LHC CRAB CAVITY PROGRESS AND OUTLOOK *

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Abstract

Three novel superconducting RF crab cavity designs proposed for the LHC luminosity upgrade have rapidly progressed. First Niobium prototypes are reaching close to the design performance and beyond. The highlights of the RF test results from the prototypes along with design modifications for initial beam tests in the SPS are presented. The status of the cryomodule development, integration into the SPS and the beam tests in view of validating the crab cavity system for LHC upgrade are addressed.

INTRODUCTION

Since the 2010 restart, the LHC was operated with proton-proton collisons at 3.5 TeV and later increased the beam energy to 4 TeV in 2012. During a period of approximately 3 years, the LHC accumulated in excess of 30 fb^{-1} at the two high luminosity experiments (ATLAS and CMS) which lead to the discovery of the Higgs boson (courtesy LHC-OP). Fig. 1 shows the evolution of the delivered integrated luminosity to each of the four experiments during 2011 and 2012.

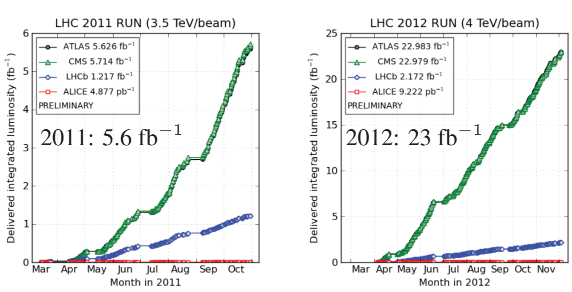

Figure 1: Integrated luminosity delivered to each of the four experiments in the LHC in 2011 (left) and 2012 (right), (courtesy LHC-OP).

The LHC is presently under a long shutdown (LS1) for approximately 18 months or longer to primarily repair the splices between the superconducting magnets and other maintaince required to push the LHC to its nominal beam energy of 7 TeV. Soon after LS1, the LHC is expected to deliver an integrated luminosity of approximately 60 fb^{-1}/yr and therefore tripling its performance from 2012. This will allow the physicists to precisely understand the characteristics of the Higgs boson and possibly other new physics.

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LHC CRAB CAVITIES & SPS TESTS

To extend the lifetime and physics reach of the LHC into the next decade, a luminosity upgrade (HL-LHC) is planeed for 2022-23 which aims to increase the integrated luminosity by ten-fold to 250-300 fb^{-1}/yr. This requires a complete revision of the LHC interaction regions and upgrade a total of 1.2 km of the LHC ring with large aperture high field magnets and an improved matching section (see Fig 2).

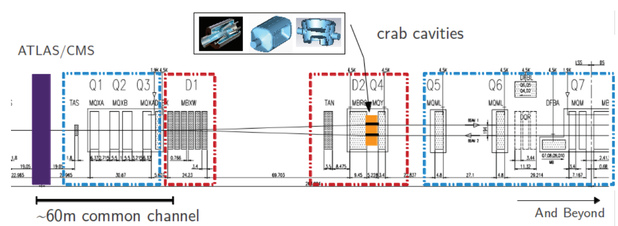

Figure 2: Schematic of the LHC interaction region and the respective magnetic elements to be upgraded with the inclusion og crab cavities for HL-LHC.

Due to the long common focusing channel between the two beams with a collision spacing of only 3.75m, a large crossing angle is required to avoid parasitic collisions [1]. The inclusion of crab cavities to compensate the crossing angle dramatically increases the luminosity reach and offers a mechanism to control the luminosity to maximize detector efficiency [2]. Some relevant parameters for the LHC design and upgrade are listed in Table 1.

Table 1: Some relevant parameters for the LHC nominal and upgrade lattices.

	Unit	Nominal	Upgrade
Energy	[TeV]	3.5-7	7
p/bunch	[10^{11}]	1.15	1.7-2.0
Bunch Spacing	[ns]	50-25	25
ϵ_n (x,y)	[μm]	2.5	2.5-3.75
σ_z (rms)	[cm]	7.55	7.55
IP$_{1,5}$ β^*	[cm]	55-100	15
Betatron Tunes	-	{64.31, 59.32}	
X-Angle: $2\phi_c$	[μrad]	250-300	590
Piwinski Angle	$\frac{\sigma_z}{\sigma^*}\phi_c$	$\leq$0.7	$\geq$3.1
Main/Crab RF	[MHz]	400	
Peak luminosity	[10^{34} $cm^{-2}s^{-1}$]	1.0	8.4

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Crab Cavity Layout

The large crossing angle and the high beam energy require an integrated transverse voltage of 10-12 MV. Such high voltages in a limited space of 10m and an almost zero beam loading operation are ideally suited for superconducting cavities. In the present layout, three crab cavities are to be placed between the D2 separation dipole and the Q4 quadrupole which is the closest position from the interaction point (IP) where both beams are completely separated into their respective beam chambers. Fig. 3 shows the concieved layout on each side of the IP for the two beams. A staggered configuration for the cavities is chosen to equalize the cavity voltages due to the rapid change of β-functions from left to right.

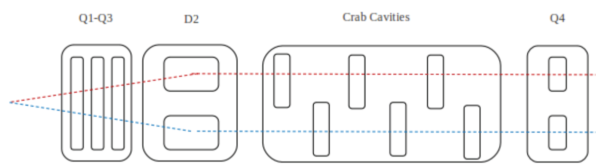

Figure 3: Schematic of the crab cavity layout on each side of the IP (not to scale).

Very compact transverse size at 400 MHz are required to fit within LHC footprint while accomodating the long proton bunches. Three candidates fulfilling such criteria were proposed and are presently under development (see Fig. 4). Conventional elliptical cavities at this frequency is atleast a factor of 4 larger than the available transverse separation between the beam chambers and would therefore be incompatible. In addition, proposed compact cavity designs show superior RF properties compared to their elliptical counterparts [3–5].

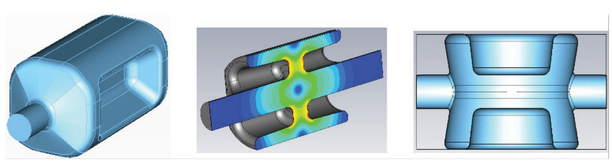

Figure 4: Three potential compact cavities under study for the HL-LHC upgrade [3–5].

SPS Beam Tests

Beam tests with one or more of the compact crab cavities with hadron beams is considered as pre-requisite to identify potential risks and to ensure the safety of the LHC. This includes the verification of crabbing and stable operation in a proton machine with no severe operational constraints. The primary issue of machine protection during cavity failures and cavity transparency should be demonstrated prior to an installation of a complete system in the LHC.

Therefore, a two-cavity test module for beam tests in the SPS is identified as an ideal test bench. The availability of a bypass (see Fig. 5) in the SPS BA4 region allows for crab cavity installation which can be moved in and out of the main beam line with mechanical movers. Due to diverse beams accelerated in the SPS, the bypass allows for the minimum perturbation of the SPS during regular operation. Aperture restrictions also exclude the use of crab cavities in the SPS ring during regular operation [6].

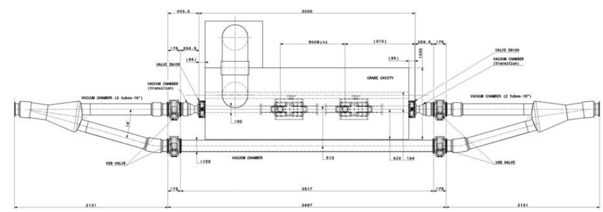

Figure 5: The SPS-BA4 region with a horizontal bypass which is the planned location for a crab cavity test module.

CAVITY & CROMODULE STATUS

All three compact cavity designs have been successfully designed and fabricated in bulk Niobium at Niowave Inc. The RF dipole and the double quarter-wave cavities were formed from Niobium sheets with the minimum number of welds at low field regions. Due to the complex inserts of the UK-4rod cavity, they were machined from a single Niobium ingot [7]. Each cavity was treated with the standard recipe of a buffer chemical polishing (BCP) to remove approximately 150 μm, a UHV bake at approximately 600 °C for more than 10 hrs followed by a light BCP of 10-20 μm and a high pressure water rinse prior to RF testing. It should be noted that the treatments were performed at different facilities for different parts and are not equivalent.

First Test Results

The three cavities were tested during 2012-13 at CERN, Jlab and BNL with varying results. All three cavities encountered some low field multipacting which was easily processed. The RF dipole reached a maximum deflecting voltage of 7 MV (more than factor 2 of the specification) before reaching a quench limit with a Q_0 corresponding to about 35 nΩ at low field. The Q_0 is only a factor of 3.5 lower than the specification is suspected to come from an acid contamination [8]. The double quarter wave reached a deflecting voltage of 1.34 MV in pulsed mode with Q_0 less by a factor of 30 than the specification [9]. In CW mode, the Q_0 degraded rapidly with increase in cavity temperature. The limited performance is suspected to occur from a local defect or a foreign material due to observation of localized heating. Detailed results of these cavities are presented elsewhere [8, 9].

The 4rod cavity underwent the bulk BCP at Niowave with the rest of the surface treatment and its first test at CERN [10]. Due to insufficient time, the cavity was tested without a light BCP during its first test. A vacuum leak was observed which was later identified to be due to improper seal between the NbTi flanges. After repair, the cavity underwent a light chemistry for approximately 20 min at a flow rate of 20 L/min to remove approximately 10-20 μm [11] prior to the second RF test. Despite the repair to all NbTi flanges and a new vacuum system insert to relieve any residual stress on the cavity during cooldown, a small but measurable vacuum leak ($10^{-8} - 10^{-7}$ mbar) was observed when the cavity was in the neighborhood of 4.5K and below. The leak was amplified by atleast an order of magnitude or more during the transition to superfluid Helium. Details on the measurements are given in Ref. [12]. Fig. 6 shows the Q vs. V_T curve for measurements performed at 4.5K down to 1.8K. The cavity performed approximately a factor of 2 better in both Q_0 and maximum V_T compared to the first tests in 2012.

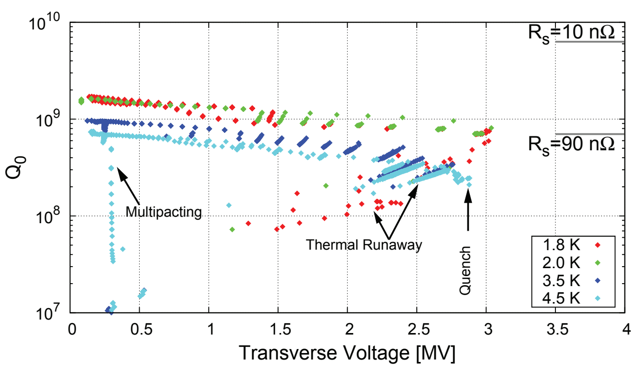

Figure 6: Second test results after light chemistry from 4.5K down to 1.8K (Courtesy BE-RF).

During cooldown from 4.5K to 2K, measurements of the Q_0 were taken at a fixed $V_T = 0.12$ MV. Fig. 7 shows the measurements fitted to the BCS curve which yields a residual resistance of approximately 45 nΩ.

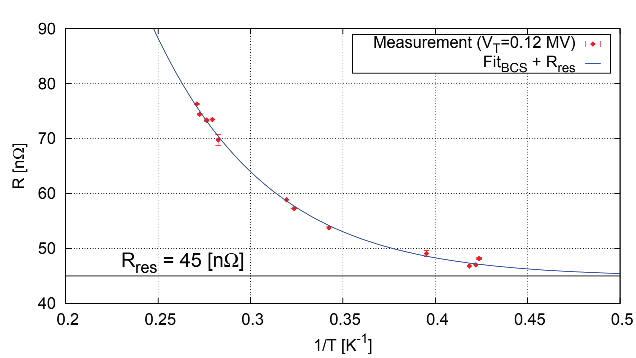

Figure 7: R$_s$ vs. temperature at a fixed $V_T = 0.12$ MV (Courtesy BE-RF).

Dressed Cavity and Tuner Assembly

The design details of the fundamental and HOM couplers are described elsewhere [4,7–9]. It suffices to say that the 4rod and the double quarter-wave cavities use adapted coaxial couplers while the RF dipole employs waveguides. Significant progress was made in the recent months to realize the Helium jacket and tuner assembly. Due to the very small spacing between the two beam pipes in the LHC, the adjacent pipe is included inside the Helium vessel. Fig. 8 shows the conceptual designs of the Helium jacket and the respective tuner assemblies for the three cavities. The 4rod cavity uses an adapted Saclay tuner with a longitudinal motion while the RF dipole uses an adapted Jlab scissor jack mechanism to do the same. The quarter-wave cavity proposes a novel design of the Helium jacket which also acts as a stiffening mechanism with controlled tuning assembly conforming to its topology. It is expected that these designs are finalized in the near future for fabrication of the test module(s) for SPS beam tests.

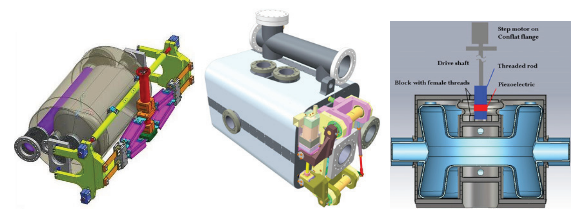

Figure 8: Dressed cavity concepts with their tuning assemblies [13].

Cryomodule Concepts & Cryogenics

Two cryomodule concepts were put forth for the SPS two-cavity test module [14] as shown in Fig. 9. A initial top loading design is now superseded by a side loaded structure with increased access and ease of assembly. A detailed 3D integration of the cryomodule concept into the SPS machine with their repsective elements is underway to identify any non-conformoties. These concepts are now being adapted to the RF dipole and double quarter-wave to maximize the cross compability of the external elements and environment in the SPS ring. The two cavities will be operated in the SPS at 2K saturated Helium. A secondary 80 K circuit will act as a thermal screen and provide the necessary intercept for the power coupler and cold to warm transitions [15].

RF System

The RF system envisioned for the two-cavity SPS test module is described briefly. The LHC system will be a natural extension with a more complex RF control system to precisely control the amplitude and phase of the 6-8 crab cavities across the interaction region [16].

Ideally, the crab cavity operation is with zero beam-loading. Therefore, it is sufficient to provide RF power to

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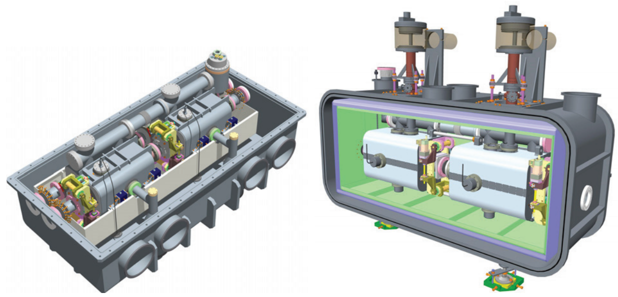

Figure 9: A top loaded and side loaded concept for the two-cavity SPS test module [14].

compensate for the cavity losses and have sufficient overhead to account for stable operation under external forces. This leads to a RF power of less than 80 kW with atleast a factor 2 margin for the LHC. For the SPS tests two independent 40 kW Tetrode amplifiers recuperated from the LEP oepration are planned to power the test cryomodule. A coaxial power coupler with a standardized interface to each cavity and with a common cryomodule interface as shown in Fig. 10 is implemented.

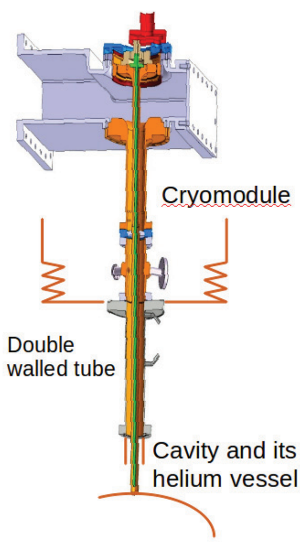

Figure 10: Standardized power coupler assembly with a single co-axial disk ceramic.

CONCLUSION

The realization of the first prototypes and promising RF test results puts the crab cavity project into an engineering phase. Design concepts for the various elements constituting the cryomodule have advanced to the fabrication phase for a two-cavity test module. Integration of such a module into the SPS beam line is underway to precisely define the interfaces to the various subsystems. The present planning anticipates one of more cavities to be tested in the SPS in 2016-17. Upon successful testing of the test module(s) in the SPS, a design and constrcution phase for the LHC crab cavity system will be launched.

Parallel beam dyanmics studies to address the field quality issues, machine protection, radiation dose to the cavities from collision debris and other relevant issues are ongoing but are not addressed here.

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