LLRF STUDIES FOR HL-LHC CRAB CAVITIES

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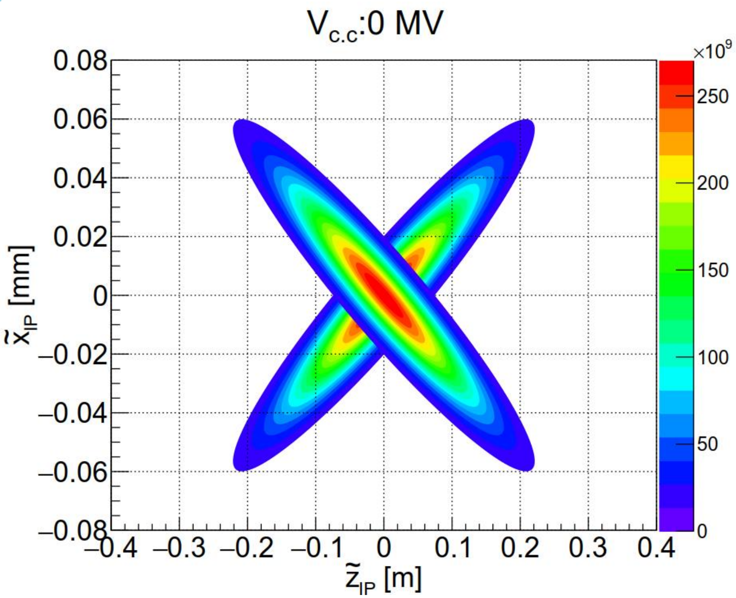
CCs in the LHC. Why?

The HL-LHC project

- **TARGET** [1]: tenfold increase in p-p integrated luminosity, by
  - Doubling of the beam current (2.2 10^{11} p/bunch, 1.1 A DC). Requires injector upgrade (LIU project). See G. Rumolo, MOA1PL02
  - Reduction of the transverse size at the IP1 – ATLAS – and IP5 -CMS (15 cm β*, compared to the *design* 55 cm). Requires upgraded insertion magnets
  - 25 ns bunch spacing and total number bunches (~2800) unchanged.
- The two LHC beams travel in separate vacuum chambers except in a 100 m section on each side of the four IPs
  - In this region the beams must be separated transversely to avoid detrimental beam-beam interaction -> crossing angle
  - **The crossing angle must scale inversely to the transverse beam size** at the IP to maintain constant normalized separation
  - HL-LHC full-crossing angle will be **500 μrad**, compared to the present **280 μrad** .

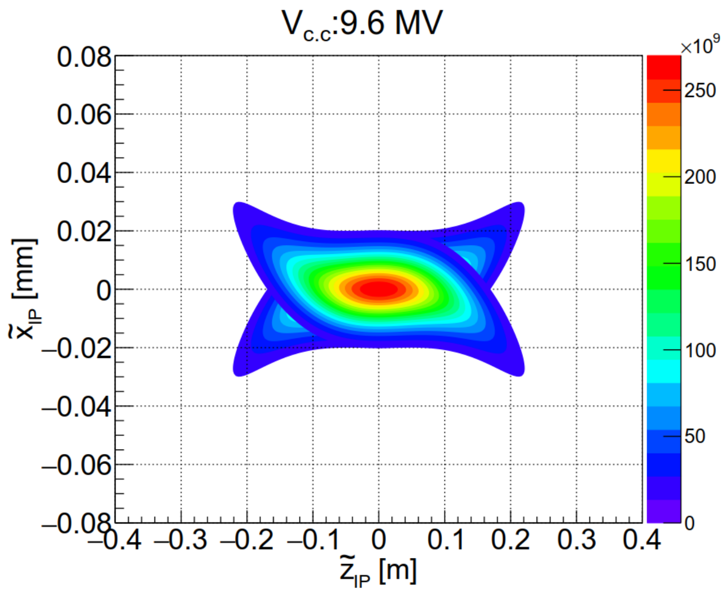
Crossing at an angle

- Large crossing angle + very small transverse beam size -> reduction of instantaneous luminosity. For HL-LHC, *R(θ)* is about 1/3
- **Mitigation:** Crab cavities = RF deflectors, phased so that the longitudinal bunch centroid receives no kick -> head and tail receive transverse kicks in opposite directions
- They rotate the bunch by $\theta_{cc}/2$ and *almost* restore head-on collisions at the IPs.



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

$$tg\left(\frac{\theta_{cc}}{2}\right) = \frac{eV}{E_s}\frac{\omega}{c}\sqrt{\beta^*\beta_{cc}}$$



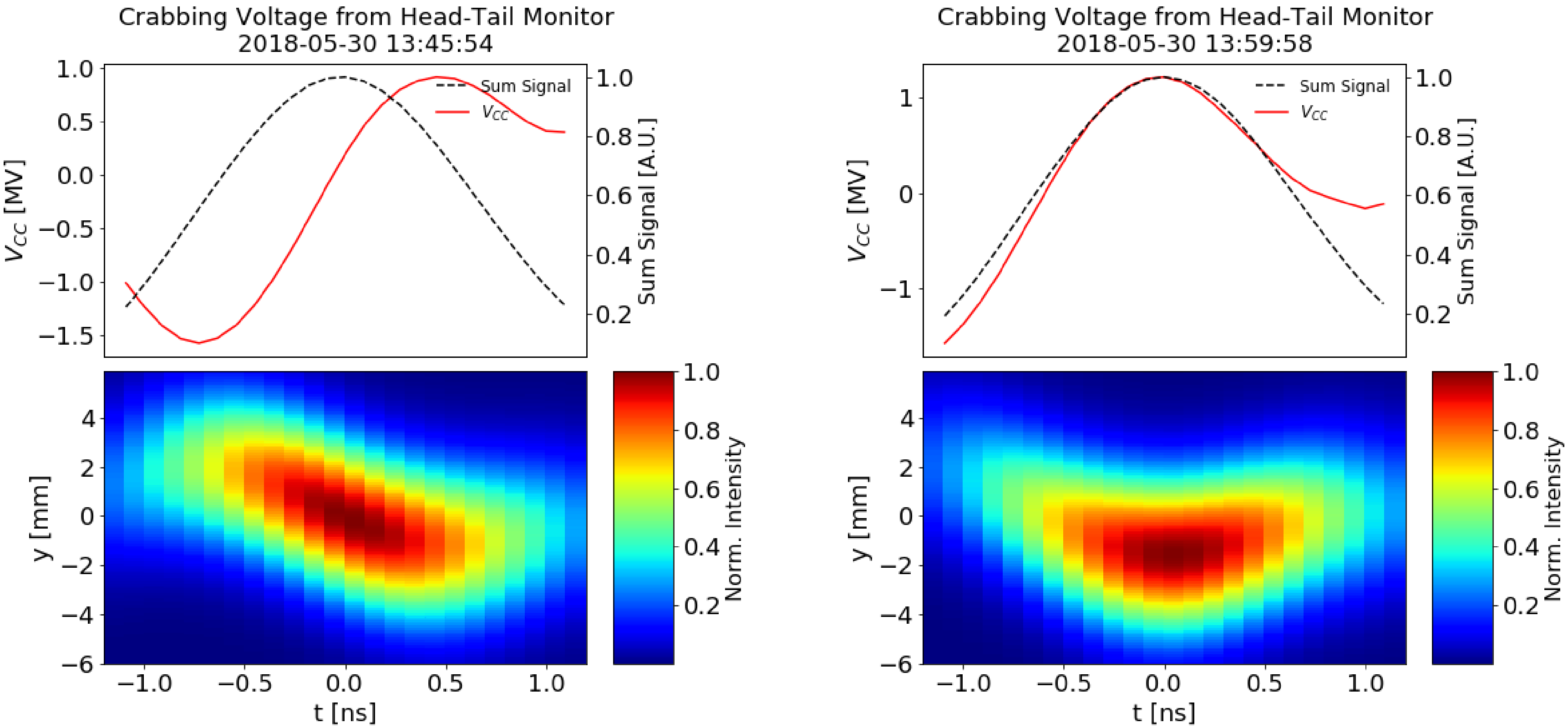
Left: HL-LHC bunch crossing without crabbing
Right: with crabbing.

SPS CC tests

Acknowledgements: many persons participate in the SPS CC tests and we cannot mention them all. Among them:
R. Calaga (project leader), O. Capatina (cryomodule), E. Montesinos (amplifiers), L. Carver (machine development organization), T. Levens (instrumentation), S. Claudet and K. Brodzinski (cryogenics).


CMU 4T

CC phase scan at 26 GeV



Head-tail monitor. CC1 Phase Scan. Left: 0 deg. Right: 90 deg. Courtesy of T. Levens (CERN) and L. R. Carver (University of Liverpool). **Clear evidence of crabbing….**

HiLumi HL-LHC PROJECT CERN

May 30th. First results are promising and we are happy…a good start.

LLRF issue. Effect of RF noise

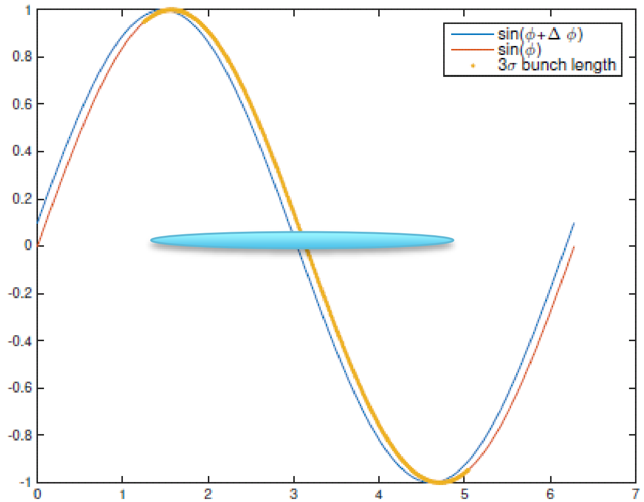
Momentum kicks due to CC noise

- With ϕ_n the particle's phase with respect to the bunch core, V_o the desired crab cavity voltage, ΔA_n the relative amplitude noise, and $\Delta \phi_n$ the phase noise. We have

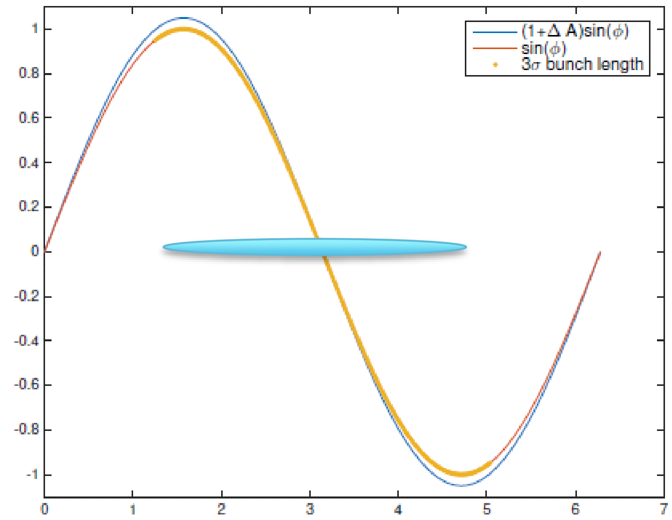
$$p_n = \sqrt{\beta_{cc}} \frac{eV_0}{E_b} \sin(\phi_n)$$

$$\Delta p_n = \sqrt{\beta_{cc}} \frac{e}{E} \Delta V_n = \sqrt{\beta_{cc}} \frac{eV_0}{E_b} \left[\sin(\phi_n + \Delta\phi_n) - \sin(\phi_n)\right] + \sqrt{\beta_{cc}} \frac{eV_0}{E_b} \Delta A_n \sin(\phi_n + \Delta\phi_n)$$

$$\approx \sqrt{\beta_{cc}} \frac{eV_0}{E_b} \cos(\phi_n) \Delta\phi_n + \sqrt{\beta_{cc}} \frac{eV_0}{E_b} \sin(\phi_n) \Delta A_n$$



Phase noise: acts strongly on the core of the bunch



Amplitude noise: acts on the head and tail in opposite directions, does not act on the core

Emittance growth. CC RF noise

Beam parameters

Geometric factor

Phase noise

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

- Depends on the **overlap** between phase noise spectrum and betatron tune distribution
- Noise spectrum is **aliased** at f_{rev}
- The "phase-noise geometric factor" **decreases** with bunch length

Amplitude noise

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

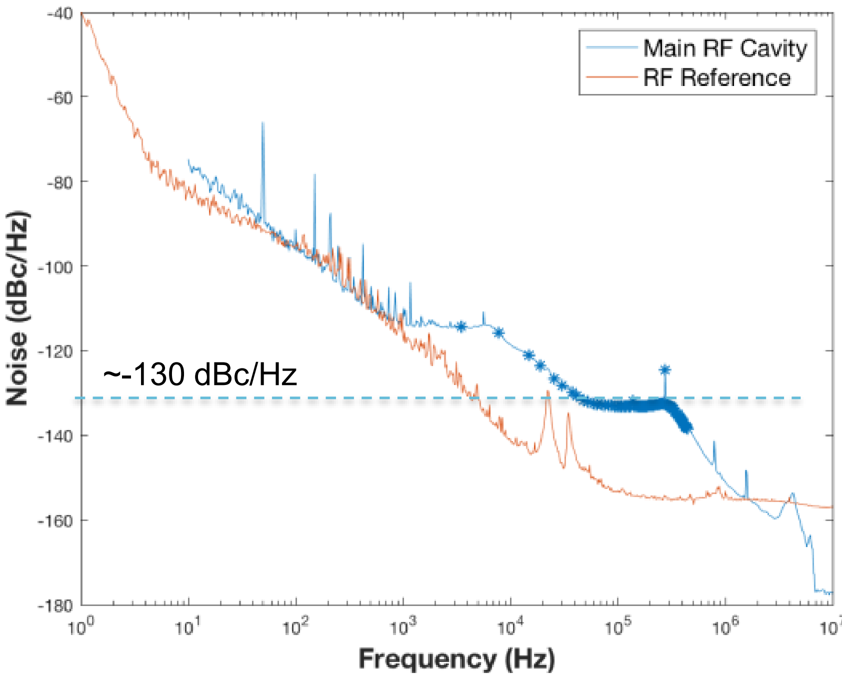
- Depends on the **overlap** between phase noise spectrum and synchro-betatron tune distribution
- The "amplitude-noise geometric factor" **increases** with bunch length.

See [6] P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001 (2015).https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.101001

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

HL-LHC parameters at the end of a fill (15 cm β*)

- We are allowed a transverse emittance growth rate (EGR) target of **1.6%/hour** [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)
- **VERY CHALLENGING** compared to the measured -130 dBc/Hz of the LHC accelerating system (ACS)
- We consider **-143 dBc/Hz** as a more reasonable target
- This in turn would generate an **unacceptable 16%/hour** reduction in integrated luminosity.



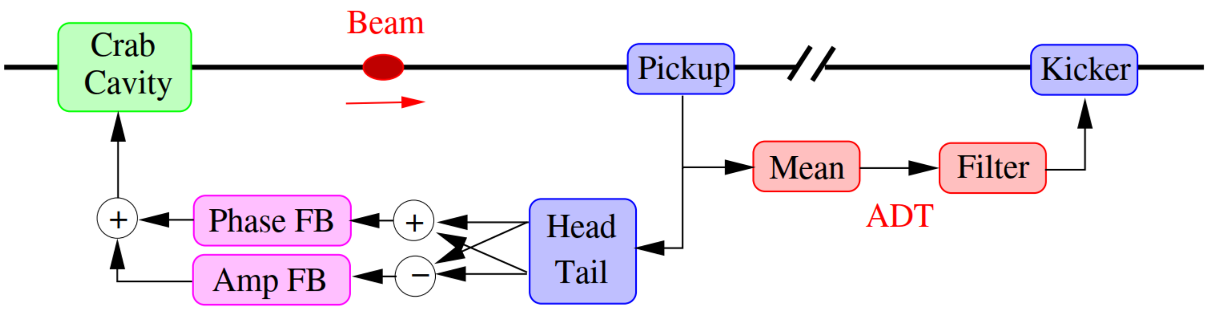
LHC ACS Single Side-band (SSB) Phase noise in cavity antenna (blue) and in RF reference (red).

RF noise mitigation.

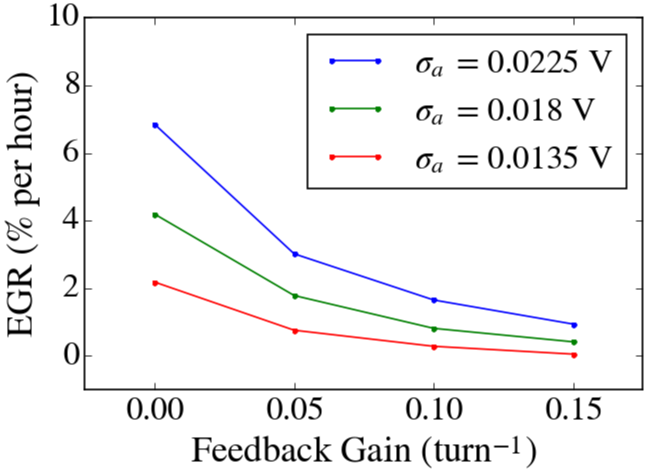
We must gain an additional 10 dB (factor 10 in effective noise power…)

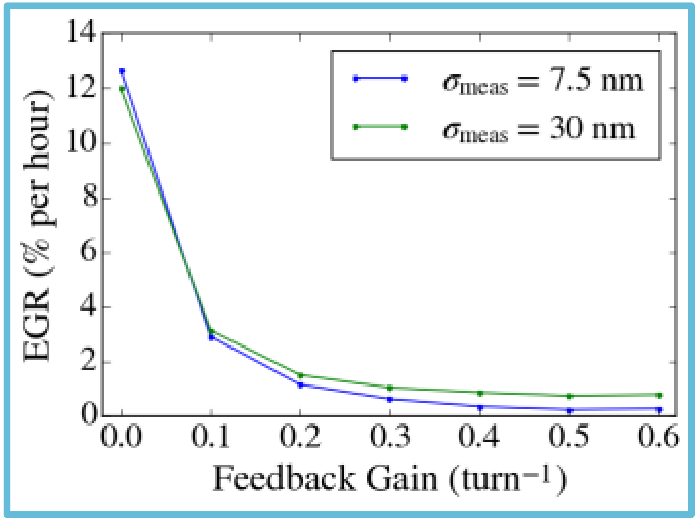
Feedback on CC amplitude/phase

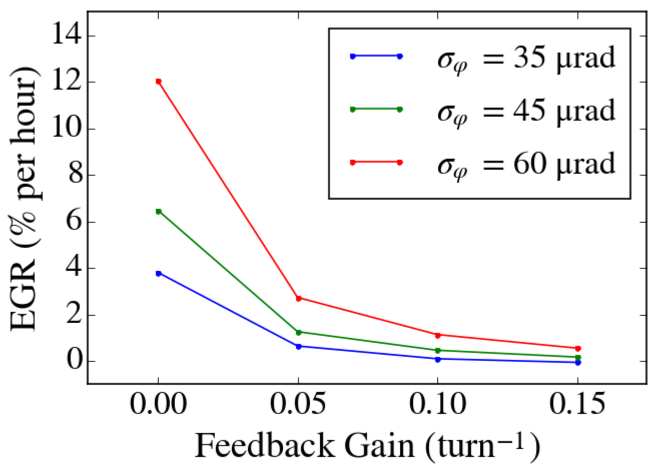
- Measure intra-bunch transverse distortion with wideband acquisition Pick-Up
- Generate two data at each bunch passage:
  1. the transverse position averaged over the whole bunch (Sum signal)
  2. the difference between averages done over longitudinal head and tail of the bunch (Difference signal)
- After processing (filtering and phase shift), these two inputs are fed back onto the CC reference voltage
  1. the **Sum** generates a correction to the CC **phase**
  2. the **Difference** signal to the **amplitude**.



Performances. PyHEADTAIL [7] simulations







- Left
  - Top: amplitude feedback acting on CC amplitude noise
  - Bottom: phase feedback acting on phase noise
- Extensive simulations done including analysis of sensitivity to loop delay, tune spread, PU noise. Publication submitted [5].
- Right: **realistic situation** with **PU noise**. The noise has about 100 kHz BW. So we can average Sum and Diff signals over 10 μs (400 bunches). We assume a single bunch precision of 150 nm -> **gain factor 10 in EGR.**

Exploiting RF noise
Tail cleaning

Tail cleaning by coloured excitation

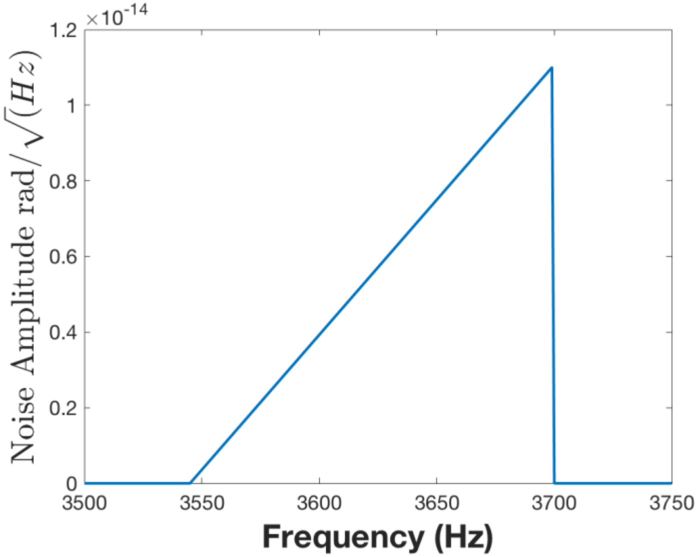
- Low tail population is important in HL-LHC [8]. In case of a CC trip, the Crabbing will propagate around the whole machine. Transverse tails would then be a heavy load on the collimator, till the beam is dumped (up to 3 machine turns later)
- Octupole field and beam-beam effects result in a monotonic relation between betatron tune and amplitude of betatron oscillation
- We can act on **particles at selected transverse position** by exciting at **specific betatron frequencies**. For example applying CC phase noise on particles of tune ν_b, their oscillation amplitude variance grows as [6]

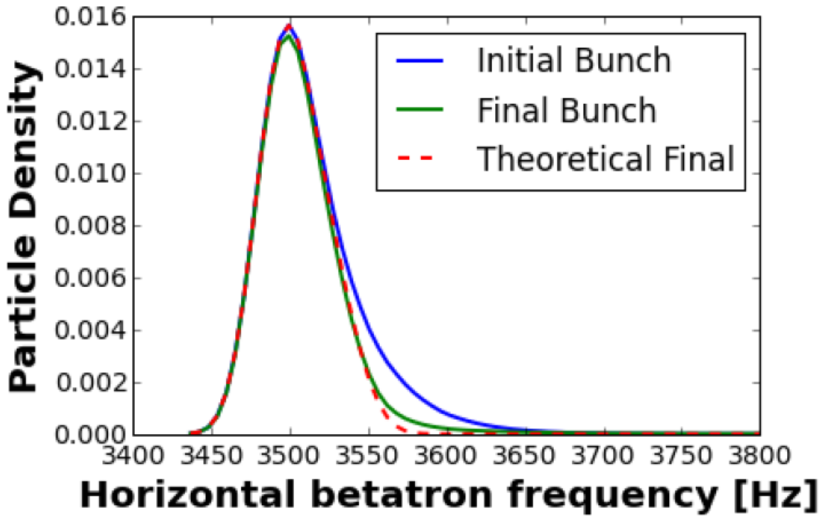
$$\frac{d}{dt}E\left[\tilde{x}_n^2 \middle| \nu_b\right] = \beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 \sum_{k=-\infty}^{\infty} S_{\Delta\phi}\left[\left(k \pm \nu_b\right) f_{rev}\right]$$

- This can be used to clean the transverse tails of the bunch. We apply noise with a spectrum chosen so that we create diffusion in the tails only
- That creates a continuous flow towards the collimators preventing accumulation in the tails.

Triangular spectrum to clean the tails

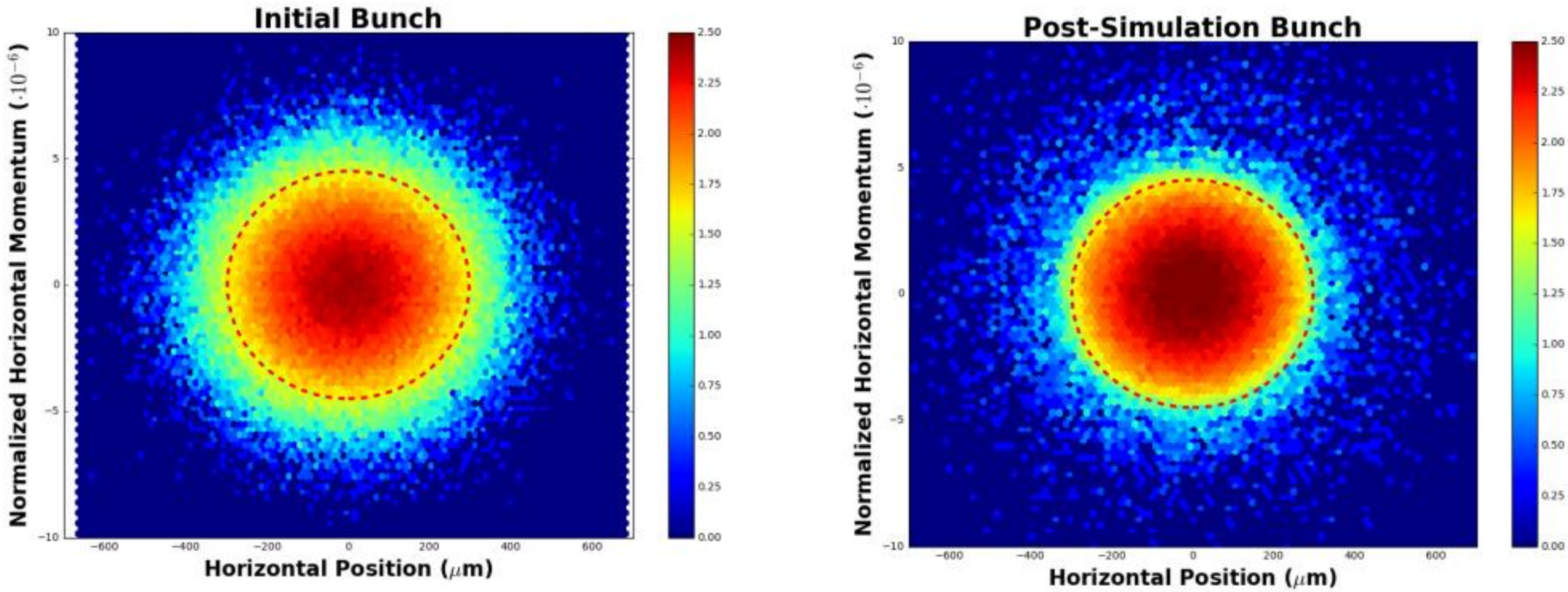
- Consider LHC with non-integer betatron tune equal to 0.3 and rms tune spread 0.003. The 2σ particles have first aliased betatron frequency above 3546 Hz
- They can be efficiently **pushed to the collimator** with a triangular CC Phase Noise spectrum starting at 3546 Hz.





Left: CC Phase Noise PSD. Right: Betatron tune distributions. Initial, final (after cleaning applied in PyHEADTAIL) and theoretical assuming all particles above 2σ removed.

Cleaning results in x-x` phase space



x-x′ phase space. Left: before the tail cleaning. Right: After the tail cleaning simulation). **The red dotted line is 2σ from the origin.**

More in [10] P. Baudrenghien, T. Mastoridis, S. Steeper, D. Tucker, D.Wieker, "Crab Cavity effects on transverse distribution evolution and tail cleaning in the HL-LHC", CERN-ACC-NOTE-2018-0042.https://cds.cern.ch/record/2320889/files/CERN-ACC-NOTE-2018-0042.pdf

Conclusions

Conclusions

- The HL-LHC CC RF noise must be scaled to fulfill the 1.6 %/hour budget allowed with the smallest β^* (15 cm) in physics
- The noise spectrum in the aliased betatron bands, from 3 kHz on, must be reduced below -153 dBc/Hz. Value to be compared to the -130 dBc/Hz level measured in the LHC Accelerating Cavities
- We think that this 23 dB reduction presents a technological challenge. We are confident that we can improve the electronics (RF receiver) to achieve -143 dBc/Hz (a 13 dB improvement)
- A mitigation has been proposed and studied to provide the remaining 10 dB: the use of a **feedback on CC amplitude/phase from a wideband transverse measurement system**. The front-end could be common with the damper upgrade, a possible wideband damper (?) and a wideband transverse diagnostic chain. The measurement noise does not appear as a show-stopper
- Finally a method was proposed for **cleaning the transverse tails** of the bunch using **colored noise injected in the CCs**. Simulations were presented. The system can be implemented very easily at almost no cost. This could come in complement to the electron lens [9].

References

[1] G. Apollinari *et al.*, “High-Luminosity Large Hadron Collider (HL-LHC). Preliminary Design Report”, CERN-2015-005, Dec 17th, 2015. http://cds.cern.ch/record/2116337

[2] Y. Funakoshi, “Operational experience with crab cavities at KEKB”. http://arxiv.org/pdf/1410.4036

[3] E. Metral *et al.*, “Update of the HL-LHC operational scenarios for proton operation”, CERN-ACC-NOTE-2018-0002. http://cds.cern.ch/record/2301292/files/CERN-ACC-NOTE-2018-0002.pdf

[4] C. Zanoni *et al.*, “The Crab Cavity Cryo-module for the SPS test”, 2017 J. Phys.: Conf. Ser. 874 012092. http://iopscience.iop.org/article/10.1088/1742-6596/874/1/012092

[5] P. Baudrenghien, T. Mastoridis, A. Daw, P. Nguyen, “Estimates of and a Cure for Transverse Emittance Growth due to RF Noise in the High Luminosity LHC Crab Cavities”, submitted for publication to Phys. Rev. ST Accel. Beams.

[6] P. Baudrenghien and T. Mastoridis, “Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities,” Phys. Rev. Accel. Beams 18, 101001 (2015).https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.101001

[7] G. Rumolo, F. Zimmermann, “Practical User Guide for HEADTAIL”,CERN-SL-NOTE-2002-036. http://cds.cern.ch/record/702717/files/sl-note-2002-036.pdf

[8] A. Garciat *et. al*., “Limits on Failure Scenarios for Crab Cavities in the HL-LHC”, Proceedings of IPAC 2015, Richmond, VA, May 2015. http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/thpf095.pdf

[9] M. Fitterer *et al.,* “Hollow Electron Beam Collimation for HL-LHC - Effects on the Beam Core”, IPAC 2017. http://accelconf.web.cern.ch/AccelConf/ipac2017/papers/weoba2.pdf

[10] P. Baudrenghien, T. Mastoridis, S. Steeper, D. Tucker, D.Wieker, “Crab Cavity effects on transverse distribution evolution and tail cleaning in the HL-LHC”, CERN-ACC-NOTE-2018-0042.https://cds.cern.ch/record/2320889/files/CERN-ACC-NOTE-2018-0042.pdf