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OPERATIONAL SCENARIO DURING LHC RAMPING SPECIFIED

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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.
OPERATIONAL SCENARIO DURING LHC RAMPING SPECIFIED

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<tr>
<th>Name</th>
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<tr>
<td>Authored by P. Baudenghein, R. Calaga, E. Jensen</td>
<td>CERN</td>
<td>18/05/2013</td>
</tr>
<tr>
<td>Edited by R. Calaga, E. Jensen</td>
<td>CERN</td>
<td>20/05/2013</td>
</tr>
<tr>
<td>Approved by L. Rossi [Project Coordinator]</td>
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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

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.

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 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 to ensure machine protection which is detailed in the following sections.

3. RF POWER AND CONTROL ARCHITECTURE

An independent powering system using tetrodes or IOTs 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, with an assumed loaded $Q$ in the order of $10^6$. 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. 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. LOW LEVEL RF SYSTEM

The low level RF (LLRF) system has the following functions: 1) a tuning control assures the cavity to remain on tune during operation and off tune during filling, ramping and when crabbing is not used, 2) a feedback system keeps the deflecting field at the command value, allowing for different fields in different cavities, counter-phasing between cavities and similar, 3) a fast RF feedback (see next paragraph), working during crabbing and when the cavity command voltage is zero to reduce the impedance of the cavity and to reduce the effect of noise, 4) synchronisation of the RF kicks with the bunch passage, i.e. an exact phase control of the deflecting RF field.

3.2. COUPLED BUNCH INSTABILITIES

Fast RF feedback can actively cancel beam excited fields and has proven to be an effective tool to reduce the effective impedance for accelerating cavities; this principle will be directly adapted to the crab cavities. A limitation of this principle results 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

\[ R_{\text{min}} \approx \frac{R}{Q} \omega_0 \tau, \]

where \( \omega_0 \) is the frequency, \( R/Q \) the classic cavity parameter and \( \tau \) 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 \( Q_t = 10^6 \) [3].

4. OPERATIONAL SCENARIO IN THE LHC [3]

As outlined above, the crab cavities will be equipped with a strong RF feedback as described under 3.2 above, which will have to be turned on at all times, i.e. during crabbing and when transparent. Transparent here denotes situations where the cavities shall have no net effect on the beam, i.e. during machine fill and ramp, but also when operating the LHC without crab fields. To make the cavities transparent, they will be detuned from the operation frequency. The field in each individual cavity will however be set to a non-zero value in order for the tuning loop to work correctly. Making the overall deflecting voltage zero is obtained by making the vector sum of the individual voltages zero, e.g. by de-phasing them by 360°/n when operating with n cavities. The RF feedback will also be used with the cavities detuned, which will allow to always control beam stability and to keep the beam induced voltage to zero even if the beam is off-centred. In this operation, the requested TX power can directly be used to measure the beam loading (and thus the beam offset).
Once the beams will have reached the flat to and before the squeeze begins, the detuning will be slowly reduced still keeping the vector sum of the deflecting voltages at zero and with RF feedback on to keep the effective cavity impedance small, also when the detuning reaches zero and the cavity is in resonance. Once in collision and when crabbing of a certain quantity is requested, predefined functions will assure that the cavity voltages are synchronously controlled to reach the correct deflecting voltage.

4.1. 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.

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 sketched. 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