Cost model status towards the CDR

Daniel Schoerling

On behalf of WP5.3

1st of June 2017

Introduction

- The cost model is established within EuroCirCol, WP 5.3.
- 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 (see presentations of D. Tommasini)
- Cost of conductor (~50% of entire dipole cost) → 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 450 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 (see also her talk in this session) 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): $J_c(B = 12\ \text{T}, T = 4.2\ \text{K}, \text{HE-LHC}) / J_c(B = 16\ \text{T}, T = 4.2\ \text{K}, \text{FCC-hh}) = 1.5$ (→ 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 (→ 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 2: Cost model (16 T dipole)

- A study has been started taking as a reference the cos-θ design; it will be adapted in case a different baseline design for the CDR is selected
- Cost of parts will be analysed and, if needed, optimized with industry; small parts will be taken into account by a lump sum
- Initiatives for cost optimization have been started; material characterization will be performed with EN/MME
- Cost of assembly will be analysed and optimized

Phase 2: Cost of parts (CIEMAT)

- Manufacturing of main components (strict fabrication tolerances):
  - Cu-Alloy wedges (contacts with three companies, different materials under investigation, samples will arrive soon at CERN)
  - Iron yoke laminations
  - End spacers
  - Iron pad laminations
  - Master keys
- Conductor and wedges insulation
- Impregnation
- Ground insulation
- Plasma coating insulation
- Aluminium shell
- Axial rods
- End plates
- Quench Heaters

F. Toral, Cost estimate collaboration meeting #11, Update on cost for parts, https://indico.cern.ch/event/623537/

Phase 2: Example of initiatives, parts

Wedges:

- Wedges for HL-LHC are currently produced by company A with special raw material of company B
- Discussion with company A and B to make the process more cost effective have been started, large potential of cost reduction has been identified
- Company C has been contacted to identify alternative materials with smaller cost and better market availability: they identified 8 potentially suitable bronze materials and offered to deliver samples
- Sample testing is planned with EN/MME to characterize the materials and to identify the most suited material(s)
- Potential of cost saving compared to HL-LHC: factor of 10

Laminations:

- Company D has been contacted to identify different commercially available steel grades (also with higher strength), samples will be provided
- Sample testing is planned with EN/MME
- Company E & F are contacted to optimize the cost of the punching process (optimum thickness, maximum force, etc.)

F. Toral, Cost estimate collaboration meeting #11, Update on cost for parts, https://indico.cern.ch/event/623537/

Phase 2: Assembly cost (CEA)

- Production rate is determined by availability of conductor and assembly time. Industry capacity for raw materials and parts is sufficiently available in Europe (and beyond)
- Assembly requires dedicated tooling and production line set-up. To estimate the cost a production rate has to be defined:
    - Required production: 4664 dipoles + spares. If as LHC (3.6 %): 170 spares (too many?)
    - 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)

M. Durante, Cost estimate collaboration meeting #12, Update on cost for assembly, https://indico.cern.ch/event/634356/

Phase 2: Assembly cost (CEA)

- Coil winding (38,672 coils, 150 coils/week)
- 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)

M. Durante, Cost estimate collaboration meeting #12, Update on cost for assembly, https://indico.cern.ch/event/634356/

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

M. Durante, Cost estimate collaboration meeting #12, Update on cost for assembly, https://indico.cern.ch/event/634356/

Conclusion

- In phase 1 the main parameters for the dipole magnets have been chosen and implemented in the EuroCirCol design study
- In phase 2 the cost drivers have been started to be identified and initiatives to determine and minimize the cost of the dipole magnets parts, assembly and specific tooling are or have been started
- 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