**Final Report**

# TFD Wire Specification Review

Review held on 28 October 2021, <https://conferences.lbl.gov/event/759/>

Report close-out (planned) 06 December 2021

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Review observers: Luca Bottura, Steve Gourlay, Ken Marken

The committee would like to thank the LBNL team for the quality and clarity of the presentations, and to compliment them for the quality of the work performed.

Terminology used in the Hi-Lumi project quality plans that are important for this report:

**QC measurements**: These are mandatory measurements performed by the conductor supplier to demonstrate compliance with specifications and provide evidence that required performance is achieved.

**Verification measurements:** These are mandatory measurements performed by the laboratory to assure received material is acceptable. Verification repeats the process of certifying required performance in the specification.

**“For information” measurements:** These are measurements in addition to QC and verification measurements that can be included as deliverables from the supplier, at increased cost of the procurement, to expand the data set delivered with the conductor. However, these measurements are not used to guarantee or certify performance according to specification requirements. Likewise, laboratory measurements can be expanded to provide additional data.

# Consolidated Findings

Magnet characteristics

* + 16 T dipole operating at 1.9 K with a 15% margin on the load line
  + Block design: 2 double-layers coils (48 and 40 runs respectively) per pole (4 double-layers coils in total) based on a 26 mm wide rectangular Rutherford cable
  + Cable constituted of 44 strands 1.1 mm in diameter
  + Calculated maximum pressure on the conductor of 166 MPa (in the low field region)
  + Protection studies showed that a Cu/non-Cu ratio equal to 0.9 is not a problem (assuming CLIQ will be included to protect the magnet in the case of extraction system failure)

Scale of procurement

* + 1.1 mm strand appears to be preferred, with 162/169 RRP design @ 3.4:1 Nb:Sn, Cu:NC = 0.9 (62.7 µm subelements)
  + 45 UL purchased per 44-strand cable, 1 UL will be 410 and 1 will be 425 m (50-50 split), plan to acquire 6 cables. 45 UL x 6 x 0.425 km ~ 110 km. Two coils are spares as are the cables for these coils; if a coil fails a cable may need to be re-made.
  + At 1.1 mm, strand density is ~ 8.8 kg / km, so total procurement is just under 1 ton. At 45 kg / billet, total procurement is about 20 billets. For reference, AUP typically receives 80-100 km per shipment.
  + Anticipated delivery is first 30 km in first half of 2022, remainder in first half 2023 with possibility of early delivery.
  + Placement of entire order now could avoid having Nb come from different lots.
  + At present, no option for additional conductor lengths is foreseen in the contract

Specification and testing of specified metrics

* + Specification largely mirrors the structure of the HiLumi strand specification.
  + Testing rate, at 50%, also mirrors the quality plan for AUP HiLumi acquisition.
  + This is a new strand, and magnet, cable, and strand all lie beyond the present state of the art. Unknowns are likely.
  + Supplier can test critical current (Ic) at fields specified, but cannot test above 1000 A which is typical Ic at 14 T. This restricts the field range over which supplier can provide information. Is testing above 16 T possible?
  + Laboratories can test above 1000 A but cannot test above 15 T field (there are some exceptions). Laboratories can get data down to about 12 T field.
  + CERN has already procured and qualified 51.6 km of this wire. Findings:
    - Vast majority of piece lengths exceeded 1 km
    - Critical current performance substantially exceeded the LBNL specification, and also exceeded the target *Jc* for 16 T: *Jc* (16 T, 4.2 K) > 1300 A/mm2
    - After 15% rolling, *Jc* is reduced by about 2% and the RRR reduction average is 22.5 %
    - 665 °C / 50 hr and 680 °C / 50 hr reactions produced properties and margins that justify strand selection

Expected cable performance

* + LBNL produced a development cable based on the 162/169 strand (using about 3 km of wire procured by CERN). Findings:
    - Acceptable sub-element shearing upon cabling; no local RRR measurements performed yet at LBNL
    - Winding trials have shown that the cable is mechanically stable
    - Critical current measurements performed on extracted strands showed a degradation smaller than 2%
    - RRR measurements on extracted strands (155 mm samples including only two kinks) showed a low RRR reduction. Measurements are full strands and do not include local RRR measurements on the kinks.
    - Some stability measurements performed on round wires: sweep field from 10-0-10T with 1000 A. A more conservative field sweep 0-10 T starting with the sample fully demagnetized has not been attempted.
    - Stability measurements on extracted strands (or on wires with a RRR representative of what Hi-Lumi observes in the kinks) were not performed
  + Prototype cable to be done by end 2021 using the 162/169 wire procured by LBNL, which arrived on the 15th of October 2021 (5 billets, 9 spools) from which extracted strands will be available for testing.
  + Ic measurements under axial strain were performed and showed an irreversible strain limit that is in line with other RRP conductors. However, measurements under transversal load were not carried out
  + This is a new wire with a very limited Cu fraction and the magnet design will accept transverse stresses larger than the 150 MPa HL-LHC limit.

# Comments regarding review charge questions

1. **Has the project properly identified conductor requirements for the TFD magnet, and identified and prioritized performance risks associated with the superconducting wire?**

**The conductor requirements are appropriate for the TFD magnet project.**

* The requirements have propagated to a specific wire design and cable configuration that is appropriate for the overall design goals of the project.
* As this is an advanced conductor and magnet design, the committee foresees that additional data will be needed to understand potential challenges related to instability critical current reduction (both reversible and permanent) due to transverse pressure. Some additional information should arrive by end of 2022, and testing capabilities exist to find answers should serious questions emerge. Testing beyond the quality plan should be encouraged as part of the project plan to gain information about unknowns.
* Performance margin appears to be adequate to mitigate problems that are presently not fully apparent. Mitigations at magnet design stage with this conductor are likely.
* Heat treatment–performance matrices appear to provide some margin to vary RRR and Ic to provide some flexibility should risks emerge

1. **Has the project identified the proper wire specification parameters for the project?**

**The wire specification is adequate for this project but could be improved quickly.**

* The present wire specification provides adequate performance margins to allow potential issues below to be managed.
* The wire specification needs to be advised by instability measurements and local RRR measurements for extracted strands at the kinks to provide data relevant to the RRR and Cu / non-Cu specifications. This data could arrive by end of CY2021.
* Prototype cable will advise on cable compaction and amount of deformation at cable edges. Present information suggests that 15% rolled strand performance specifications are conservative and that compaction may be less.
* The project team should identify a quality plan that includes Ic data for information at a minimum of three magnetic fields spaced by ~1 T to allow for robust fitting and extrapolation of the irreversibility field H\* and the ESE strain-scaling upper critical field Hc2\*. For example, information tests could be done by the supplier at 14.5, 15.5 and 16.5 T in addition to QC of the present Ic specification of 600 A at 16 T and 760 A at 15 T.
  + Such a quality plan is difficult to conceive because BOST cannot measure above 1000 A (the typical critical current at 14 T), and some of the laboratories cannot measure above 15 T.
  + Three points are much better than two for identifying scaling fits, or lack thereof due to material error. The Hi-Lumi procurement avoided a material error using this approach.
  + The verification Ic test could be a single measurement at 15 T, and the labs can obtain informative data at lower field.
  + For verification (see also Charge #5) the ESE spreadsheet appears to be very useful for extending measurements to parameter space where measurements cannot be done.
  + We leave it to the project team to identify a suitable combination of supplier QC, verification, and information testing (including the testing rate) to obtain the requested data at a wider variety of field values.
* Strain sensitivity is amplified at high field, which exacerbates measurement variations. While 2.5% is the result of inter-lab comparisons at 12 T, variations of 5% to 10% have appeared at 15 T. In Hi-Lumi, the supplier’s measurements are conservative, so the measurement uncertainty does not eat into the performance margin. Increased verification measurements could advise about the measurement uncertainty with respect to acceptance criteria and margin.

1. **Is the team pursuing the appropriate wire performance metrics? Do the data presented provide sufficient confidence in the wire specifications? Are there additional measurements that should be considered?**

**Yes, the performance metrics are appropriate**

**Yes, the data presented provide confidence in wire performance**

* See comments under other charge questions: Additional verification measurements could provide better assessment of measurement uncertainties. Verification measurements of rolled strand are advisable given the potential challenges with instabilities.

1. **Are the wire specifications sufficiently well defined, and properly formulated, to balance project risk with efficient procurement?**

**Yes, the wire specifications for the supplier are sufficiently well-defined.**

* Potential improvement has been identified under charge question #2. The committee makes further comments on the overall quality plan in the next question (Q5).
* Please see the committee’s recommendations to the verification testing plan.
* Exercising the procurement option ameliorates project risk for conductor performance and cabling unknowns

1. **Is a reasonable quality plan presented that will assure receipt of material meeting the specifications?**

**The quality plan is marginally adequate and can be greatly improved with small additions.**

* The 162/169 strand is completely new for an acquisition of ton scale, and the QC measurements are more challenging than for HiLumi. See comments under Q2.
* RRR of rolled strand is an important acceptance criterion. Verification measurements of RRR for rolled strand should be added.
* Increasing the number of verification measurements could increase understanding about the degree to which measurement uncertainties affect overall margin, especially at high field.
* Since there are ~20 billets, this number of increased measurements should not significantly impact the project.

# Recommendations

1. **Move ahead with procurement with the present specification.**
2. **Add the option for 40 km additional length, for 2 additional cables, within the same procurement.**
3. **Increase the amount of informative testing, possibly both at the supplier and the verification lab.**
   1. **Add verification testing of RRR for 15% rolled strand.**
   2. **Obtain test data at one lab over a sufficient field range to ensure fidelity of the ESE scaling method**
   3. **Add testing to mitigate higher uncertainty due to inter-lab test differences at 15 T.**
4. **In parallel with procurement, and prior to finalization of magnet design, complete stability threshold measurements:**
   1. **0-10 T field sweep (of zero-field-cooled sample) per D. Turrioni plan**
   2. **Extracted strand cable edge RRR**
   3. **Field sweep at 1.9 K for a strand with RRR representative of the local value at cable edge**
5. **In parallel with procurement, and prior to finalization of magnet design, complete other planned measurements**
   1. **Response to transverse pressure**
   2. **Inter-laboratory comparison of 1.1 mm diameter wire critical current and RRR measurements**
   3. **Heat treatment optimization**