Cost model status towards the CDR

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On behalf of WP5.3

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Introduction

- The cost model is established within EuroCirCol, WP 5.3 and is accompanying the EuroCirCol study since the beginning.
- The cost model considers both an extrapolated approach from past projects, in particular from the LHC, and an analytical approach.
- Members of WP 5.3 are CERN (coordination), CIEMAT (cost of parts), and CEA (cost of assembly) with help from other members of WP5
- The focus is on the cost of the dipole magnets as they will largely dominate the cost of the magnet system
- In phase 1 (concluded) the cost model helped to define all dipole magnet parameters
- In phase 2 (started) a cost model for a FCC CDR baseline 16 T dipole magnet is being worked out. The main cost drivers of the assembly and the magnet parts are identified. Work with industries on the cost reduction of the main cost drivers (laminations, wedges, end spacers, poles, etc.) has been started.

Phase 1: Parameters defined

Establishment of a full and cost-effective parameter set for FCC-hh dipoles:

- 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 cost comparison of the different optimized design options to each other based on past experience
- the establishment of a target cost of the magnetic system for the FCC CDR based on past experience

Presentation of results at several workshops and conferences, compare D. Schoerling et al., “Considerations on a Cost Model for High-Field Dipole Arc Magnets for FCC”, *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. No. 4003105

Phase 1: Cost

- Choices of parameters have been fully implemented in the design of EuroCirCol
- Cost of conductor (~40% of entire dipole cost) $\rightarrow$ largest single cost item
- 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 430 EUR/kg for a Cu/Non-Cu ratio of 1/1 and the target performance
- This cost model is insensitive to the Cu/NCu ratio in the wire
- Target critical current performance of **J_c= 1500 A/mm^2 at 16 T and 4.2 K** (J_c= 2300 A/mm^2 at 16 T and 1.9 K, 50% above HL-LHC specification)

Phase 1: Cost of conductor

- **Baseline**: Ballarino, 2015 obtains the specified target cost 5 EUR/kA.m at 16 T and 4.2 K by scaling from the present cost (10 EUR/kA.m, 12 T, 4.2 K, 2300 A/mm^2, HL-LHC):
  1. If the volume production cost is the same for HL-LHC and FCC-hh wire (50% larger performance than HL-LHC wire): $J_c(B = 12\text{ T}, T = 4.2\text{ K, HL-LHC}) / J_c(B = 16\text{ T}, T = 4.2\text{ K, FCC-hh}) = 1.5$ ($\rightarrow$ 15 EUR/kA.m, 16 T, 4.2 K, 1500 A/mm^2)
  2. Scale-up: Production cost HL-LHC/FCC-hh = ~3, achievable according to the analysis of Cooley, 2005 by increasing the billet mass and yield by ~10 ($\rightarrow$ 5 EUR/kA.m, 16 T, 4.2 K, 1500 A/mm^2)
- Scanlan, 2001 proposes a cost of \$1.5/kA.m (12 T, 4.2 K, J_c = 3000 A/mm^2), which scales for the FCC-hh target performance to 4 EUR/kA.m in 2016 with a PPI industry data factor of 1.4 (2001 to 2016; BLS, 2017)
- Zeitlin, 2001 proposes a price (including 40% gross margin!) of \$0.67-0.82/kA.m (12T, 4.2 K, 3000 A/mm^2) according to his analysis of raw material and production cost

References:

A. Ballarino and L. Bottura, “Targets for R&D on Nb_3Sn Conductor for High Energy Physics”, *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art no. 6000906.

L.D. Cooley, A.K. Ghosh and R.M. Scanlan, “Costs of high-field superconducting strands for particle accelerator magnets”, *Supercond. Sci. Technol.* 18 (2005) R51-R65

R.M. Scanlan, “Conductor Development for High Energy Physics - Plans and Status of the U.S. Program”, *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, Mar. 2001, pp. 2150-2155

BLS, U.S. Bureau of Labor Statistics, Producer Price Index (PPI) Industry Data 2001-2016, www.bls.gov/data/

B.A. Zeitlin, E. Gregory, and T. Pyon, “A High Current Density Low Cost $Niobium_3Tin$ Conductor Scalable to Modern Niobium Titanium Production Economics”, *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, Mar. 2001, pp. 3683-3687

Phase 1: Target cost

- Scaling the FCC-hh dipole magnet cost from LHC, taking the higher complexity and double number of coil layers into account (double the cost +20%) and magnet assembly (+20%), would yield a target cost for coil fabrication and assembly of about 600 kEUR/magnet, and for parts of about 420 kEUR/magnet (30% above LHC)
- According to the present cost model the target cost for a 16 T magnet for FCC-hh built according to the cos-θ design would be:

Conductor cost:	670 kEUR/magnet
Assembly cost:	600 kEUR/magnet
Parts cost:	420 kEUR/magnet
Total cost:	**1690 kEUR/magnet**

- The calculation of the target conductor cost has been performed by assuming that the cost is insensitive to the Cu-amount in the strand.
- 4664 dipole magnets are required for FCC-hh. Assuming the same percentage of spare magnets as for LHC (around 3.6%) a total production of about 4834 magnets is required, yielding a total target cost of 8.2 GEUR for the dipole magnet system of FCC-hh.

Phase 2: Cost model (16 T dipole)

- A study has been started to analytically estimate all costs of production of a 16 T cos-θ FCC-hh magnet and is separated into:
    - Cost of parts: Being analysed and, if needed, optimized with industry; small parts will be taken into account by a lump sum. Industry capacity for raw materials and parts is sufficiently available in Europe (and beyond)
    - Assembly cost: Concerning the assembly costs the number of assembly lines and tools, such as for example the number of heat treatment ovens, reaction fixtures and impregnation moulds is being estimated, as well as the labour cost for each assembly step are considered, depending on the required production rate (tentatively 20 magnets/week to complete the production in 5 years).

Phase 2: Cost of parts (CIEMAT & CERN)

- Manufacturing of main components (strict fabrication tolerances):
  - Cu-Alloy wedges: Contacts with three companies, different materials under investigation, samples are currently under investigation at CERN
  - Iron yoke laminations: Material characterisation of high-strength steel and invar currently under investigation
  - End spacers: Optimization for additive manufacturing and study of Metal Injection Moulding (sample production on-going, could be competitive despite small number of parts 20,000/type)
  - Iron pad laminations
  - Master keys
- Conductor and wedges insulation
- Impregnation
- Ground insulation
- Plasma coating insulation
- Aluminium shell
- Axial rods
- End plates
- Quench Heaters

Phase 2: Assembly cost (CEA)

- Production rate is determined by availability of conductor and assembly time.
- Assembly requires dedicated tooling and production line set-up. To estimate the cost a production rate has to be defined:
  - Required production: 4834 dipoles
  - Total 16 T dipole production time: 13 years
    - Industry prototypes: 4 years (2 magnets/company)
    - Pre-series fabrication: 4 years (~90 magnets)
    - Series fabrication: 5 years (~20 magnets/week)

Phase 2: Assembly cost (CEA)

- Coil winding (38,672 coils, 150 coils/week, 2 week/coil)
- Coil heat-treatment (38,672 coils, 150 coils/week, 2 weeks/heat treatment)
- Transfer from reaction fixture to impregnation mould (38,672 transfers, 150 transfers/week)
- Main lead splice manufacturing (77,344 splices, 300 splices/week)
- Coil instrumentation
- Coil impregnation (38,672 coils, 150 coils/week, 1 week/impregnation)
- Coil pack assembly (9,668 coil packs, 40 coil packs/week)
- Coil quality control including magnetic measurement at RT
- Structure assembly and splicing
- Cold mass assembly (4834 cold mass, 20 cold mass/week)

Phase 2: Assembly cost (CEA)

Establish a production flow chart to be able to estimate the:

- tooling cost. Examples of initiatives:
  - Coil winding automatization (study started within FCC to establish and determine windability factors of Rutherford cables)
  - Cost estimation of ovens (open questions: maximum number of coils per heat treatment, cost of large ovens)
  - Coil impregnation (change of moulding currently requires large amount of time, optimization required for such a large series production)
- labour cost. Methodology:
  - Estimate the total number of required working hours
  - Calculate the required number of workers (48 weeks/year and 40 hours/week) and add supporting staff: (production engineer (1 per 50), quality assurance (1 per 50), administrative assistance (1 per 50), foreman (1 per 10))
  - Multiply the required hours of labour with the labour cost per hour: 32.20 EUR/h, in the EU-19 for manufacturing industries (cat. C according to NACE) in 2016
- indirect cost (water, gas, electricity, maintenance, insurance, administrative and financial management, etc.): add 25% to direct costs, i.e., tooling and labour costs, according to the guideline for EU H2020 projects

Conclusion

- In phase 1 the main parameters for the dipole magnets have been chosen and implemented in the EuroCirCol design study
- A target cost of 1.7 MEUR/magnet for a series production of 4834 magnets has been set based on a scaling from LHC experience yielding to 8.2 GEUR for the dipole magnet system for FCC
- In phase 2 an analytical cost model is being established and initiatives to determine and minimize the cost of the dipole magnets parts, assembly and specific tooling are pursued
- The cost of the other magnets will be scaled from the dipole magnet cost based on their size, complexity and conductor amount, once their design parameters and conceptual designs are established