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International Review of the
Crab Cavity System Design and Production Plan for the HL-LHC

19 - 21 June 2019

Review Panel Report

Review Panel members:
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Executive Summary

General

The international review of the Crab Cavity (CC) system design and production plan for the High-Luminosity LHC (HL-LHC) upgrade program was held at CERN on 19–21 June 2019.

The Review Panel was requested to assess (i) the present design to meet the required performance and (ii) the production plan to provide adequate technical optimization, considering the complex scheme with many in-kind contributions (See Appendix).

The Panel received 33 reports from the CC collaboration and has recognized significant and appropriate advances in the CC technology required for HL-LHC CC system construction (See Appendix 2).

The Panel congratulates the collaboration on excellent progress in the Double-Quarter-Wave (DQW) CC test at SPS, achieving the first crabbing for a proton beam, as a very important milestone.

The Panel acknowledges excellent team work with very effective cooperation between CERN, US Accelerator Upgrade Project (US-AUP), UK and Canada strengthening the collaboration itself.

Finding and Comments:

- The Panel confirms that the current strategy is adequate for the HL-LHC CC system design concept employing two complementary CC designs of Double-Quarter-Wave (DQW) and RF-Dipole (RFD) with a unified CryoModule (CM) design.

- This allows common interfaces to associated RF, vacuum, instrumentation and cryogenics systems. This concept enables to respond to complementary requirements for horizontal and vertical crabbing in two ATLAS and CMS beam interaction regions,

respectively, allowing to swap the horizontal and vertical scheme if requested by physics in the future.

- The prototype DQW cavity developed in-house at CERN has successfully demonstrated first "crabbing" of a proton beam, finding no adverse effects on beam operations caused by the CC and CM structure, which can be transparent to the beam. This test has been crucial for the HL-LHC CC system design, withdrawing a major project risk.

- Performance test results of prototype DQW and RFD cavities developed by CERN and US-LARP/AUP, respectively, have been very satisfactory in terms of verification of their design parameters and expected performances.

- Following competitive tender, contracts for the CC production (both DQW and RFD) have been placed with European companies.

- There is some concern regarding the potential cause of tuner performance issues that were discovered during the CC and CM testing at SPS.

- The CERN-UK collaboration has made much progress on the development of a common CM design, and the Panel notes that the design presented is somewhere between preliminary and final design stages. The effort will be reinforced by the Canada-TRIUMF participation.

- The Panel recognizes team work well integrated to advance the CC and CM system design and development with associated sub-systems with HPRF, LLRF, control, cryogenics, general service systems, and their performance tests at SM18 and SPS.

- The Panel endorses the project plan in terms of number of CC systems to be produced: four CMs, for each CC type, to be installed in the LHC with one additional spare ready for installation.

- The Panel recognizes that the overall project management and quality assurance plan centered at CERN is well-organized. It contains appropriate elements to allow monitoring and maintaining technical, cost, and schedule baselines. It is functioning for proper project integration amongst the partners.

Recommendations:

1. Complete the RFD CC and CM tests at SM18, to cover all acceptance criteria, taking ample time during LS2. Then, validate the overall system performance at SPS, after LS2 as soon as possible.

2. Extend the DQW CC-CM system test at SPS within a limited time before the RFD CC and CM system to be ready for the SPS installation. It will be very useful to extend precise understanding of the CC and CM system performances with the beam, in particular for validating specific aspects of the maximum SRF voltage-reach, quench behavior linked with the beam, pressure stability, advanced high-power testing, and others.

3. Complete thermo-mechanical analyses including cool-down/ warm-up scenarios and

lessons learned from SPS testing (see more: Recommendation in *CQ-1, -2*).

4. Evaluate possibility and implement additional equipment, such as heaters, valves, and others, for enabling thermal cycles to de-gas CCs, so called "independent warm-up & cool- down" from other systems.

5. Perform analyses and tests of the CC and CM components that incorporate incremental design changes: e.g. changes in HOM antenna material, 25 Ohm feedthroughs, and others.

6. Establish and confirm acceptance criteria for parts, components, and systems, including how to verify it. This may require updates of technical specifications in some cases (see more: Recommendation in *CQ-3, -4*).

7. Conduct readiness reviews prior to procurement of CM components and systems.

8. Complete remaining high-level inter-laboratory agreements in order to formally identify in-kind contributions and scope of work.

Synthetic Report

1. Introduction

The international review of the Crab Cavity (CC) system design and production plan for the HL-LHC was held at CERN on 19 – 21 June 2019, and the Review Panel was requested to assess: if (i) the present design to meet the required performance, for the CC system integration with their cryomodules, HPRF, LLRF, and other services, including some updates since 2014, and (ii) the production plan to provide adequate technical margin, considering the complex scheme with many in-kind contributions in the HL-LHC project.

The specific charges/questions (see Appendix 1) given to the Panel are summarized as follows:

1) SPS-CC experience and lessons learned to be implemented into HL-LHC CC?
2) SPS beam tests and extrapolation to HL-LHC, open questions?
3) Readiness of RFD pre-series cryomodule?
4) Readiness for series production? Open points being addressed implying changes?
5) Status of HPRF, LLRF and other auxiliary components? Do we need further attention over the coming years?
6) Baseline schedule including collaborations with respect to HL-LHC schedule? Management of in-kind and preparations for work framework – risks for production and testing?
7) Is CERN ready to finalize the agreements: status of acceptance criteria & procedures of different sub-components?
8) QA/QC and risks for deliverables between partner laboratories?

The Panel has received 33 reports (see Appendix 2) and has been very much impressed with the major progress recognized with high-quality reports from the CC collaboration advancing the CC technologies to prepare for HL-LHC CC system construction. The Panel responses to

the charges/questions as summarized as follows.

2. Responses to the Individual Charges/Questions:

CQ-1*: SPS-CC experience and lessons learned to be implemented into HL-LHC CC?*
CQ-2*: SPS beam tests and extrapolation to HL-LHC open questions?*

Finding/Comments:

The Panel congratulates the collaboration on excellent progress in the Double-Quarter-Wave (DQW) CC test at SPS, resulting the first crabbing demonstrated for the proton beam as a very important milestone. This was achieved thanks to excellent teamwork within the HL-LHC CC collaboration.

The prototype DQW cavity beam test at SPS did not reveal adverse effects on beam operations caused by the CC-CM structure which can be made transparent to the beam. The result of this test has been crucial for the HL-LHC CC system design, withdrawing a major project risk.

The CC-CM system including associated subsystems generally functioned as designed.

There is a concern, however, regarding the cause of potential tuner performance issues that were discovered during the CC and CM testing at SPS.

Recommendations:

- Perform the full set of RFD CC and CM tests in SM18 to cover all acceptance criteria, using the time available during LS2. Then, validate the RFD CC-CM system performance with the beam at SPS, as soon as possible after LS2.

- Extend the system test of the DQW CC-CM at SPS within a limited time before the RFD CC-CM system to be ready for the SPS installation. It will be very useful for a precise understanding of the integrated CC-CM system performances with the beam, and for validating specific aspects such as SRF voltage-reach, quench behavior linked with the beam, pressure stability testing, advanced high-power testing, and others.

- Complete thermo-mechanical analyses including cool-down/warm-up scenarios and lessons learned from SPS testing. In particular, it is important to confirm thermo-dynamic conditions of interfaces connected to associated components such as fundamental power couplers, tuners, mechanical supports, as well as thermal-shield assembly.

- Evaluate the implications of a thermal cycle to outgas CCs, so-called “independent warm-up & cool-down”. Obtain additional equipment (heaters, valves, etc.) required.

CQ-3: *Readiness for series production? Open points being addressed implying changes? Readiness of RFD pre-series cryomodule?*
CQ-4: *Status of HPRF, LLRF and other auxiliary components? Do we need further attention over the coming years?*

Finding/Comments:

Performance test results of the prototypes of DQW and RFD cavities developed by CERN and US-LARP/AUP, respectively, have been very satisfactory in terms of verification of their design parameters and expected performances.

The CC production procurements with industry have been settled in both DQW and RFD with European companies.

Progress in engineering analyses for several sub-systems was presented. In some cases, preliminary analyses do not necessarily include all operational conditions that may be expected, e.g. thermal and magnetic shields cool-down and warm-up.

There are still remaining details in optimization for the auxiliary components.

Recommendations:

- Perform analyses and tests of the CC and CM components which have incremental design changes, e.g. changes in HOM antenna material, 25 Ohm feedthroughs, and others.

- Establish and confirm acceptance criteria including how to measure the values, for parts, components and subsystems, in particular for industrial components with high-pressure code constraints, magnetic shields, RF devices, and others. This may require updates of technical specifications in some cases.

CQ-5: *Baseline schedule including collaborations with respect to HL-LHC schedule? Management of in-kind and preparations for work framework – risks for production/testing?*

Finding/Comments:

The proposed plan for RFD CM production ramp-up includes using prototype dressed cavities for TCM-0 (mock up CM) at TRIUMF. This proposal may help to improve the delivery schedule of the RFD CM production.

Recommendation:

- Consolidate the plan to clearly establish how many components of each type will be produced in order to assess the risks to achieve nominal performance on all CMs, e.g. yield vs. spares for critical components.

CQ-6: *Is CERN ready to finalize the agreements (status of acceptance criteria & procedures of different sub-components)?*

Finding/Comments:

The collaboration agreements have been completed, or nearly completed. The in-kind contributions for CC and CM have been agreed or in final negotiation stage from:

- US-AUP (8 + 2 spares, all jacketed RFD CCs),
- UK-STFC and Lancaster Univ. (4 DQW CM assemblies) and
- Canada-TRIUMF (5 RFD CM assemblies).

The construction of the DQW jacketed CCs by industry for CERN is already under way

- CERN (8 + 2 spares, all jacketed DQW CCs, and 1 DQW CM assemblies)

Recommendations:

- Complete remaining high-level inter-laboratory agreements in order to formally identify in-kind contributions and scope of work.

CQ-7: *QA/QC and risks for deliverables between partner laboratories?*

Finding/Comments:

The Panel recognizes that the QA/QC plan has been well prepared and documented, and has been impressed with the team work for the QA/QC centered at CERN.

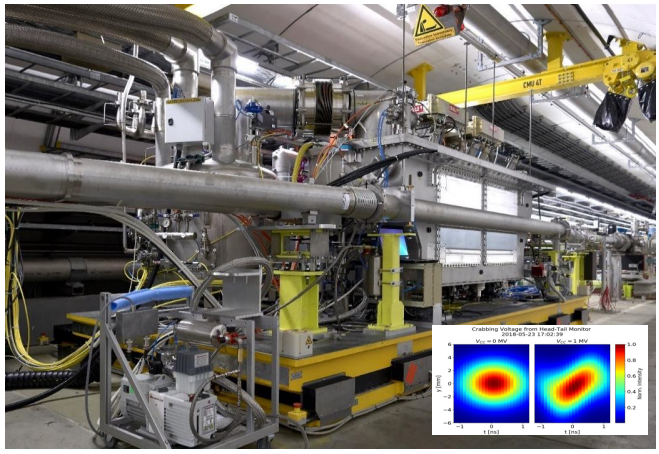
The Review Panel finds, however, some uncertainties and risks for delay of deliverable that would be caused by differences of project implementation system between the US-AUP collaboration and CERN.

Recommendation:

- Prepare for a backup plan, just in case, how to adapt/absorb the delay of delivery.

Acknowledgments

The Review Panel would express sincere thanks to all participants for his/her outstanding effort for advancing the SRF crab cavity technology, in particular demonstrating for the first time crabbing of the proton beam at SPS, and for preparing the high-quality reports and intense discussion at this international review held on 19 – 21 June, 2019. Special thanks to Ms. Elodie Kurzen for her kind cooperation and assistance in the successful organization of the review.



An important Milestone achieved by SPS Test

A Group Photo from the Int'l CC Review, 2019

Appendix

A1. Review Mandate and Charges/Questions

- CQ1-a: Have the experience and lessons learned from the first phase of CC construction in the US, CERN and UK, and
- CQ1-b: in particular the **SPS** crash construction program, successfully been implemented into the HL-LHC Crab Cavity design and construction program?
- CQ1-c: What points need to be addressed with the RF-Dipole prototype tests in the SPS?

- CQ2-a: Did the SPS beam tests show relevant results to extrapolate to HL-LHC?, and what are still the open questions? [e.g. different beam and bunch parameters in the SPS] and to what extend are these results affecting design choices (HPRF, LLRF, Control, Hom damping, noise transfer level etc.) for the final (HL-LHC) Crab Cavity systems?
- CQ2-b: Are we ready to launch tender for the RFD prototype (go to SPS) cryomodule? Is the UK plan for RFD pre-series cryomodule production and assembly sufficient?

- CQ3-a: Is the Crab Cavity system design, including cryomodule, sufficiently developed for this stage of the project, and ready for launching the series production? If any, what points are still being optimized/iterated on for the pre-series production - both for the DQW and RFD designs?

- CQ4: Are the auxiliary components for the Crab Cavity system, like LLRF feedback, controls and power sources (HPRF), sufficiently developed for this stage of the project? If any, what support systems need further attention over the coming years?

- CQ5-a: Is the baseline production schedule for the RFD and DQW RF systems well adapted to the overall HL-LHC schedule [are the potential critical milestones in the overall CC production matched to the HL-LHC schedule]?
- CQ5-b: Is the planning appropriately considering the boundary conditions implied by the distributed production planning with the abovementioned in-kind contributions?
- CQ5-c: Is the work framework and management adequate to manage such complex multiple interfaces system? What are the risks inherent to the current production and testing planning

- CQ6: Is CERN ready to finalize the agreements with the international partners on the key performance parameters and acceptance criteria & procedures? – Acceptance criteria & procedures are in preparation for the different sub-components

- CQ7: Is the Quality Plan for the Crab Cavity production addressing sufficiently the risks throughout the production phases at the various partner laboratories [cold tests after each transport versus visual inspections and mechanical measurements etc.]?

A2. Agenda for the CCC performance Review for the HL-LHC

https://indico.cern.ch/event/787363/overview

19 June:	
• Executive Session	
• Introduction and Overview	L. Rossi & O. Bruning
• Overview of WP4-CC in HL-LHC	Rama Calaga
• WP4 Strategy for CM	Ofelia Capatina
• WP4 Strategy for RF system	Eric Montesions
• WP4 Strategy for (SPS) Integr. & HL-LHC interface	Giovanna Vandoni
Coffee break	
• US contribution to SPS CC prototype & Lessons Learned	Alessandro Ratti
• CERN-Crash Program for SPS-DQW CM	Marco Garlasche
20 June:	
• Vacuum layout & experience from SPS	Chiara Pasquino
• Cryogenics experience from SPS	Krzysztof Brodzinski
• SPS experiment with beam	Lee Robert Carver
• HOM damping & SPS measurements	James A. Mitchell et al.
Group Photo and Coffee Break	
• Freq. tuning system & lessons learned	Kurt Artoos
• LLRF experience for SPS & HL-LHC outlook	Philippe B audrenghien
• APA-CC operation challenges/Limitation & outlook for 2021	Rama Calaga
• Machine protection lessons learned from SPS	Daniel Wollmann
Lunch	
• CERN RFD-SPS cavity manufacturing status	Marco Garlashe
• CERN/RI DQW-Series Cavities for HL-LHC CC	Nuria Valverde Alonso
• US-AUP RFD Dressed Cavities for HL-LHC CC	Leonardo Ristori et al.
• CERN FPCs & Other Couplers for HL-LHC CC	Eric Montesinos
• US-AUP RFD Couplers for HL-LHC CC	P. Berrutti
Coffee Break	
• HL-LHC CC Cryomodule Design	Teddy Capelli
• SPS-RFD & Series DQW Cryostating Plans	Thomas Joseph Jones
• Series RFD Cryostating for HL-LHC CC	Robert Laxdal
• Transport Aspects	Kurt Artoos et al.
21 June:	
• SM18 Assembly and Testing Infrastructure	Katarzyna Turaj
• LHC Environment Constraints & Integration	Paolo Fessia
• Vacuum for HL-LHC CC	Germana Riddone
• Cryogenics for HL-LHC CC including sectorization	S. Claude, K. Brodzinski
• Alignment & Monitoring from SPS to HL-LHC	Mateusz Sosin
Coffee Break	
• RF Conditioning Strategy during HL-LHC	Eric Montesinos
• Tech. Spec. & Guidelines for Compl. w/ CERN Safety Rules	Luca Dassa
• WP4 QA/QC Status, Risks & Documentation	Isabel Bejar Alonso
• Coodination for HL-LHC CC construction and Int'l collab.	O. Bruning, R. Calaga
• Executive Session	
• Close out	

A3-a. Past Reviews and Outcome (summarized by R. Calaga)

- **May 2014:** Cavity design review
  Led to down selection to 2 cavities (DQW, RFD) for SPS-test/LHC

- Feb 2015: 1st HOM coupler review
- Mar 2015: Cost & Schedule review I
  Study the effect of only ½ of system (16 instead of 32)
- May 2015: CERN-STFC Helium vessel review
- **Nov 2015:** SPS Cryomodule review
  Develop minimum goal for SPS tests, review individual critical components, integrated production/test planning including infrastructure

- Oct 2016: Clean room assembly review
- Oct 2016: Cost & Schedule review II
  Reduction to ½ system, HPRF 40 kW-CW
- Nov 2016: Operational safety review in SPS

- **April 2017:** Crab cavity performance review for HL-LHC
  Perform SM18 tests prior to SPS installation with minimum success criteria, establish formal agreements, specifications, acceptance criteria and interfaces

- Mar 2018: Cost & Schedule review III
  Endorsed with new strategy (UK, US-AUP, Canada)

A3-b. Highlights, since last Review (summarized by R. Caraga)

- DQW-SPS prototype demonstrates with first ever crabbing with protons, transparency & high intensity demonstrated. Detailed studies will continue in 2021,

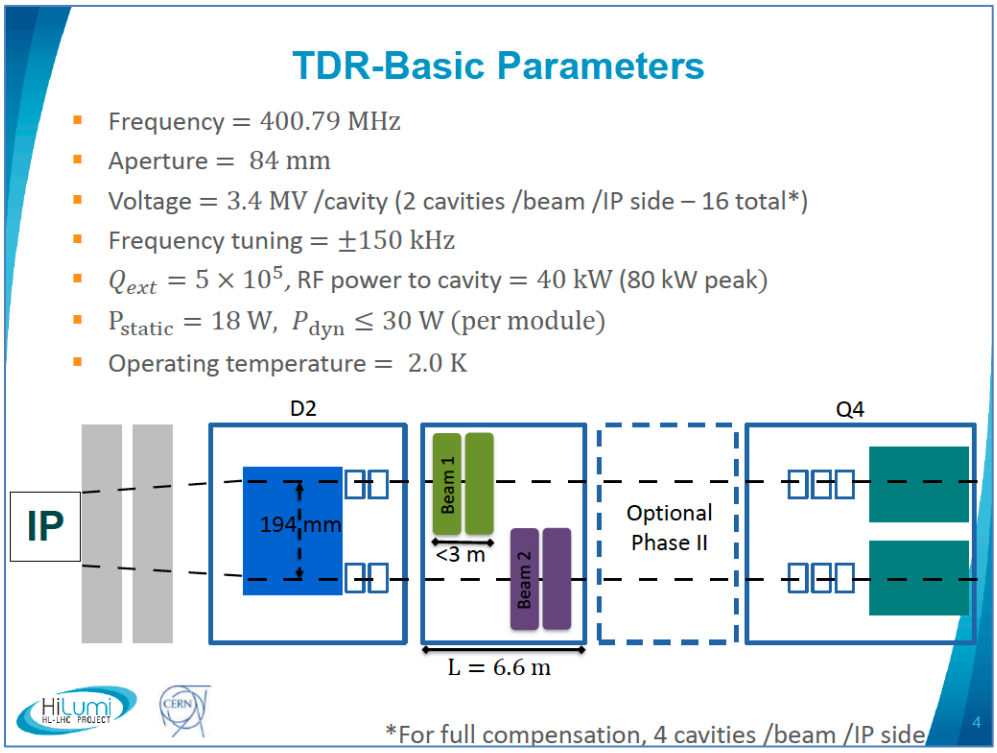
- DQW-HL-LHC jacketed cavities contract with RI signed & ongoing,
- DQW-HL-LHC cryostating in final stages of negotiation for building 1-CERN and 4-UK,

- RFD-SPS cavity fabrication started at CERN, cryostating to be performed at UK and the conceptual design is almost complete,
- RFD-HL-LHC dressed cavities in-kind contribution from US-AUP with CD2 approval & progressing well (in contract with E-Zanon),
- RFD-HL-LHC cryostating as in-kind from Canada-TRIUMF, detailed agreement in preparation,

- Discussions ongoing with Novosibirsk for an in-kind contribution of high-power RF amplifiers using solid-state technology, and

- Big effort on integration for HL-LHC, including design adapted for left/right IP symmetry and IR1/5 swappable option.

Appendix 4: HL-LHC Crab Cavity Parameters (presented by R. Calaga):



Appendix5 . HL-LHC Crab Cavity Timeline (presented by R. Calaga):