2nd ESAC Review Report of the task 7.3 Fresca2 dipole

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Charge of the review:

- 1. Is the magnet construction process sufficiently studied to start coil construction?
- 2. Is the conductor technically ready for this magnet?
- 3. Are there risks which have not been covered?
- 4. Is the quench protection for the dipole sufficient?
- 5. Is the schedule credible?

Presentations can be found at:

http://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=174335

This report is arranged in the form of responses to the questions presented in the charge, preceded by a few general remarks.

General remarks

- The Committee was impressed by the amount of work performed since the last review, by its quality, and by the significant progress. There is still a long way ahead of the final goal; nonetheless the pace demonstrated in the last year is very promising. The Committee congratulates the team leader and all members, and encourages all of them to keep working this way.
- The awareness of the challenges of this project has significantly increased since the last review. The introduction in the plan of the RMC, for instance, is a sign that the Team has recognized these challenges. This is another promising development.
- The deliverable within the EuCard time frame has changed to a single coil, to be tested in the Fresca2 structure. Nonetheless CERN and CEA have an informal agreement and remain committed for achieving the original goal (a complete Fresca2 magnet). The Committee agrees with this change, because it sets a more attainable goal and provides the Team with a more realistic plan. Now the benefits and implications of this change should be fully understood and exploited. For instance the Committee recommends focusing the analysis on the single coil test, and adding another milestone to review RMC and 1st coil test results before investing a significant amount of conductor in the fabrication of the other coils.
- There were a few minor inconsistencies among the presentations (the material of the pole in analysis and in fabrication talks; the time of 1st coil test in schedule and test talks). The plan should be fine-tuned to resolve these inconsistencies.

1. Is the magnet construction process sufficiently studied to start coil construction?

Since last year review the design team made significant progress in understanding the mechanics issues and how they are related to the construction process, which has been studied in a detailed way. Indeed one critical point is the contraction of the coil after the heat treatment of Nb₃Sn, causing stress and strain in the winding, and possibly peak stresses in the ramp regions and the coil ends. A clear analysis of this effect has not yet been done. This analysis is recommended in order to have a complete understanding of stress and strain in the coils, resulting from the heat treatment, the cooldown, and the magnet energization.

The plan of testing the first Nb₃Sn coil in the Fresca2 structure with a mirror configuration involving iron blocks appears to be a good idea in the framework of a step by step process aimed at maximizing the degree of understanding of the system under construction. Of course this approach is technically valid provided that detailed magnetic and mechanical analyses are performed for this special case. In facts this first coil could be considered a sort of practice coil. Under this view the construction of the remaining three coils should start after the cold test (in the present schedule it starts at the same time of the beginning of cold test). This advice seems to be in contrast with the feeling of the design team, worried that a late availability of the test station will cause delays to the construction of the complete magnet (objective beyond the present EUCARD target). Nevertheless the design team has to make a clear choice about the strategy, which should be oriented to learn as much as possible through the achievements of intermediate objectives.

The Fresca 2 magnet construction depends partly on the results of RMC especially for Ic degradation. The design team should put maximum efforts for having the test result of RMC before the winding of first coil starts.

As minor technical point, the impregnation of the small gap between two double pancakes is a good point, but it could be a difficult and critical operation (risk of large voids inside). Some test shall be done using the copper dummy coils.

The answer to the above question can be consequently formulated as follows: <u>Though a large</u> <u>degree of understanding of the magnetic system has been achieved, some developments is still</u> <u>necessary and a clear strategy defined in relation to the EUCARD and post-EUCARD objectives.</u>

2. Is the conductor technically ready for this magnet?

There has been considerable progress in the delivery of Powder-in-tube (PIT) wire from Bruker-EAS. Already there is 30 km of wire in-house with additional 25 km expected to be delivered in Feb'13. Since the FRESAC2 magnet coils require ~ 46 km of wire, there is sufficient strand for fabricating the magnet. In addition, 35 km of RRP[®] strands from Oxford Superconducting Technology is expected to be delivered by July'12.

The PIT conductor with 192 filaments meets the J_c and RRR specifications and the first 8 billets show fairly consistent properties and good piece lengths indicative of good process control at Bruker. Preliminary data for the RRP[®] conductor, which is based on the 132/169 design, show that J_c requirement is easily met, but so far no RRR data are known.

The magnet design is based on a 40-strand cable, 20.9 mm wide and 1.86 mm thick. The cable design was optimized using critical current degradation and mechanical stability as the criteria. For the cable design chosen the cabling degradation is acceptable (~ 10%), based on round and extracted strand tests. We do note however that in experimental cabling runs, cabling degradation as high as 19 % has been observed. Additional cabling studies are on-going to further validate the cabling design and reduce cabling damage. Cabling studies using RRP[®] strands are yet to be performed. The first long cabling run for the RMC would be a good test of the cable for the FRESCA2 magnet coils.

The Committee concludes that the PIT conductor is technically ready for fabrication of magnet coils. Even with 20 % degradation, the cable operation of 10.9 KA at central field of 13 T is very conservative (45% of calculated short sample limit at 4.2 K and 13.3 T based on strand performance) and assures a good chance of success in reaching the design field.

We outline a few recommendations:

- 1. Although there is sufficient strand for the 2 inner and 2 outer coils required for the magnet, consider acquiring additional strand for spare coils.
- Using "inexpensive" bronze wire for qualifying coil winding/reaction/impregnation is not advisable, as the ITER-type wire is quite different – mechanical properties, cabling properties, length changes during reaction etc. – from the high-J_c PIT or RRP[®]-wire.

3. Are there risks which have not been covered?

A lot of progress has been made since the last review and many of the potential risks have now been addressed.

Unforeseen risks can be reduced by increasing the amount of superconductor and therefore the margin, accepting the increase of conductor cost. This seems to be the strategy adopted by the FRESCA2 team. The team has also recently redefined the EuCARD target and the plan in order to reduce risks:

- 1) The RMC magnet allows testing the Nb₃SN cable, the layer jump, the leads and tolerances.
- 2) The change of the EuCARD deliverable to a single flared end coil to be tested in a mirror configuration (using the full-scale structure and replacing the 3 other coils with iron and dummy coils) may allow meeting the program dead line with a success.
- 3) The mirror configuration eliminates the impact of a soft bore and provides new technical information on the flare ends only. At that point most of the magnet components (except the 3 other coils) would be tested and ready to be used for the final magnet construction (assuming no surprises). Before proceeding with the final construction with additional coils, test results will have to be analyzed and followed by an external review.

Other comments:

Since the last review the team has spent more time on understanding the mechanical structure, assembly and cold pre-stress, putting them at a better position when results will be tracked and compared using strain gauges. The LBNL HD program pointed out that the inner supporting tube impacts magnet performance and training. The choice for FRESCA2 was to replace the inner tube with a thick supporting mandrel that also provides top bottom alignment. The contribution of the proposed alignment to the inner structural rigidity should be calculated and compared.

The interaction (displacements) between the inner layer pole and the outer layer island should be looked at.

The RMC magnet is a simpler design compared with the final Fresca2 magnet. We therefore expect its performance to be closer to its predictable target. Unexpected results may impact expectations and raise doubts of the final FRESCA2 coil performance. Additional tests may therefore be required and time need be allocated for such an unforeseen situation.

Continue R&D work on insulation and supplemental coating to reduce potential risk of shorts.

The analysis of conductor strain due to heat treatment and cool-down appears to be incomplete. Therefore the Committee suggests adding/improving the following steps:

- FEM analysis of strain in the coil during and after cool-down depending on pole material.
- Study of conductor behavior during heat treatment including tests with gaps in the pole for both RRP and PIT conductor.
- All tooling and coil fabrication procedures should be designed and engineered in order to allow for longitudinal gaps, in case the experimental tests show they are needed.

4. Is the quench protection for the dipole sufficient?

Yes.

Comments on specific points are below in *italic*.

- 1. The detect-and-dump active protection technique adopted is appropriate.
- 2. *T_{max}* computation based on zero NZP (normal zone propagation) velocity is conservative and appropriate.
- 3. A thermal delay of 20 ms was presented as result of 2D simulations. This delay is consistent with measurements performed on LARP Nb₃Sn magnets, which showed shorter times, with less insulation. Nonetheless, since there is no margin in this estimate, it would be quite beneficial, if time and resources are available, to have this 2D simulation result validated with one of the RMC coils.
- 4. The nominal heater power density is 50 W/cm². In the 2D computation a conservative value of 25 W/cm² was used to take into account the real spatial distribution of the heaters. 50 W/cm² looks a realistic value and is consistent with tests performed on other Nb₃Sn magnets in order to achieve 20 ms delay.
- 5. Dump voltage: 1000 V at Iop=10.5 kA. Center-tapped, ±500 V to the ground is well within a typical arc voltage of 700-800 V, i.e., the system should be free of arcing without elaborate precaution. Within the system, e.g., between the vapor-cooled current leads, across the coil terminals, a voltage of 1000 V appears. The system should be prepared accordingly.
- 6. The dump resistor should always have enough mass for it to absorb the entire magnet energy, regardless the quench-inducing/quench-propagating heaters work or fail. It is acceptable to allow a dump resistor to be heated up to 500-800 °C, provided it is well-isolated and not readily accessible for safety.
- 7. Hot spot temperature analysis is appropriate.
- 8. I agree with the rest of the review panel that an assumption of a 100-ms delay for triggering this active protection technique is reasonable.
- 9. In addition to a threshold trigger voltage (1 mV, 10 mV, 100 mV, or whatever appropriate) as well as a dV/dt level, consistent with a time delay of 100 ms, a criterion based on an $\int V dt$ (where the integral time duration should be in the 10-50 ms) is recommended. The dump should be triggered only when there is a genuine **non-recovering quench**, not on localized quenches that often recover even in the absence of convective cooling.

- 10. In order to have redundancy, the protection system should be based on 2 heaters per coil, 4 heaters should be used, and each pair connected to a separate capacitor bank. Two dump switches should be used, as planned, for the same reason.
- 11. The protection system should be designed regardless the location of the quench start: high-field or low-field.

5. Is the schedule credible?

The current schedule already shows that the deliverable to EuCARD, "Test structure with 1 SC double pancake by April 2013", appears to be very challenging. The obvious show-stopper is the testing cryostat where the first cold test can be anticipated only at October 2013 or later. The Committee strongly suggests the team to speed up the preparation of the testing cryostat so that the first test can be made by April 2013. It is worth to explore the possibility of testing in a simple horizontal cryostat, even at 4.2 K only; while the final vertical cryostat and facility are prepared.

Apart from the testing cryostat, there are some other potential issues that may compromise the schedule.

The cable performance was evaluated only by using extracted PIT strands. The cable specification must be ready very earlier than the start of the coil fabrication. The Committee suggests that the team should accelerate the cable study to thoroughly understand the performance and finalize the cable parameters for both PIT and RRP conductors as soon as possible.

The Committee agrees that the RMC development is a very essential way to evaluate the cable performance as well as some design features (such as layer jump) utilized in the FRESCA2 magnet. Nevertheless, this new development to be made by the same team in parallel with the FRESCA2 development may increase schedule delays and lead to the overload of the team. To avoid them, the Committee suggests the team to strengthen the human resources and appropriately to allocate them to the tasks.

The Committee is pleased that a detailed resource loaded schedule as well as a manufacturing schedule have been prepared and implemented in accordance with the last Committee's suggestion. For future reviews, the Committee would like to ask the project leader to provide a concise project schedule showing all important milestones, including the RMC development, and underlining deadlines and target dates.