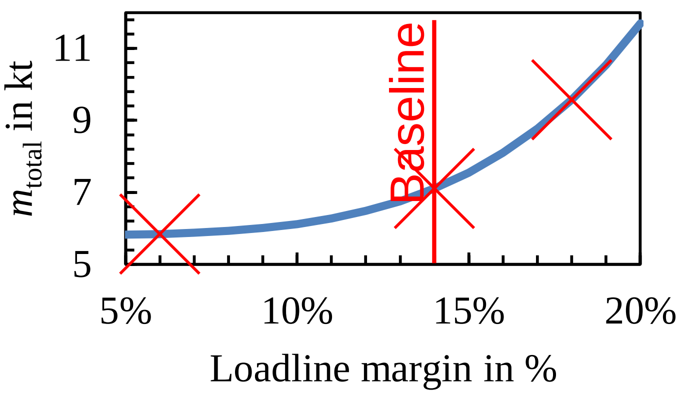
Operating temperature

The operating temperature has been set to 1.9 K

- The experience of LHC shows that a large cryoplant at 1.9K is manageable
- The difference in cryogenic cost (total) between 4.5K and 1.9K is ~400 MCHF
- The operation at 1.9K provides a number of advantages, among others:
    - corresponds to a reduction by around 4% on the loadline ~ 1 GCHF
    - avoids designing a forced flow network in the magnet cold mass
    - greatly simplifies the vacuum and beam-screen system

Design margins

- Loadline margin is selected and the relevant physical temperature, enthalpy, and current margins are a result of this choice for a given magnet design strategy
- From the experience of SMC, 11 T and MQXF it seems that a value of 14%, if an appropriate companion R&D program is established, may be on reach for the FCC. This would require testing all magnets with thermal cycle to ensure memory is kept
- Long magnets and long-term quench behaviour still need to be tested
- Most quenches occur at discontinuities of the coil (layer jumps, ends, heads), can we use the margin better?
- ERMC, RMM and Demonstrator will give important information about the amount of training quenches for the specified margin in different configurations.



Design	Loadline %	Temperature [K]	Enthalpy [mJ/cm^3]	Current %
14% EuroCirCol	**14**	**3.3**	**7.8**	**47**
18% EuroCirCol	18	4.0	11.1	36
SMC 3a	14	3.4	6.6	65
MQXF	23	5.2	17.4	30
11 T	20	4.4	11.9	48
LHC dipoles	14	1.6	2.5/70.6 (He)	50

Nature and extent of grading

- By performing a 2-layer graded coil around 2 times less conductor is used.
- Four-layer grading would save only a moderate 10% of additional conductor compared to two-layer grading, at the cost of increased complexity (splices)
- Using Nb-Ti in the low-field region (internal grading within a layer) is possible and would allow to save ~5-15% of Nb_3Sn conductor, but increases the technical complexity. Furthermore, if the “performance based” target cost for Nb_3Sn can be achieved, it can be shown that this option does not result into a cost saving. At this stage we then decided to focus on Nb_3Sn and review the situation once a credible cost model for the conductor is established.

Baseline: 2-layer grading

Cost drivers: parts

- We believe that a cost of 5 EUR/kA.m at 16 T and 4.2 K is within reach for FCC
- We start with a cost model for the cos-theta design option
- Though the magnets are bigger, they are more numerous than the ones of the LHC. A simplified scaling form the LHC gives about 360 kEUR/magnet (30% above cost for LHC dipole parts)
- Preliminary list of magnet cost drivers (list is evolving and study of the cost of this items has been started):
  - End spacers
  - Cu-alloy wedges
  - Iron yoke laminations
  - Iron pads
  - Conductor and wedges insulation.
  - Impregnation
  - Ground insulation
  - Plasma coating
  - Quench heaters
  - CLIQ
- Detection and rest of circuit shall not be part of this cost model

Cost drivers: parts

- End spacers. Currently produced by 3D printing. Scaling by volume leads to 54 kEUR/magnet
  - Specific optimization of parts for 3D printing (for example hollow inside)
  - Find/Develop a suited end spacer material for fast machining (no excessive grain growth during heat treatment, none magnetic, fulfil mechanical/structural specifications) -> Production of a couple of tons?
- Wedges. Currently produced from CEP DISCUP C3/30 and a multi-stage extrusion process (Cost around 90-180 EUR/kg; 560 kg/magnet; 100 kEUR/magnet)
  - Specific tooling is cheap ~1500 EUR/profile
  - Currently only small extrusion press available (~5 kg material)
  - Optimal length ~3.5 m (LHC experience)
  - Material selection under discussion: See slides during discussion; cost reduction of material and process?
- Iron yoke and iron pad laminations
  - Stamping force: $F_s = 0.9\ L\ s\ R_m$ (L: developed length, s: material thickness); larger force for fine-blanking -> Size of press; tolerances
  - Discussion for tolerances and thickness will be done with Feintool (choice of material is important -> see discussion)
- Electrical Insulation is under study -> less priority

Cost drivers: quench protection

- Quench heaters: HiLumi LHC data scaled leads to 140 kEUR/magnet -> not acceptable
- LHC quench heater technical and commercial data is collected to derive a more realistic estimate
- First model for CLIQ/heater power supplies are (not part of the magnet cost):
  - Electronics & box: 1.2 kEUR (constant)
  - Capacitors (900 V / 7 mF): 1.2 kEUR (scales linear with capacitance, to be checked)
  - PS cost for heaters: 55 kEUR/magnet
  - PS cost for CLIQ: 30 kEUR/magnet
- Detection equipment and circuit protection is not part the EuroCirCol cost model

Cost drivers: assembly

- A simplified scaling from the LHC gives about 360 kEUR/magnet (30% above cost for LHC dipole assembly), with the hypothesis that the industrial process will minimize the cost difference between the manufacture of Nb_3Sn coils and Nb-Ti coils.
- Preliminary list of magnet cost drivers (list is evolving and study of the cost of this items has been started):
  - Coil winding
  - Coil heat-treatment
  - Splicing
  - End spacers replacement
  - Coil instrumentation
  - Coil impregnation
  - Coil pack assembly
  - Structure assembly
  - Cold mass assembly

Preliminary comparison

- A first preliminary estimate shows that the cost of the magnets is dictated by the cost of the conductor with around 50% of the total expected cost.
- Any effort to reduce the cost of conductor and minimize the required amount is in order at this stage, to optimize the cost efficiency of the dipoles

Design	Nb_3Sn excl. Cu [kt]	Nb_3Sn incl. Cu [kt]	Performance cost Conductor/Total [GEUR]
Cos-θ	3.1	7.6	2.8/6.1
Block	3.1	7.6	2.8/6.1
CC	2.9	8.6	2.6/5.9

Conclusion and outlook

- The initial phase of the cost model is completed and input for the main design choices has been provided (see ASC paper)
- Based on the initial design, and the LHC experience target costs have been formulated and first cost estimates have been provided
- The advanced design phase has been started and a preliminary list of cost drivers has been prepared
- Studies on how the cost of these items may be reduced to reach the target cost have been launched. A decision of the desired depth of this studies has to be taken now

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