Report of the Hi-Lumi-LHC/LARP International Review of the Superconducting Cables for the HL-LHC Inner Triplet Quadrupoles (MQXF)

CERN

5-6 November 2014

1. Introduction

The HiLumi-LHC/LARP International Review of the Superconducting Cables for the HL-LHC Inner Triplet Quadrupoles (MQXF) was held at CERN on 5 and 6 November 2014.

The review panel was made up by:

- Arnaud Devred, ITER-IO (Chairman)
- Herman ten Kate, CERN
- David Larbalestier, NHMFL
- Bruce Strauss, DoE
- Akira Yamamoto, KEK.

* Charges to the committee are in Appendix A.
* The agenda of the review meeting is in Appendix B.
* In Appendix C are the Chairman's minutes, which are provided for reference only.

2. Executive Summary

2.1 Introduction

- This is a critical and important project, which provides the unique opportunity to make high-performance, space-effective accelerator magnets using Nb_3Sn conductors and to implement them in a real working accelerator. If successful, this significant milestone will open up the route to much higher energy accelerators than the LHC using for the first time superconductors beyond Nb-Ti in its main magnets.
- This project is handled by an enthusiastic transatlantic team bringing a new generation of magnet engineers into the field. There is good communication between the Hi-Lumi and LARP teams, in particular on the magnet side; conductor activities could benefit from strengthened interactions.
- There has been great progress recently, both on understanding the issues limiting magnet performance and in the industrialization of high-performance Nb_3Sn wire manufacture and cabling.
- After 16 years of R&D effort in the US and 10 years of R&D effort in the EU, the project is confronted with a crucial transition, to become a real and successful construction project including the professional management needed.
- It remains a great challenge, but the committee is confident that, with proper resources, strengthened focus and continuous synergy between the LARP and Hi-Lumi efforts, MQXF completion can be achieved.

2.2 Overall status and schedule

- The design goals need to be conservative because Nb_3Sn accelerator magnet technology is still experimental, and impregnated Nb_3Sn coils operated at 1.9 K are prone to self-field instabilities.
- It is noted that, though significant progress has been reported, after more than 20 years of making various model magnets at a few laboratories, still the production technology is not sufficiently mature and a realistic full-size Nb_3Sn based accelerator magnet with a practical bore achieving 11-12 tesla level within 1 to 3 training steps is not yet existing. The team is encouraged to engage in full and push forward the frontier.
- Therefore, the committee unanimously and strongly recommends in this particular case, and in this phase of the project, maximizing the operating margin of the superconductor by all means possible, such as lowering the nominal gradient, increasing the magnet length in an appropriate balance of the magnet reliability with achievable integrated luminosity, revisiting the Cu-to-non-Cu ratio, and so on.

- Development is necessary of an integrated qualification plan, from virgin and extracted strand tests, to local and full-size cable tests, to magnet model and prototype tests to validate conductor and magnet designs and to assess operating margins; the qualification tests should be the same for both LARP and Hi-Lumi.

- Use of the model and prototype phase for finalizing the wire and cable specifications is essential for project success, including development of clear criteria for acceptance tests on strands and cables.

- It is crucial and today critical, for this project and beyond, to keep at least two strand suppliers. If one supplier shows less maturity in their wire production, more resources shall be allocated to foster its development or industrialization.

- In view of earlier comments and the requirement to deliver within LARP and Hi-Lumi many full-size production magnets within less than 8 years, the schedule is very challenging. To limit schedule risks and to allow corrective actions in an efficient and cost-efficient way, clearly defined decision points between the phases of the R&D model, the first prototype and construction programs shall be developed in the USA and at CERN.

- It is vital to clearly identify risks, such as failure of a wire supplier or cabling machine, so as to enable realistic risk mitigation measures, such as transfer of wire procurement to the other supplier, or arranging a back-up cabling machine.

- Since the project apparently shows a significant risk for serious delay in wire procurement and coil manufacturing because of the volume of wire orders and number of coils to be made; also a plan B covering the case of partial completion has to be addressed in the case goals of magnet production are not met on time for installation in the tunnel.

2.3 Technical specification of the superconducting wire

- The specification are not complete at this time:
    - The relationship of superconductor properties to magnet performance has not been clearly defined, making a realistic definition of the margin for the magnet unclear.
    - In particular, magnet design criteria have been extrapolated from those used in the case of Nb–Ti accelerator magnets, where other factors come into play in limiting the performance of Nb_3Sn magnets at 1.9 K. The new constraints of Nb_3Sn in magnets need to be much better understood and a more pragmatic and suitable operating margin defined that would include: cabling degradation, self-field instabilities, stress degradation, and so on.
    - The database of already tested short magnet models and long prototypes can be used as a reference.

- A requirement on strand cleanliness and surface conditions during transport, cabling and temporary storage, especially for bare OFHC copper strands that are prone to difficult to control oxidation effects, is required. This may have consequences for finding predictable electrical properties between strands and resin wetting and binding quality during impregnation.

- A variety of other issues need addressing:

  - Clarification of the scheme for approval of unit lengths originating from certain billets. Excessive number of breakages during the processing of a billet may be a sign of hidden defects or insufficient homogeneity which cannot be discovered when unit length approval is not referred to billets.

  - The present are the technical specifications of the conductor, all of which are challenging and ones not yet being met in production strands:

    - strand I_c: 361 A at 4.2 K and 15 T;
    - RRR: 150 on virgin strand/100 on extracted strand.

  - The allowable values of R_a and R_c in the cables need to be addressed.

2.4 RRP Nb_3Sn wires

- It is recommended to go ahead with the 132/169 and lower Sn content layout as proposed by OST. A final decision on strand layout can be made in one year for the series production contract (back up being the 108/127 layout).

- Seriously consider the proposal to reduce cable keystone angle from 0.55° to 0.40° in view of the effort to increase margin and reduce risk, however, the committee does not consider it as a show stopper if for good schedule and procurement reasons the LARP part of the project decides to stay with 0.55°.

- A parallel effort to continue optimization of heat treatment is recommended.

2.5 PIT Nb_3Sn wires

- In view of the crucial 2-supplyer policy at CERN that is essential for this project and beyond, the panel highly recommends a substantive support program for the PIT wire to further optimize strand properties and establish performance baseline for series production.

- In the meantime, CERN should go ahead with RRP strands and cabling for its model magnet production and should optimize phasing of strand and cable deliveries between RRP and PIT in order to create maximum flexibility for using the best possible PIT wire and coping with delivery delays.

- In support of the above, define a clear timeline for the decision making process regarding PIT wire development and production.

- Reducing the cable keystone angle in the PIT based cables from 0.55° to 0.40° is a must in order to avoid unnecessary performance risk.

2.6 Quality assurance and control

- A convincing QA/QC plan and inspections procedures in writing must be finalized during the upcoming model and prototype phase. It shall be reviewed before launching of wire and cables series production contracts.
- ITER experience has shown that the emphasis has to be on benchmarking and cross-checking of the suppliers' acceptance tests, which enable a faster feedback on production. The level of verification measurements at reference laboratories can be phased in time.
- It is recommended to split the series productions in several phases to enable establishment of control limits of statistical process control (SPC).
- Promote the development of in-line video quality control of cable, in particular at the thin edge to see out of range local strand damage, as this presently is the only technique that will enable 100% inspection of the cable unit lengths.
- Better identify qualification tests and series production tests.
- Better integrate the QC plan on virgin wires, extracted strands, local measurements and full-size cable tests to ensure consistency and suitable monitoring of wire and cable productions.
- For series productions: all acceptance tests should have clear criteria. The acceptance test requirements and criteria should be identical for both LARP and Hi-Lumi.

2.7 Brief answers to the questions to be addressed (see Appendix A)

1. Are the Functional or Technical Specification for conductor strand and cable adequate to the scope of the MQXF?

Incomplete; see comments and recommendations here above.

Are they sufficiently developed and reasonably finalized?

Incomplete; see comments and recommendations here above.

2. Does the design of strand and cable meet the specifications in terms of minimum Ic, maximum allowed degradation, minimum RRR, maximum D_{eff}, stability request, cable size, and unit length ?

I_C and minimum RRR have to be revisited.

D_{eff} is not critical around 50 μm.

3. Assess the likelihood of meeting – with adequate margin – the chosen specifications and requirements based on the decade long experience acquired by LARP in cables and magnet construction and the most recent experience in Europe.

Very optimistic, needs more optimization including the balance of long-term magnet reliable operation with integrated luminosity.

4. Is the plan for two types of strand architecture (RRP and PIT) correctly managed inside the program?

PIT needs more support to accelerate since having two suppliers is crucial.

5. Is the procurement schedule, with associated QA and test plan, credible and adequate for the prototyping phase (where applicable) and for the construction phase?

No yet; need to better articulate the different project phases and the decision points.

Appendix A: Charges to the Review Committee

HL-LHC/LARP International Review of the Superconducting Cable for the HL-LHC Inner Triples Quadrupoles (MQXF)

CERN, Switzerland – November 5^{th} to 7^{th}, 2014

Charges

The High Luminosity LHC project has been approved as first priority by the special CERN Council held in Brussels on 30 May 2013. In May 2014 HL-LHC has been rated among the priority project for US HEP in the next decade by the P5 committee and in June 2014 the CERN Council has approved its financing in the years 2015-2025.

HL-LHC is entering in the final stage of design and prototyping: all technologies for the hardware upgrade must be fully proven by 2016-2017. The replacement of the present Inner Triplet (IT) quadrupole magnets with new quadrupoles (MQXF), featuring much larger aperture and higher peak field, is the cornerstone of the upgrade plan. Tests of the short models of final design, foreseen in 2015-16, and of the long prototypes, planned for 2016-17, are on the critical path. US-LARP program has worked steadily for ten years to reach the present maturity in cable and quadrupole for the LHC upgrade.

As it is well known the SC cable is the component with the longest design, validation and procurement time for SC magnets. This characteristic is even more accentuated with a complex conductor such as Nb_3Sn. In particular the Nb_3Sn cable for HiLumi (LARP) magnets has unique characteristics: a J_c about three times the one specified by ITER; limited degradation and high stability despite strong plastic cabling and deformation. Therefore this relatively large size procurement (approximately 20 metric tons including prototypes and production amgnets) will be the real test of Nb_3Sn industrial maturity for Collider Magnets.

The HL-LHC Project Leader and the LARP Director call an International Review with the following goals:

1. Are the Functional or Technical Specification for conductor strand and cable adequate to the scope of the MQXF ? Are they sufficiently developed and reasonably finalized ?
2. Does the design of strand and cable meet the specifications in terms of minimun I_c, maximum allowed degradation, minimum RRR, maximum D_{eff}, stability request, cable size, and unit length ?
3. Assess the likelyhood of meeting – with adequate margin – the chosen specifications and requirements based on the decade long experience acquired by LARP in cables and magnet construction and the most recent experience in Europe.
4. Is the plan for two types of strand architecture (RRP and PIT) correctly managed inside the program?
5. Is the procurement schedule, with associated QA and test plan, credible and adequate for the prototyping phase (where applicable) and for the construction phase?

The review is schedule for November 5^{th}-6^{th} with the close-out on the 7^{th} at CERN.

We would appreciate a presentation with the main comments and recommendations at the close-out of Nov. 7th, with a written report few weeks later.

Appendix B: Agenda of the Review

Wed 05/11 | Thu 06/11 | All days

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09:00	**Welcome and review charge**	*Prof. Lucio ROSSI et al.*	*IT Amphitheatre, CERN*	09:00 - 09:20
	MQXF goals and plans	*Dr. Giorgio AMBROSIO*	*IT Amphitheatre, CERN*	09:20 - 09:50
10:00	**MQXF design and conductor requirements**	*Dr. Paolo FERRACIN*	*IT Amphitheatre, CERN*	09:50 - 10:20
	Mechanical stability and QXF coil winding	*Dr. Paolo FERRACIN et al.*	*IT Amphitheatre, CERN*	10:20 - 10:50
11:00	**Coffee break**		*IT Auditorium Coffee Area, CERN*	10:50 - 11:10
	Conductor technical specifications	*Dr. Amalia BALLARINO et al.*	*IT Amphitheatre, CERN*	11:10 - 11:55
12:00	**MQXF RRP-strand for Q1/Q3**	*Dr. Arup GHOSH*	*IT Amphitheatre, CERN*	11:55 - 12:20
	MQXF RRP-strand for Q2	*Dr. Bernardo BORDINI*	*IT Amphitheatre, CERN*	12:20 - 12:45
13:00	**Lunch break**			12:45 - 14:15
14:00	**MQXF cable for Q1/Q3**	*Dr. Daniel DIETDERICH*	*IT Amphitheatre, CERN*	14:15 - 14:45
15:00	**MQXF cable for Q2**	*Dr. Luc-Rene OBERLI*	*IT Amphitheatre, CERN*	14:45 - 15:15
	PIT strand & cable for Q2	*Dr. Amalia BALLARINO*	*IT Amphitheatre, CERN*	15:15 - 15:40
16:00	**Lessons learnt from CERN experience**	*Dr. Luc-Rene OBERLI*	*IT Amphitheatre, CERN*	15:40 - 16:10
	Coffee break		*IT Auditorium Coffee Area, CERN*	16:10 - 16:30
	Lessons learnt from LARP experience	*Dr. Arup GHOSH et al.*	*IT Amphitheatre, CERN*	16:30 - 17:00
17:00	**US-HiLumi conductor procurement**	*Dr. Arup GHOSH*	*IT Amphitheatre, CERN*	17:00 - 17:25
	HiLumi conductor procurement	*Dr. Amalia BALLARINO*	*IT Amphitheatre, CERN*	17:25 - 17:50
18:00	**Closed session**		*31-2-029, CERN*	17:50 - 18:50

Appendix C: Chairman Minutes of the Meeting

MQXF Superconducting Cable Review

Date: 5-6 November 2014	Time: 09:00-18:00	Location: CERN
	Arnaud Devred (v1.0)	

Participants

ITER-IO	Arnaud	Devred
FSU	David	Larbalestier
DOE	Bruce	Strauss
CERN/Ph	Herman	Ten Kate
KEK	Akira	Yamamoto

Agenda

No.	Topic	Participants
1	MQXF Goals and Plans	G. Ambrosio
2	MQXF Design and Conductors	P. Ferracin
3	Mechanical stability of MQXF coil	P. Ferracin
4	LARP-GARD Experience	G. Ambrosio
5	Conductor Technical Specification	A. Ballarino
6	MQXF Cable Specifications	A. Ghosh
7	MQXF strand experience	A. Ghosh
8	MQXF RRP strand for Q2	B. Bordini
9	MQXH Cable for Q1/Q3	D. Dietderich
10	MQXF Cable for Q2	L. Oberli
11	PIT strand and cable for Q2	A. Ballarino
12	Lessons learned from CERN experience	L. Oberli
13	Lessons learned from LARP experience	A. Ghosh
14	Q1/Q3 conductor procurement	A. Ghosh
15	Hi-Lumi conductor procurement	A. Ballarino
16	QA/QC plans for Q2 strands	B. Bordini
17	QA/QC for cables at CERN	C. Scheuerlein
18	QA/QC for LARP Materials	I. Pong
19	Answers to committee questions	P. Ferracin, G. Ambrosio, B. Bordini

Reference to Documents

Ref.	Document
ppt	Presentations

Discussions and Agreements

No.	Description

No.	Description
	MQXF Goals and Plans
D1.1	- Magnets will be operated at 1.9 K - Installation in 2023 - 140 T/m in 150 mm aperture - Q1/Q3 (US): 8 m, Q2a and b (CERN): 6.8 m - Large aperture is to implement a Tungsten absorber that makes radiation not a concern
D1.2	- Q1 and Q3 will be split in 2: 4 m each (450 m UL) - Q2a and b (710 m UL) - Same design for both magnet types, 2-layer coils without splice - Shell structure preloaded by bladders and keys - Axial preload by tie rods - Active heaters and/or CLIQ
D1.3	- Short model program: 5 x 1.2 m models (2014-2016) - Long model program: 2 CERN + 3 LARP: 2015-2018, first magnet test in 08/2016 (LARP) and 07/2017 (CERN) - Series production: 10 CERN and 10 LARP starting in 2018-2021
D1.4	- Strand + 0.85 mm diameter, less than 50 microns filament size + 1.2 to 1 + 361 A at 15 T (632 A at 12 T) + Joverall (including insulation) 480 A/mm2
D1.5	- Cable + 40 strand cable + 18 mm width + Keystone angle of 0.55 degreee + 109 mm + SS core (12 mm)
D1.6	- Herman asked if there is a specification on the number of quenches to reach nominal current. It is being considered. - Akira mentioned that internal guideline at KEK for IQ was very conservative: no natural quench under nominal operating conditions when delivered to CERN (except for beam induced quench). - There was a broad agreement that one needs a large enough operating margin. Ezio pointed out that the margin along load line has been increased from 85% to 80% and from 1.6 K to 5 K in terms of temperature between LHC magnets and MQXF magnet designs. - Herman asked what could be done to increase the margin: lower Cu-to-non-Cu ratio, make the coil slightly bigger, make the magnets longer
D1.7	There was a large variation in the RRR of model magnet coils

No.	Description
	MQXF Design and Plans
D2.1	- 2 strand types: + OST RRP 132/169 + BEAS PIT 192 (42 microns) - Cable + 1.525 mm mid-thickness + 70 microns after HT + 18.15mm after cabling + 360 microns after HT + 109 m pitch length - RRP and PIT strand cables show similar expansion after HT ; however, PIT shows larger axial contraction - Cable insulation + AGY S2-glass fibers, 66 Tex, with 933 silane sizing + Target is 145 microns per side
D2.2	- End design has 6 blocks; peak field margin is 1% lower with respect to the straight section. Arnaud and Herman argue that it would be preferable to increase this margin. - +/-20% variations can be expected on magnetization at injection; this can produce 2.4 units comparable to 10 units; it can be handled
D2.3	- With current specs (assuming 361 A at 15 T at 4.2 K, 527 A at 15 T at 1.9 K and with 5% cabling degradation): margin on load line in 80 to 81%; it leads to a temperature margin of 4 K on inner pole turn and between 5 and 6 K on midplane turn where the maximum energy deposition takes place. - The above computations use “ITER” barrel Ic data. - An Ic variation of 10% translates in an additional loss of temperature margin of 3%.
D2.4	- Peak coil stress is 160/175 MPa - Up to 100 MPa, one can achieve up to ITER barrel short sample limit (SSL) in a magnet. Arnaud asked what happens when going beyond. There seem to be data available showing that a significant degradation is only observed when going beyond 200 MPa.
D2.5	- Hot spot temperature is 263 K (with Cu-to-non-Cu of 1.2 to 1). - Effect is 6 to 7 K when RRR varies from 100 to 200, and Cu-to-non-Cu ratio varies from 1.1 to 1.2
	Mechanical stability of MQXF coil
D3.1	- Winding trials have shown cable instability while winding around the ends - A solution has been found using a kind of clamp. - Both cable types show instability in the unfavorable direction - The core does not seem to play a significant role
D3.2	- LARP and CERN have each wound 3 x 1.5 m long coils - Another option is to use ceramic binder, using a heat gun with a temperature of 150 C - Feedback is positive - Akira indicated that this manual operation with binder/heat gun may depend on the

No.	Description
	operator and may lead to variability during mass-production. Efforts for the mass production technology and quality control shall (should) be anticipated.
	LARP-GARD Experience
D4.1	- issue of Nb3Sn cable instability is well known and has been addressed in previous programs at Fermilab - recommendation is to use both winding tools and binders - Arnaud asked if the issue occurs on all turns or is limited to pole turn; answers is that it occurs every time there is a deformation in the unfavourable direction, therefore on all turns - Conclusion is that it is more a QA/QC issue and that it can be addressed properly during production.
	Conductor Technical Specification
D5.1	- Procurement will be for strands; cabling will be done at CERN and fermilab - Functional specifications for strands - CERN specifications address 2 manufacturers: OST and BEAS - LARP specifications only address OST - specifications are independent on wire technology, layout to be proposed by the company; any subsequent changes require formal CERN or LARP approval
D5.2	- 0.8500 +/- 0.003 - Ic at 15 T and 4.2 K greater than 361 A (non Cu Jc: 1400 A/mm2 at 4.2 K and 15 T) n-value greater than 30 (Arnaud indicated that ITER uses 20, CERN indicated that this is a good QA/QC parameter: if value is below 30, this is usually an indication that there is an issue) - Dsub-element: less than 50 microns - Magnetization width at 3 T and 1.9 K (in a region without flux jump) less than 330 mT ; Arnaud asked about error bar, Amelia replied CERN was thinking of applying +/-20% - Cu-to-non-Cu: 1.1 to 1.3 - RRR on virgin strands greater than 150 (this is due to stability requirements of achieving an RRR greater than 100 on extracted strands) - Twist pitch: 19+/-2 mm - Right hand screw - 800 m for Q2, 500 m for Q1 and Q3: Arnaud indicated that the philosophy adopted for LHC and ITER was to accept strands on a billet basis, so as to encourage the supplier to improve production and limit the number of breakages, the issue being to ensure homogeneity along the length.
D5.3	- Short sample limit is 540 A assuming 5% degradation - Iop = 17460 A, Bpeak = 12.07 T; operating strand current is 436.5 A
	MQXF Cable Specifications
D6.1	- Cable development at LBNL using RRP 108/127 Ti Ternary strands - Cable optimization was done looking at: mechanical stability, sub-element damage, Ic

No.	Description
	and RRR - Cable development at CERN using RRP 132/169 and PIT-192; generally, degradation limited to 5% - The wires appear robust in terms of Ic degradation; focus is on local RRR degradation (greater than 100). - Trade-off is between: cable stability and strand RRR degradation
D6.2	- Baseline design: + 1.525 mm +/- 0.010 mm + 18.15 mm +/- 0.050 mm + 0.55 deg +/- 0.10 deg + Pitch length: 109 mm +/- 3 mm + Core width 12 mm, core thickness 0.025 mm; Arnaud asked what is the coupling current reduction introduced by the core, Arup indicated that measurements on model magnets demonstrated the reduction is 95%. + Target for Ic degradation is less than 5% + Target for local RRR at the cable edges greater than 100; Herman pointed out that this was probably not achievable in a large production and asked what was the minimum value acceptable; David asked what was the measurement method used to carry out this local measurement; Arnaud asked what was the criterion used to assess whether or not this target has been achieved; Luca and Lucio explained that the cabling work was still underway and that these acceptance criterions have not yet been set.
D6.3	- Arnaud asked if there are differences between the 2 cabling machines at CERN and LBNL; the answer is yes (different number of spools, different angles, different ranges for the tensioning of the spools) - Arup replied that, so far, observations made at one place could be reproduced at the other place, so there is some confidence that similar optimizations can be carried out on the two machines.
D6.4	- Herman pointed out he did not see any specification on cleanliness; Arnaud indicated that bare copper strands had been a big issue at the time of the SSC.
	MQXF Strand experience
D7.1	- 108/127 at 0.85 mm is 55 microns - 108/127 at 0.77mm is 50 microns - 132/169 at 0.85 mm: 50 microns - At present, billet weigh is 45 kg and should yield 8 km
D7.2	- LARP ordered 410 kg, which used 12 billets of 108/127 - 6 billets used standard tin content (Nb/Sn ratio of 3.4) - 6 billets used 5% reduced tin content (Nb/Sn ratio of 3.6); resulting in better RRR performance
D7.4	- LARP also placed an order for 255 kg of 132/169 (with exception of min Ic of 350 A and minimum Cu to non-Cu of 1.1); 9 billets were produced - Average value of Ic was 373 with a sigma of 12 A (337 A Lower Control Limit); some billets are below the 361 A limit; of course, this will not improve over a large

No.	Description
	production. - Average RRR value is 315 with a sigma of 32 - BNL did a benchmarking of OST data; Ic and RRR are in good agreement
D7.5	- Arup showed that the present strand layout and HT have a large margin on RRR and that there is a possibility to increase the HT duration to achieve higher Ic at the expense of a lower RRR; but this would need to be confirmed on a larger production. - The RRP 132/169 can be produced, but the manufacturing margin in Ic needs to be increased by control of Nb/Sn ratio and by reaction optimization; Arnaud pointed out that this is a very critical issue, as strand optimization is a long lead time item. He brought up again the idea that we should not be too over optimistic and that if there are ways to mitigate this risk (e.g., reduce Ic specs and increase length), this should be considered.
	MQXF RRP strand for Q2
D8.1	- CERN has ordered 1.087 tons of 132/169 tons for FRESCA 2 - So far 8 billets of regular tin and 2 billets with reduced tin have been have been delivered to CERN + Average Ic is 368.5 A, minimum is 353 A; for regular tin, average RRR is 200, minimum is 172 + Average Ic is 365.2 A and minimum 355 A; for reduced tin, average RRR is much larger - Margin at operating field is about a factor of 2.
D8.2	- Reduced tin wire was heat treated to 665 C (instead of 640 C) for 50 hours; this resulted in an increase from 362 to 393 A and a RRR decrease from 312 to 293. - Bernardo thinks there is potential of improving the performance further when raising the temperature to 670 or 675 C (while keeping the same plateau duration).
D8.3	- Mechanical deformation: + wire Ic is robust against deformation + however, local RRR measurements show a decrease of a factor 3 at the thin edge for extracted strands - Simulating this kind of degradation, would require a rolling to 25%
D8.4	- Magnetization: + flux jumps are observed at 1.9 K below 3 T, which dumps magnetization + variations in delta magnetization is 278-282 mT; expectation is that, since the sub-elements are fully reacted, this is what is driving the magnetization.
D8.5	- Conclusion: + 25% of piece lengths do not meet Ic specs with 640 C HT + However, reduced tin RRP wire with a reaction temperature increase from 640 to 665 C improves Ic by 9% with minimum RRR degradation.
	MQXF Cables for Q1/Q3
D9.1	- A number of cable runs were done + First cable runs had a 10 mm wide core

No.	Description
	+ Last cable runs were produced with a bias of the 12 mm wide core towards the thick edge; this was done to reduce wire deformation at the thinner edge and improve mechanical stability at the thicker edge.
D9.2	- Micrograph examination on regular tin cable shows typically 0 to 3 sub-elements are sheared in any of the 3 strands at the thin edge. Worst case has 6-8 sheared sub-elements. - Dan proposes a way to establish at quality score method based number of sheared sub-elements in the 3 strands at the edge.
D9.3	Some cable residual twist is observed, but this seems acceptable for winding.
D9.4	- Cables with annealed wires appear to have less strand damage during cabling (lower quality score), cable is flatter and has less residual twist; Arnaud asked what is the annealing treatment (160 to 180 C for 50 hours) - Samples are being prepared to check the RRR values, Dan’s expectation is that it has a higher RRR - Work is in progress on this issue; Dan’s interpretation of the physical process is that, during the annealing heat treatment, there is some intermetallic formation at the Cu/sub-element interface, which changes the mechanical properties of the sub-elements during subsequent mechanical deformation and may improve the situation.
D9.5	- Herman asked if a specification should be added regarding the bias of the core. - Herman also asked about Ra; Arnaud brought back the issue of strand surface conditions - Arnaud asked if the quality score could be turned into a spec? Dan replied that this was still under development.
	MQXF Cables for Q2
D10.1	- 16 cabling runs dedicated to MQXF cables + 4 cables with “first iteration” RRP 132/169 (4 cabling runs and a total of 650 m of cables) + 14 RRP and 10 PIT cables with different parameters (10 cabling runs and a total of 250 m of cable) to derive the “first iteration”
D10.2	- Data were presented for 9 cables with RRP 132/169 regular tin content wires (with same or similar billets) - Ic degradation stays between 0.5 and 5%. - Strain at thin edge should not exceed 16% to limit RRR degradation.
D10.3	- First iteration on cable parameters were derived after this R&D program + Thin edge strain (1-(t/2d)) was set to 15.4%. + Attempts were then made to improve cable mechanical stability. - All cables are unstable in the unfavourable direction; use of winding tool is effective. - A decrease of keystone angle to 0.4 degree for RRP strands reduces the risk of strand - pop-out.
D10.4	- 4 cables: one with reduced Sn, all others with regular Sn - core shows a tendency to move towards the thick edge

No.	Description
	- all Ic degradations are around 3%; RRR values are above 150 (virgin RRR is close to 300) with a 640 C for last plateau - more investigations were carried out to look at the RRR variation along the lengths; they show significant reductions at both edges with respect to straight section
	PIT strand and cable for Q2
D11.1	- 5 km produced at the end of 2012, delivered in March 2013 - 35 km ordered in June 2013 (42 km in total, UL greater than 400 m); delivered from November 2013 to October 2014; Arnaud asked why the production was so slow, Amalia indicated that BEAS was busy with other projects; Amalia indicated that she already had discussion with BEAS regarding ramp up; she believes BEAS could meet the requirements of CERN, but they would need additional manpower. - 20 km ordered in February 2014, to be delivered next year - 200 km, order being prepared
D11.2	Proposed strand: PIT Nb-Ta 192 with 41 microns 534 kg of a similar layout but with a wire diameter of 1 mm has been delivered for FRESCA2
D11.3	- Results from received wire batches + 5 km: average Ic is 330 Am, RRR is 180 + 3.5 km: average Ic is 353 +/- 5 A for billet 34162 + 5.9 km: average Ic is in the 329 to 340 A for billet 34162 (this is the same billet as above, there might have been issues with powder quality) + 31.6 km in 7 ULs coming from 3 billets; Ic in the 330 A to 353 A in the range; RRR is in the 140-200 range.
D11.4	- Amalia made the argument that the lower Ic with respect to RRP may be due to the smaller filament diameter. - A strategy was discussed at BEAS in March 2014 for increasing the performance: move from PIT 192 to PIT 156 (to go from 41 micron to 45 microns in tube diameter). This will enable BEAS to use a more aggressive HT with the hope of achieving a higher Ic.
D11.5	- Cable optimisation: initial goal was to have identical geometries for PIT and RRP cables and to achieve mechanical stability - All cable trials have shown that mechanical stability called for the use of assisted winding; attention now focused on Ic and RRR degradation. - Amalia pointed out that, compared to other magnet designs, MQX cables are using lower packing factors and higher aspect ratios, which could be the cause of the mechanical instability.
D11.6	- Ic degradation is 5 to 6% degradation. - 10% rolling: no degradation on Ic and RRR - 15% rolling: limited degradation on Ic (less than 2%) and RRR - 20% rolling: significant degradation in both Ic and RRR - Amalia showed that both aspect ratios of the filament and local thinning of the Ta barrier are problematic

No.	Description
D11.7	- Proposal is a second iteration: to reduce keystone to 0.4 degree, increase thin edge to 1.462 mm and reduce thin edge strain to 14%. - This would also be beneficial for the RRP - First results show that filament with aspect ratio of less than 0.6 is reduced from 40 to 30% and percentage of filaments with local Nb-Ta thickness of less than 5 microns reduces from 6 to 3% - Ic degradation is less than 3% and RRR is in the 106 to 118 at thin edge; 168 to 147 at thick edge.
	Lessons learned from LHC Cable Experience
D12.1	- Cabling needs: + MQXF: 32 km for Q2 (45 ULs of 710 meters), + 40 km cable for Q1 and Q3 - In comparison: LHC was 7500 km - 2 wires producers for MQXF, 6 wire producers from LHC - Cable fabrication done at CERN and LBNL, while for LHC it was done in industry - QA/QC system developed for LHC can be applied
D12.2	- For 11 T: CERN has produced 3700 m - For MQXF: CERN has produced 250 + 650 m of cables
D12.3	- Luc explained the QA/QC plan implemented for strand and cable approval for LHC, which was used as a model for the ITER QA/QC. - Luc insists that magnetization measurements were mandatory for LHC (one per billet) and should be also mandatory for HiLumi. - Present CERN cabling machine was used in industry before. A few cables were refused due to mid-thickness.
D12.4	- distribution of piece lengths: 50% of piece lengths expected to be less than 1600 m - cabling job is expected to last 6 months. - Luc indicated that during LHC production, the machine shaft broke and it took 5 months to replace it. - Lucio asked which machines could do such cabling in the world: CERN, LBNL, Fermilab (with some adaptation), Babcok-Noell (with some adaptation).
	Lessons learned from LARP experience
D13.1	- 108/127, 0.7 mm used in TQS03 - 1.3 tons for LARP in 2009-2012 used for LQ, split as + 9 billets (31 out of 35 kg) + 9 billets (29 out of 35 kg) + 21 billets (27 out of 35 kg) + 8 billets (26 out of 35 kg) + 12 billets (34 out of 35 kg) - Lower yields correlate with time of ITER production + 90% of piece lengths above 550 m

No.	Description
	+ 80% greater than 1000 m + 20 to 30% better than 3000 m + 10% better than 5000 m - Ti ternary has better yield than Ta ternary
D13.2	- Overall, large fraction of billets surpassed Jc, but minimum RRR of 60 was challenging (average was 101; 2 batches were below 60; they were used for practice winding). - To meet specs, HT plateau was lowered to 650 C.
D13.3	Ti-ternary at 0.778 mm with reduced tin content shows a large improvement in RRR.
D13.4	108/127 design took several years to be a stable product. Arup estimates that of the order of 50 billets is required to assess process stability.
D13.5	Akira asked who would be able to access data in the LARP database? Arup said it will be managed by LBNL.
	Q1/Q3 conductor procurement
D14.1	Procurement will be split as follows - Model and prototype - Production in 2 phases
D14.2	- 3 coils of 1st short model with 108/127, 4th coil will come from CERN and will use 132/169 - All other models will use 132/169 - Technical specs as discussed in previous presentations - Areas of problem: 361 A at 15 T at 4.2 K - Changes with respect to LARP: Ic was 684 A at 4.2 K and 12 T, now reduced at 632 A, but this is not an issue
D14.3	Model Prototype - 6 coils for MQXF, UL is150 m, 16 coils for MQXF, UL is 450 m - 12% cabling loss - 250 kg for short, 1750 kg for long - Close to 2 tons, 50 billets (over 10 millions dollars) - Single tender
D14.4	Series production - 90 coils, UL is 450 m, 12% cabling loss, total length is 22.4 km, about 10 tons, 225 to 250 billets (billet size: 45 Kg, billet yield 42 Kg, 1 cable UL uses wire from 3 billets) - RFP in October 2015, contract signed by Jan 2016, first delivery after 12 months - Phase 1: 500 kg by April 2017, Phase 2: April 17 to October 18. - Goal for Phase 1 is to set SPC limits - production rate is about half that of ITER
D14.5	Arnaud asked how much of the 2 tons will be produced by the time of the big contract: 600 kg in 2014, and the rest next year if contract placed this winter. Only the data from

No.	Description
	the 600 kg will be available.
D14.6	- QA/QC from billets SPC will be applied OST data will be checked periodically - QA/QC on cables Ic and local RRR measurements No full size cable test as no facility available Arnaud asked if there is any full-size conductor qualification test planned? It is not planned at present. To be considered.
	Hi-Lumi Conductor Procurement
D15.1	Quantity: Need: 8.4 tons to be split between RRP and PIT procurement 4.54 tons for each (plus 2.27 tons option)
D15.2	- Mid-2012: 5 km+5 km of each - Mid-2013: 35 + 35 km - Ordered in Feb 2014: 20 + 20 km (545 kg) - 200+200 km in March 2015 for Long Prototypes (1.8 tons) - 2.35 tons total for RRP and PIT - Expectation for RRP is: 132/169 with reduced tin and for PIT there is a question mark on which layout they will propose. Arnaud pointed out he would have a more proactive approach with BEAS to incite them to promote the 156 design. - Amalia explained that although the contracts are placed at the same time, the delivery dates may be phased between RRP and PIT.
D15.3	- For series production: 2 * 1000 km (+ option 500 km) by end of next year. - Boundary conditions are: start of coil winding by January 2018; this implies the contract must be signed in March 2016; this implies documentation preparation by fall of 2015. - Then, wires would be delivered from Jan 17 to September 19. - Arnaud pointed out that this schedule does not enable to get a lot of results from the 200 km PIT contract before going to the Finance Committee. Lucio explained that there is some built in-margin in the fact there can be a delay between the authorization of the Finance Committee and the actual signature of the contract.
D15.4	- Arnaud suggested to implement a Phase I (500 kg) and a Phase II into the contracts as presented by Arup, to enable establishment of the SPC limits
D15.5	Assumptions for production: - 3 to 6 months between wire delivery and cabling runs - 2 cabling runs per month; 6 months between cable assembly and cable ready for characterization - 3 months between cable ready for characterization and cable delivery for coil winding - Last cable ready for winding in March 2020.

No.	Description
	- Present schedule does not include a phasing in wire delivery; but it can accommodate a one year delay. - Arnaud pointed out that in case of a shift of procurement to one supplier, it would take time for this supplier to ramp up, however, the total required monthly rate is still less than what was required at the peak of ITER production.
	QA/QC plans for Q2 strands
D16.1	- Supplier will have to provide + a QA plan + a manufacturing plan (corresponding to the ITER Disclosure statement); Arnaud pointed out that it is important to trace the suppliers of raw materials - Arnaud also explained the concept of Manufacturing and Inspection Plan, which lists all the main manufacturing and testing steps, with reference to relevant internal procedures and test reports, which, in the case of ITER, need to be signed and provided for all billets.
D16.2	- CERN is planning a 100% verification measurements. - 455 Ic, 80 DM magnetization and 535 RRR per year over 4 years (assuming 1.5 km piece length, which is a factor 2 better than what is achieved now). - Arnaud explained that the ITER strategy was to do a phasing of the verification measurements: 100 % at the beginning (first 500kg), then 50 % (next ton), then 25%.
D16.3	In addition - 2 witness strands per coil (2 x 55) - 3 to 5 per cable UL (165 to 275 Ic); Arnaud asked if it means one extracted and one virgin? Bernardo indicated that it was not planned at this time to measure virgin strands - 500 RRR measurements for extracted strands - 2200 local RRR measurements
D16.4	Arnaud suggested that ID assignment should be done by suppliers, not upon arrival at CERN, so that everybody uses the same ID. This ID scheme can be part of the contract.
D16.5	Arnaud pointed out that acceptance should not be done on isolated piece lengths but per lot of pieces lengths coming from the same billet. This is the philosophy used for LHC and ITER and there is no reason to change as it is the most effective way to follow up production at the suppliers.
	QA/QC for cabling at CERN
D17.1	10 ULs for prototype, 45 ULs for series production (32 + 13 spare)
D17.2	- Similar business flow for control points as for LHC cable - However, there should be some specific tests carried on destructive examination samples at both ends of each unit length - possibility of cable imaging during production , but his would require the development of new analysis tools
D17.3	- Present plan includes: + Ten-stack measurements

No.	Description
	+ Extracted strand Ic measurements: 3 to 5 stands + Extracted RRR measurements: 10 strands per UL - There is still some work to be done on how to optimize the procedure. - Arnaud pointed out that it was important to think ahead of time on how to proceed with establishing acceptance criterion. - Bruce indicated that one should go through all the proposed tests and make two columns: what is needed and what is wanted - Akira pointed out that it was critical not to lock oneself up in too stringent requirements. - Herman indicated he did not see how these local measurements could be used to assess cable performance which involves a collective behaviour. - Not included: interstrand resistance measurements, cable cleanliness, mechanical stability
D17.4	- Arnaud pointed out there should be a better identification of qualification versus production tests, including a plan for full-size conductor tests. - There should also be a better coordination between CERN and LARP: measurements that are needed, should be done for both programs.
	QA/QC for LARP Materials
D18.1	- it is planned to have an Ic versus strain measurement on final layout at NIST for RRP
D18.2	- Arnaud indicated that he was open to make the ITER database available for CERN/LARP use. The only issue being how to export the final data set for archival (which can be done under the form of excel spreadsheets). This work could be placed under the umbrella of the CERN/ITER agreement.
D18.3	After cable fabrication, there will be measurements on extracted strands and on 10-stacks.
	Answers to Committee's questions
D19.1	Effect of strain: After cool down, peak stress is at the pole After energization, peak stress moves to midplane, while pole stress decreases - One model (TQS03) was tested with 3 levels of stress: + 200 MPa plateaued at 93% + 220 MPa plateaued at 91% + 250 MPa plateaued at 88% - When reset to 250 MPa it stayed at 88% - in HQ02b + 200 MPa plateaued at 95%
D19.2	- QXF-like magnets can reach SSL extrapolated from strand measurements on ITER barrels - Mirror configuration, with peak stress up to 100 MPa + TQM05: 100%

No.	Description
	+ LQM01: 99% + HQM04: 98% - on Al-shell based magnet can reach similar values, with good coils HQ02a: 98% at 4.5 K, which corresponds to 20% less Lorentz force and about 170 MPa) - HQ02b: 95% at 1.9 K at 200 MPa - However, all these magnets exhibit significant training starting from 85%
D19.3	- Training memory LQS01: reached 90% of SSL in 3 quenches on first cycle and in 2 quenches after second cooldown. - Herman made the comments that one needs to differentiate between mechanical margin and operating margin to sustain irradiation.
D19.4	- Test of SMC shows it is possible to achieve 100% of SSL at 4.4 K but to have erratic behavior at 1.9 K due to self-field instabilities - Measurement on single wire shows a strong influence of wire RRR on instability domain. - Requirement of 100 comes from some simulation.
D19.5	- LQS03 reached 91% at 4.5 K and 82% at 1.9 K. Limiting coil has an overall RRR of 70 RRR value on extracted strands is 50 - HQ02 reached 98% at 4.5 K and 95% at 1.9 K Worst coil is coil 15, it has on overall RRR of 70-80 RRR value on extracted strand is 50
D19.6	- Giorgio indicated that the plan of LARP was to test every cold mass vertically at 4.2 K and 1.9 K before it is cryostated.
D19.7	Present schedule of model magnet manufacture is: RRP short model 1, followed by PIT short model 1, RRP short model 2 There is time to implement a design iteration before RRP short model 1 and PIT short model 1