HL-LHC RF Roadmap

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Abstract

In view of the HL-LHC parameters, the present and the future RF systems for the LHC are reviewed with a focus on technological aspects. This paper will describe the preparation and the test program of the SPS beam tests with crab cavities. Some aspects related to the integration of the crab cavity RF system in the LHC and the potential impact of the crab kissing scheme are addressed. The mode of operation for the 400 MHz accelerating RF system with HL-LHC beam currents and the associated issues are briefly outlined with possible improvements to the ACS system. Finally, the use of a harmonic system both at 200 MHz and 800 MHz for bunch profile manipulation and the associated technological challenges are described.

INTRODUCTION

The HL-LHC upgrade to enhance the integrated luminosity by a factor 10 will require that the present and the foreseen RF systems to be compatible with beam currents exceeding 1.1 A. This paper will cover the following RF systems:

- Crab cavity R&D upgrade status for SPS tests
- Compatibility of the existing RF system for HL-LHC
- Harmonic RF system for bunch manipulation and increased stability

Some relevant beam and machine parameters used to design the RF systems. are listed in Table 1. A more detailed parameter list is found in Ref. [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	2.2
Bunch Spacing	[ns]	50-25	25
Bunch Length (4σ)	[ns]	1.0	1.0
ϵ_n (x,y)	[μm]	2.5	2.5
$\text{IP}_{1,5}$ β^*	[cm]	55	15
Betatron Tunes	-	{62.31, 60.32}	
X-Angle: $2\phi_c$	[μrad]	285	590
Piwinski Angle	$\frac{\sigma_z}{\sigma^*}\phi_c$	0.65	3.14
Main/Crab RF	[MHz]	400.79	
Peak lumi ($\times 10^{34}$)	[$1/cm^2 s^1$]	1.18	19.54

All RF systems being considered for the HL-LHC rely on the RF superconductivity (SRF) as the driving technology. The benefits from the high stored energy and low surface losses therefore allowing for large aperture and lower impedance is vital. The SRF history at CERN dates back to the 70's with the RF separator in the SPS in collaboration with Karlsrushe [2]. Over four decades, significant developments in the SRF took place in the context of LEP, LHC, HIE-ISOLDE, crab cavities, SPL and other R&D projects.

For crab cavities, the demand of 3.4-5.0 MV kick voltage corresponds to surface fields in excess of 40 MV/m and 100 mT. Therefore, the challenge remains to robustly produce the kick voltage with adequate margin. For longitudinal RF systems, the main challenge is to cope with the strong transient beam loading and reliably provide the required RF power.

STATUS OF SPS CRAB CAVITIES

A test of crab cavities in a hadron machine (for example the SPS) prior to a final installation in the LHC was deemed as a pre-requisite [3]. The test will first address important aspects such as cavity performance and reliability, RF controls, machine protection and other operational aspects. These tests are regarded as a vital step to identify the possible differences between electrons and protons and to quantify the associated emittance growth and other crab cavity induced beam perturbations. A dedicated working group (CCTC) was put in place to address various aspects including integration, cryogenics, infrastructure of a two-cavity prototype [4].

Cavity Performance Tests

As a result of R&D in collaboration with USLARP and UK, three very compact superconducting cavity designs were conceived and prototyped in bulk Niobium. All three cavities reached design kick voltage of 3.4 MV or higher (in some cases factor 2) within a surface resistance higher than the specified 10 nΩ. Fig. 1 shows the three compact prototype cavities, the double quarter wave (DQW), the RF dipole (RFD) and the 4-Rod designs fabricated for field performance tests.

A technical review in May 2014 provided a recommendation to proceed with only two cavity types (DQW and RFD) based on several technical aspects and schedule constraints [6].

Figure 1: Prototype Niobium cavities of the DQW, RFD and the 4-Rod respectively [5].

Cryomodule Development

A detailed conceptual design of a cryomodule for the three cavities was performed prior to the technical review decision. However, following the review recommendation, only the DQW and the RFD designs were followed up towards an engineering design for fabrication. Fig. 2 shows a sequential development of the cavity, interfaces, service and the cryomodule concept with all the ancillary equipment. The Helium vessel was chosen to be made of Titanium to minimize the differential contraction between the Niobium cavity and the cold mass due to the numerous asymmetric interfaces [8]. A double insulation for magnetic shielding, one inside the He-vessel and one outside, is used to bring the stray magnetic fields to below the required 1μT level. A novel tuning concept using concentric cylinders to differentially apply a push-pull force on the cavity body is also employed [9]. Using a special frame a symmetric force on opposite sides of the cavity for a symmetric deformation. A warm actuation system is used to ease the maintenance. A rectangular vacuum vessel with side loading concept is adopted to provide adequate access for all major components during assembly and testing at this R&D stage [10].

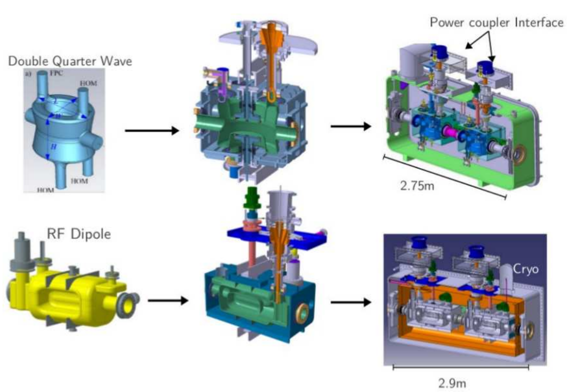

Figure 2: Schematics of the cavity interfaces, Helium vessel and the two cavity cryomodule with all the ancillary equipment (courtesy EN-MME).

It is presently planned that USLARP along with DOE-SBIR program will fabricate four cold masses (commonly referred to a the dressed cavity) including the Titanium Helium vessels and HOM couplers towards the SPS tests [7]. The dressed cavities are tested and qualified to the nominal kick voltage prior to their assembly in the cryostat. The RF power coupler and the cryomodule assembly will be carried out in collaboration between CERN and the UK collaboration. The assembled cryostat is expected to be completed by mid-2016 and then put through a comprehensive horizontal test in the SM18 prior to an installation into the SPS.

Integration

A special region in the BA4 section of the SPS hosting the present COLDEX experiment was identified as the best location for a test of the crab crab cavity This region consists of a movable horizontal bypass and essential cryogenic infrastructure for future crab cavity tests. The bypass allows for an easy displacement of the cavities during regular SPS operation (see Fig. 3). The complete infrastructure requirements including cryomodule integration, vacuum, cryogenics, RF power and all other services is being carried out under the CCTC working group [4]. Recent considerations to equip the SPS with a second bypass in LSS5 is under investigation as an alternative to LSS4 to allow for COLDEX to continue for a longer period [11].

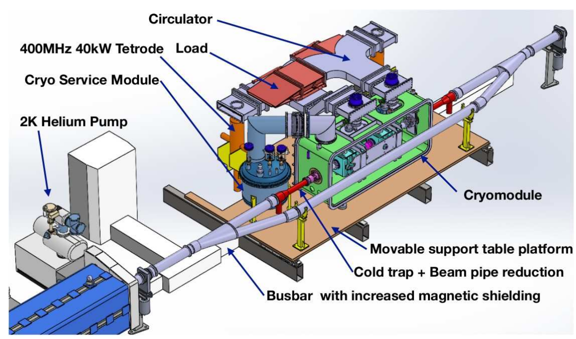

Figure 3: Schematic of the two-cavity installation in the SPS-BA4 region [4].

Test Objectives & Challenges

The SPS beam tests are foreseen to take place during the run period of 2017 until the start of Long Shutdown 2 (LS2).

The primary test objective in the SPS is the demonstration of cavity deflecting field with proton beam and active control of cavity field (amplitude and phase) along with Multi-Cavity Feedback (MFB). Following the verification of operational frequency, tuning sensitivity, input coupling, power overhead and HOM signals, the comprehensive operational cycle as foreseen in the LHC will then be established. The possibility to operate w/o crab cavity action (make them invisible) by both counter-phasing the two cavities or by appropriate detuning (to parking position) at energies ranging from 26-450 GeV will be performed. Beam measurements for orbit centering, crab dispersive orbit and bunch rotation with available instrumentation such as BPMs and head-tail monitors will also be carried out.

Other aspects such as the demonstration of non-correlated operation of two cavities in a common CM (triggering a quench in one cavity without inducing quench in the other), implementation of interlock hierarchy and verification of machine protection aspects and functioning of slow and fast interlocks will also be studied. It will be important to test HOM coupler operation with high beam currents, different filling schemes and associated power levels. Measurements of impedance and instability thresholds for the main deflecting mode and HOMs are vital. Finally, the emittance growth measurements induced by the crab cavities and general long term behavior with proton beams is also necessary objective.

The beam tests (or MDs) in the SPS can be generally classified into three main categories:

- RF commissioning with low intensity beam, single to few bunches. Establish the proper RF parameters, including cavity tune, phase and operating kick amplitude. Verify both, crab cavity action and invisibility.

- High intensity single bunches to trains of bunches to investigate the effect of cavity performance, impedance, machine protection and characterize the transient behavior of the crab cavity system as a function of beam current. Verify cavity stability over several hours (as relevant for LHC physics fill).

- Long term behavior of coasting beams in the SPS with relatively low intensity to study the effects of emittance growth and possibly non-linear effects such as RF multipoles.

Despite the extended winter shutdown in 2016-17, a complete installation during this shutdown appears challenging. The continued running of COLDEX precludes any pre-installation. A careful coordination is required between the different equipment groups to perform the installation. In the LHC, several challenges exist including machine protection, impedance, RF noise, installation and maintenance of a large RF system in a highly radioactive environment.

Impact of CK scheme

The crab kissing (CK) scheme is proposed as one of the schemes to reduce the pile-up density, a key feature desired by the experiments [12]. The baseline scheme requires 4 cavities per IP side and per beam with a nominal cavity voltage of 3.4 MV or less. In the CK scheme, two of the four cavities are needed in the crossing plane while the other two are oriented in the opposite (parallel) plane. The present optics requires that the cavities operate between 5-6 MV which lead to cavity surface fields close to the typical quench fields.

The change in orientation of two cavities implies that the CK scheme is not backward compatible to the original crab crossing scheme. Due to the 50-70% higher voltage requirements, degradation in cavity performance or a failure will have a significant impact on the performance and possibly on machine protection. If the newer optics allows for reduction in the required voltage, the baseline scheme can also be implemented with fewer cavities in the ring in view of impedance reduction. Hence, a phased installation approach where only half the system followed with beam experience can be envisioned to leave open the choice of installation plane at a later stage.

MAIN RF, ACS-400 MHZ

The accelerating RF system in the LHC (ACS) comprises of 8-cavities per beam operating at 400 MHz to provide a nominal voltage of up to 2 MV/cavity. The system is described in detail in Ref. [13]. The primary functions of the ACS cavities include the injection and energy ramping of 2808 bunches of up to 1eV-s and more importantly store the high intensity beams at 7 TeV. The longitudinal emittance is increased by controlled blow up to 2.5 eVs to keep the bunch length approximately constant (see Table 1). Fig. 4 shows the approximate bunch length as a function of emittance for LHC injection and for 4.0 TeV run in 2013 and 6.5 TeV run in 2015. A 6 MV capture voltage and 12 MV at flattop was used in 2013. A similar voltage program is likely to be used in the 2015 run [14].

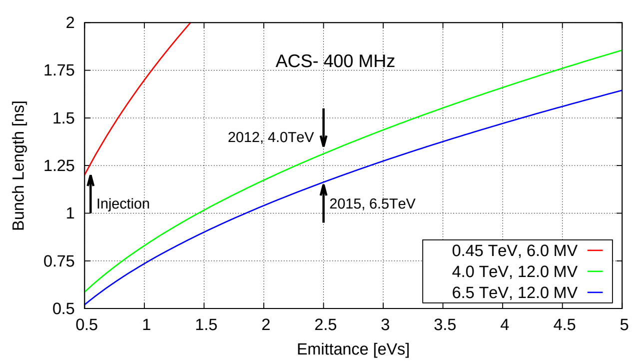

Figure 4: Bunch length vs emittance for injection and flattop voltages in the ACS-400 MHz system.

The primary limitation in the operation of the ACS-400 MHz system comes from the installed and available RF power. Due to the uneven filling scheme, the voltage vector is strongly modulated. The present scheme employs a $\frac{1}{2}$-detuning scheme [15]. In this scheme, the cavity detuning is set to value where the RF power required is equal in the segments with and without beam and only the sign of the klystron phase is flipped. Therefore, the required peak power and bucket spacing is kept constant. The present RF power chain (Klystrons, circulators, loads and RF power coupler) are all limited to approximately 300 kW-CW. To provide a 20% margin for operations, the klystron power is further limited to 250 kW. Fig. 5 shows the power requirements as a function of Q_L for nominal and HL-LHC beam parameters assuming the present $\frac{1}{2}$-detuning scheme.

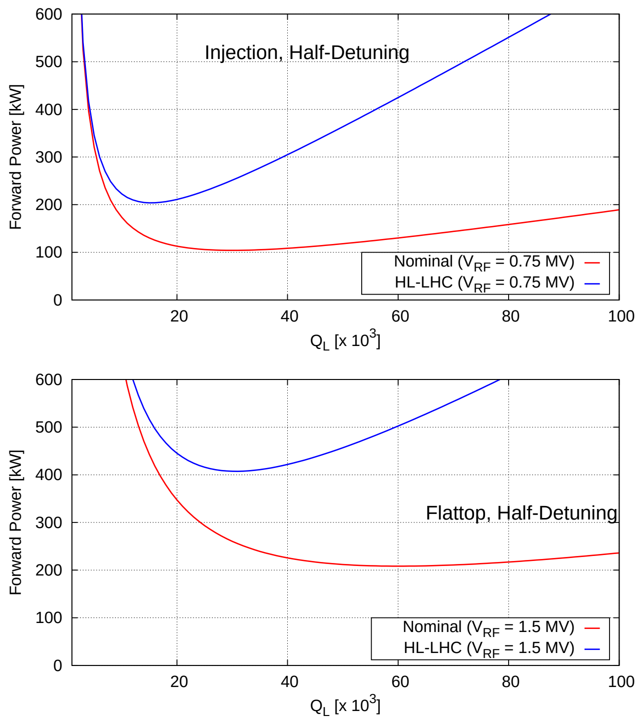

Figure 5: Forward power at injection (top) and flattop (bottom) required in the ACS-400 MHz system operated in the $\frac{1}{2}$-detuning scheme for HL-LHC beam parameters and cavity voltage of 1.5 MV. The nominal LHC is plotted as comparison.

At injection with a total voltage of 6-8 MV, the HL-LHC beams are still compatible with the 300 kW limit. It is important to use the $\frac{1}{2}$-detuning scheme during beam injection to preserve the regular bucket spacing and minimize transfer losses between SPS and LHC. However, at flattop, the power is exceeded significantly even at a total voltage of 12 MV and much more for the nominal 16 MV.

The baseline solution to overcome the power limitation is to use the optimal detuning (AKA Full Detuning) as discussed in Ref. [16]. The consequence of the optimal cavity detuning (Δf=10 kHz for HL-LHC parameters) during the beam presence is the strong modulation of the RF phase by gaps in the beam. If one allows the inter-bunch distance to slide w.r.t each other, the forward power is minimized and becomes independent of the beam current. Fig. 6 shows the RF phase modulation over one full turn for a standard 25ns LHC filling scheme.

The required voltage for an optimal $Q_L = 3.5 \times 10^4$ is 180 kW for a $I_B = 1.1$A and a voltage V=12MV which is within the power capability of the present RF power chain. The power simply scales inversely with the Q_L and can be further reduced if needed. In this scenario, the inter-bunch distance as seen in Fig. 6 changes by about 85 ps (or

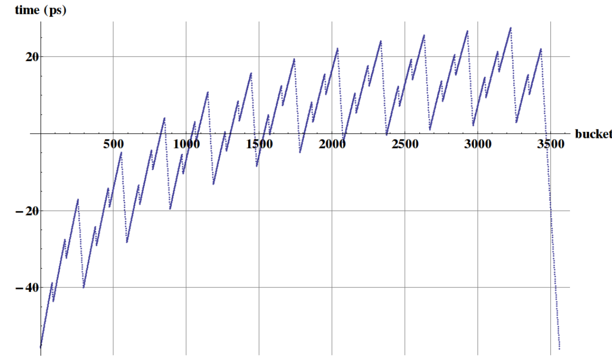

Figure 6: Phase modulation over one full turn with an optimal detuning and HL-LHC beam parameters (Courtesy P. Baudrenghien).

25mm). However, due to the symmetric filling schemes in both rings, the luminosity is not effected. Only the collision time is modulated by 85 ps over the full turn which is quite small compared to nominal bunch spacing of 25ns.

Potential issues for HL-LHC

Operation of HL-LHC will begin approximately 15 yrs or more from the first start of the LHC nominal. This implies certain aging effects of the RF power systems and the cryomodule components. In particular, the power coupler operating at high power is susceptible to failures. Some statistics from past coupler experiences from LEP, SPS and other machines indicate first development of failures in the time span of 15yrs [17]. A replacement of a power coupler will imply a replacement of the module and lead to significant down time. The re-qualification of the complete module removed from the LHC and the preparation of a second spare is underway [18].

Possible new strategy

The preparation of a second identical spare module will require a non-negligible time to recuperate or build four cavities, cold masses and cryomodule with all the required components including the power couplers [18]. It should be noted that 8-spare couplers are presently available [17].

It is however prudent, in the view of the future operation of HL-LHC, to embark on an upgrade of the ACS module (ACS-Gen II). The aim of the Gen II module would be to generate higher RF performance from a compact 2-cavity module (4 MV and 500 kW per cavity) as compared to the present system. A possible 2-cell extension with dual power couplers could also be considered in view of projects beyond HL-LHC. The two main advantages are:

- A more compact module with upgraded hardware with similar voltage reach, thereby giving higher modularity and improve spare policy.
- Significant reduction in static heat load Table **??**

The Gen II module can become the second spare or possibly replace the existing modules with higher reliability in the future. As an alternative option, the Gen II module can be added to existing machine to recover the 1/2-detuning scheme if necessary by operating the present modules at reduced voltages. The Gen II module would mainly require a cryostat update for minimizing the static heat load and an update of the power coupler design to reach the 500 kW level. The klystrons, circulators and loads would also need to be updated to the 500 kW level. The cavity design could be identical to that of the present module with improved performance on Nb-coating.

HARMONIC RF SYSTEMS FOR HL-LHC

Two categories of harmonic RF systems are considered for HL-LHC but not presently in the baseline:

- A higher harmonic (800 MHz) for changing the bunch profile in bunch lengthening (BL) mode or change the synchrotron frequency distribution to improve the beam stability in BL or bunch shortening (BS) mode. Depending on the mode of operation, the RF system can be used to reduce the beam induced heating, effect of intra-beam scattering, improve longitudinal beam stability and in some scenarios help level the luminosity. The detailed overview and past studies can be found in Ref. [19].

- 2. A sub-harmonic (200 MHz) system can either completely replace the existing main RF system or work with the 400 MHz RF system. The main aim of a lower harmonic RF system is to improve the capture efficiency for longer and very high intensity bunches. The benefits of operating in conjunction with the exiting 400 MHz system are similar to that of the second harmonic system.

ACS-400 + 800 MHz

For the higher harmonic system, the maximum required voltage is 8 MV to maintain the ratio between the 400 MHz and the 800 MHz to 1/2. The key challenge in the operation of the harmonic system is to maintain the fixed phase w.r.t to the main RF system. The phase modulation of the main RF system over one full turn is 85 ps which implies a 25° modulation at 800 MHz. In the BL-mode the phase difference between the main RF system and the 2^{nd} harmonic has to be controlled to within 1-5° to ensure stability. In the BS-mode, the phase difference between the main RF and the 2^{nd} harmonic system is less critical [19].

A detailed cavity and HOM coupler design from the scaled 400 MHz ACS cavity was carried out [20]. A 300 kW maximum RF input power is assumed with fixed coupling. A possible 4-cavity configuration similar to the ACS module is shown in Fig. 7. The flange-to-flange longitudinal distance would be approximately 3.5m. A 2-cavity configuration would approximately be 15% longer, but will provide additional modularity, ease of maintenance and reduction in the number of spares.

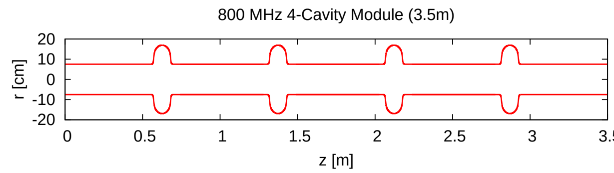

Figure 7: Four cavity configuration for 2^{nd} harmonic RF system in the LHC at 800 MHz.

During beam injection and energy ramp, the 2^{nd} harmonic system in the LHC, will present a large impedance. Parking the cavities in a detuned stage and passively damping them is not ideal. It is possible to use them with a reduced voltage in conjunction with the ACS-400 or possibly counter-phasing them. During injection, the ACS-400 MHz will be operated in the 1/2-detuning scheme for efficient transfer between the SPS and LHC.

The main RF will be moved to an optimal detuning with large phase swing before the energy ramp. The 800 MHz system has to strictly follow the phase swing in the 800 MHz cavities and this phase difference is much more constrained in the BL-mode [19]. The power requirements for the two modes of operation are calculated in detail in Ref. [21] and are summarized in Table 2.

Table 2: Power requirements in the 800 MHz with phase modulation.

Mode	V [MV]	Q_L	RF Power [kW]
BS-mode	1.6	10^5	80
BL-mode	1.0	10^4	260

In the BS-mode, the power required is significantly reduced by choosing an optimum ratio of the detuning between ACS-400 and the 800 MHz systems. Approximately 2-4 cavities are sufficient to provide the maximum 8 MV with ample margin in power capability. Note that in the BS-mode, the 1/2-detuning scheme could also be recovered using four 800 MHz cavities and operating the ACS-400 at a reduced voltage of 8 MV at flattop.

However, the power requirement in the BL-mode is significant and the voltage per cavity is reduced to 1 MV to stay within the 300 kW. Therefore, at least 8-10 cavities are required in the BL-mode to provide the 8 MV total voltage and therefore at least doubling the RF system. A more detailed analysis is required to quantify the exact number of cavities including realistic phase differences between the RF systems during the entire operational cycle of the LHC.

The benefit of generating flat longitudinal profile using the BL-mode can possibly be realized phase modulation close to f_s as shown in machine developments in LHC-RUN I [26]. Further machine development is required to robustly establish the procedure in operations over long fill time.

ACS-400 + 200 MHz

A normal conducting 200 MHz system was already planned as a capture system if the extracted emittance from the SPS becomes large [13]. The bunches are then transferred adiabatically to the ACS-400 prior to energy ramp. An superconducting system at 200 MHz with conventional elliptical cavities was discarded due to the physical size.

However, a new concept using $\lambda/4$ resonators at frequencies of 200 MHz or below become very attractive. A similar system was conceived at 56 MHz for the RHIC accelerator and presently under commissioning [23]. Fig. 8 shows a preliminary design of a such a 200 MHz $\lambda/4$ resonator compared to the e existing ACS-400 system.

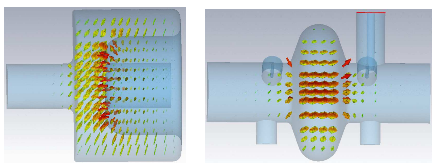

Figure 8: Preliminary design of a 200 MHz $\lambda/4$ resonator (left) for the LHC compared to the existing ACS-400 MHz system (right).

Table 3 shows some relevant RF parameters of the 200 MHz system compared to the existing ACS-400 system in the LHC. It is important to note that the $\lambda/4$-resonator is 20% smaller in transverse size as compared to the existing ACS-400 MHz system.

Table 3: Relevant cavity parameters for the 200 MHz compared to ACS-400.

Voltage	[MV]	2.0	2.0
Cavity Type		Co-axial	Ellipitcal
Frequency	[MHz]	200.3	400.7
Gap Length	[mm]	133.5	377.3
R/Q (circuit)	[Ω]	51	45
Aperture	[mm]	168	300
E_{pk}, B_{pk}	[MV/m, mT]	29, 68	12.5, 30
Cavity Envelope	[mm]	284	344

R&D to develop the 200 MHz $\lambda/4$ resonator is mandatory. However, advances on the HIE-ISOLDE Nb-Cu program have shown promising results to reach beyond the surface fields shown in Table 3 at Q_0 values exceeding 5×10^8 which is at least a factor 2 better than the ACS-400 cavity performance. Another significant advantage of $\lambda/4$ resonator is the large spacing between the accelerating mode and the higher order modes which makes the damping scheme simpler.

A detailed study both from electromagnetic simulations and beam stability is required to establish the path of using a 200 MHz system as a main RF system for which several advantages can be foreseen. The primary advantage is the ability to capture more intense (up to 2.5×1011) and longer bunches offering an alternative scenario for luminosity optimization and possible mitigation of the electron cloud effect [24]. With the SPS RF power upgrade and manipulations, it is shown in simulations to extract up to 2.4×10^{11} p/bunch [25]. Although, only a minimum of 3 MV is required to inject, ramp and store the LHC beams [19], 6 MV is assumed as a baseline. Fig. 9 shows the bunch length as a function of the longitudinal emittance injection and flattop in a single 200 MHz RF system.

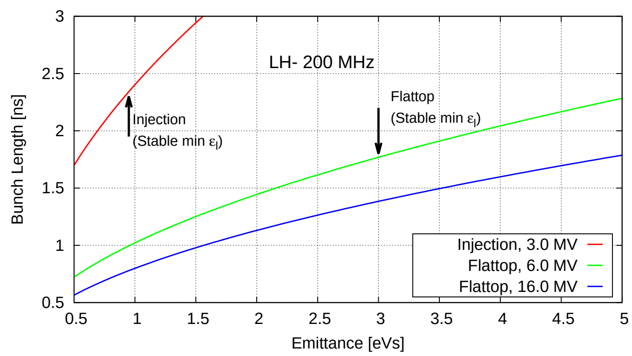

Figure 9: Bunch length vs emittance for injection and flattop voltages in the 200 MHz system.

An minimum stable injection emittance in the 200 MHz is estimated to be 1 eVs while at flattop is 3 eVs in the 200 MHz system alone [26]. It would be a natural choice to use the existing ACS-400 to achieve smaller bunch lengths ($\leq$ 1.5ns) and with a modest voltage requirement in both systems as opposed to using only 200 MHz RF system. In addition, the ACS-400 MHz system as a second harmonic could help provide stability with smaller emittances.

Fig.11 shows that with an optimized Q_L of approximately 2×10^4, the forward power in the 200 MHz system with 1/2-detuning scheme is 420 kW. Existing expertise from SPS and LHC can be used to develop a power coupler and the RF chain capable of handling power levels of 500 kW [17]. The Q_L is also compatible at injection energy and sufficiently low enough to act against injection transients. This allows for fixed coupling, thus greatly easing the design of the high power coupler. Commercial power sources at this frequency and power levels already exist in the form of diacrodes.

If the maximum voltage is limited to 6 MV in the 200 MHz system, four cavities will be sufficient. It is also possible to envision dual couplers per cavity to reduce longitudinal footprint if necessary. However, a proposed four cavity module is quite compact with a length of 3.5 m as shown in Fig. 11 and approximately 15% longer with x2

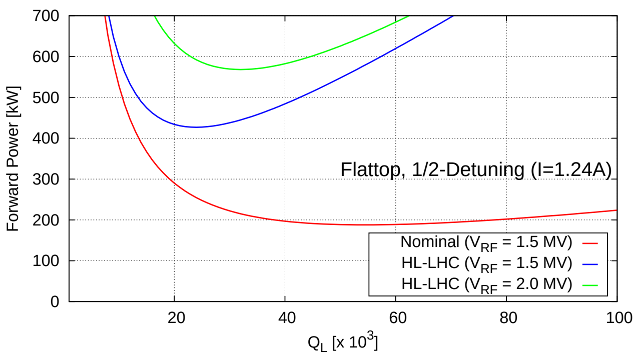

Figure 10: Forward RF power as a function of Q_L at flattop assuming I_b = 1.24 A for a 200 MHz RF system.

two cavity module.

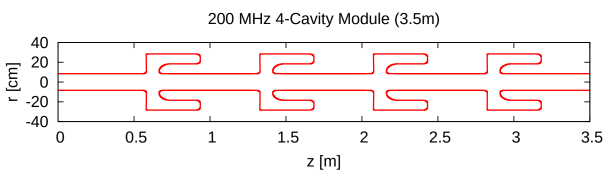

Figure 11: Four cavity configuration for the 200 MHz $\lambda/4$ resonator as the fundamental RF system for the LHC.

With this configuration, a maximum of only 3 MV in the 400 MHz is sufficient to provide the RF voltage at the 2^{nd} harmonic. This can be easily provided by a single existing 4-cavity module or possibly even with only two cavities. With the addition of the 2^{nd} harmonic, the bunch lengths can be brought down to approximately 1.35 ns in the BS-mode and well beyond 1.8 ns in the BL-mode depending on the maximum acceptable bunch length (luminous region) by the experiments.

HEAT LOADS

The heat loads for the existing ACS-400 MHz and the future RF systems in the LHC are estimated in Table 4. For the crab cavities, the heat load constraint is primarily in the SPS. The existing TCF20 plant has a maximum liquefaction capacity of 1.5 g/s with a LN_2 boost [27]. However, the total estimated heat load at 2K is 1.6 g/s ($\sim$ 30 W) and therefore not operationally practical. A new cryogenic plant was identified to increase the capacity to 2.1 g/s and is the installation is under study [27]. This new plant along with a buffer tank of 150 L gives sufficient capacity to handle higher heat loads and continued operation over 10h. For the LHC, assuming similar heat load at 2K, each IP with 8 modules (16 cavities) would account of 0.48 kW.

For the longitudinal RF systems, the static heat load of the existing ACS-system exceeds 60 W at 4.5 K per cavity. A new Gen II module will aim to reduce this heat load by at least a factor 2-3 with improved cryostat design. For the 800 MHz harmonic system, the dynamic heat load at 4.5 K is quite low due to the low voltage (1 MV) per cavity. At 2 MV, the heat load can reach 60 W mainly due to the BCS resistance. Therefore, it might be beneficial to operate at 2 K. The exact heat loads for the higher and lower harmonic systems will have to be determined after a detailed cryomodule design is prepared.

CONCLUSIONS

A brief outline of the RF systems in the HL-LHC era and their performance limitations were presented. For the crab cavities, the hardware and infrastructure preparation towards the SPS tests are in an advanced state. The main challenge comes from the simultaneous installation activities all concentrated during the long shutdown prior to the 2017 run.

The longitudinal RF system choices for HL-LHC can be summarized as follows:

- Option I, ACS-400 MHz: A full detuning scheme as outlined by Ref. [16] will be sufficient to ramp and store the HL-LHC beams and overcome the present RF power bottleneck. However, the consequence of phase modulation of up to 85 ps over a full LHC turn is inevitable. A new proposal to develop a Gen II module will provide added flexibility and lifetime in a more compact footprint than the present ACS module. It could in addition recuperate the 1/2-detuning scheme acting along with the present system.

- Option II, ACS-400 + 2^{nd} harmonic 800 MHz: The higher harmonic in the BS-mode appears feasible with 4-cavities operating at 1 MV each with fixed coupling. They could both provide stability margin and possibly restore 1/2-detuning. In the BL-mode the system is at least twice as large with tight constraints on phase errors and potentially needing a variable coupler operating at 300 kW.

- Option III, 200 MHz + 2^{nd} harmonic with ACS-400: This option can be realized with compact $\lambda/4$ resonators which will require some R&D to establish the technology. However, the benefits by pursuing the path of longer bunches (1.3-2 ns) both for luminosity and e-cloud mitigation is promising [24]. The technology could potentially be used to alleviate bottlenecks in the SPS.

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Table 4: Estimate static and dynamic heat loads for the different RF systems foreseen in the LHC.

	Crab Cavities	ACS- 400 MHz	HH- 800 MHz	LH- 200 MHz
Temperature	2K	4.5 K		
Voltage [MV]	3.4	2.0	1.0	1.5
Static Load [W]	8	$\approx$50	10	10
Dynamic Cavity [W]	3	25	15	5
Dynamic Other [W]	4	$\approx$10		
Total/4-cavities [W]	60	340	140	100

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