OPERATIONAL SCENARIOS

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Abstract:
The operational concept of the crab cavity system with 12 independent cavities for each IP during the injection, energy ramp and collisions is outlined. The RF system to accomplish RF cycle is briefly summarized.
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Executive summary

The operation of the crab cavities in the LHC in their final configuration with 6 independent cavities for each interaction point per beam during the energy full cycle of the LHC is described. The RF system to perform the operational cycle is outlined.

1. INTRODUCTION

To reach the goal of (200 ... 300) fb$^{-1}$ per year with the LHC, stronger focussing to reach smaller beam sizes and non-zero crossing angles are studied in HiLumi LHC; the geometry of such beams however require crab cavities to realign the bunches in the interaction point (IP) for maximum overlap. A pair of crab cavities placed on either side of a high-luminosity interaction region (IR), separated by an integer multiple of half the betatron period, will create a closed bump – localized to the IR – for the head of each bunch to one side, for the tail to the other side.

In physics operation of the HL-LHC, it is mandatory that the crab cavities are invisible during the injection of beams and the energy ramp of up to 7 TeV. They are adiabatically brought in to resonance and to the nominal set point voltage with the two LHC beams in collision. In the scenario of luminosity levelling with crab cavities, the appropriate voltage is programmed from an initially small value to the nominal set point during the course of a physics fill to maximize the integrated luminosity by carefully controlling the crossing angle and trajectory at the collision point.

This document summarizes the concept envisioned and the RF system to operate the 6 cavities per interaction point (IP) per beam to control the crossing angle and trajectory during a typical physics fill with crab cavities in operation. Aspects of cavity transparency and machine protection are also addressed.
2. CRAB CAVITY LAYOUT FOR HL-LHC

Using the ATS optics for the HL-LHC [1], three cavities 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 conceived 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 $\beta$-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 to ensure machine protection which is detailed in the following sections.

![Figure 1: Schematic of the crab cavity layout on each side of the IP (not to scale).](image)

3. RF POWER AND CONTROL ARCHITECTURE

An independent powering system using LEP type 400 MHz tetrodes (or an equivalent IOT) of (40…80) kW is assumed. Advances in solid state technology in this decade could lead to power sources within the required range and provide a cheaper and more robust platform. This range of power provides adequate overhead in a compact footprint ideally suited for the proposed crab cavity layout. This scheme also would allow 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. Most importantly, the fast control of the cavity fields will 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. For such a fact and active feedback, a short overall loop delay between the RF system and the cavity is required [2].

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 ($0^\circ$ 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 $x$. 
For a 1 mm offset (tentative specification on the beam centring in the crab cavities), the power versus $Q_L$ curve shows a broad minimum from about $3 \cdot 10^5$ to $1.5 \cdot 10^6$. 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 range comes from a compromise: a large $Q_L$ reduces the field fluctuations created by the LLRF electronics and TX noise. But for tuning, a low $Q_L$ is usually favourable as it relaxes the precision needed for the tuning mechanism. To 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 (low $Q_L$). Selection of the optimal $Q_L$ will follow from the SPS tests.

3.2. 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.

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 transient beam loading caused by the modulated beam current (presence of gaps between bunch trains) to keep the field exact for all bunches.

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 electronics, transmitter noise, fluctuations in cryogenic pressure, mechanical vibrations) 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. Smooth transition between no-crabbing and crabbing must be realized.

This system also synchronizes the phase of the RF kicks with the exact 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). An alternative would be to re-generate the bunch phase from a local Pick-Up. 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.

3.3. COUPLE 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

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

where $\omega_0$ 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 ($< 1 \mu$s). With this figure we can reduce the impedance by 350 linear for $Q_L = 10^6$ [3].

3.4. 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 six cavities of a given ring at a given IP in a 6-IN, 6-OUT feedback. Figure 3 shows the proposed architecture. Each cavity had 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 a cavity, the Multi Cavity feedback would adjust the field in the other cavities on both sides of the IP, so that the rotation quick remains closed during the critical three turns. This mechanism will be developed and tested in the SPS with two cavities.
4. **OPERATIONAL SCENARIO**

4.1. **CAVITY TRANSPARENCY AND OPERATION**

The crab cavities are used only with stable beams in collisions to control the luminosity at each IP. During the injection of the beams into the LHC and the energy ramp, the crab cavities are detuned from their resonant frequency to stay in between the revolution harmonics. In addition only a very small voltage is induced into the cavities for feedback control while minimizing any perturbation to the beam when not in use. An additional orbit feedback system is required to suppress the effects of injection oscillations and other inevitable offsets during the injection and energy ramp. Active feedback is required to compensate beam loading.

4.2. **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 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. If the crab cavities are operated from the fixed RF frequency references, it will result in a 60 ps maximum displacement of a bunch centre from the zero phase in the crabbing field. This may be acceptable given the 1 ns bunch length. If not, the LLRF must synchronize the bunch-by-bunch crabbing field with the actual phase modulation. The effect can be measured in the SPS test-stand and corrections can be tested if needed.

Figure 3: Proposed LLRF architecture for one ring at one IP.
4.3. OPERATIONAL SCENARIOS IN THE LHC

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 cavity is detuned, but kept with a small field requested for the active tuning system. Parking the cavity half distance between two revolution frequency sidebands would be ideal for stability. As the kick is provided by a pair of cavities, counter-phasing can 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 voltage set point very small. 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 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.

4.4. SPS BEAM TESTS

The addition of crab cavities to the LHC should ensure a robust functioning through the entire sequence of the LHC physics cycle. Since crab cavities of such type have yet to be realized and used with Hadron beams, beam tests with a prototype two-cavity cryomodule is a prerequisite to identify potential risks of the technology for a safe and reliable operation of the LHC. Therefore, an essential milestone for a crab cavity in the SPS is to demonstrate the machine protection and cavity transparency. All RF manipulations and cavity-beam interactions will be first validated and commissioned in the SPS with a prototype two cavity crab cavities system. This is anticipated to be performed in 2016.

For the LHC, the cavities will be detuned and at “zero-voltage” (but with active feedback) to be invisible at injection and energy ramp. Therefore, accumulation of beam with “zero-voltage” in the SPS with active feedback will be tested. Other issues related to beam loading and transient effects with and without RF feedback & slow orbit control will be studied to evaluate the stability and tolerances required from the feedback systems. Induced RF trips and its effects on the beam will be studied in detail to guarantee machine protection and to devise appropriate interlocks. Long term effects with crab cavities on coasting beams at various energies will also be tested.

For beam tests in the SPS a slow mechanical tuner system is required to bring the cavity on resonance in the energy range of the SPS (±60 kHz). In addition the tuner in conjunction with the RF feedback should allow for detuning or retuning of the cavity at a safe frequency, including cavity transparency and the suppression of the coupled bunch instabilities. Table below summarizes the potential energies at which SPS can be operated for crab cavity tests and their corresponding RF frequencies compared to that of the LHC operation.
Table 1: Detuning ranges for the LHC and SPS

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<th>Unit</th>
<th>LHC</th>
<th>SPS</th>
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<tr>
<td>Energy</td>
<td>GeV</td>
<td>450…7000</td>
<td>120</td>
</tr>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>400.79</td>
<td>400.73</td>
</tr>
<tr>
<td>$\Delta F_0$</td>
<td>kHz</td>
<td>0</td>
<td>-58.2</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>kHz</td>
<td>0.4…4</td>
<td>0.4…4</td>
</tr>
<tr>
<td>Detuning</td>
<td>Hz</td>
<td>±5.5</td>
<td>±21.7</td>
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During the LHC beam injection, ramp and flattop, the cavity should be maintained as transparent as possible by means of detuning. A detuning frequency should be kept away from $Q \cdot f_{\text{free}}$ where $Q$ is the betatron tune to suppress coupled bunch instabilities in the crabbing mode for the growth rate to stay below the threshold set by the transverse damper ($\tau_D = 60$ ms). The largest detuning expected is approximately ±5.5 kHz in the LHC and approximately ±21.7 kHz in the SPS. The detuning requires a resolution of at least ¼ of the final cavity bandwidth due to available power limits. Additional studies have to be carried out to verify if a tuning speed higher than the mechanical tuner is required if limitations arise from feedback and/or orbit control.

5. CONCLUSION

A concept using independent RF powering for each cavity with a combined LLRF system to operate the 6 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. The precise control of the crossing angle and beam trajectory at the interaction point during a luminosity run and RF manipulations to ensure cavity transparency during the beam filling and energy ramp were also described. These concepts will be thoroughly tested in the SPS using a prototype crab cavity system to validate the technology, controls and beam related aspects including machine protection.

6. REFERENCES

## ANNEX: GLOSSARY

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<tr>
<td>ACS</td>
<td>Superconducting Accelerating Cavity</td>
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<tr>
<td>IOT</td>
<td>Inductive Output Tube</td>
</tr>
<tr>
<td>IP</td>
<td>Interaction Point</td>
</tr>
<tr>
<td>IR</td>
<td>Interaction Region</td>
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<tr>
<td>LEP</td>
<td>Large Electron-Positron Collider</td>
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<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
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<tr>
<td>LLRF</td>
<td>Low-level RF</td>
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<tr>
<td>TX</td>
<td>Transmitter</td>
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