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LLRF STUDIES FOR HL-LHC CRAB CAVITIES

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Abstract

The HL-LHC upgrade includes sixteen Crab Cavities (CC) to be installed on both sides of the high luminosity experiments, ATLAS and CMS. Two issues have been highlighted for the Low Level RF: transverse emittance growth (and associated luminosity drop) caused by CC RF noise, and large collimator losses following a CC trip. A prototype cryomodule with two CCs has been installed in the SPS, and tests have started in May 2018 with beam. This paper briefly reports on preliminary results from the SPS tests. It then presents emittance growth calculations from cavity field phase and amplitude noise, deduces the maximum RF noise compatible with the specifications and presents a possible cure consisting of a feedback on CC phase and amplitude. To reduce the losses following a CC trip we propose to implement transverse tail cleaning via the injection of CC noise with an optimized spectrum, which selectively excites the particles of large transverse oscillation amplitudes.

INTRODUCTION: LHC CRAB CAVITIES

The HL-LHC upgrade aims at a tenfold increase in p-p integrated luminosity compared to the present LHC. This will be achieved with a doubling of the bunch intensity (2.2 10^{11} p/bunch) and a reduction of the beam transverse size at the Interaction Points (IP) 1 (ATLAS experiment) and 5 (CMS). The bunch spacing (25 ns) and the total number of bunches (~2800) will not be changed. An upgrade of the LHC injector chain was launched to achieve the bunch intensity increase, and should be completed by early 2021. Stronger insertion magnets will be installed on each side of the two experiments to reduce the transverse emittance. The β^* will be reduced from the design 55 cm to 15 cm [1].

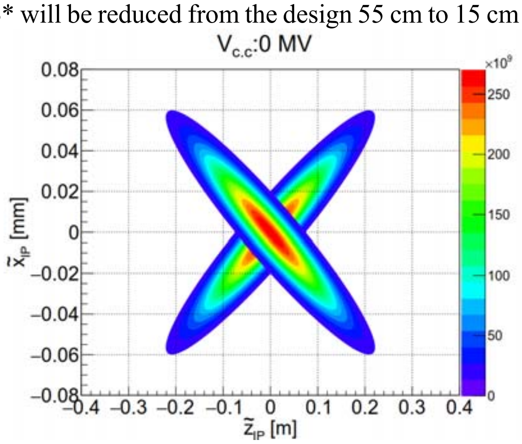

Figure 1: HL-LHC bunch crossing without crabbing.

The LHC beams circulate in a common chamber for ~100 m on each side of the IPs. In this zone the beams must be separated transversely to avoid detrimental long-range beam-beam interactions. Separation is accomplished by introducing a crossing angle, which must scale with the inverse of the transverse beam size at the IP to maintain a constant normalized separation. The HL-LHC full crossing angle will be 500 μrad, to be compared to the present 280 μrad.

Bunch crossing at an angle with very small transverse beam size leads to a reduction of luminosity, quantified by a factor R. Figure 1 shows the HL-LHC bunches (σ_z= 9 cm) crossing at a 250 μrad half-crossing angle, assuming a Gaussian distribution. The luminosity reduction factor is

$$R(\theta)=\frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_t^*}\frac{\theta}{2}\right)^2}} \qquad (1)$$

where θ is the full crossing angle, σ_z is the rms bunch length and σ_t* is the rms transverse bunch size at the IP in the crossing plane. The later alternates between vertical and horizontal (ATLAS and CMS). Without crab cavities the peak luminosity is reduced by a factor of 3 compared to head-on collision.

Crab cavities are RF deflectors, phased so that the longitudinal bunch centroid receives no kick, while the head and tail receive transverse kicks in opposite directions, to rotate the bunch and restore almost head-on collisions at the IPs (Fig. 2).

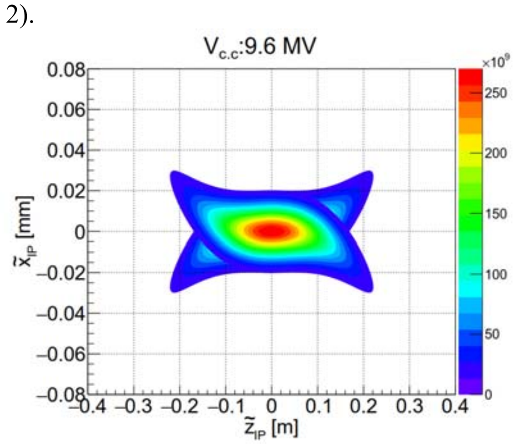

Figure.2: HL-LHC bunch crossing with full crabbing.

The LHC crab cavities operate at the 400.8 MHz fundamental that is also the accelerating frequency. The effect of the RF curvature is clearly visible, caused by the large bunch length. KEK used a Global Crabbing Scheme, with the bunch rotation propagating all around the machine [2]. In the HL-LHC the crabbing will be localized around IP1 and 5: there will be two CCs at -90 degree betatron phase advance ahead of the IP initiating the rotation, and two CCs at 90 degree phase advance after the IP to stop the rotation. Crabbing therefore does not propagate in the rest of the ring. The LHC will not use the full crabbing shown on Fig.

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2 since the experiments would not cope with the peak luminosity due to pileup. Instead, we will use a partial compensation with 6.8 MV only, that can be provided using two crab cavities (Fig. 3). Both β* and crabbing voltage will actually be programmed during an HL-LHC fill to optimize integrated luminosity while keeping instantaneous luminosity at a level comfortable for the detectors [3], a strategy called lumi-leveling. HL-LHC will include sixteen CCs total, two per beam and per IP side around ATLAS and CMS.

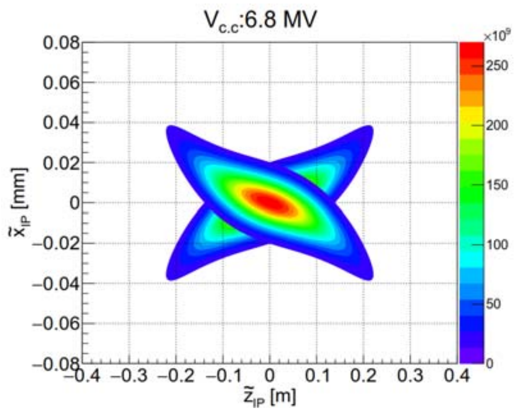

Figure.3: HL-LHC bunch crossing with the planned partial crabbing.

FIRST SPS TESTS

Before installing the sixteen cavities in the LHC during the Long Shutdown 3 (2024-2025?), it was decided to first test two cavities in the SPS, with a high intensity proton beam. Although CCs have been operated successfully in KEK [2], the HL-LHC differs in several points: first we will use local crabbing, and it is important to show that we can regulate individual CC voltage amplitude/phase precisely to null the effect outside the IP1-5 regions. Second, CCs have never been used with hadrons. In lepton machines, synchrotron radiation provides a very fast damping mechanism for the emittance growth caused by RF noise. Bunch shortening is observed in the LHC at 6.5 TeV but the damping time is tens of hours. As a consequence RF noise can be very detrimental in the CCs when used with protons. Third, it is essential to measure the exact HOM frequencies in operation and the extracted power with high intensity beam.

A cryomodule containing two CCs has been installed in the SPS during the 2018 winter break. The two cavities are of the Double Quarter Wave type (DQW), oriented to produce vertical crabbing [1]. With two cavities we can test the precision of field regulation by operating them in counter-phasing mode. Figure 4 shows the cryomodule and cavities [4]. Each cavity is intended to be operated at 3.4 MV. There is zero beam loading in a CC if the beam is centered. In the HL-LHC design we have accepted a ±2 mm beam offset. The Q_L was then selected to minimize the required power with this offset, for the HL-LHC beam intensity (1.1 A DC), resulting in Q_L=500000 [1]. The coupling is identical in the SPS CCs.

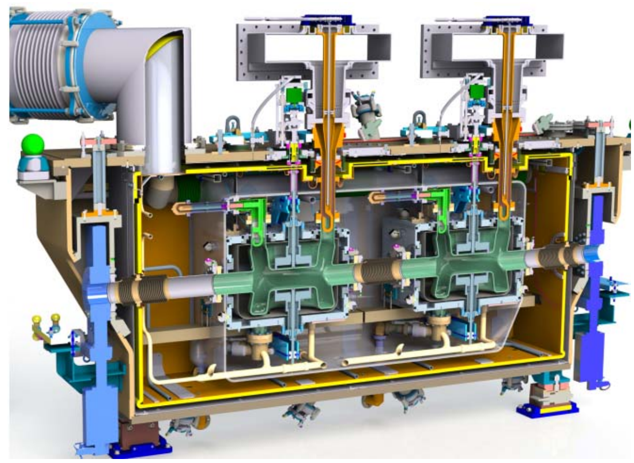

Figure. 4: The SPS cryomodule with two CCs.

The CCs are made of plain Niobium, to be operated at 2 deg K. Due to problems with the cryogenics, the May 2018 tests were done at 4.5 deg K. At that temperature, He ebullition leads to a fluctuation of the cavity tune by more than one cavity bandwidth (400 Hz, single sided), observed with a period around one second. The CC tuning system acts by mechanical pressure on the deflecting gap, and is not fast enough to track these fluctuations. Fortunately, the tune is reasonably stable over a timescale of a few minutes. Tests were therefore possible without a tuning loop, at a reduced voltage (1 MV for CC1, 100 kV for CC2 due to poor conditioning). The first SPS test was conducted at a fixed 26 GeV energy corresponding to 400.528 MHz RF frequency that is still in the tuning range. Although the tune was not controlled, field regulation was provided by a strong RF feedback with a small loop delay (< 2 µs). We used a single $1.1\ 10^{11}$ p bunch. Before injection the CCs were switched ON, the amplifier drive was ramped-up and the RF feedback was closed. Then the bunch was injected, followed by the rephasing of the bunch to the CC RF. A phase scan was performed at 26 GeV and the crabbing was measured with a Head-Tail monitor (Fig. 5). The instrumentation was not calibrated (no correction for cable attenuation). Nevertheless comparison with Fig. 1-3 clearly indicates the expected crabbing. A second test was performed at 270 GeV: the CCs were OFF at injection and during the acceleration ramp. At the beginning of the 270 GeV plateau the single bunch was rephased to the CC reference RF. Then the CCs were ramped up in voltage and crabbing was observed during the 10 s long 270 GeV plateau. We observed no measurable degradation of intensity or emittance during these ten seconds, but the timescale is of course orders of magnitude from the 5-10 hours of an LHC physics fill. In June the CCs will be warmed-up for an intervention on the cryogenics that will enable operation at 2 deg K in July, with batches of up to 288 p bunches.

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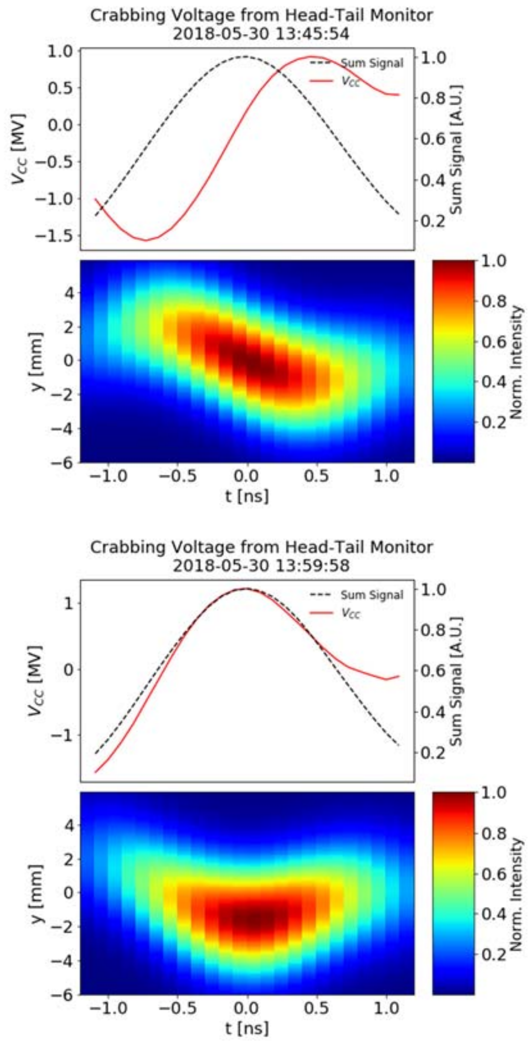

Figure.5: SPS test. Crabbing measured with a Head-Tail monitor. The monitor measures the transverse position (Delta signal) and the longitudinal profile (Sum signal), along the z-direction. The 2-D plots are then reconstructed assuming Gaussian distributions. Top: 0 deg CC phase w.r.t. bunch core, bottom 90 deg.

LOW LEVEL RF

General Architecture

The cavity field is measured and regulated via a strong feedback. The method is similar to the one used for the LHC accelerating cavities. The gain of any feedback system is limited by the loop delay. The delay was therefore minimized in the HL-LHC layout: amplifiers and LLRF will be installed in four caverns located close to the CCs. The resulting loop delay of less than 2 µs allows a regulation bandwidth up to 100 kHz. Within this band, the noise in the CC field will follow the imprecision of the demodulator (receiver noise) [5].

Detrimental Effects of RF Noise

The CC RF noise reduces luminosity through transverse emittance growth. The RF noise in the CC gives random transverse kicks to the passing particles, resulting in emittance growth in the crabbing plane. The un-normalized emittance growth rate due to both phase and amplitude noise was derived by the authors [6]. For phase noise we have

$$\frac{d\varepsilon_t}{dt} = \beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}\left(\sigma_\phi\right) \sum_{k=-\infty}^{\infty}\int_0^{\infty} S_{\Delta\phi}\left[\left(k\pm\nu\right)f_{rev}\right]\rho\left(\nu\right)d\nu \tag{2}$$

$$C_{\Delta\phi}\left(\sigma_\phi\right) = e^{-\sigma_\phi^2}\left[I_0\left[\sigma_\phi^2\right] + 2\sum_{l=1}^{\infty} I_{2l}\left[\sigma_\phi^2\right]\right] \tag{3}$$

where e is the charge of a proton, V_o is the voltage of the crab cavity, f_{rev} is the revolution frequency, E_b the beam energy, σ_ϕ the rms bunch length (in radian), I is the modified Bessel function of the first kind, $\rho(\nu)$ is the betatron tune distribution, and $S_{\Delta\varphi}$, is the phase noise power spectral density (with units of rad^2/Hz). Eq. 2 can be interpreted as follows: the effect of phase noise depends on the overlap between noise spectrum and betatron tune distribution. As the particle samples the noise at each turn, the phase noise spectrum is aliased at f_{rev}. Phase noise gives dipole kicks to the core of the bunch but does not shake the particles at $\pm\pi/2$ phase offsets. This effect is represented by the "geometric factor" $C_{\Delta\phi}$ that decreases with bunch length [6]. The phase noise induced emittance growth is reduced by the transverse damper. As it gives the same kick to all particles, the damper efficiency decreases with bunch length. Its effect can be described by a correction factor R_d, dependent on both bunch length and Beam Transfer Function. Refer to reference [6] for details. Amplitude noise induces head-tail motion of the bunch that the damper cannot correct as the mean bunch signal is zero. Formulas have also been derived for the resulting emittance growth

$$\frac{d\varepsilon_x}{dt} = 2\beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta A}\left(\sigma_\phi\right) \sum_{k=-\infty}^{\infty}\int_0^{\infty} S_{\Delta A}\left[\left(k\pm\nu\pm\nu_s\right)f_{rev}\right]\rho\left(\nu\right)d\nu \tag{4}$$

$$C_{\Delta A}\left(\sigma_\phi\right) = e^{-\sigma_\phi^2}\sum_{l=0}^{\infty} I_{2l+1}\left[\sigma_\phi^2\right] \tag{5}$$

where ν_s is the synchrotron tune and $S_{\Delta A}$ is the (relative) amplitude noise power spectral density (with units of $1/Hz$). The voltage power spectral density is $S_{\Delta V} = V^2 S_{\Delta A}$. The effect depends on the overlap between amplitude noise spectrum and the aliased synchro-betatron bands. The "geometric factor" now increases with bunch length as amplitude noise kicks the head and tail more than the core. The HiLumi LHC beam parameters at the *end of the fill* are presented in Table 1.

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Table 1: Parameters at the End of Fill, with 15 cm β^*

f_{rev} (Hz)	ν_t	V_o (MV)	β_{CC} (m)	ε_n (µm. rad)	E_b (TeV)	σ_ϕ (rad)	σ_{vb}
11245	62.31	3.4	4000	2.5	7	0.67	0.003

We quote the normalized transverse emittance. The transverse damper gain will be 0.04 (50 turns damping time) giving a reduction factor of 0.097 for the phase noise effect. We are considering 100 kHz regulation bandwidth. The receiver noise will thus appear in the cavity field in that range and will contribute to the infinite integrals of Equations 2 and 4. The noise from the four cavities per beam and per plane are added in power, assuming that they are uncorrelated. We are allowed a transverse emittance growth rate target of approximately 1.6%/hour to sufficiently reduce the integrated luminosity loss over a physics fill [3]. Using the above equations we can calculate the maximum acceptable phase and amplitude noise: we get -153 dBc/Hz at offsets from 3 kHz (first betatron band) to 100 kHz (regulation bandwidth). Compared to the measured -130 dBc/Hz of the LHC accelerating system, such a low noise spectrum is very challenging. We consider -143 dBc/Hz as a more reasonable target. This in turn would generate an unacceptable 16%/hour reduction in integrated luminosity.

RF Noise Mitigation

We propose to reduce the effect of the CC RF noise using a dedicated feedback system that would use the CCs as transverse kicker [5]. The intra-bunch transverse distortion measured by a wideband acquisition Pick-Up (such as the Head-Tail monitor shown on Fig.5) can be processed to generate two data at each bunch passage: one is the transverse position averaged over the whole bunch (Sum signal), the second one is the difference between averages done over longitudinal head and tail of the bunch (Difference signal). After processing (filtering and phase shift), these two inputs are fed back onto the CC reference voltage: the Sum signal generates a correction to the CC phase and the Difference signal to the amplitude. The amplitude and phase feedback systems were first examined separately, by only using one type of noise kick and feedback at a time. Simulations were done using the Python package PyHEADTAIL, a software package developed at CERN for simulation of multi-particle beam dynamics [7].

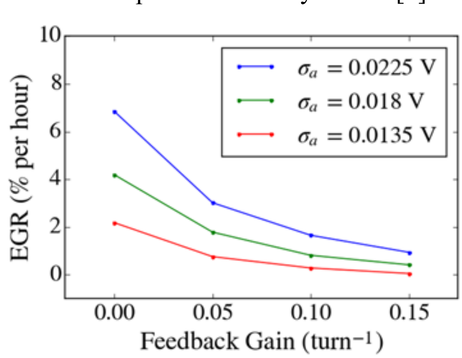

Figure.6: Emittance growth rate from amplitude feedback acting on amplitude noise.

Results are shown on Fig. 6, 7. The vertical axis of these figures represents the percent increase in emittance per hour. A significant reduction in emittance growth rate is achieved as the feedback gains are increased. Then both feedback systems were combined to act on both types of noise simultaneously. As expected, the two feedback systems behave independently, without interference from one another.

Such a feedback system will see its performances degraded by loop delay or betatron tune spread. Sensitivity to these parameters has been studied [5]. An additional limitation is the noise in the Pick-Up measurement chain. The Head-Tail monitor signals of Fig. 5 are averaged over many turns. For the proposed CC feedback system to work, averaging can be done over a time-span that is the inverse of the 100 kHz RF noise bandwidth (400 bunches). The feasibility of the system depends on the maximum acceptable level of measurement noise before it becomes inefficient (excitation vs. damping). Detailed simulations have been performed [5]. The design of a wide-band, high-precision transverse measurement system will be done in synergy with the HL-LHC transverse damper upgrade. We count on this scheme to gain the extra 10 dB noise reduction required.

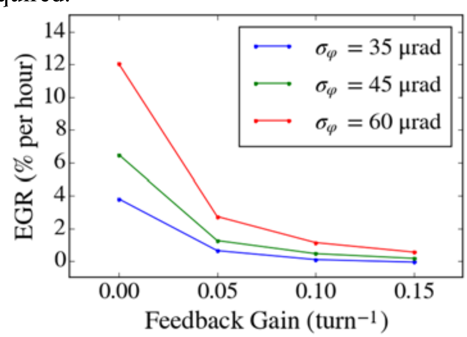

Figure.7: Emittance growth rate from phase feedback acting on phase noise.

Exploiting RF Noise.

Recall that the HL-LHC will use a local crabbing scheme. The companion cavities on the other side of the IP must cancel the rotation initiated by the cavities at the entry side. Outside the IP region there is no crabbing and the transverse collimators can be placed very close to the beam. If a CC fails (RF trip, quench, etc…), the crabbing will propagate outside the IP. A trigger will immediately be sent to the beam dump system and the beam will be extracted to protect the machine. But the beam dump system requires up-to three machine turns to react. During that time, the collimators will scrape the transverse tails of the beam and high tail population could cause damage [8]. We must therefore keep the tail population controlled during the physics fill. One solution is the electron lens collimator [9]. We propose an alternative (or complement) method using the CCs. The particles in the transverse tails have a different betatron frequency than the ones in the core. This dependence is a result of the non linearities caused by beam-beam effects and octopole field. The RF noise action can then be limited to tail particles if shaped correctly.

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Simulations were done with the injection of RF phase noise in a CC [10]. A white RF noise does not change the functional form of the transverse action and tune distributions. The final distribution is a scaled version of the original. Equations 2, 4 indicate that the term in the summation is proportional to the product of the noise power spectral density and the tune distribution. As a result, the noise PSD must be large at the tunes of the particles that we wish to continuously drive to the collimators in order to keep a low population in the tails. Figure 8 shows an example noise distribution used in simulations. Noise amplitude increases at a constant rate from 0 to a maximum over about 154 Hz. Zero noise is injected at and above the third-integer tune, to avoid resonance. This noise distribution was specifically designed to trim particles 2σ from the phase space origin in the x-dimension. 3546 Hz corresponds to the approximate betatron frequency of particles oscillating out to 2σ in the horizontal plane for a non-integer average betatron tune of about 0.3. Figures 9 show the resulting tune distribution. The dashed line presents the initial distribution with all particles removed past the 2σ threshold. It is evident from these figures that this tail cleaning scheme performs very well.

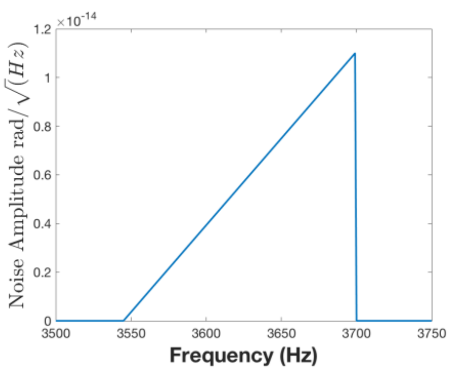

Figure 8: 2σ tail cleaning noise for the x-dimension.

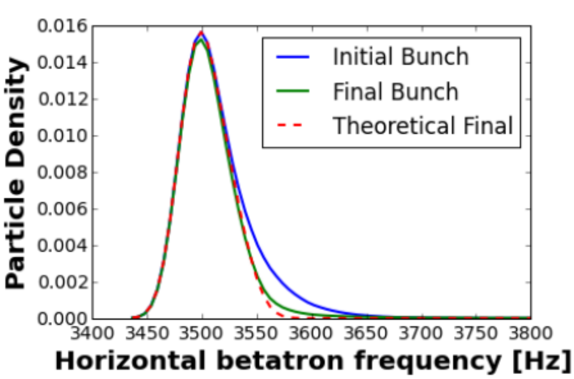

Figure 9: Tune distribution before and after 2σ tail cleaning simulation.

Figure 10 shows the bunch distribution in phase space before and after the simulation. The majority of particles beyond 2σ were pushed out and removed by the collimators.

CONCLUSION

We have reported on the first CC tests with beam in the SPS. Analytical formulas have been presented for the emittance growth rate caused by CC phase and amplitude noise. Given a budget of 1.6 %/hour with the *end of fill* parameters, the noise must be reduced to -153 dBc/Hz at offset larger than 3 kHz. We consider -143 dBc/Hz as a challenging but reasonable target. In order to gain the extra 10 dB we propose a feedback system that measures bunch transverse displacement plus head-tail motion, and feedback on the CC voltage phase and amplitude respectively. Simulations show that the method can provide the required extra 10 dB if we keep the noise in the Pick-Up chain sufficiently low. A possible use of the CC for transverse tail cleaning was presented. We propose to continuously inject phase noise in the CC, with a spectrum such that it excites the particles with large betatron oscillations only. Simulations were presented that confirm the feasibility.

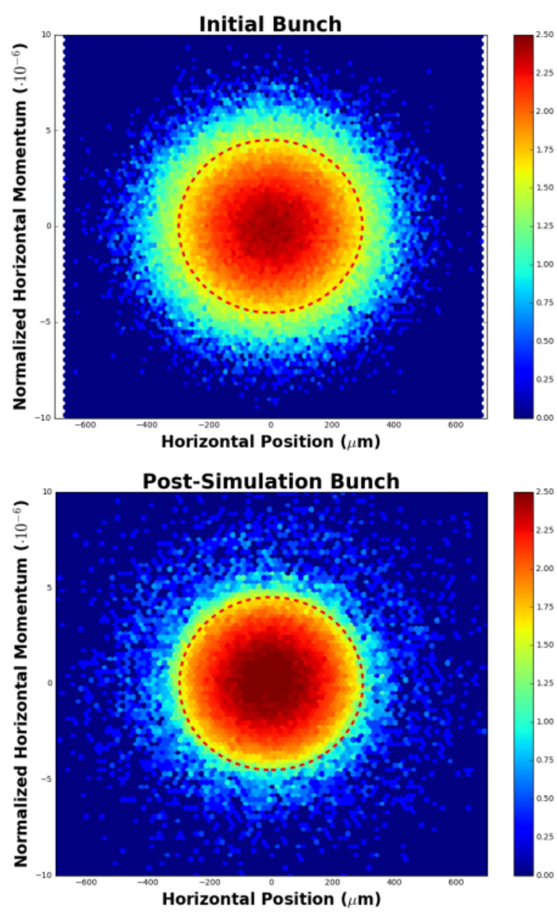

Figure 10: Phase space before a 2σ tail cleaning simulation (top) and after the cleaning (bottom). The red dotted line is 2σ from the origin.

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