FUNCTIONAL SPECIFICATION

DRESSED RFD CAVITIES

Abstract

This document specifies the functional requirements for the Dressed Radio Frequency Dipole (RFD) crab cavity readapted for the American contribution. If all the requirements specified in this document are met, then the U.S. HL-LHC AUP Dressed RFD cavities deliverables will be accepted by CERN for the HL-LHC project.

Please note that the definition of threshold as it is being used by the American contribution is not the same as objective, according to the HL-LHC quality policy.

TRACEABILITY

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Approved by: R. Calaga, P. Collier, E. Jensen, L. Rossi	***Date:*** DD/06/2017
Distribution: US LARP	
Ref. Doc: LHC Crab Cavities Conceptual Specification (EDMS 1363172)	

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
0.5	02/06/2017	Version for verification

U.S. HL-LHC Accelerator Upgrade Project

DRESSED RFD CAVITIES FUNCTIONAL REQUIREMENTS SPECIFICATION

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Revision History

Revision	Date	Revision Description
Draft	4/18/2017	First Draft
Draft 2	5/23/2017	Second Draft after preliminary circulation in WP4

CONTENTS

1. PURPOSE

This document specifies the functional requirements for the Dressed Radio Frequency Dipole (RFD) crab cavity. If all the requirements specified in this document are verified, then the U.S. HL-LHC AUP Dressed RFD cavities deliverables should be fit for the intended use and satisfy CERN's needs for the HL-LHC upgrade. The quality of the US HL-LHC AUP RFD deliverables will be measured by the degree to which its characteristics fulfill the requirements specified in this document.

2. SCOPE

Each dressed cavity system is composed of the bare cavity, the cold magnetic shield, the helium tank, all HOM suppressors and the pickup field antenna as described in Figure 1. The material choices for the various components are described in Table 1.

A minimum of 8 of these cavities are to be fabricated, chemically processed, tested in a vertical stand and delivered to CERN by the U.S. HL-LHC AUP as part to the U.S. contributions to the HL-LHC. These cavities will provide a time varying deflecting field to perform a bunch rotation in the horizontal plane in the interaction region of the CMS experiment to impose a head-on collision to increase and level the luminosity, while maintaining the required beam separation to minimize parasitic collisions.

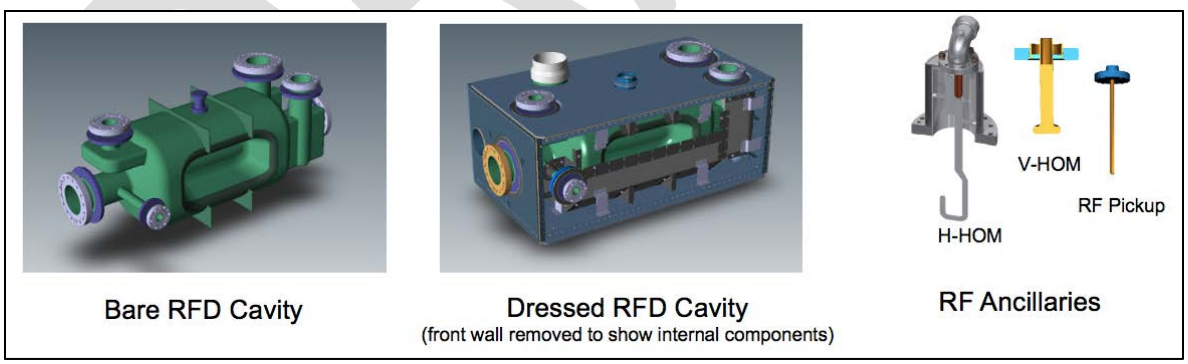

Figure 1 Left: conceptual view of the bare RFD Cavity (in green). Center: conceptual view of the dressed RFD Cavity with magnetic shields (in gray) and helium tank (in blue). Right: conceptual view of the set of RF ancillaries to be installed on the dressed cavity.

Table 1 : components (and materials) of the dressed RFD cavity system

Equipment	**Material**
Bare RFD Cavity	RRR Niobium, Niobium-Titanium, 316LN
Magnetic Shields	Cryophy
Liquid Helium Vessel	Titanium, 316LN
Vertical HOM filter	RRR Niobium, 316 LN
Horizontal HOM filter	OFE Copper, 316 LN
Input RF Loop (Low Power)	OFE Copper
Pick-up Antenna	OFE Copper
Vacuum Hardware	UHV & ISO4 Clean Room Compatible

3. INTRODUCTION

The two counter-rotating beams need to be separated transversely to avoid parasitic collisions in the LHC's interaction regions. Separation is accomplished by introducing a crossing angle at the interaction point, which implies an inefficient overlap of the colliding bunches.

For HL-LHC beam parameters, the reduction compared to the case of a head-on collision can be 70% or larger, depending on the final β^* value and the beam emittance. Therefore, the effective gain in luminosity by simply reducing the beam size at the collision point diminishes rapidly.

To recover the loss, the scheme adopted by HL-LHC uses RF deflectors (also known as crab cavities) on either side of the collision point to perform a rotation around the center of the bunch. The kick is transformed to a relative displacement of the head and the tail of the bunch to impose a head-on collision as shown schematically in Figure 2 .

Figure 2 Schematic of bunches colliding with a crossing angle at the interaction point. Without crabbing (left) and with crabbing (right).

For a full compensation, 4 cavities are required per IP side per beam at CMS (a total of 16 cavities). However, only half the system or 8 cavities, are to be installed. The option to install the second half is retained as a potential upgrade beyond Long Shutdown 3 (LS3). See Figure 3.

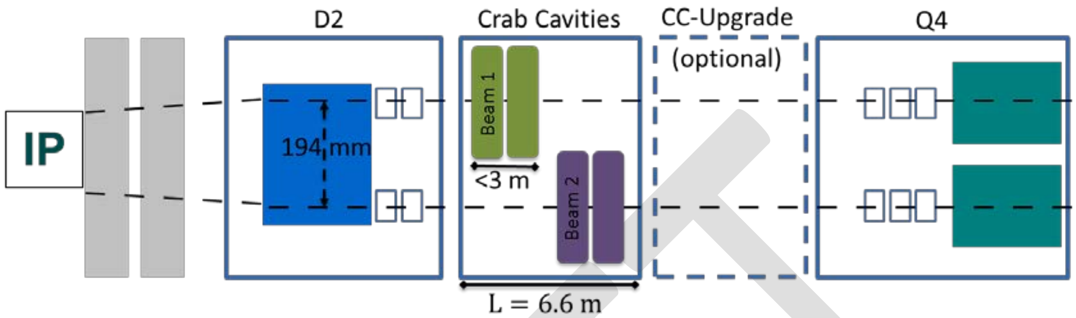

Figure 3 Schematic layout of the crab cavities (green and purple) near the interaction point. Only 2 cavities per beam per side of the IP are planned.

4. FUNCTIONAL REQUIREMENTS OVERVIEW

The RFD cavities need to satisfy a minimum list of requirements in terms of design and performance together with certain constraints on physical dimensions.

Although a strict distinction between functional and technical requirements is subjective, the intent is to relegate to the technical requirement specification document all aspects of the specific electromagnetic design, mechanical design, adherence to safety standards, construction materials, chemical processing and so on.

Each functional requirement will be verified through a quality control process such as a performance acceptance test. Detailed verification procedures and acceptance criteria will be defined in separate documents.

At CERN's discretion, deliverables that fall short of the threshold requirements may still be acceptable.

If all the requirements specified in this document are verified, then the US HL-LHC AUP RFD dressed cavity deliverables will be fit for the intended use and satisfy CERN's needs for the HL-LHC upgrade.

Table 2 : Threshold Requirements for the RFD Dressed Crab Cavity

RF and Performance Requirements	
F (Resonant Frequency at 2 K)	400.790 ± 0.15 MHz
V_T (Deflecting Voltage)*	≥ 4.1 MV
P_{dyn} (Dynamic Heat Load at 2 K and 4.1 MV)	≤ 10 W
Q_0 (Quality Factor at 2 K and 3.4 MV)**	$\geq 3.9\ 10^9$
LFD (Lorentz Force Detuning Coefficient)	$\leq 865\ Hz/MV^2$
dF/dp (Sensitivity to L_{He} pressure fluctuations)	≤ 150 Hz/mbar
Pole Symmetry (Electrical Center deviation)	≤ 0.7 mm
HOM Couplers Output Power (at 400.79 ± 0.1 MHz)	≤ 1.5 W
Physical Requirements	
Beam Aperture	84 ± 3 mm
Maximum Envelope	R ≤ 145 mm
Fundamental Power Coupler Port	D = 62 ± 0.5 mm
Maximum deviation of interfaces	± 0.5 mm
Cryogenic and Safety Requirements	
Maximum Working Pressure	≥ 1.8 bar

*nominal (operating) voltage is 3.4 MV

**calculated from P_{dyn} (with R/Q = 429.7 Ω)

5. RF AND PERFORMANCE REQUIREMENTS

All requirements on performance are intended for the cavity in the dressed state. Cavities in the bare state will be tested to obtain a reference on their performance with almost exclusive attention to deflecting voltage, field emission and dynamic loads. Certain operational parameters such as sensitivity to helium pressure fluctuations can only be assessed in the dressed state.

RESONANT FREQUENCY

The resonant frequency for the RFD cavity in operating conditions in the HL-LHC will be 400.790 MHz. The operating frequency of the crab cavity system was chosen as a compromise of several factors. On one side, machine space restrictions near the interaction region require cavities to have a limited transverse dimension favoring higher resonant frequencies. On the other, since the fundamental frequency of the main RF system in the LHC is 40 MHz, machine's bunches are relatively long and a high frequency could introduce distortions due to the curvature of the RF bucket at higher frequencies. A lower RF frequency also helps with the dynamic load on the cryogenic system.

The cavity is maintained on resonance during operation by means of an active tuning system. The tuning system is limited in range by the maximum force that the actuator can produce and also by the elastic limit for the cavity walls. Such range is expected to be > 200 kHz, therefore the tolerance for the nominal resonant frequency in operating conditions was set to be smaller to allow a margin for tuner operation, resulting in a requirement of **F = 400.790 MHz ± 150 kHz**.

The shifts induced by the later installation at CERN of the fundamental power coupler and integration inside the 2-cavity cryomodule are estimated to be < 5 kHz and are therefore negligible.

DEFLECTING VOLTAGE

In order to provide a safety margin for the operation of RFD cavities in the LHC, the threshold requirement for the deflecting voltage is set to $\mathbf{V_T \geq 4.1\ MV}$ which is 20% above the operating value of 3.4 MV. This threshold will ensure the absence of hard quenches or strong field emission at the operating field. Another reason is to provide a margin for potential degradation of performance during cavity string assembly or due to years of operation.

The requirement for a nominal deflecting voltage of $V_T \geq 3.4$ MV is driven by the need for an integrated deflecting kick of 11-12 MV at each side of the interaction point. The initial baseline consisted of 4 cavities in series which allows approximately 10-20% of margin above the actual required voltage (total $4 * 3.4$ MV = 13.6 MV).

Due to a recent re-baseline of HL-LHC the cavities are now only two 2 per IP side per beam in series with the nominal deflecting voltage unchanged (total $2 * 3.4$ MV = 6.8 MV).

DYNAMIC HEAT LOAD (ALSO RESIDUAL RESISTANCE AND QUALITY FACTOR)

The crab cavity cryomodule containing 2 identical cavities, is designed to withstand a total (static plus dynamic) heat load of 50 W to the 2 K bath. The static heat load is estimated to be 15 W per cavity, for a total of 30 W per cryomodule. The requirement for the dynamic load is therefore 20 W per cryomodule which corresponds to a requirement for each cavity of $\mathbf{P_{dyn} \leq 10\ W}$.

$P_{dyn} \leq ½ * (50\ W – (2 * 15\ W)) = 10\ W$

The dynamic heat load increases with the deflecting voltage, therefore in order to allow testing of a complete cryomodule up to the threshold requirement of 4.1 MV per cavity (20% above nominal), the requirement on the maximum dynamic heat load is set at the threshold deflecting voltage of 4.1 MV. This also gives some margin to the facility when operating at 3.4 MV.

For an RFD cavity having the geometry presented in the conceptual design report (US-HiLumi Document 164) and with geometrical parameters of R/Q = 429.7 Ω and G = 106.7 Ω, from the above requirement for P_{dyn} one can calculate the residual resistance and quality factor to be respectively $\mathbf{R_{res} \leq 27\ n\Omega}$ and $\mathbf{Q_0 = 3.9\ 10^9}$.

Lorentz Force Detuning

When the cavity is subject to RF fields, a Lorentz force appears on the cavity surfaces resulting from the high radiation pressure on the cavity walls. This results in local deformations and therefore a detuning of the cavity resonant frequency.

For continuous-wave operation such as envisioned for HL-LHC, there will be a static shift due to the nominal amplitude of the RF signal, and a dynamic shift due to the fluctuations of the RF signal. The static detuning should be less than 10 % of the assumed tuning range of ± 150 kHz on the dressed cavity. The requirement on the static detuning is set to be ≤ 10 kHz at 3.4 MV which corresponds to a Lorentz force detuning coefficient **LFD ≤ 865 Hz/MV^2**.

$LFD \leq 10^4\ Hz / (3.4\ MV)^2 = 865\ Hz/MV^2$

Dynamic detuning should be within the cavity bandwidth. With an expected voltage fluctuation of 10^{-4} or better, the dynamic detuning accounts for less than few hertz in nominal operation which is well below the cavity operating bandwidth of 800 Hz.

Sensitivity to Liquid Helium Pressure

The niobium bare cavity is immersed in liquid helium and subject to variations of the hydrostatic pressure acting on the cavity walls. Pressure variations cause shape variations that translate into shifts of the resonant frequency. In order to minimize the chances that such variations cause the cavity to drift outside its RF bandwidth, the electromagnetic design and the structural design are carried out to optimize the behavior of the cavity under such varying loads. With an expected variation of ± 1 mbar for the liquid helium pressure and a cavity bandwidth of 800 Hz, the RFD cavity must be designed with a sensitivity of df/dP << 800 Hz/mbar, considering that other perturbations will contribute to the overall budget of 800 Hz.

A threshold requirement of **df/dP < 150 Hz/mbar** was chosen for the design.

POLE SYMMETRY

A specification on pole symmetry was set considering the combined requirements for respecting the beam aperture, the RF multipoles, the inter-cavity alignment and the related beam loading aspects. The threshold requirement for pole symmetry is met for an RFD dressed cavity having a misalignment between the geometrical center and the electrical center of ≤ 0.7 mm.

HOM COUPLERS

Three criteria are outlined to describe the threshold requirement:

Each of these devices must not pass more than 1.5 W of fundamental power output within a bandwidth of 10 MHz relative to the nominal frequency. This bandwidth is specified to account for fabrication variations resulting in the notch frequency change.

From a mechanical perspective, all orientation and manufacturing errors should be within the tolerances defined in the specification drawing derived from HOM damping requirements. A simpler way to interpret this requirement in RF terms at 2K, is that the deviation of the main HOMs cannot exceed the design value by more than 10 %.

Lastly, the HOM filters need to be able to effectively pass through all HOMs. A practical way to specify this requirement is to measure the transmission curve in a frequency range of 0.4 - 2.0 GHz on a reference cavity (or on a test box): such curve should deviate by less than 3 dB when compared to the theoretical curve calculated from simulations.

Simulation results have been checked with the beam physics group and have been deemed acceptable.

6. PHYSICAL REQUIREMENTS

A short list of physical requirements for the RFD cavity was included in these functional requirements document. It is foreseen that the values are unlikely to change at this advanced point in the design of HL-LHC and constitute a non-negotiable envelope for the cavity due to the interfaces with components and systems provided by CERN.

The maximum envelope is limited by the presence of the second beam pipe containing the other beam traveling in the opposite direction, which cannot run through the cavity walls. It can run through the helium vessel walls, and it most likely will, due to the overall space constraints inside the cryomodule.

The RFD Cavity aperture requirement is set by the inner diameter of the beam opening at room temperature after all chemical processing and other necessary cavity preparation.

The maximum deviation for the interfaces is included in this document as a general tolerance requirement. The details of this requirement are specified in the technical drawing for the dressed RFD cavity (cfr. paragraph 8).

7. CRYOGENIC AND SAFETY REQUIREMENTS

The helium tank will contain superfluid helium at 2 K, cooling the cavity and allowing the extraction of the heat dissipated in the cavity and adjacent cold components.

The dressed RFD cavity must be capable of sustaining a sudden rise of liquid helium pressure up to 1.8 bar without failure at the cavity walls or at any other location.

The RFD cavity, the helium tank and all other components comprising the deliverables, will be designed, fabricated and documented in accordance with commonly agreed pressure safety and quality assurance plans between CERN and US HL-LHC AUP.

In general, available CERN guidelines such as the safety requirements (EDMS 1494776) and the Dressed Cavity Engineering specifications (EDMS 1389669) will be followed.

8. INTERFACE REQUIREMENTS

The Dressed RFD Cavities interface in the HL-LHC with the following systems:

1. The Crab Cavities Cryomodule System, including:
    i. The beam vacuum interface including cavity beam ports, Fundamental Power Coupler interface and the adjacent cold bore
    ii. The frequency tuner mechanical interface
    iii. The electrical and RF transmission line interface for the HOMs and pickups
    iv. The cavity support system and alignment system interfaces
2. The CERN supplied Cryogenic System interface, consisting of:
    i. The CERN supplied cooling system including Helium lines
    ii. The CERN supplied pressure relief system
3. The CERN supplied power system interface
4. The CERN supplied instrumentation system interfaces

Interfaces described above are defined in detail in the top-level assembly drawing jointly developed by CERN and HL-LHC AUP for the dressed RFD cavity.

A procurement readiness review will be carried out jointly between CERN and HL-LHC AUP prior to launching the construction of the series for the dressed RFD cavity to ensure the geometries of the deliverables including all interfaces are defined to the appropriate level of detail and with the necessary tolerances to meet CERN's ultimate needs for successful installation, commissioning and operation.

9. CERN PROVIDED PARTS

The installation of the fundamental power coupler, the string assembly of two RFD cavities, installation of tuners and the assembly into the cryomodule will happen after shipment of cavities from HL-LHC AUP and will be performed at CERN or collaborating institutions.

Therefore, it is not foreseen that any component, hardware or material will be needed from CERN to complete the fabrication, processing, qualification and shipment of the dressed RFD cavities in the U.S. by HL-LHC AUP.