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HL-LHC WP4 (Crab Cavities):
SPS Cryo-module Engineering Review
CERN, 10-11 November, 2015

Review Report

Reviewers:
Pierre Bosland, Philippe Lebrun, Vittorio Parma, Leonardo Ristori, and Akira Yamamoto (Chair)

Executive Summary

The HL-LHC WP4 (Crab Cavities) SPS Cryo-module engineering review was held at CERN on 10-11th November 2015

The reviewers wish to thank all the participants for their well-prepared oral reports and comprehensive documents received soon after the review meeting. We have been very impressed with the crab cavity (CC) and cryomodule (CCCM) team activities for the engineering design and for the SPS test preparation.

We congratulate the team on the progress achieved, and recognize the excellent teamwork. The engineering design presented is sound and the general design concept should be kept. We have understood that the idea to accommodate two complementary CC designs of Double Quarter Wave (DQW) and RF Dipole (RFD) into thsoe CCCMs so as to provide common interfaces to RF power and cryogenic system layout in the accelerator tunnel.

On the other hand, we are concerned that the general plan/schedule is very challenging to realize the SPS beam test within the LHC Run-2 period before the termination scheduled in end of 2018. Starting the installation of a new dedicated cryogenic system for the SPS test planned in the technical stops of 2016-17 (followed by further work in the technical stop of 2018-2018) would be the most critical issue, and this must be well managed.

We recommend the basic CCCM design to be kept as already achieved, and encourage to establish the preparation plan to be more robust to ensure that the SPS test is stably supported, and to provide backup plans with an aim of reaching the minimum goal necessary to demonstrate viability.

1. Introduction

The installation of CCs to the HL-LHC accelerator is to be realized during Long Shutdown 3 (LS3), scheduled in 2024-25.

A beam test of CCs is planned in the SPS, within the LHC Run-2 period and before LS2 scheduled in middle 2018, where one or more CCCMs and as many different types of CCs as possible will be installed in the SPS beam and tested for performance. A significant effort

towards the SPS test has resulted in a detailed design of the CCCMs for the double quarter wave (DQW) and the RF dipole (RFD).

This review team has been charged to comprehensively review and address any outstanding issues related to the SPS cryomodules component design. The maturity of the technical status of the CCCM and its readiness towards an installation in the technical stop of 2017-18 should be assessed.

Specific charges and questions to be addressed by the review are:

1) Does the design meet all the functional requirements of such a cryomodule?
2) Have all the important issues been covered by the project team?
3) Have all the design aspects been studied sufficiently in detail in preparation for manufacturing? Are-there particular area where extra design effort is needed?
4) Are there risks associated with the design that could or must be removed or mitigated at this stage?
5) Is the proposed schedule related to SPS tests realistic?
6) Are the general plans and criteria for cryomodule development past the SPS application and into the HL-LHC period (post-2024) correctly defined? Is there any particular area that should be studied in more detail at this stage?

The full text for the charge is attached in Appendix 1, and a list of presentations during the review meeting and documents given to the reviewers after the meeting is attached in Appendix 2.

2. General Comments

We acknowledge the thorough and detailed work performed and presentations given by the project team on the engineering design of the CCCM for the SPS test.

We were not presented by a systematic list of functional requirements and boundary conditions with a clear exposition of the CCCM design principles, during the review meeting. These shoud have been presented as fundamental information, for better understanding at the beginning. It should be also note, however, that relevant information was given to the reviewers soon after the review meeting, and it is available at the reference document on the review.

Given the late timing of the engineering design review in the project, we have no way to question the CCCM design principles, as we have not seen major difficulties that could result in a show stoppers.

We note the large number of people who have contributed – most of them part-time – to the CCCM project, with the possible risk of losing general coherence, conformity with the basic design principles chosen by the project management, and of not reaching overall optimization of the design. The project management has a critically important role and must exert it fully to maximize the general coherence and overall efficiency of the project.

3. Advices from Reviewers

3.1 Responses to individual charges

Charge 1:

Does the design meet all the functional requirements of such a cryomodules?

Findings and Comments:

- We were not presented by a systematic list of functional requirements and boundary conditions, nor with a clear exposition of the design principles of the CCCM during the review time.
- The important boundary conditions should have been presented, so that reviewers could have understood better the reasons for certain choice, and to enable them to address appropriately the specific questions.
- It should be noted that the relevant information was however provided soon after the review, and is now available as part of the reference documents on the review URL. The follow-up effort by the team is appreciated.

Recommendation:

- We recommend to clarify "the minimum functional requirement/goal" for the SPS CC test to be prepared in case of difficulties to be met in the course to the SPS test.

Charge 2:

Have all the important issues been covered by the project team?

Findings and comments:

- The general plan to realize the SPS test has not been yet well covered.
- The proposed cryogenic system for testing the CCCM in the SPS at Point 6 appears adequately designed and sized. However, a major concern is the cryogenic-system procurement and installation schedule, which appears to be very tight.
- We were presented with elaborate contact-less measurements of the dressed cavities in the CCCM, based on two different optical systems (FSI and BCAM), thus requiring many windows on the outer vessel and free lines of sight inside the cryomodule. While this is an interesting approach to monitor the behaviour of the prototype in operating conditions, it is probably not necessary for the series CCCM production, or it may be much simplified by focusing on the most critical information, thus allowing substantial savings in cost and thermal budget.
- This review addresses the CCCM as an integrated system, and does not cover the detailed design of each critical component. Technical reviews of critical components such as fundamental power couplers (FPCs) and tuners should have been already done.
- We note that no relief device for the helium enclosures is foreseen on the CCCM directly. , Its protection is ensured by a relief device located on the adjacent service module. We point out that this requires all tests and operation, at any temperature, of the CCCM to be performed together with the Service Module or other adequately protected piece of equipment, in particular intermediate pressurization which could have to be made during assembly. This point is particularly important in view of the relatively low design pressure of the CCCM helium enclosure.

Recommendations:

- A decision on the implantation/location of the refrigerator cold box (at ground level or in tunnel) needs to be urgently taken.
- The critical components such as FPCs and tuners shall be individually reviewed in timely manner, if they have not already been done.

Charge 3:

Have all the design aspects been studied suffiently in detail in preparation for manufacturing? Are there particular area where extra design effort is needed?

Findings and comments:

- The cryomodule integration process has not yet been studied sufficiently.
- The vertical installation/assembly of the FPC increases the risk of contamination.
- The possibility to maintain the cryomodule system after the installation into the SPS should be sufficiently studied in detail.
- Pre-integration tests are important for key ancillary components, such as couplers, tuners, and others.
- The CCCM safety analysis has been made from a component viewpoint, and reported with a document submitted. However, the safety and extreme failure mode analysis in the SPS tunnel environment during the SPS CCCM test has not been found yet.

Recommendations:

- The system integration workflow, including efficient tooling, fixtures, and intermediate tests must be studied in greater detail, especially with regard to preventing contamination of the CC and degrading its performance.
- Cryogenic-safety and the extreme failure-mode analyses should be performed, considering the specific SPS test environment to be well prepared.,

Charge 4:

Are there risks associate with the design that could or must be removed or mitigated at this stage?

Finding:

- The scheme for supporting the CC in the cryomodule present some risk because of low stiffness.
- The system integration/assembly process lacks sufficient detail.

Recommendation:

- We advise the project team to consider reinforcing the stiffness of the supporting system while, at the same time, limiting forces on the FPCs.

Charge 5:

Is the proposed schedule related to SPS tests realistic?

Finding:

- The schedule presented is very optimistic, with a first hard deadline given by the shutdown 2017-2018 for installing the CCCM into the SPS, a necessary condition for being able to operate it and get results in 2018, i.e. before LS2 (the second hard deadline).
- The cryogenics preparation/procurement and the construction time may be the highest risk

in the schedule, as largely dependent on components to be supplied by industry.

Recommendations:

- We recommend taking fast action, such as ordering cryogenic refrigerator, as well as tracking closely the milestones of the project schedule and working out mitigation paths in case these milestones are not met.
- Prepare for various scenarios, at least to reach the minimum requirement for the SPS test.

Charge 6:

Are the general plans and criteria for cryomodule development past the SPS application and into the HL-LHC period (post-2024) correctly defined? Is there any particular area that should be studied in more detail at this stage?

Finding:

- The plan has not been yet well defined. In particular, the cryogenics schedule sounds very optimistic.

Recommendation:

- We recommend to provide clear documents for the general plan, at least for the goal of the CC-CM test at SPS with various scenarios including the minimum requirement to be achieved. Further scope for the HL-LHC period shall be re-visited after certain progress in the SPS test preparation.

3. 2 Further findings and comments

The following findings/questions and comments on individual components may be useful, even though they would be in details. .

Cryostat and Helium Vessel design:

- The 2nd beam line is not installed inside SPS CM (to limit heat loads).
- Windows for in-situ maintenance is included for the SPS CM, but their usefulness is not clear enough. These features constrain the design of the cryostat that becomes considerably more complex (design of vessel, construction, stiffness, thermal and magnetic shields etc.). For the SPS it could be acceptable as it is a prototype (still, the need should be better justified), but for the LHC the needs for maintainability should be included in the design, and should consider the radioactive environment;

Cold magnetic shielding:

- Test plans with an overview of measuring techniques are presented. It should be made more clear what is the foreseen as QA plan.
- The permeability at 4.5 K should be well confirmed/understood.

Tuning system:

- Basic principles and engineering design studies are presented as well as first measurements made with a tuner prototype mounted on a test bench.
- The principle of the cavity frequency tuning has been carefully analyzed. However an important analysis that has not been made: the possible plastic deformation of the cavity niobium sheets that may be caused during the thermal cycles by the differences in the

thermal shrinkages or expansions between the stainless steel tuner frame and the niobium cavity. The basic principle of the tuner makes us think that this risk is very high and may cause systematic deformation of the cavity. We advise to make this study.

- The advantages of having the tuner motor outside the vacuum tank have the counterparts of a heavier mass fixed on the cavity but far from it. This can generate low frequency vibrations, and the floating actuation center system may not damp them or increase their frequencies. First analyses of simplified models have been done, but they are not sufficient to exclude dangerous vibrations once the tuner is mounted on the CC.
- We advise to organize a review of the tuner..

Fundamental Power Couplers (FPCs):

- The presentation was much of an overview of the history rather than focused on the FPC engineering design. We did not much seen the engineering design and the manufacturing and assembly tolerances.

CC support system:

- Supporting system requirements were not clearly presented, but main alignments needs were explained in the following presentation on alignment.
- FPC external conductor is used as main support and fixed point. The SPS CM will not have actively cooled double-walled tube, but simply an 80 K thermalisation. Plans are for double-walled cooling for the LHC. In this case, the temperature profile will be different and the thermo-mechanical movements of the cavity as well (with a level of few tenths of mm). The SPS prototypes may therefore not be fully representative.
- Suspended supporting system is not very rigid (first mode at 12 Hz), and prone to “swing”. Transport restraints are apparently planned but were not explained;
- Only a partial picture of load cases was presented (bellows forces missing). Considering the reduced stiffness of the system, a complete load case analysis and positioning analysis should be done.
- Are the first low-frequency modes compatible with operation?
- Thermal contraction calculations do not consider heat intercepts on blade supports. These will affect the final positioning of the cavity.
- Interfaces to vacuum vessel for initial assembly positioning and alignment was not illustrated. There will have to be bellows to allow alignment while ensuring insulation vacuum leak-tightness.
- Overall supporting concept seems to be sound, but still quite some design and analysis work needs to be done. Considering the importance of the system, it deserves close attention;

Alignment and positioning system:

- Positioning accuracy/reproducibility of the CC is to be within 0.5 mm
- The screw adjustment seen is probably not achieving this (backlash, stick-slip), in the process of the positioning adjustment at assembly to be investigated,
- Is active monitoring of cavity positions needed for LHC (baseline today)? For the prototype a monitoring system is necessary to qualify the design/operation of the CM. It could be limiate to SM18 tests of the cryomodule.
- Active monitoring methods proposed (FSI and BCAMs) rely on retro-reflectors in the cryostat. Cryo-condensation of outgassed species can blur the reflective surfaces to be further investigated.

Cryogenics:

- Level gauges are not replaceable. Acceptable for SPS but for LHC replaceable ones should be considered (for fast exchange considering the radioactive environment): cryostat feed-through for level gauges and helium guards, as for the LHC Short Strait Sections could be adopted.

Thermal/radiation shield and Magnetic shields:

- The design is still too preliminary.
- There is very little space for MLI specially at the top of CCs.
- Warm magnetic shield should be thermalized to RT for the stable and well known characteristics at RT.

Heat loads and thermal budgets:

- Preliminary heat loads are presented. There is still work to do (heat intercepts still to be designed and calculated, these will affect the heat load table).

Vacuum vessel:

- Side opening for maintenance constrains the stiffness design, but does not seem to be a show stopper at this stage.
- A double gasket instead of single elastomer gasket at the cryomodule top plate with intermediate pumping could be considered in case of doubts on the tightness design, and for a redundant design specially for the possible repeated work.

Cryostating:

- Further engineering design study is still to be integrated.
- The clean-room class need to be defined as the choice impacts the type of tools and equipment to be used.
- The clean-room infrastructure to be used was not cearly defined. This could also be a schedule issue if construction and commissioning of new facilities are required for the project.

(end of the main text)

Appendix

A1. Review Charge (with the full text given by the CCCM team)

The installation of Crab Cavities (CC) is planned during Long Shutdown 3 (LS3), scheduled for beginning 2024-25.

Due to lack of experience of CC performance in hadron machines, a beam test of CCs is planned in the SPS before LS2 where one or more Cryomodules and as many different types of CC as possible will be installed in the SPS beam and tested for performance.

A significant effort towards the SPS tests has resulted in a detailed design of the cryomodules for the double quarter wave (DQW) and the RF dipole (RFD).

This review is charged to comprehensively review and address any outstanding issues related to the SPS cryomodules components design:

- Vacuum vessel, thermal and magnetic shielding, thermal insulation, cryogenic distribution, internal support structure, RF internal lines, alignment adjustment and monitoring; as well as
- Physical and functional interfaces to the: RF cavities and helium vessels, cryogenic and vacuum systems.

Some important elements of the cryomodule are being prototyped to understand the performance of the design choices (He-vessel, tuner etc..).

The maturity of the technical status of the cryomodule and its readiness towards an installation in the technical stop of 2017-18 should be assessed.

Specific questions to be addressed by the review:

1) Does the design meet all the functional requirements of such a cryomodule?
2) Have all important issues been covered by the project team ?
3) Have all the design aspects been studied sufficiently in detail in preparation for manufacturing? Are-there particular area where extra design effort is needed?
4) Are there risks associated with the design that could or must be removed or mitigated at this stage?
5) Is the proposed schedule related to SPS tests realistic?
6) Are the general plans and criteria for cryomodule development past the SPS application and into the HL-LHC period (post-2024) correctly defined? Is there any particular area that should be studied in more detail at this stage?

A2. Agenda for the CCCM-review presentations:

	Subject of reports	reported by
10th Nov.		
1	Introduction and overview of the CM	Ofelia CAPATINA et al.
2	He vessel design, prototyping and tests	Carlo ZANONI
3	Cold magnetic-shielding & Proposal for …	Niklas TEMPLETON
4	Tuning system	Kurt ARTOOS
5	HOM couplers	Marco GARLASCHE
6	Fundamental power coupler and RF …	Eric MONTESINOS
7	Support system of the dressed cavity	Thomas JONES
8	Alignment and position monitoring system	Mateusz SOSIN
	(lunch break)	
9	Cryogenics and cryolines	Krzysztof BRODZINSKI
10	Thermal and outer magnetic shields	Niklas TEMPLETON
11	Thermal budget and heat loads	Federico CARRA
12	Vacuum vessel	Norbert KUDER et al.
13	Cryostating	Pierre MINGINETTE
14	Integration in SM18 bunker tests	Alick MACPHERSON
15	Integration in SPS	Giovanna VANDONI
11th Nov.		
1	General plan (Schedule) to reach SPS Test	Ofelia CAPATINA
2	Requirement/Goal for CC system at LHC Requirement/Goal for CC test at SPS Minimum requirement/goal for CC test at SPS	Rama CALAGA

The following documents have been reported to the reviewers right after the review meeting on 10 – 11th November, 2015.

1) "Functional Specifications of the LHC Prototype Crab Cavity System" P. Baudrenghien et al., CERN-ACC-NOTE-2013-003, Feb., 2013
2) "Compact Crab Cavity Cryomodule" K. Srtoos et a., CERN-ACC-2015-0130, Oct. 2015.
3) "Conceptual specification: Crab Cavities", LHC-EQCOD-ES-xxxx, Draft.
4) "Dressed bulk niobium radio-frequency crab cavities", LHC-ACFDC-ES-0001, June 2014.
5) "Conceptual specification: SPS Crab cavity validation run installation", LHC-EQCOD-EX-xxxx, Draft June 2014.
6) "Crab cavities prototype cryomodule, a proposal for compliance with CERN safety requirements", EDMS No. 1494776, August 2015.

All information is online available:

https://indico.cern.ch/event/435319/