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HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Report

Report of the HiLumi-LHC/LARP Crab Cavity System External Review Committee

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M. Kelly (ANL), H, Padamsee (Cornell Univ. /Fermilab),
C. Pagani (INFN-LASA/Univ. Milano), and A. Yamamoto (Chair, KEK/CERN)

June 6, 2014

Submitted to

Hilumi-LHC/LARP Collaboration

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Executive Summary

An external review on HiLumi-LHC/LARP Crab Cavity design and development was held at BNL, 5-6 May, 2014. The committee received reports from three different design studies and their technical developments in progresses, and reviewed their progress and preparation for beam tests planned to be held at CERN-SPS. The review committee has the following advice.

- We suggest that two cavity designs be selected for the beam tests at SPS. These cavities should incorporate complementary different HOM coupler configurations , as were presented for:

  - Double Quarter Wave (DQW) design proposed by Brookhaven National Laboratory (BNL) with Coaxial HOM Couplers, and
  - RF Dipole (RFD) design proposed by Old Dominion University (ODU) with a waveguide HOM Coupler.

- We suggest that further development and the beam test preparation be prioritized with the DQW design because the engineering design work appears to be better advanced to meet a very limited preparation time. However, we encourage the RFD cavity development to be continued with strengthening the waveguide HOM Coupler development. We note that either the DQW or the RFD could be tested first in SPS, depending on the readiness of the cavity and CM preparation.

- The prototype cavity and the cryomodule fabrication should be started as soon as possible in order to cold test at SM18, prior to the SPS beam test expected in 2016 – 2017.

- The Lancaster University (LU) group is recommended to work on further CC development and test programs including HOM couplers, cryomodule development work, as well as CC SPS beam tests.

- A clear and plausible plan to realize the SPS beam tests within the limited time should be developed with strong leadership from the project management.

1. Introduction

The use of Crab Cavities (CC) in the high Luminosity Insertion Regions of LHC (ATLAS & CMS) is the baseline of the HL-LHC project. The cavities, originally intended mainly for the correction of the geometrical factor, have recently become an important tool to reduce the pile up density, thus improving the quality of data taking by the experiments. Installation of CC is planned during 'Long Shutdown 3' (LS3), scheduled for the beginning of 2023 and continuing through the first half of 2025.

The CC teams have developed three distinct RF cavity models with subsystems referred to as:

(1) RF Dipole (RFD),
(2) 4-Rods, and
(3) Double Quarter Wave (DQW).

All three models are being pursued on roughly equal footing in terms of project personnel effort at this time.

In view of the lack of experience of CC performance in hadron machines, a beam test of prototypes is planned at the SPS before the long shut-down, LS2, in August 2018 – end 2019. One or more sets of cavities and/or cryomodules will be installed in the SPS and be tested.

It was expected that the CC design would be frozen by April 2014, and the cryomodule (CM) design by 2015. The first CC and CM production and assembly shall be completed by 2016 for an initial CM test, before installation into the SPS during the LHC extended year end technical stop (EYETS) of early 2017.

2. Charges to the Review Committee

The review committee was charged to evaluate and to report on the maturity of the technical status for the CC system, the reliability and expected efficiency of the management plans required for a successful SPS testing by 2017 – early 2018, and the maturity of the development of down-selection criteria.

The review committee was asked to report the comments and recommendations at the LARP Collaboration meeting taking place at BNL on May 7-9, 2014. Specific charges for CC and Cryomodule systems are listed below.

<u>Crab Cavities Review Goals</u>

1) Review - for completeness - the CC Functional Specifications and assess the compliance of the various developed prototypes to the specifications.
2) Review the status of the three cavities including VTS test results.
3) Review implemented solutions for CC peripherals such as choices of materials for the He vessel, fast and slow tuning systems, power coupler, HOM couplers, etc. Review

the status of the design of these cavity components. Assess these solutions and identify their risk in comparison to other systems presently in operations elsewhere in the world capable of providing useful information.

4) Where solutions are still under development, assess the plans and likelihood of convergence on the timescales delineated above.
5) Assess the proponents' understanding of different operating conditions between the SPS test and the LHC application in view of beam loading, dynamic quench development, etc. highlighting the relevance of the SPS results toward the LHC application.
6) If available, endorse or criticize appropriately the CC frozen design of April 2014.
7) Provide appropriate criticism and feedback to the down-selection criteria developed by the CC proponents and presented at this review.

Cryomodule Review Goals

1) Review - for completeness - the CM Functional Specifications.
2) Review the CM design options.
3) Review possible limitations of the CM design caused by environmental constraints of the SPS tunnel.
4) Assess the feasibility for the development of a "Common Cryomodule" for the 3 types of cavities. Assess the solutions presented and identify their risk in comparison to other systems presently in operations elsewhere in the world capable of providing useful information.
5) Where solutions are still under development, assess the plans and likelihood of convergence on the timescales delineated above in view also of available resources.
6) Comment on the proposed timescale for assembled cryomodules by 2016. Based on historical experience of similar system, identify weaknesses – if any – in the proposed CM development plans.
7) Review the general plans and criteria for cryomodule development past the SPS application and into the HL-LHC period (post-2024) highlighting, when possible, simple and effective solutions for interfacing between the CC Cryomodule and the LHC cryogenic system.

3. Review Committee Members

The review committee has the following membership:

M. Champion (ORNL/SNS)
A. Facco (INFN-LNL/MSU)
M. Kelly (ANL)
H. Padamsee (Cornell Univ. /Fermilab)
C. Pagani (INFN-LASA/Univ. Milano)
A. Yamamoto (Chair, KEK/CERN)

4. Findings/Observations

4.1. Findings on crab cavities design and development

1) RF-dipole (RFD) design proposed by ODU

- The RFD design is highly optimized in terms of electromagnetic design. Field distributions including higher order modes have been studied in detail. The cavity is the result of the evolution of many different rf models thoroughly studied in a university environment. Most important aspects of beam dynamics have been analyzed.

- The cavity is longer than the others, but nonetheless fits the proposed slot length and has the lowest peak fields E_p and B_p. Sensitivity to He pressure (df/dP) and Lorentz Force Detuning (LFD) is relatively high and frequency excursions are expected to be larger than the loaded cavity RF bandwidth foreseen in operation.

- There are no lower order modes (LOMs), but several HOMs require heavy damping using 2 couplers, including, possibly, both a coaxial and a waveguide type. HOM coupler configurations are yet to be fabricated or tested. HOM coupler issues were clearly presented, but their practical implementation may require development that is not consistent with the present schedule.

- A reasonable tuner was proposed.

- Surface treatment, including BCP and possible preliminary EP, seems to be under control.

- A prototype tested (naked) largely above the required 3.4 MV deflecting voltage.

- The system is promising with respect to performance requirements, but schedule risk seems high.

2) 4-Rod design proposed by LU

- The 4-Rod design is very innovative although its operation principles have not been presented with sufficient detail. Its shape is more complicated and harder to obtain than the RFD one, and its peak magnetic field appears to be the highest among the three proposed designs. The EM field components, including the unwanted ones, have not been explained with the same precision as in the RFD. The cavity includes LOM and HOM, and the proposed damping techniques are still in an early stage.

- A proof-of-principle (PoP) cavity was built by machining an ingot and only the outer conductor was obtained from forged material. The complex construction procedure might cause difficulties (unwanted welding) and unsolved leak problems like those that prevented reaching a satisfactory vacuum level. Cold testing was performed, but the preliminary results could not reach design value reliably. It is considered that the gradient was limited because of a weld that will not be used in the final design. The tuning requires deformation of the rod shape on one side and the beam dynamics consequences are not clear.

- The helium vessel design was presented. Although well advanced it seems complex and lacking maturity at the present stage.

- The 4-rod cavity appears to be the most complicated of the three, the least performing one and the most risky one.

3) Double Quarter Wave (DQW) design proposed by BNL

- The DQW design is the simplest of the three, the most symmetric, and the easiest to build. Its EM properties are good and fitting requirements, although E_p and B_p are above the RFD ones. The field distributions have not been presented with many details.

- The cavity symmetry promises the lowest number of unwanted EM components and the lowest density of HOMs. No LOM is present. Two HOMs with high impedance require heavy damping (true for the other cavities as well). Mechanical properties are rather good concerning mechanical modes (the lowest mode is above 150 Hz). df/dP and LFD are relatively high but within reasonable values (LFD comparable with RF bandwidth foreseen in operation) and will be partially mitigated by the proposed externalsupport frame.

- The latest prototype testing was good and exceeding the field specifications with sufficient margin.

- The helium vessel design is rather advanced. However, it appears somewhat complicated and can probably be simplified through further design efforts.

- Suitable HOM couplers have been studied and presented in detail. Their practical development appears challenging, as much as observed for the RFD and 4-rods cavities.

- The double QWR design appears at present the most advanced one and the less risky. However, it still requires time especially for the HOM couplers development and implementation.

4) General findings

As a reference, three designs are compared in Table 1.

Table 1 : Parameters of the three crab cavity designs.

Property	**Spec Value**	**RF-Dipole**	**4-Rod**	**DQWR**
Proposed by		**ODU**	**LU/STFC**	**BNL**
Features		**Simple, and EM design best optimized**	**Best Stiff/rigid**	**Simple and best compact,**
E-p (@ 3.4 MV)	smallest	32.6	32.7	41 (prototype)
H-p (@3.4 MV)	smallest	56	77	71
R/Q	highest	427	580	430
# HOMs coupler	As few as poss.	2	4 (incl. LOM)	3
HOM QL	102 - 103	$<10^3$	$<10^3$	$<10^3$
HOM couplers		Integrated in cavity	Integrated in cavity	Detachable
LFD (@3.5 MV)		1.6 kHz	0.4 KHz	0.8 kHz
MP	None or weak	Weak	Weak	Weak
Complexity	As low as possible	Medium	High (4 rods)	Medium

V. test reached	3.4 – 5.1 MV	7	3 ~ 3.5	4.3
Q (test)	> $8x10^9$	$8x10^9$	10^9	$4x10^9$
Test problems	None	None	Leak	Quench at HOM flange
MP	None or weak	Weak	Weak	Weak
Complexity	As low as possible	Medium	High (4 rods)	Medium
Issues		HOM coupler	LOM HOM coupler	HOM coupler
Note			Crab mode is not the fundamental mode	

- We don't see any show stoppers in each cavity design and construction. However, significant development effort will be needed to produce, on time, a realistic CC integrated system including HOM couplers.

- All proof-of-principle cavities have led to design improvements for the prototype cavities of the next stage.

- It would be useful to calculate FE trajectories for emitters in high E field regions. If FE electrons impact the HOM or FPC coupling loops, it could lead to excessive heating as found at SNS.

- HOM damping has an important impact on the beam quality (transverse emittance growth) and possibly on cavity performance. Realistic HOM damper design and the prototypes must have very high priority since it is difficult to estimate the amount of time needed to produce reliable hardware. HOM Simulation needs to have a high level of reliability, e.g. by benchmarking them with different codes.

- The cavity helium vessel and tuner need additional engineering design work and prototyping.

- Three independent design works are not plausible in the foreseen time schedule.

- Management needs to establish a prioritized design and a secondary prioritized design to keep a redundant and reliable backup.

- The resources freed by the choice of 2 out of 3 cavity types could be profitably used in the cryomodule and HOM dampers development.

- The RFD cavity should be developed preferably with the waveguide HOM coupler to guarantee an alternative approach to the coaxial HOM dampers developed in the DQW cavity.

- Many of the ranking criteria in the proposed evaluation document should be rather considered as acceptance criteria or as good construction rules.

- There is a substantial risk with having only a single manufacturer in the future.

4.2. Cryomodules design and engineering

- CM design for SPS should be as similar as possible to the final (engineering) design for the LHC for efficient and constructive work for future. A single cavity type should be chosen for the final implementation for LHC, minimizing the design variations for best reliable engineering.

- Remaining technical issues with respect to cryomodule design are not major or fundamental. It does, however, seem improbable that there is enough time or resources to prepare more than one cryomodule for testing before 2018.

- The most important technical question directly related to cryomodule design is how to handle the need for crab cavities working in both transverse planes.

- More detailed work on overall cavity alignment scheme and tolerances should be completed in time for the helium vessel fabrication.

- The technical approach for hanging the cold mass off the couplers is not convenient for all cases.

- Cooling with liquid nitrogen instead helium gas will require some moderate redesign to go from SPS to LHC.

- The Daresbury carbon steel vessel used to shield from the external magnetic fields is a typical technical approach.

- Alignment issues include:
  - niobium structure fabrication tolerances and how to measure them,
  - deformations of the niobium during fabrication/installation of the helium vessel,
  - translation of cavity beam axis to fiducials,
  - monitoring or measurement of cold cavity fiducial positions from outside the module,
  - alignment of the module.

4.3. Technical requirements and Specifications

- The technical requirements were basically well defined; however, the existing specification document needs to be updated, as well as the technical requirements presented in the review. It should be prioritized, in order to start the fabrication of prototype cavities and to progress the cryomodule engineering work.

4.4. Project Management

- We encourage strong and systematic project management to establish a clear and reliable plan for the SPS CC tests to be realized.

- An additional comment for future scope: the HiLumi-LHC/LARP Collaboration should consider engaging additional manufacturers to minimize supply-chain risks.

5. Recommendations

Based on the two days review work, the external review committee comes to the following conclusions as given in the executive summary.

- We suggest that two cavity designs be selected for the beam tests at SPS. These cavities should incorporate complementary different HOM coupler configurations , as were presented for:
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Appendix – CC ReviewAgenda (held at BNL, May 5 – 6, 2014)

May 5		
Start	**Title**	**Speaker**
8:30	Committee Closed Session	Chair (Akira Yamamoto)
9:00	HL-LHC Overview and CC relevance	Lucio Rossi / Oliver Bruning
9:15	CC Program Overview including LARP-UK Contribution	Rama Calaga / Erk Jensen
10:00	Break	
10:20	RFD Design and PoP test results	Subashini de Silva / Jean Delayen
11:20	RFD SPS Prototype design	HyeKyoung Park / Rocio Olave
12:00	Lunch	
13:30	4-Rod Design and PoP test results	Graeme Burt / Ben Hall
14:30	4-Rod SPS Prototype design	Tom Jones
15:00	Break	
15:20	DQW Design and PoP test results	Qiong Wu / Binping Xiao
15:50	DQW SPS Prototype design	Silvia Verdu Andrews
16:20	Cavity Specifications, Fabrication Req. & Interface to CERN	Ofelia Capatina
16:50	Fabrication Aspects & Interface to CERN	Terry Grimm
17:20	Committee Closed Session	
19:00	***Dinner*** : ***many thanks for warmest hospitality!***	

May 6		
Start	**Title**	**Speaker**
8:30	Committee Closed Session	Chair (Akira Yamamoto)
9:00	SPS Tests Overview, Goals & Planning	Alick Macpherson
9:30	Beam Physics Requirements for CC (Impedance, HOMsm	Benoit Salvant
10:00	RF Operational Aspects in SPS & SM18	Philippe Baudrenghien
10:30	Break	
10:45	Cryomodule Technical Approach	Shrikant Pattalwar
11:15	Cryogenics Constraints & Solutions	Krzysztof Brodzinski
12:00	RF Power and Coupler Status	Eric Montesinos / Erk Jensen
12:30	Lunch	
14:00	DQW Integration in CM	John Skaritka
14:20	4-rod integration in CM	Tom Jones
14:40	RFD Integration in CM	HyeKyoung Park
15:00	Functional & Engineering Spec, Quality Control (Design to Fabrication)	Ofelia Capatina
15:30	Break	
16:00	Path to the LHC	Alex Ratti
16:20	Cavity Selection Criteria	Erk Jensen
16:50	Discussion, Q&A	Akira Yamamoto
17:30	Committee Closed Session	Akira Yamamoto