HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Deliverable Report

RF System Conceptual Layout

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30 January 2014

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package **4: Crab cavities**.

Grant Agreement No: 284404

HILUMI LHC

FP7 High Luminosity Large Hadron Collider Design Study

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures,
Collaborative Project, Design Study

DELIVERABLE REPORT

RF SYSTEM CONCEPTUAL LAYOUT

DELIVERABLE: D4.2

Document identifier:	HILUMILHC-D4.2
Due date of deliverable:	End of Month 24 (October 2013)
Report release date:	04/02/2014
Work package:	WP4: Crab Cavities
Lead beneficiary:	CERN
Document status:	Final

Abstract:

The conceptual RF system layout for a local crab crossing scheme for the HL-LHC upgrade is presented. The choice of powering system and the input coupler to drive 6 or 8 independent cavities per IP per beam with a central control system to precisely regulate the cavity voltages and phases is described. Some integration aspects leading to space requirements are briefly outlined.

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The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. HiLumi LHC began in November 2011 and will run for 4 years.

Delivery Slip

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TABLE OF CONTENTS

1. INTRODUCTION 4

2. CRAB CAVITY LAYOUT FOR HL-LHC 5

3. RF POWER 5

3.1. BEAM LOADING AND CHOICE OF LOADED Q 5
3.2. RF POWER COUPLER ASSEMBLY 6
3.3. RF POWER SYSTEM AND ANCILLARIES 8
3.4. PICKUP & HOM COUPLERS 9

4. LOW LEVEL RF SYSTEM 9

4.1. COUPLED BUNCH INSTABILITIES 10
4.2. RF NOISE 11
4.3. LLRF ARCHITECTURE 11
4.4. PHASE MODULATION ALONG THE BEAM 12
4.5. CAVITY TRANSPARENCY AND OPERATION 13

5. INTEGRATION INTO SPS & LHC 13

5.1. SPS-BA4 TEST SETUP 14
5.2. LHC INTEGRATION CONSTRAINTS 15

6. CONCLUSION 16

7. REFERENCES 17

ANNEX: GLOSSARY 17

Executive summary

The conceptual design of the crab cavity RF system for 6-8 cavities per IP for each beam in the LHC is described. The independent powering of the each cavity combined together with a central control system to synchronously tune the crossing angle at the interaction point during regular physics and regulate the set points of all cavities to mitigate cavity failures is presented.

1. INTRODUCTION

The nominal HL-LHC with crab crossing scheme requires at least 6 (maybe up to 8) independent cavities per IP for each beam to impart the necessary transverse kick to compensate the crossing angle at the interaction point and recuperate the luminosity. Due to potentially large orbit deviation in an event of a cavity failure, independent powering system for each cavity is vital. A fast control of the cavity fields is imperative to minimize the transverse emittance growth caused by TX noise and to reduce the cavity impedance at the fundamental frequency. For an efficient active feedback, a short overall loop delay between the RF system and the cavity is required [2]. In addition we must minimize the risk to the LHC during an abrupt failure of one of the cavities to ensure machine protection before the beams can be safely extracted. An additional central slow control system is used to synchronize the 6 to 8 cavities[1] across the IP during regular operation and in an event of a failure.

This document summarizes the concept envisioned and the RF system including the powering and the control of the crab cavities for HL-LHC. The nominal beam and lattice parameters for the HL-LHC are used to define the specifications where it is required.

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[1] At the moment of writing of this report the baseline number was 3 per IP per beam per side, but during the revision this baseline was changed to 4.

2. CRAB CAVITY LAYOUT FOR HL-LHC

Using the ATS optics for the HL-LHC [1], three to four cavities are placed between the D2 separation dipole and the Q4 quadrupole which is the closest position from the IP where both beams are completely separated into their respective beam chambers. Figure 1 shows the concieved layout of the three crab cavities in each side of the IP for the two beam. 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. An independent powering system for each cavity with a short transfer lines is adopted to minimize the overall loop delay for efficient control as detailed in the following sections.

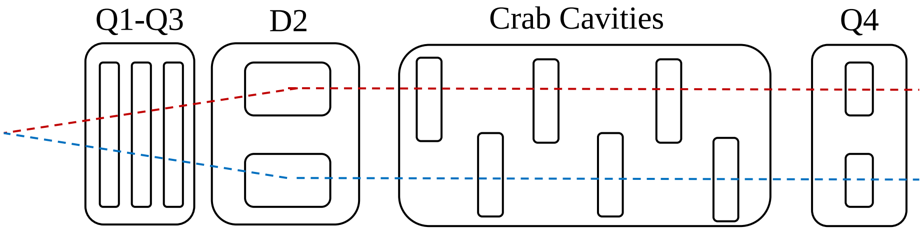

Figure 1 Schematic of the crab cavity layout on each side of the IP (not to scale).

3. RF POWER

An independent powering system using 40 kW Tetrodes at 400 MHz or an equivalent IOT is assumed. If necessary regarding power requirements, two tubes will be combined together. Advances in solid state technology in this decade could lead to power sources within the required range and provide an alternative platform. This range of power provides adequate overhead in a compact footprint ideally suited for the proposed crab cavity layout. This scheme also allows for a fast and independent control of the cavity set point voltage and phase to ensure accurate control of the closed orbit and the crossing angle in the multi-cavity scheme.

3.1. BEAM LOADING AND CHOICE OF LOADED Q

In deflecting cavities operated in the crabbing phase, the RF phase and the RF component of the beam current are in quadrature (0 degree stable phase, synchrotron convention). For a beam centred, there is no beam loading: the TX does not pass power to the beam. With a superconducting cavity (negligible loss) the needed power then decreases monotonically with

Q_L. The situation is different for a beam circulating at an offset x.

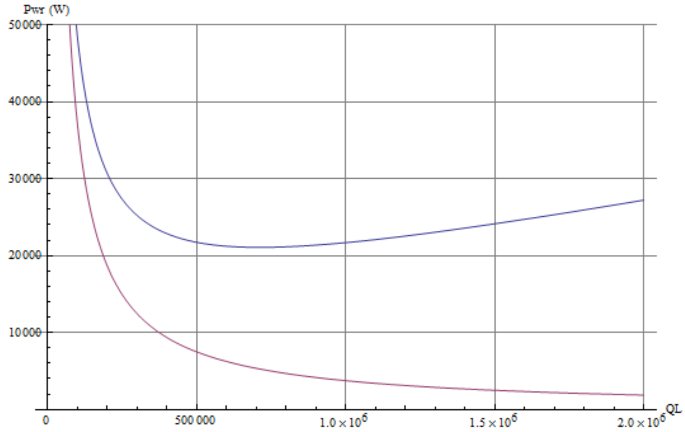

Figure 2: TX power vs. cavity Q_L *for centred (red) and 1mm offset (blue) beams.* $R/Q = 300\ \Omega$*, 3 MV RF, 1.1 A DC.*

For a 1 mm offset (tentative specification on the beam centring in the LHC crab cavities),

For a 1 mm offset (tentative specification on the beam centring in the LHC crab cavities), the power versus Q_L curve shows a broad minimum from about $3x10^5$ to $1.5x10^6$. The cavity field control system will adjust the TX drive to keep the deflecting kick unaffected by the beam displacement. But the required TX power must be available. Selection of an optimal value in the above ranges comes from a compromise: a large Q_L reduces the field fluctuations created by the TX noise. It is also favourable from a Machine Protection point of view, in the case of a TX trip: in such an instance, the cavity stored energy will flow out, through the waveguide and circulator, and will be dissipated into the circulator's load. The cavity field will decay to zero with a time constant $\tau = 2\, Q_L/\omega_0$. With a Q_L equal to 10^6, the time constant is 800 µs. Assuming three cavities with a total voltage of 3 MV, and a single TX trip, the field would drop from 3 MV to 2.7 MV in the three turns delay (267 µs) until the beam dump is fired. In the cas of a quench, the stored energy is dissipated in the cavity walls and the main coupling (Q_L) has no effect on the field evolution. Lessons will be learnt from the SPS tests.

On the other hand, a low Q_L is favourable for the tuning system as it relaxes the precision needed by a mechanical system. To minimize the power needed to compensate for fast frequency variations it is also desirable to keep the cavity bandwidth larger than the frequency of the mechanical modes leading to a low Q_L. Selection of the optimal Q_L for the LHC will be finalized from the SPS beam test experience. For the SPS beam tests, a Q_L of $3\text{-}5x10^5$ is a reasonable assumption.

3.2. RF POWER COUPLER ASSEMBLY

The crab cavity power coupler adopted will use a single coaxial disk window type to separate the cavity vacuum and the air side. The antenna shape is specific to each cavity as the coupling mechanisms to the different cavities are not identical. However, a common platform starting from the cavity flange followed by the ceramic and double wall tube is imposed. To respect the common platform, the inner antenna is dimensioned to 27 mm diameter with the outer coaxial line of 62 mm diameter. Cavity flange and Outer Line cavity side flange will be DN63 Stainless Steel 316LN, with their inner diameter of 62 mm.

The inner line is made of a copper tube and the outer line is Stainless Steel 316LN with inner coated with copper. The vacuum to air separation is achieved with a coaxial ceramic window (Al2O3) with the outer flange made of titanium. The rest of the items are built from massive OFE 3D forged copper blocks. The coupler body is made of a conical line to increase the near the ceramic region to limit arcing with the primary aim to enlarge the air side to the maximum while keeping the 62/27 mm dimensions for the input antenna in the vacuum side. A coaxial to waveguide transition is performed with a WR2300 half-height without a doorknob. This will be built in order to connect the coupler to the power amplifier line. It will be derived from the SPL coupler design. The air side of the coupler will be air cooled as the antenna itself will be water cooled. The waveguide design includes the possibility of a DC polarisation in order to avoid multipacting effects. Each coupler is equipped with three ports to equip it with a vacuum gauge, electron monitoring and arc detection devices. The vacuum gauge, mandatory to protect the window during conditioning as well as in operation, will be oriented along the air line in order to minimize the cryo-module flange size. Special test boxes to RF condition the couplers are also designed.

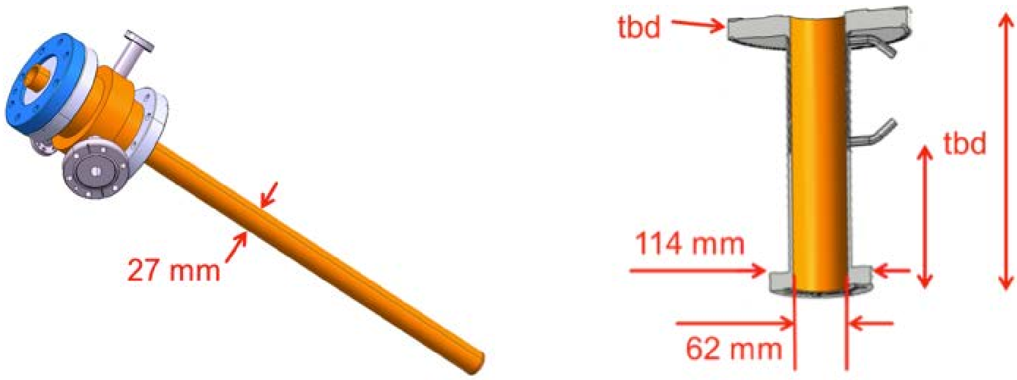

Figure 3 The RF coupler vacuum side with the inner antenna , c, coupler body and the double wall tube.

The Outer Line inside the cryo-module could be partially plain metal and partially a Double walled Tube (DT). Coupler ports will have to be perpendicular to beam pipe, and the location of the port is to be confirmed by each cavity design team, but it is preferred that the port be on the top of cavity. Further, the cavity vessel has to be designed to stand the weight of the couplers and the waveguide. Total weight of the window and the Outer Line will approximately be 15 kg. Total weight including waveguide system will be close to 35 kg. The alternating crossing angle scheme will require that the orientation for a coupler assembly be robust for horizontal and vertical deflections. A specific support on the cryo-module side will have to be designed.

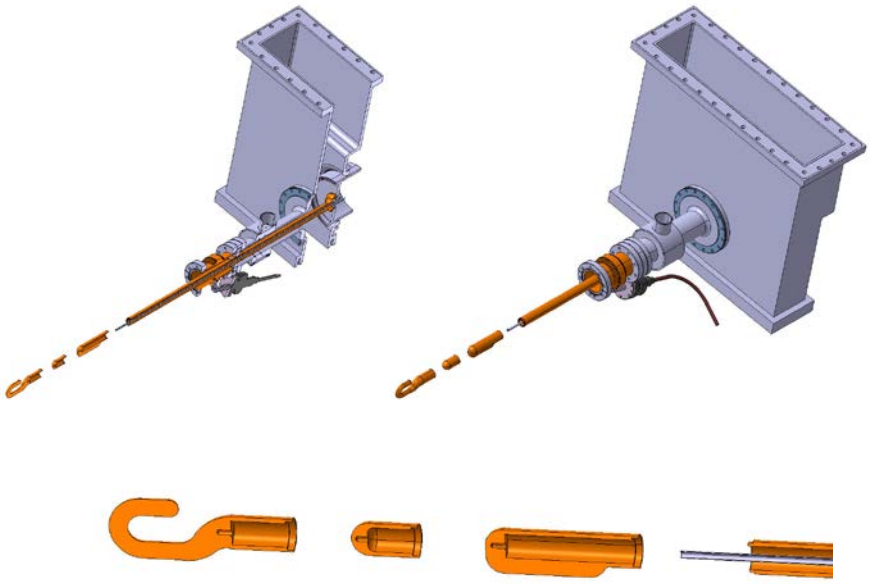

Figure 4 The fundamental power coupler; items (window assembly; Outer Line and Wave guide); three different end shapes to be adjusted to the antenna.

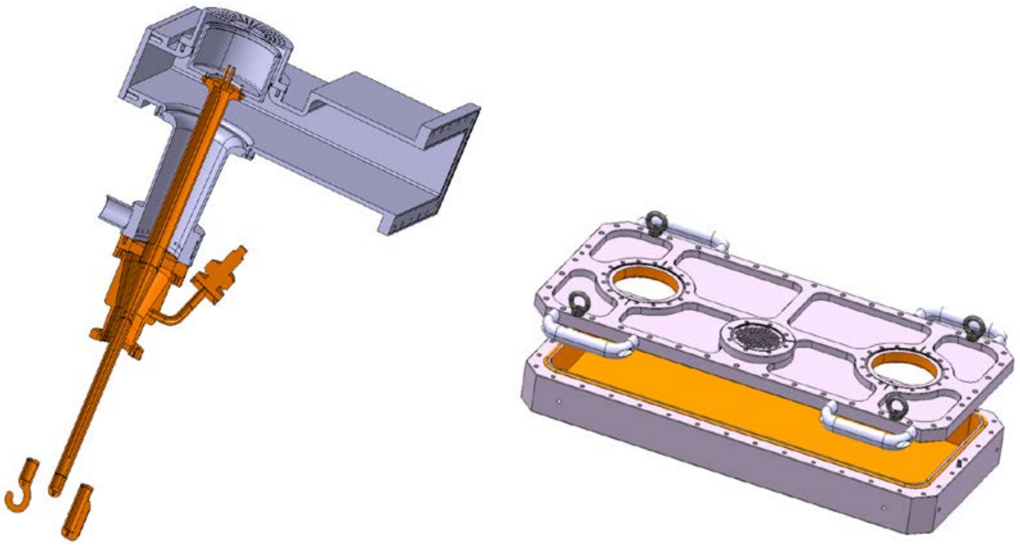

Figure 5 The entire coupler assembly (left) and the coupler test box.

3.3. RF POWER SYSTEM AND ANCILLARIES

For the SPS tests two independent 400 MHz, 40 to 80 kW RF power amplifiers will be prepared with a bandwidth of 1 MHz. During the SPS for LEP operation, four 352 MHz tetrode amplifiers were in service in the SPS. An additional one was later designed to operate at 400 MHz with a maximum output power of 40 kW. Regarding the requested power level for the crab cavities SPS test, up to seven amplifiers will be modified for 400 MHz operation. They could potentially reach 40 kW output, and tests will be performed beginning 2014 to verify their maximum output power, efficiency and stability.

A short distance between the cavity and Tetrode amplifiers with a very short waveguide as shown in Figure 5 is compact and the preferred solution. A circulator will protect the amplifier from reflected power. It will be in between the cavity and the amplifier.

A 2.5 kW solid state driver and high voltage power supplies along with other peripherals may reside either in the SPS ECX4 cavern or BA4 surface building and therefore shielded from radiation. Limitations from the round turn loop delay for cavity control should be taken into account for the fast feedback, which will be necessary in the LHC to reduce the cavity impedance and the effect of TX RF noise.

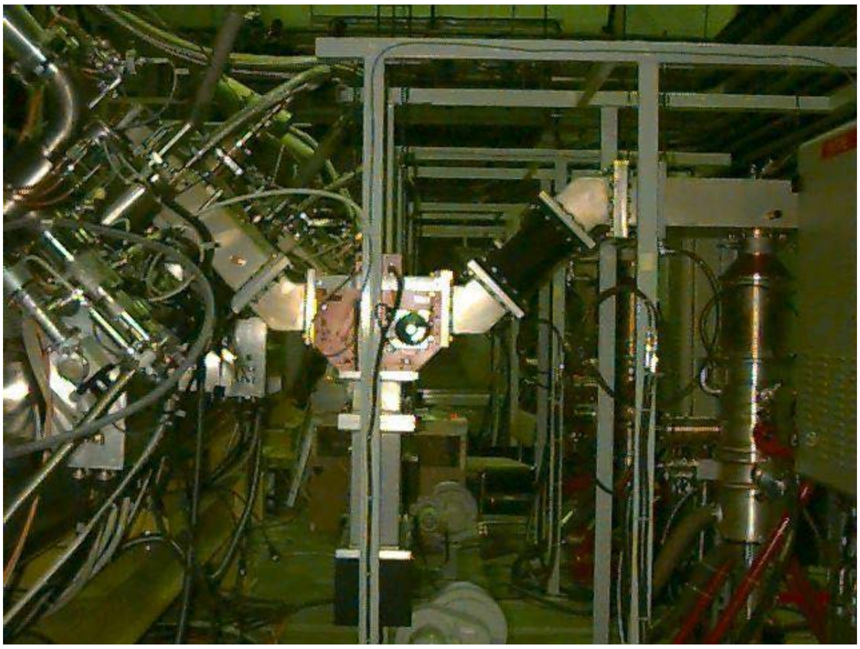

Figure 6: LHC main RF module test layout in the SPS circa 1996.

For a later LHC installation a short distance between the crab cavity and the amplifier chain is desired if not necessary to allow fast feedback loops. The LHC tunnel size however makes this extremely difficult. Present studies concentrate on a) the possibility to use the RR caverns – about 150 m away from the CC locations or b) the possibility to have new, dedicated parallel tunnels to locate the amplifiers optimally close.

3.4. PICKUP & HOM COUPLERS

A minimum of one pickup probe for each cavity is required with an appropriate coupling to fundamental deflecting mode of the cavity resulting in approximately 1W of output power at the cryostat. The number of HOM couplers is cavity specific to meet the impedance budget for a total of 12 cavities per beam (see impedance budget). A small amount of HOM output power (few watts) should be available for measurements for each coupler which will be used for impedance analysis during the SPS beam tests and potential safety interlocks in the final LHC.

4. LOW LEVEL RF SYSTEM

The RF control system, also commonly referred as the low level RF system (LLRF) includes several functionalities. First, a tuning control is required to keep the cavity resonant frequency on-tune with the beam during the crabbing operation. In addition the LLRF also has to ensure that the cavity is safely parked at an optimal detuned position during filling, ramping and collisions without crabbing. Given the non-integer betatron tune around 0.3 in the LHC, the proposed parking position is 0.15 Frev (1.6 kHz) away from the RF frequency.

A cavity field control keeps the deflecting field at the exact demanded value. This system must allow for synchronized variations in several cavities including field ramping, counter-phasing between cavities and other configurations as required during operation. It must compensate for the beam loading if the beam is not perfectly centred. The LLRF must guarantee the longitudinal stability (coupled-bunch oscillations) with the high beam current by effectively reducing the impedance of the cavity at the fundamental resonance [3]. The system must also reduce the noise in the cavity field (caused by transmitter noise, fluctuations in cryogenic pressure, mechanical vibrations and electronics) to minimize transverse emittance growth. Field control must be achieved during collisions with crabbing, but also during filling and ramping with a zero crabbing field (“transparent” cavities). Smooth transition between no-crabbing and crabbing must be realized.

This system also synchronizes the phase of the RF kicks with the passage of the bunches for both beams. For each ring, the eight accelerating LHC cavities are driven from a single reference generated in a surface building above IP4 [3]. These two signals must be sent over phase-compensated links to IP1 (ATLAS) and IP5 (CMS). In addition, we propose to use a local Pick-Up for fine adjustments. The system must also cope with the planned modulation in bunch spacing (see below). For the SPS test, the 200 MHz reference must be sent from BA3 to LSS4 and multiplied to 400 MHz.

4.1. COUPLED BUNCH INSTABILITIES

With accelerating cavities, in high beam current machines, the problem of (in)stability caused by the cavity impedance at the fundamental is now routinely cured by active feedback. This principle will be directly adapted to the crab cavities. The amplifier driven by a feedback system feeds a current into the cavity, which attempts to cancel the beam current. The cavity impedance is then effectively reduced by the feedback gain. The limitation comes from the unavoidable delay in the loop. Above some gain level the delay will drive the feedback into electrical oscillations (not related to the beam). For a proportional feedback gain, the minimum effective impedance is

$$R_{\min} \approx \frac{R}{Q}\omega_0 T$$

Where ω_0 is the RF frequency in rad/s, *R/Q* the classic cavity parameter and *T* the loop delay (including TX group delay). For the crab cavities in the LHC, the installation of the LLRF and TX units should be foreseen in a cavern located close to the tunnel installation of the cavities. This will ensure that the RF feedback delay is kept small (< 1 μs). With this figure we can reduce the impedance by 350 linear for a $Q_L = 10^6$, reaching $R_{min} = 6.3$ MΩ/m per cavity. For narrow-band transverse impedance in the LHC, the impedance budget has been estimated at 1-2 MΩ/m per cavity [4]. With the strong RF feedback, the narrowband cavity resonance is transformed into effective impedance covering several revolution frequency lines (few 100 kHz BW) and this leads to a very important reduction to the instability growth rate from the competition between damping and undamping modes [3].

4.2. RF NOISE

The strong RF feedback will reduce the TX noise. Its gain is limited by the loop delay. The beam strongly responds to the noise spectral density on the betatron sidebands. We intend to implement a “Betatron Comb Filter” that effectively increases the gain of the feedback in the betatron sidebands. Within the feedback bandwidth, the noise floor limit will be the accuracy of the measurement of the cavity field (demodulation of the antenna signal).

4.3. LLRF ARCHITECTURE

In case of the rapid change of the field in one cavity (quench or TX trip), the LHC Beam Dump System (LBDS) will dump the beam after a three turns maximum reaction time. The LLRF must help minimize the beam losses during these critical three turns. We propose to couple the 6 cavities of a given beam and IP in a 6-IN, 6-OUT feedback. Figure 2 shows the proposed architecture in principle – of course to be scaled if 8 cavities are used instead of 6. Each cavity has its independent short delay controls loop (Cavity Controller represented in blue colour and mentioned in the above sections). Per ring and IP, we add a central controller that receives measurements from all relevant cavities and that can make corrections to the drive of all individual TX (Multi Cavity Feedback represented in red). If the field starts changing in one cavity, the Multi Cavity feedback would adjust the field in the other cavities on both sides of the IP such that the kicks by the CCs continue to compensate each other and form a closed bump and do not perturb the orbit during the critical three turns. This mechanism will be developed and tested in the SPS with two cavities.

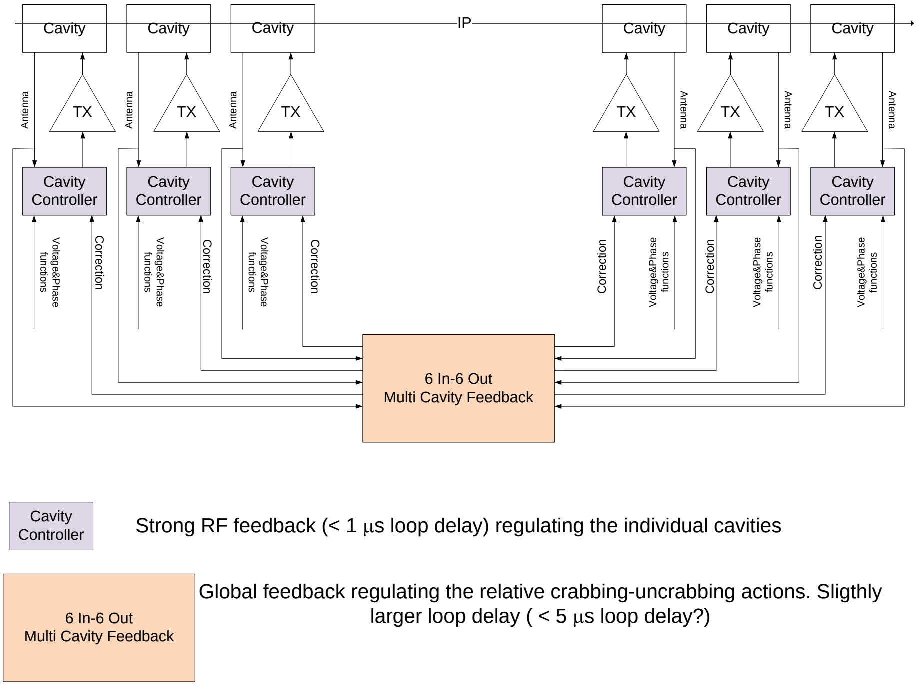

Figure 7: Proposed LLRF architecture for one ring at one IP.

4.4. PHASE MODULATION ALONG THE BEAM

At present the spacing between LHC bunches is strictly constant along the ring. A large amount of RF power is used to fully compensate the transient beam loading caused by the 3.2 µs long abort gap and the smaller gaps required by the injection kicker. This scheme cannot be extended into the HiLumi-LHC era as it would require an RF power that is not available from the ACS system. The plan is to allow phase modulation of the ACS cavity field by the beam gaps while adjusting the voltage phase set point accordingly, bunch per bunch. With HiLumi LHC beam, this will result in a 70 ps modulation of the bunch centre with respect to a fixed RF frequency reference [5]. The power required to make the Crab Cavity field follow this phase modulation is incompatible with the opening for the cavity main coupler. We propose to drive the cavities with the fixed reference RF, resulting in a phase error $\delta\phi$, with respect to the individual bunch centre. This phase error causes an offset of the bunch rotation axis, resulting in a transverse displacement Δx at the IP

$$\Delta x = \frac{c\phi}{\omega_{RF}} \delta\varphi$$

For a phase drift of 30 ps the transverse displacement is 5 µm, approximately equal to the transverse beam size. Fortunately the filling patterns are identical for both rings (except for the first six or twelve bunches of each batch) and the phase errors will be equal for colliding pairs in IP1 (ATLAS) and IP5 (CMS) because the bucket numbering convention makes the bucket one of both rings (first bucket after the abort gap) “collide” in IP1 and IP5. There will therefore be no loss of luminosity, only a modulation of the transverse position of the vertex over one turn. This is acceptable by the experiments.

4.5. CAVITY TRANSPARENCY AND OPERATION

The crab cavities must cope with the various modes of the collider cycle: filling, ramping and physics. During filling of the 2808 bunches into the LHC, ramping or operation without crab cavities, the cavities are detuned (1.5 kHz), but kept with a small field requested for the active tuning system. With a positive non-integer tune (Q_h=64.3, w_b/w_{rev} above an integer), the cavity should be tuned above the RF frequency to make the mode l=-64 stabilizing (see Figure 8). As the kick is provided by a triple or quadruple pair of cavities, counter-phasing will be used to make the small cavity field invisible to the beam. The RF feedback is used with the cavity detuned to provide stability and keep the Beam Induced Voltage zero if the beam is off-centred. We can use the demanded TX power as a measurement of beam loading to guide the beam centring. We could also use the RF signal from another dipole mode, measured in the HOM couplers but keeping in mind that it may not have the same electrical centre as the crabbing mode.

On flat top, we reduce the detuning while keeping the cavity voltage very small and counter-phasing. The RF feedback keeps the cavity impedance small (beam stability) and compensates for the beam loading as the cavity moves to resonance. Once the cavity detuning has been reduced to zero, we drive counter-phasing to zero and use the functions to synchronously change the voltage in all crab cavities as desired. Any levelling scheme is possible. With a circulator between TX and cavity, the TX response is not affected by the cavity tune. This is very favourable for the proposed active compensation scheme, with a cavity being gently moved from parked position to tune.

In physics, with the crabbing on, we must have an active RF feedback for precise control of the cavity field. The RF feedback reduces the peak cavity impedance and transforms the high Q resonator into effective impedance that covers several revolution frequency lines (see Figure 8). The actual cavity tune has no big importance for stability anymore. The growth rates and damping rates are much reduced, and we have no more dominant mode.

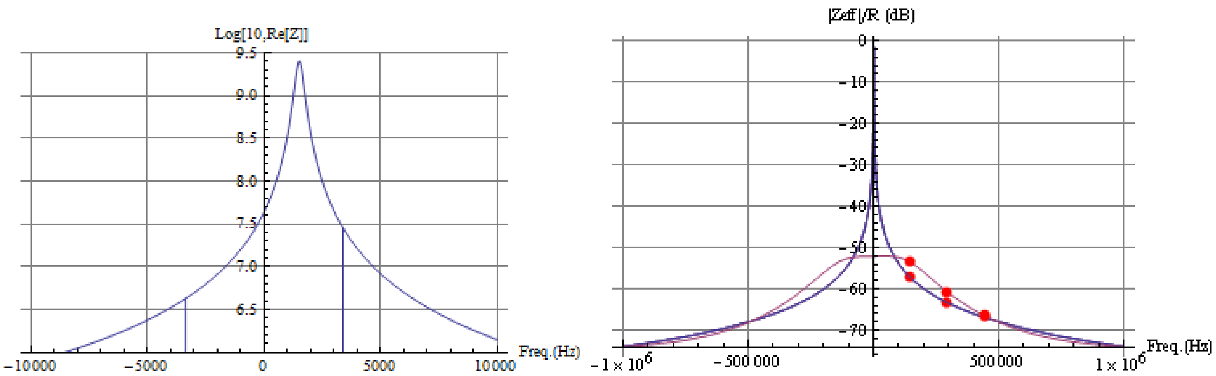

Figure 8 Left: Real part of the deflecting mode impedance as a function of detuning from 400 MHz.Right: Effective impedance seen by the beam with the RF feedback on (red) and off (blue).

5. INTEGRATION INTO SPS & LHC

The first proof of principle system is foreseen to be tested in the SPS prior to the realization of the full LHC crab cavity system. The primary aim of these tests is to validate the technology with proton beams and establish a robust operational control of a multi-cavity system for the different modes of operation.

5.1. SPS-BA4 TEST SETUP

The SPS ring is equipped with a special bypass (Y-chamber) with mechanical bellows that can be displaced horizontally (see Figure 7). This allows for a test module to be passively placed during the regular operation of the SPS and only moved in during the dedicated experimental periods with crab cavities. This setup is essential both due to aperture limitations of the crab cavities and the risk associated with leaving the cavities in the beam line with different modes of operation in the SPS.

A two cavity cryomodule of the same cavity type is envisioned for installation in the 2016-17 end of the year shutdown period. This crymodule will consist of all the main elements that need to be validated with the LHC type beams prior to a full installation in the LHC interaction regions. The cryomodule is placed on a movable table which will enable it be brought in and out of the SPS circulating trajectory. An LHC type circulator, although over dimensioned, is preferred for the reasons of maintenance and spare policy. The TCF20 cryogenic box in the BA4 region is presently being re-commissioned and upgraded to deliver 2K Helium for the operation of the crab cavities [7]. Due to the limited capacity available in the SPS cryogenics, the static load of the cryomodule should be minimized below the present estimated 22W. A special working group (crab cavity technical coordination) is set up to follow up the various integration issues including the RF and cryogenic systems.

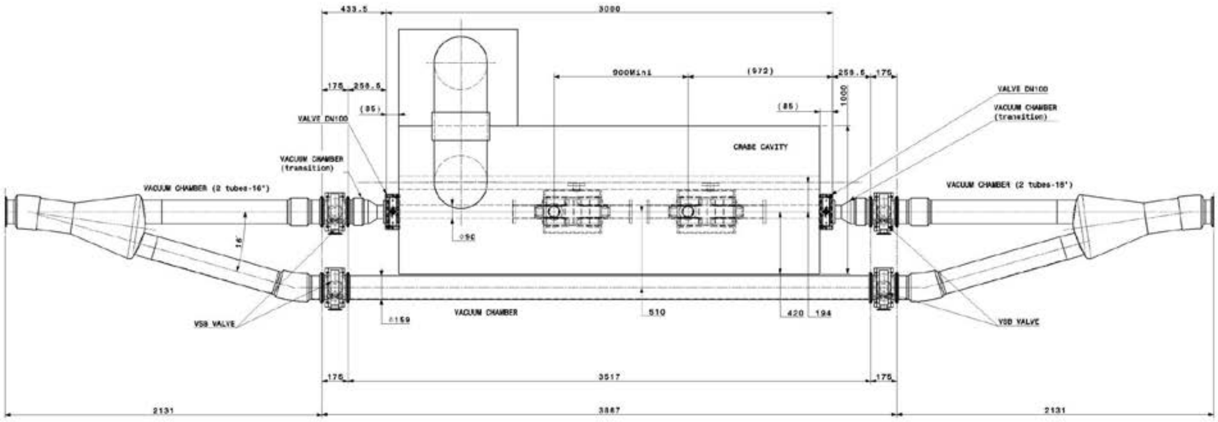

Figure 9 SPS-BA4 bypass for the installation of a 2-cavity crab cavity module for the first beam tests.

Two “flexible” coaxial line will feed the RF power from the Tetrode amplifiers to the respective cavity (see Figure 8). The placement of the amplifiers on the movable table will depend on the full integration of the cryomodule, transmission lines and the circulator. A 3D integration of the cryomodule and the RF assembly in the BA4 region is shown in Figure 10.

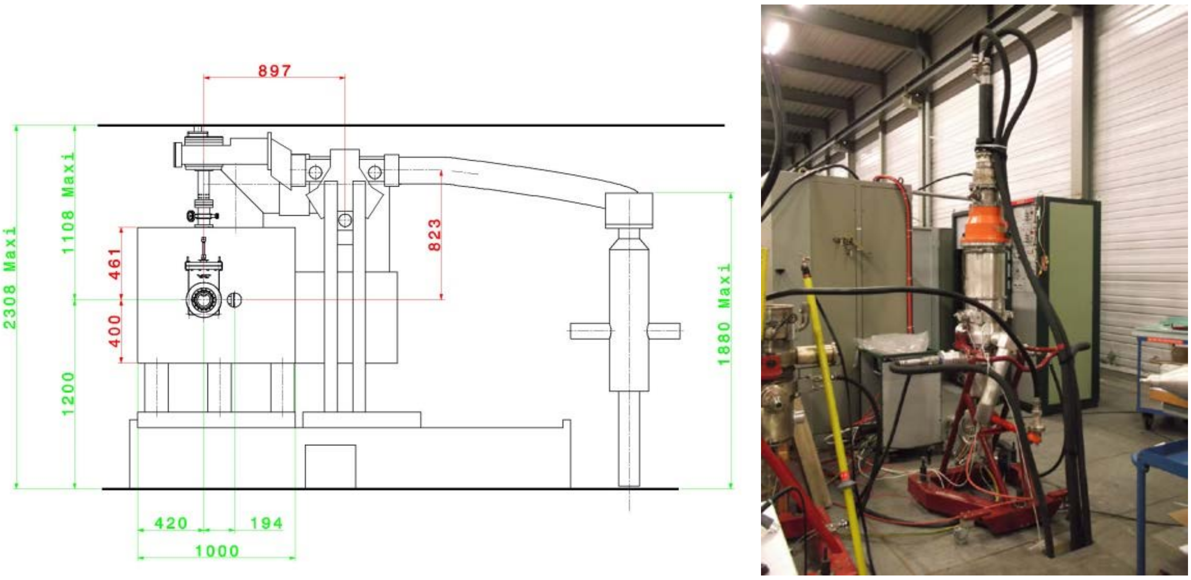

Figure 10 Cryomodule and RF system layout in the BA4 cavern (left) and a 400 MHz Tetrode amplifier under test (right).

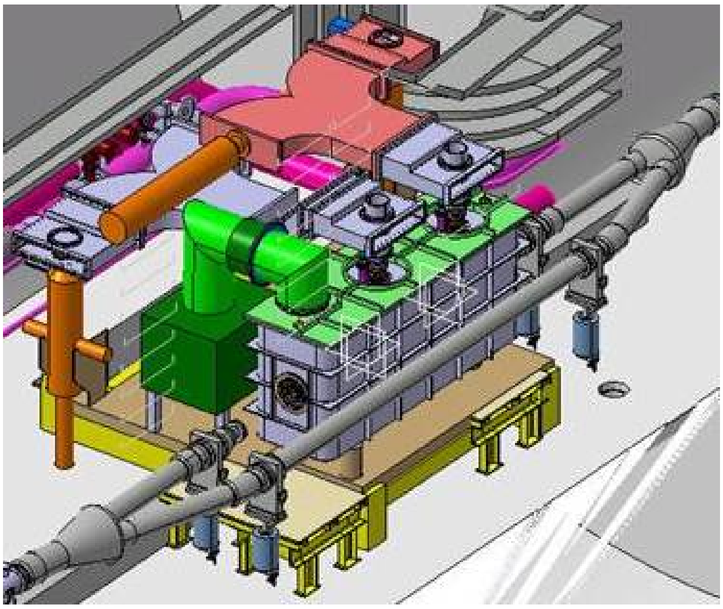

Figure 11 3D integration of the cryomodule, RF assembly and the cryogenics in the BA4 region of the SPS.

5.2. LHC INTEGRATION CONSTRAINTS

Due to a complete change of the interaction region, the integration of the crab cavities in the LHC is combined with the rest of the magnetic elements and undertaken by Work Package 15 with input from WP4 and WP2. The RF system demands an independent control of each of the 6-8 cavities per IP side with the shortest delay loops between the RF transmitter and the cavity (see Figure 12). To provide a strong feedback, the low level RF system requires the total loop delay to be less than 1ms. This includes the round trip delay of the driver, amplifier, circulator and associated cable delays. Therefore, a distance not greater than 40m is highly recommended for the separation between the amplifier, electronics and the cavity in the tunnel. Such a type of short delay is already in place for the ACS main RF system in Point 4. The service gallery parallel to the tunnel allows for sufficient shielding to sensitive RF electronics and possibly allow for easier access to the RF equipment.

Near Point 1 and 5, the closest area to house any equipment is in the RR caverns which are further away from the interaction point. The distance to the crab cavities from the RR cavern exceeds the 40m loop delay. The transmission line waveguides or coaxial lines are of significant dimension and passing 8 such lines over a distance of 80-100m can involve major redesign of the interaction region to accommodate them. Just the volume consumed in the tunnel might make it impractical. The most significant factor is that the radiation near the RR caverns may not be negligible to place sensitive RF equipment. Considering these factors In addition, the estimated space requirements for the RF equipment also exceed the space available by some significant amount [8].

Considering these reasons, it is highly desirable to extend the experimental service gallery until the crab cavity region near Point 1 and 5 to solve all the above issues. A study is ongoing to determine the feasibility of the civil engineering with minimal perturbation to the LHC running.

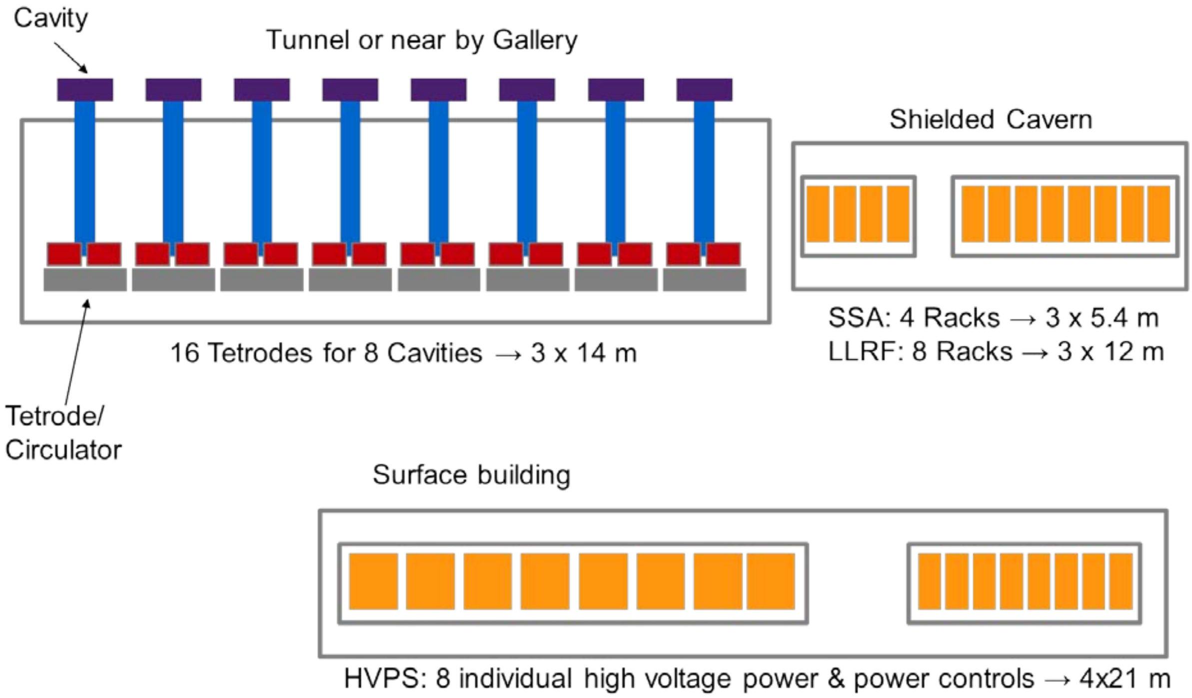

Figure 12 Schematic of the RF system layout in the LHC tunnel with respective number of electronics racks required close to the cavities and on the surface building.

6. CONCLUSION

A concept using independent RF powering for each cavity with a combined LLRF system to operate the 6-8 cavities per interaction point per beam was described. A compact RF system both to maximize the efficiency and minimize the risk to the LHC is presented. However, the lack of shielded space in close proximity to the crab cavities will prove challenging either for integration within the tunnel or entail substantial civil engineering which ultimately might prove as the most effective solution.

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ANNEX: GLOSSARY

Acronym	**Definition**
LHC	Large Hadron Collider
LLRF	Low level RF
IP	Interaction point
ACS	Superconducting accelerating cavities