Report from the

11 T dipole informal coil and assembly readiness review

CERN, September 23-24, 2013

1. Review committee

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2. Review goal

After a number of practice coils and trial windings the CERN team has completed the first 2m-long Nb_3Sn poles for the 11 T dipole short model program.

These poles, which will be heat treated and impregnated in the following weeks, are used to assemble the first collared coil where after yoke and support cylinder assembly will follow and finally a cold test of the 1st 1-in-1 model scheduled for March 2014.

The main purpose of this first model is to verify the entire chain of fabrication procedures and tooling with some first data from magnetic measurements at warm and cold and feed-back on the electrical integrity.

The next step is then to implement the lessons learned on the first fully functional 1-in-1 model for which the coils are being prepared.

The primary goal of this informal review is to have early feed-back from the committee on the Nb_3Sn coil fabrication and CERN's readiness for assembly of 2m long model magnets and second to get feed-back on the plans for realizing the 5.5m long full-size magnets.

3. Review agenda

http://indico.cern.ch/e/CERN_11Tcoil_review

Background information regarding the 11 T dipole project and recent developments are found here:
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4. Executive Summary

Mikko Karppinen, project leader of the 11T magnet program at CERN called for an informal readiness review of the 2m model magnet program and outlook to the manufacturing of the full-size 5.5m magnets.

A charge was formulated, agenda agreed, and presentations given, see review agenda.

The progress on the 11T project was reported through 13 presentations providing the present state of design and construction addressing general project status, conductor development, coil winding, heat treatment, impregnation, assembly of support structure, instrumentation and some outlook to the next phase of constructing full-size 5.5m long magnets.

For CERN this project is in fact the first occasion that a Nb_3Sn type cos-Θ magnet is designed and manufactured, largely based on the experience developed during the last 10 years at FNAL, whose efforts are greatly acknowledged.

The team at CERN seems highly motivated, which is a very good basis for achieving success.

The work performed so far is of high quality.

Given the rather limited human resources in this early phase the results are impressive. The team is to be congratulated with these achievements and encouraged to continue in the same spirit.

The project is characterized as “work-in-progress”, first coil windings for the short models have been completed and the next assembly phase is imminent for which however considerably more human resources are needed in order to respect the very aggressive schedule presented for the short model coils, and even more for the full size magnet program.

Given the importance of the 11T project, not only for realizing these few magnets in the frame of HL-LHC, but more in general as the most logical and mandatory step towards 15T class Nb_3Sn magnets for HE-LHC at CERN, the project deserves a high attention.

Success is needed but also not easy to accomplish in view of the already long history of more than 10 years of 11T-class dipole model magnet constructions generally showing insufficient training behavior.

Mastering the problems within this 11T project is a true challenge and a great asset for the organization when successfully concluded.

5. Responses to the charge as formulated with questions

5. 1. Project organization, planning, bottlenecks, resources

5.1.1. Is the planned CERN short model program adequate to qualify magnet design and fabrication process for the 5.5-m-long prototype magnet?

In general yes.

All relevant issues are being addressed and complementary R&D proposed. Success may come provided sufficient resources are made available to execute the program correctly and timely.

When overviewing the progress in Nb_3Sn dipole developments of the last 10 years a key issue is to demonstrate a model magnet that reaches 11T after first cool down within a few trainings steps and not showing detraining or retraining. This minimum performance requirement is not achieved yet. Therefore fighting training and finding solutions shall have the highest priority. When not solved, a continuation of this program (and may be others as well) towards full-size, longer and twin-aperture magnets will be questioned. The success of this 11T dipole project at this particular point in time seems crucial.

Given the limited resources, solving the training problem on short coils is considered mandatory before proceeding and investing considerable resources in longer magnets.

The magnet's training behavior is determined by the performance of its winding pack, in particular by the combined behavior of conductor, insulation, mechanical interfaces to axial and end spacers, bonding properties of the resin as well as the mechanical properties of the materials used. The winding pack external structures are considered less relevant provided correctly designed and assembled. Therefore the first step to complete is a working short model fulfilling all requirements and iterate as long as needed to arrive at this point.

Regarding the next steps, it is recommended to assemble and test MBHS105 (108/127) as a single coil test paired with coil MBHSP104 (54/61), the plan B as presented.

5.1.2. Is the time scale realistic?

The schedule as presented is very success oriented, shows no free float and no provisions for eventual alterations in the technologies required. It also assumes uncritical human resources, currently not fulfilled.

A more detailed resource loaded project schedule for the model program is needed to better see the consequences of lacking manpower. For the long magnet program a realistic schedules has to be developed as well as the presented activities were limited to next year only.

The period between now and summer 2014 is particularly critical, and will affect the destiny of the project. Major milestones set during this period shall provide hints about the real feasibility of the project to be implemented within the LS2/LS3 deadline, in particular for what concerns performance.

These short term milestones are:

a) October 2013 mirror test in FNAL
b) November 2013 dummy coil assembly test in CERN
c) December 2013 mirror test with staggered ends coils at FNAL
d) March 2014 test of 1-in-1 model at CERN
e) April 2014 test with enhanced coil ends featuring flexible spacers at FNAL.

All efforts shall be put in place to meet, or at least not to diverge from, this ambitious planning. Though this seems to be the case at FNAL, it does not seem yet the case at CERN.

It is recommended fitting the LMF team in the short model program until the completion of the 1-in-1 model. Any other scenario for reinforcing the team than the one above with expert LMF reinforcement may not be sufficiently effective considering the short time available. Another advantage would be the pre-training effect and technology transfer to the LMF team required anyway for the next steps towards the full size magnets.

In particular, on short term, the March 2014 magnet test at CERN is unrealistic with the present labor force and requires either rescheduling or adjusted resources.

Another short term issue as example: if the February 2014 delivery date of the 5.5m long winding mandrel is to be believed, it is risky to have a vendor making 3 to 6m long single-piece mandrels. Using much shorter segments can be easily monitored for tolerance quality as the parts become available from the manufacture.

5.1.3. What are the possible bottlenecks?

See comments here above regarding the needed priority to arrive at the minimum coil performance concerning training, a condition to proceed to the next phase and the human resources required.

5.1.4. Are there sufficient human resources to execute the plan?

For the short term, in particular for next year, presently not.

On the long term it is difficult to assess as manpower released from LS1 activities will become available. As said, the priority has to be on next year's activities to get a working 2m model. The resources for this phase seems insufficient in particular for commissioning the tooling and performing the assembly, instrumentation and test.

It is recommended to strengthen the team significantly, eventually at the expensive of the long-coil program since first the success of the 2m program is considered mandatory.

Develop a core team of technicians for the key delicate tasks.

5.2. Conductor

5.2.1. Are cable design, cabling process, and quality control of dimensional and electro-magnetic parameters well established?

In general yes.

Improving cable stability for winding, avoiding popping strands, is still an issue to be addressed seriously as this eases and shortens coil winding significantly.

Also making PIT cables should continue with the primary aim to construct a similar 2m model with PIT conductor considered useful to verify and compare its performance with the OST/RRP conductor based coils.

The conductors used were not yet tested for transvers pressure degradation up to 200MPa. It is recommended to do so for all cable variants used as this information is needed to judge coil test data.

5.2.2. What short and longer term improvements could be implemented?

Nothing in particular, cable winding stability and PIT progress already mentioned.

5.2.3. Is the procurement plan compatible with the model magnet program?

When the project is proceeding well, there has to be sufficient strand available for the first 700m long cables scheduled for Oct 2014 to practice 5.5m long coil winding. This requirement has to be checked and proper action taken.

5.2.4. Does the conductor and cable meet the requirements for 5.5m coils?

The cabling and proven performance of 700m long units for the 5.5m magnets has yet to be demonstrated.

Consider using Nb_3Sn scrap cable for training and practice 5.5 m coil winding instead of copper dummy.

5.3. Coil tooling, lessons implemented, process, QA, instrumentation, protection

5.3.1. Is all the coil fabrication tooling and infrastructure ready and operational?

The committee wishes to acknowledge the excellent visual quality of the coil winding.

A concern is the complexity of the end spacers made in several pieces, and their alterations needed to achieve good coil performance; but at this stage CERN shall go ahead with what has been established until the first 1-in-1 model is tested; more on this in section 5.3.3.

Carefully monitoring is required of any significant void in the coil winding pack, in particular the longitudinal spaces between wedges and between spacers. In the case space will remain after the reaction heat treatment any effort shall be devoted to fill them as much as possible with inorganic fillers like glass fibers for the larger voids and for example glass spheres for the smaller voids, before impregnation. It is noted that the double layer winding technique prohibits corrective space-filling in between the two layers which may be a problem, entry points to this interlayer space may be created (for example by allowing holes in the end spacers).

5.3.2. Are the lessons from FNAL model program implemented?

Yes, as far as relevant and appropriate (and presented to the committee). It is noted that many issues are related to mechanical tolerances, correctly closing molds and applying pressure and squeezing onto the coils introducing mechanical damage in the conductor.

The preceding work at FNAL was extremely useful and all information was freely transferred and used.

It is noted that an important difference with the FNAL models is the different axial and end spacer materials and shapes as well as type of cable insulation. The impact of this on coil performance is uncertain and an important issue for the coil test.

5.3.3. Is the coil fabrication process and quality control at the required level to ensure: dimensional accuracy, electrical integrity; reproducibility; traceability?

No, not sufficient. Given the limited human resources it seems the effort of the team is mainly on making progress in coil manufacturing rather than spelling out procedures and writing proper quality control documents, which can be understood and forgiven.

Impregnation is performed of the two layers together meaning that the quality cannot be checked internally by visual inspection; one is blind for this. Since vacuum impregnation quality is crucial, it has to be checked that resin is present inside the cable. It is recommended to section a coil to verify epoxy impregnation throughout the winding pack and in particular inside the cable.

The concept of using hard spacers made by the Selective Laser Sintering process is new and its effect on coil training performance to be seen, and is in fact one of the key differences with other coils. Such axial and end spacers are not yet qualified for use in accelerator magnets and this has to be done. Given this, it is not excluded that another technology has to be used when the test results of the first coils are insufficient. The team should be aware of this and be prepared to swap to another spacer technology.

Related to the present end spacers design, develop coil winding techniques to help reducing the corner radii of the springy leg end parts or their possible impact on the coil windings.

When resources permit, a parallel R&D effort is to be developed to validate the internal splice design for use in the long magnets if needed.

A small R&D effort is recommended on the effect on glass fibers of the ceramic binder presently used and to check the effect on the mechanical properties of the winding pack. A standard test of a stack of impregnated cables would suffice. Finding an alternative binder not affecting the glass fibers is interesting as well and the search should continue when resources permit.

The design and quality control documentation of each assembly step shall be reinforced.
Few examples to mention are:
- the force needed to close the reaction mold or the impregnation mold are not monitored (may come for example from measuring the torque on the bolts);
- the space between wedges and between end spacers before and after reaction is not carefully monitored or the available measurements were not presented;
- the cleaning procedure of the cable, brushing and an alcohol wash (which kind);
- measurement (for example on a "bad coil") or FE analysis or other kind of cross check of stress distribution and modulus in the coil ends after impregnation is not performed;
- the precise procedures for the reaction are not set yet.

5.3.4. Does the coil instrumentation provide sufficient information to understand and monitor the magnet behavior during testing?

The coil instrumentation is not yet specified in any detail other than mentioning taps, heaters, and temperature sensors. A complete instrumentation plan is to be established.

5.3.5. Can the magnet be safely operated and is the proposed protection scheme scalable for full-size magnets?

Yes for the short model.

For the model coil, heating the outer layer is sufficient as a relatively high hot spot temperature can be tolerated for a model magnet.

For the long magnets design work is in progress. When resources permits, the development of a good solution for inner layer heating is recommended in due time (not a high priority today though); since for the final long magnets to be installed in the tunnel the lowest possible hot spot temperature should be aimed at. Also the development of band-interval type of heaters periodically heating all conductors in the winding pack is recommended.

When the experimentally determined 13 ms delay between inner and outer layer is confirmed the cable hot spot temperature can be re-computed and arrive sufficiently below 400K. Then for the short models the quench heaters only on the outer layer is considered sufficient, which greatly simplifies the design and implementation in this early stage of the project.

The situation for a quench at a lower magnetic field, which could also be critical being the margin higher, was not presented and an analysis is welcome.

Priority wise it is not recommended to complicate the coil assembly and take any risk (i.e. quench heaters in the inner bore or between layers) until successful quench performance of a first magnet is demonstrated.

5.4. Magnet mechanical behavior, instrumentation, tooling and assembly

5.4.1. Is the understanding of the mechanical behavior of the magnet clear and applicable for the real-life construction process?

The FEA numbers shown at 11T/1.8K of 190 MPa are too high and further work is needed to understand. The various FEA models should be reconciled.
When solved a tool is ready to simulate the magnet structure, which is needed to predict the internal stress and strains. It is noted that the input data for the simulations have been worked out and agreed with FNAL.
Based on the first model assembly valuable information will be collected, which enables to adapt the shims for the real case and avoid coil damage during assembly.

The work of coil mechanical assembly is substantial and a data owner, a responsible person is full time needed for this work in the coming months, a person to be named and committed.

5.4.2. Is magnet assembly tooling adequate and operational?

Yes, for the 2m models, but commissioning is still in progress, yet to be completed.

Not for the 5.5m program, however. The design works is just starting. A furnace and impregnation set-up were ordered based on the 2m equipment; winding machine to be exercised and commissioned; handling tooling to be designed in detail.

The welding tooling in combination with the press seems to be fully understood and a new welding procedure is being prepared enabling the required stress levels in the support cylinder.

5.4.3. Does the mechanical instrumentation provide sufficient information to understand and monitor the magnet behavior during construction and testing?

Yes, the collars and pole instrumentation are in good shape.

Correct resources are in place for mechanical instrumentation, contrary to the situation with the coil instrumentation.

5.4.4. Is the magnet assembly process appropriate and scalable for long magnet?

It is preferred to build a 5.5m single aperture long model first before embarking on a more risky and relatively expensive double aperture magnet.

Consider using the mirror configuration with a dummy pole for early test of poles.

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