Chapter 7

Crab Cavity Development

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The HL-LHC upgrade will use deflecting (or crab) cavities to compensate for geometric luminosity loss at low β^* and non-zero crossing angle. A local scheme with crab cavity pairs across the IPs is used employing compact crab cavities at 400 MHz. Design of the cavities, the cryomodules and the RF system is well advanced. The LHC crab cavities will be validated initially with proton beam in the SPS.

1. Crab Cavities

For higher luminosity operation, proton beams are squeezed to very small β^* at IP1 and IP5 (well below the nominal 55 cm). Controlling the effect of the large number of parasitic collisions requires a non-zero crossing angle. A non-zero crossing angle in combination with small β^* however implies a geometric reduction of the luminosity $R_\varphi = (1 + \varphi^2)^{-1/2}$ due to non-perfect overlap of the colliding bunches, illustrated in Fig. 1, left.

Here we use the Piwinski parameter $\varphi \equiv \frac{\theta_c \sigma_z}{2 \sigma_x}$, which is half the crossing angle $\theta_c/2$ normalized to the bunch aspect ratio (width/length). Crab Cavities are able to deflect the head and the tail of a bunch sideways in opposite directions such that their tilt at collision exactly compensates for the crossing angle (Fig. 1, right).

Fig. 1. Schematic of bunches colliding with an inefficient overlap due to non-zero crossing angle (left) and the geometry of crab crossing (right).

Fig. 2. Luminosity reduction factor R_ϕ as function of β^* for typical LHC parameters ($\Delta = 9.5\sigma$, $\varepsilon_n = 3.75\mu\text{m}$).

The dependence of R_ϕ on β^* for typical LHC parameters is plotted in Fig. 2. Consequently the potential gain with crab cavities is approximately a factor two in luminosity for $\beta^* = 20\text{ cm}$, even larger with smaller β^* .

2. Global and Local Schemes

Two schemes were considered for crab crossing in the LHC, the global scheme (cf. Fig. 3, left) and the local scheme (Fig. 3, right). The global scheme would require a single crab cavity per beam, installed, e.g. near Point 4, where presently all LHC RF systems are installed.^a The transverse kick introduced by this cavity, different for the head and the tail of each bunch, is equivalent to a closed orbit distortion, i.e. head and tail would follow their individual closed orbit around the ring, their tilt wobbling around the unperturbed closed orbit of the bunch center. It is clear that this scheme introduces severe constraints on the betatron phase advance between the location of the crab cavities and the IPs. It is also inconsistent with the different crossing angles implemented in IP1 (vertical crossing) and IP5 (horizontal crossing). Furthermore, the collimator settings would have to allow for the wobbling bunches. The advantage however is that the existing dogleg region near Point 4 with more available space and an increased beam separation of 42 cm would allow for larger cavities and more RF infrastructure.

The local scheme on the other hand introduces a localized perturbation upstream of the IP where crabbing is required and compensates for it downstream, such that through the rest of the ring the bunches remain unperturbed. This scheme requires 2 to 4 cavities per beam and per IP, so at least 8 cavities (and up to 16) if

^aMore than one cavity may be required if the required kick voltage cannot be obtained with a single cavity.

only the high luminosity regions (IP1, IP5) are considered. This scheme does not have the optics constraints of the global scheme between the two IP's and allows for the different crossing planes in IP1 and IP5. On the other hand, it requires more cavities and in particular cavities that are compact enough for the nominal beam pipe distance of 194 mm.

Fig. 3. Schematic for a global scheme (left) at IR4 and local scheme (right) at IP1 and IP5.

For its significantly better performance reach and its compatibility with machine protection, the local scheme has been chosen for the LHC luminosity upgrade and the resulting challenging spatial constraints and technology choices are discussed in the following section.

3. Technology Choice and Spatial Constraints

The upgrade lattice for a 7 TeV proton beam calls for superconducting crab cavities at a frequency of 400.79 MHz. The frequency choice is primarily driven by the

long proton bunches, but it is also convenient to use the same frequency as for the accelerating RF system. Four modules per experiment at the two high luminosity experiments (ATLAS and CMS) will be used to perform the rotation locally without perturbing the rest of the LHC machine. Each module consists of nominally four cavities and is expected to provide the required nominal kick voltage of 12 MV per beam per side of each collision point [1]. Seen from the IP, the cavities are placed outside the recombination dipole D2, where the beams are completely separated and in their individual beam pipes spaced by 194 mm, and the β -functions in the crossing plane are sufficiently large to minimize the required voltage. Due to remaining optical constraints, the ideal betatron phase advance of $\frac{\pi}{2}$ between IP and crab cavities may not be realized exactly; the orbit bump from the crossing angle is closed prior to the entry into the crab cavities to minimize beam loading effects with trajectory offsets.

The tightest constraint results from narrow beam pipe spacing in the transverse plane. Measuring from the electric center of the cavity (where the integral $\int_{-\infty}^{\infty} E_z e^{j\frac{\omega}{c}z} dz$ of the operating mode vanishes), the beam pipe at both ends of the cavity must leave a disk of radius 42 mm clear; this will allow the transverse alignment of the cavity without reducing the aperture for the beam. To allow passage of the second beam pipe (distance center to center 194 mm) it is required that the cavity transverse size does not extend beyond 145 mm from the same electric centre. Since both vertical and horizontal crossing are used, these tight constraints have to be respected in the crossing plane and the plane orthogonal to it, as indicated in Fig. 4.

In the longitudinal plane, the constraints are primarily dictated by the proximity to the neighboring elements, namely the D2 recombination dipole and the Q4 matching section quadrupole. A total of 13.3 m is reserved for two pairs of four cavities per IP [2]. The β -functions around IP5 are sketched in Fig. 5.

Fig. 4. Beam pipe separation and the maximum allowed cavity envelope in the LHC for crab cavities.

Fig. 5. Optical function in the interaction region 5 with lattice elements dipoles (red), quadrupoles (blue) and crab cavities (green).

4. Compact Cavity Design Options

Until 2006, compact crab cavities were considered “exotic” — they seemed to violate the rule of thumb for the transverse size of a superconducting cavity for the ratio radius to wavelength of 0.45 for the accelerating mode, 0.6 for the dipole mode. For a 400 MHz cavity crab cavity, this would imply a cavity equator radius of 450 mm — too large even for the dogleg area near Point 4. For this reason, the baseline frequency for an LHC crab cavity before 2008 was an 800 MHz cavity [3]. However, for this high frequency, the tails of nominal length bunches ($\sigma_z = 75$ mm, $4\sigma_z \sim 0.4\lambda$) would already suffer from the curvature of the sinusoidal RF wave. The challenge for “compact” crab cavities at 400 MHz was to have a “radius” of 145 mm as indicated in Fig. 4, requiring a ratio of radius to wavelength of below 0.193. Already for this reason, compact crab cavities are “unconventional” and have to be considered a real novelty in the panorama of new accelerator technologies.

Studies on compact crab cavities were intensified on both sides of the Atlantic and in April 2009 one of these unconventional designs, the 4-rod cavity (originally proposed by JLAB [4]), became task 10.3 in the FP7 project EuCARD [5] and was further developed in a collaborative effort led by University of Lancaster. In November 2011, the LHC crab cavities became a key part as Work Package 4 of the project HL-LHC, started as FP7 Design Study HiLumi-LHC. After only three years of intense research on compact crab cavities, four valid proposals had emerged, namely the 4-rod cavity, the ridged waveguide deflector, the parallel-bar cavity and the quarter-wave resonator (cf. Fig. 6, left to right).

Shortly after, the parallel-bar cavity and the ridged waveguide deflector designs merged to become the RF dipole (RFD), and the quarter-wave resonator was symmetrized and became the double quarter-wave resonator (DQWR); prototypes of the three remaining designs were subsequently fabricated by industry (see Fig. 7).

Fig. 6. Four candidate designs for compact crab cavities in 2011 [6].

Fig. 7. Nb prototypes fabricated by Niowave Inc. of the three remaining compact crab cavities.

5. Present Status of Prototype Cavities

These new topologies make it possible to integrate the cryomodules in the present LHC interaction region and simultaneously be used for the alternating crossing schemes in the two IPs. As a first step of RF design validation, the prototypes of all three cavities underwent comprehensive vertical tests to validate their performance (field levels, quench limit, ramping behavior, microphonics and multipacting).

The 4-rod cavity was first tested in November 2012 at CERN of up to a deflecting voltage of 1.5 MV (nominal 3.4 MV) and further surface processing was necessary before proceeding further which is suspected as a moderate multipactor zone cavity [7]. A vacuum leak due to irregular features on the knife edge of the NbTi flanges posed additional limitations. Further tests after the repair

of the flanges and additional surface treatments resulted in kick voltage of approximately 3 MV before quenching. The RF dipole cavity was tested in April 2013 at Jefferson Laboratory to a maximum of 7 MV kick voltage. The Q_0 of the cavity at the nominal field of 3.4 MV was approximately $3 \cdot 10^9$ corresponding to a surface resistance of 34 n Ω cavity [8]. At the quench voltage of 7 MV, the peak surface electric and magnetic fields are 75 MV/m and 131 mT, which are close to or above the state of the art in the field of superconducting RF. The RF dipole also reached well beyond the nominal voltage at 4.2 K and was limited by the available input power. The double quarter-wave cavity was tested in November 2013 at Brookhaven National Lab to a maximum of 4.6 MV kick voltage. The Q_0 of the cavity at the nominal field was approximately $2 \cdot 10^9$ with a surface resistance of 28 n Ω at low field [9]. The observed cavity quench at approximately 5 MV was due to localized heating in one of the HOM ports where the surface magnetic field is the highest.

6. RF Multipoles, Coupler Kicks and Limits

The crab cavity designs presently considered are such that they lack axial symmetry. Therefore, they can potentially exhibit all higher order components of the main deflecting field. Assuming an azimuthal variation of $\sim \cos(n\varphi)$ of the dipolar field, the transverse kick for a particle traversing the cavity can be expressed as sum of its multipolar components (using the notation and formalism derived in [10],

$$\Delta p_{\perp}(r, \varphi) = \frac{1}{c} \int_0^L F_{\perp} dz = \sum_{n=1}^{\infty} \Delta p_{\perp}^{(n)}(r, \varphi),$$

where $\Delta p_{\perp}^{(n)}$ are the multipolar components of the RF kick expressed in terms of the transverse electromagnetic fields integrated over the cavity length. For ultra-relativistic particles it is useful to express the RF multipoles in same units as standard magnetic multipoles with an essential difference being that RF multipoles are complex in nature:

$$b_n = \frac{1}{ec} \int F_{\perp}^{(n)} dz = \frac{nj}{\omega} \int E_{acc}^{(n)} dz \quad [\text{Tm}^{2-n}].$$

Due to certain symmetries inherent to each design, only odd multipoles have a non-zero component. Therefore, the first important multipole is the sextupolar component b_3 of the deflecting field. Long term tracking simulations with the

optical functions of the HL-LHC indicate that the b_3 -component should be limited to approximately 1 Tm^{-1} to limit the degradation of the dynamic aperture by less than 1σ for orbit offsets of 1.5 mm [11]. For all three cavities, the imaginary part of the kick of all multipoles is negligible within the accuracy of the calculation. Hence their contribution in the crabbing phase is generally small. This orbit stability is compatible with the beam loading specifications [12].

7. Frequency Tuning System

A number of procedures from the fabrication, final surface treatment and cavity cool-down will determine the final shape and the frequency of the cavity. During the cavity filling with RF fields, the Lorentz forces on the cavity will further perturb the frequency by (0.5–1) MHz in some of the cavities. A “slow” mechanical tuning system is required to alter the cavity shape to compensate for the frequency changes and bring it in resonance. The frequency can fluctuate during the operation due to external forces, which has to be compensated dynamically by an ancillary tuning system. Different tuning mechanisms have been proposed and adopted for each cavity design. A modified Saclay II type tuner with longitudinal force on the cavity to elongate or contract the cavity is designed [13]. A JLAB scissor jack mechanism to contract or elongate the cavity for the RF dipole is proposed due to the symmetry of the cavity along the beam axis [14]. Exploiting the coaxial symmetry of the double quarter-wave in the plane of deflection, a coaxial tuner combined with the Helium vessel is being designed [15]. The 3D models of the three designs are shown in Fig. 8.

Fig. 8. Tuning Concepts adopted for the 4-rod cavity (left), the RF dipole (middle) and the double quarter-wave cavity (right).

To make the cavity transparent to the beam if crabbing is not needed, two options are considered: either the cavities are independently detuned by $Q \cdot f_{\text{rev}}$ from resonance, where Q is the betatron tune to suppress coupled bunch instabilities in the crabbing mode or counterphasing of a group of cavities is used.

A tuning resolution of a quarter of the final cavity bandwidth is required due to the available RF power. Therefore, a dual tuning system with a large span in the MHz range and an ancillary fine tuning system with a resolution in the 100's of Hz range is yet to be realized.

8. RF System and Controls

8.1. Beam loading and RF power requirement

For a beam centered in the crab cavities, there is no beam loading. Therefore, the minimum required power is dictated by the losses in the superconducting cavity (negligible) and the required power to maintain the cavity stably on resonance. This power decreases monotonically with Q_L . However, due to unavoidable offsets and drifts in a circulating beam (for example, injection oscillations), a non-zero beam loading proportional to the shunt impedance and the circulating beam current is induced. A sufficient bandwidth and the corresponding power are required to compensate for the unavoidable orbit offsets. Figure 9 shows the required forward power as a function of Q_L for a beam that is centered and off-centered by 1 mm.

The power has a broad minimum of approximately 25 kW for Q_L between $3 \cdot 10^5$ and $1.5 \cdot 10^6$. The cavity field can be kept constant by adjusting the forward power for the corresponding displacement. Selection of an optimal value in the broad minimum is a compromise between the tuning precision feasible and the minimization of the field fluctuations from the amplifier electronics [16]. To

Fig. 9. Forward power vs. cavity Q_L for centered (red) and 1 mm offset (blue) beams. Assumed $R/Q = 300 \Omega$, 3 MV RF, 1.1 A DC [12].

minimize the power needed to compensate for fast tune variations it is also desirable to keep the cavity bandwidth larger than the frequency of the mechanical modes which favors a lower Q_L .

8.2. Power amplifier and input coupler

A LEP type 400 MHz (40–80) kW tetrode is presently being tested as a possible option for the power amplifier for their efficiency and stability [12]. The bandwidth is approximately 1 MHz. Two such tetrodes can be combined to provide a maximum of 80 kW which would provide sufficient margin for RF and beam manipulations. It is perhaps imaginable that solid state amplifiers replace the tetrodes in the power range of interest on the longer term. The input coupler design corresponding to this power level resulted in a choice of inner diameter of 27 mm and a corresponding coaxial outer tube diameter of 62 mm. Due to the relatively low average power, air cooling of the inner antenna can be considered. The cavity will interface with the cryomodule assembly via a double wall tube, which will serve as a common platform for all three cavities. A coaxial ceramic will provide the air to vacuum interface with appropriate bellows between the double wall tube and the cryomodule. The window assembly will be equipped with vacuum gauge, electron monitor and arc detection devices. These types of windows have been

Fig. 10. Crab cavity input antenna (top left), ceramic windows and the double wall tube assembly (top right) and the complete power coupler assembly (Courtesy E. Montesinos).

widely used in the SPS cavities reliably at high power for many years [17]. Schematic of the input antenna and the ceramic assembly with the double wall tube is shown in Fig. 10.

8.3. RF controls and machine protection

Limitations from the round turn loop delay for cavity control should be taken into account for the fast feedback to cope with effects from fast RF failures. The amplifier driven by a feedback system feeds a compensating current to cancel the beam current. The cavity impedance is then effectively reduced by the feedback gain. Therefore, the limiting factor in the RF chain is the round-turn group delay. Therefore, a short distance between the cavity and the power amplifiers is preferred [16]. Above a certain feedback gain, the loop delay will drive the feedback into electrical oscillations. The minimum effective impedance is

$$R_{\min} \sim \frac{R}{Q} \omega_0 T,$$

where ω_0 is the RF frequency, R/Q the classic cavity parameter and T the group delay of the feedback loop. Therefore, a radiation free cavern close to the crab cavity location in the LHC tunnel is required to keep the RF feedback delay to less than about $1.5 \mu\text{s}$. This allows a significant reduction of the cavity impedance seen by the beam.

A phase modulation of the accelerating cavities is required to minimize the transient beam loading effects. If the crab cavities are operated from the fixed RF frequency references, it will result in a 60 ps maximum displacement of a bunch center from the zero phase in the crabbing field. For the longitudinal displacement of the luminous region this may be acceptable given the 1 ns bunch length; the resulting transverse offset of the bunch centroid in the IP however (see below under “RF noise and stability”) will require that the LLRF synchronizes bunch by bunch correctly taking the actual phase modulation into account. The effect of phase modulation and the correction methods can be measured in the planned crab cavity test in the SPS.

A rapid change of the field in one cavity (for example a fast quench or a power supply trip), the LHC Beam Dump System (LBDS) will act to extract the beam in a minimum time of three turns ($270 \mu\text{s}$). Two kinds of interlocks are foreseen: slow (on BPMs) and fast (on RF). The RF controls should minimize the effect on the beam within the three turns to avoid abrupt displacements which can potentially damage the machine elements. Therefore, independent power systems of each cavity with a short delay cavity controller are proposed [16]. Figure 11

shows the proposed LLRF architecture. A central controller between the two systems across the IP makes the required corrections to adjust the cavity set points as necessary.

Fig. 11. Proposed LLRF architecture for one ring at one IP. Cavity controller: strong RF feedback ($< 1.5 \mu\text{s}$ loop delay) regulating individual cavities; 8-in-1 multi-cavity feedback controller: global feedback regulating the relative crabbing-uncrabbing actions. Loop delay about $5 \mu\text{s}$ [16].

The BPM interlock post-mortem, i.e. the last recorded trajectories could be used to study the effect on beam during a cavity failure. Operationally, it is preferred to have a low $Q_{\text{ext}} (\sim 10^5)$, as the cavity frequency is less sensitive to perturbations. However, it is assumed that machine protection may benefit from a high $Q_{\text{ext}} (\geq 5 \cdot 10^5)$ to help avoid fast reaction on the frequency and phase changes of cavity. Consequently, the cavity will be more sensitive to external perturbations.

8.4. RF noise and stability

Cavity voltage amplitude jitter introduces a residual crossing angle at the IP proportional to the error as shown in Fig. 12, left. It is sufficient that this residual crossing angle is much smaller ($< 1\%$) than the geometric angle leading to a tolerance of electronics [18]:

$$\frac{\Delta V}{V} \ll \frac{1}{\varphi},$$

where φ is the Piwinski parameter. A phase error in the RF wave causes an offset of the bunch rotation axis translating into a transverse offset at the IP (cf. Fig. 12, right). The offset at the IP is given by

$$\Delta x_{\text{IP}} = \frac{c \cdot \theta_c}{\omega_{\text{RF}}} \delta \varphi_{\text{RF}}$$

Fig. 12. Schematic of cavity voltage amplitude error leading to a residual crossing angle (left) and a phase error leading to an offset at the IP (right).

where θ_c is the full crossing angle (cf. Fig. 1) and φ_{RF} is the crab cavity phase with respect to the synchronous particle. For the HL-LHC parameters, the voltage error ratio should be kept to below 0.1%. The challenging aspect is to control the phase jitter across the IP to below $5 \cdot 10^{-3}$ degrees to minimize transverse emittance growth. This corresponds to a transverse displacement of 5% of the beam size at the IP [19].

The amplitude and phase control must be achieved also during filling and ramping with “zero” field in the cavities. Smooth transition between no-crabbing and crabbing must be realized. A single reference generated in a surface building above the accelerating cavities is sent over phase-compensated links to respective crab cavities at IP1 (ATLAS) and IP5 (CMS). An alternative would be to regenerate the bunch phase from a local pick-ups [12].

8.5. Impedance budget and higher order mode damping

On resonance, the impedance of the fundamental deflecting mode is canceled between the positive and negative sideband frequencies, which are symmetric around ω_{RF} . When the cavity is not operational the impedance of the fundamental deflecting modes has to be damped by appropriate feedback.

For higher order modes (HOMs), both narrow band and broadband impedance should be minimized throughout the entire energy cycle as LHC will accelerate and store beams of currents of 1.1 A (DC). Tolerances are set from impedance thresholds estimated from [20].

The longitudinal impedance has approximately a quadratic behavior in the region of interest with the minimum threshold value at approximately (300–600) MHz. The total maximum allowed impedance from each HOM, summing over all cavities in one beam, assuming that the HOM falls exactly on a beam harmonic, is set at $< 200 \text{ k}\Omega$, so if all 16 cavities have identical HOM frequencies,

the longitudinal impedance must not exceed $12.5 \text{ k}\Omega$ per cavity. For frequencies higher than 600 MHz, the threshold is higher ($\propto f^{5/3}$), but the same threshold was imposed. Modes with frequencies above 2 GHz are expected to be Landau-damped due to natural frequency spread and synchrotron oscillations.

In the transverse plane, the impedance threshold is set by the bunch-by-bunch feedback system with a damping time of $\tau_D = 5 \text{ ms}$ [12]. Assuming the pessimistic case that the HOM frequency coincides with the beam harmonic, the maximum impedance is set to be $< 4.8 \text{ M}\Omega/\text{m}$. Again, assuming 16 cavities per beam, the maximum allowed impedance per cavity is $0.3 \text{ M}\Omega/\text{m}$. Analogous to the longitudinal modes, frequencies above 2 GHz are expected to be Landau-damped due to natural frequency spread, chromaticity and Landau octupoles. It should be noted that there are nominally only eight cavities per each transverse plane, so the threshold per cavity is higher, but the $0.3 \text{ M}\Omega/\text{m}$ is given assuming that the crossing plane between the experiments could become the same as a worst case scenario.

Due to the very tight impedance thresholds, the distribution of the HOM frequencies due to manufacturing errors can help relax the tolerances. The beam power deposited in the longitudinal HOMs can become significant when the frequencies coincide with bunch harmonics. The HOM couplers were dimensioned to accept a maximum of 1 kW to be able to cope with HL-LHC beams [21].

8.6. 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 2748 bunches into the LHC, ramping or operation without crab cavities, the cavities are detuned ($+1.5 \text{ kHz}$). With a positive non-integer tune ($Q_h = 64.3$, $\omega_b/\omega_{\text{rev}}$ above an integer), the cavity should be tuned above the RF frequency to make the mode $l = -64$ stabilizing (see Fig. 13). Although RF feedback is not mandatory for stability with a detuned cavity, however, for accurate knowledge and control of the cavity tune and field, active feedback is preferred. Active feedback will also keep the beam induced voltage zero if the beam is off-centered. As the kick is provided by a set of four cavities, counter-phasing is preferred to make the cavity invisible to the beam.

On flat top, detuning (if used) is reduced while keeping the cavity voltage small using counter-phasing. The RF feedback keeps the cavity impedance small (beam stability) and compensates for the beam loading. Subsequently the crab cavities are rephased synchronously to obtain the desired kick voltage. Any leveling scheme is possible. With a circulator between TX and cavity, the TX response is not affected by the cavity tune. This is very favorable for the proposed active

compensation scheme, with a cavity being gently moved from parked position to on-tune.

In physics, with the crabbing on, the active RF feedback will provide precise control of the cavity field. The RF feedback reduces the peak cavity impedance and transforms the high Q resonator into an effective impedance that covers several revolution frequency lines (Fig. 13). The actual cavity tune has no big impact on stability anymore; the growth rates and damping rates are much reduced.

Fig. 13. 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).

9. Integration into SPS and 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.

9.1. SPS-BA4 test setup

The SPS ring is equipped with a special bypass (Y-chamber) with mechanical bellows that can be displaced horizontally (see Fig. 14). This allows for a test module to be placed out of the beam during regular operation of the SPS and only moved in during the dedicated machine development. 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 2-cavity cryomodule is envisioned for installation in the 2016–17 end of the year technical stop. This cryomodule 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. A cryogenic box in the BA4 region is presently being prepared to deliver 2 K Helium for the test operation of the crab cavities [12].

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Fig. 16. Possible 3D integration of the cryomodule, RF assembly and the cryogenics in the BA4 region of the SPS.

Fig. 17. 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.

with the shortest delay loops between the RF transmitter and the cavity (see Fig. 17). To minimize RF group delay a short distance between amplifiers and cavities is required. Short delay is already in place for the ACS main RF system in Point 4. A service gallery parallel to the tunnel would allow for sufficient shielding to sensitive RF electronics and possibly easy access to the RF equipment.

Near Points 1 and 5, the closest area to house any equipment is in the RR caverns at about 80 m from the crab cavities. They were considered to place RF electronics. However, the transmission lines are of significant transverse dimension and passing eight such lines through the tunnel cross-section is a major challenge. More importantly, high radiation levels in the RR caverns practically exclude placement of sensitive RF electronic equipment in them.

Considering these reasons, it is highly desirable to either extend the experimental service gallery towards the crab cavity regions near Points 1 and 5 or to consider surface installations above them for RF equipment. A study is ongoing to determine the feasibility of the civil engineering with minimal perturbation to the LHC running.

9.3. Positioning and alignment

The positioning and alignment of the 4-cavity system in the LHC is an important challenge in order to respect the tolerances set forth from the beam dynamics and RF. These can be generally classified into four groups and effects are briefly described:

- (1) Transverse rotation of the individual cavities with respect to each other or the cryostat introduces a parasitic crossing angle in the non-crossing plane, thereby counteracting the compensation scheme. In addition, it can also cause a non-closure of the crab bump in the crossing plane. Using a similar analogy to voltage modulation of the cavity, a transverse rotation of approximately 0.3° per cavity can be tolerated.
- (2) Tilt of the cavities with respect to the longitudinal cryomodule axis in the crossing plane introduces a beam loading in part of the cryomodule proportional to the tilt. Analogous to the 1 mm tolerance from the power requirements, the tilt with respect to the longitudinal axis should be less than 0.06° . The tilt in the non-crossing plane is nominally more relaxed, but due to the alternating crossing scheme, the same tolerance is imposed in both planes.
- (3) Transverse displacement of cavities with respect to each other inside a cryostat. This is analogous to (2) and an intra-cavity alignment of approximately 0.7 mm is set primarily to minimize the beam loading and multipolar effects.
- (4) Longitudinal displacement of cavities with respect to each other inside a cryostat from their nominal position is less critical as the deviation can be compensated by adjustments of the individual cavity set point voltages to account for changes in the optical functions. The tolerance is set by respecting a change less than 0.1% of the nominal voltage, which corresponds to approximately (1–2) cm.

The SPS tests will play a key role in establishing the feasibility of such tight tolerances and the use of remote alignment techniques, both passive and active to achieve the requirements. In the SPS, this includes the movement of the support table into and out of the beam by approximately 55 cm while respecting the internal alignment tolerances.

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