LLRF experience for SPS & HL-LHC Outlook

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HL-LHC International Review of CC system design, June 20th 2019

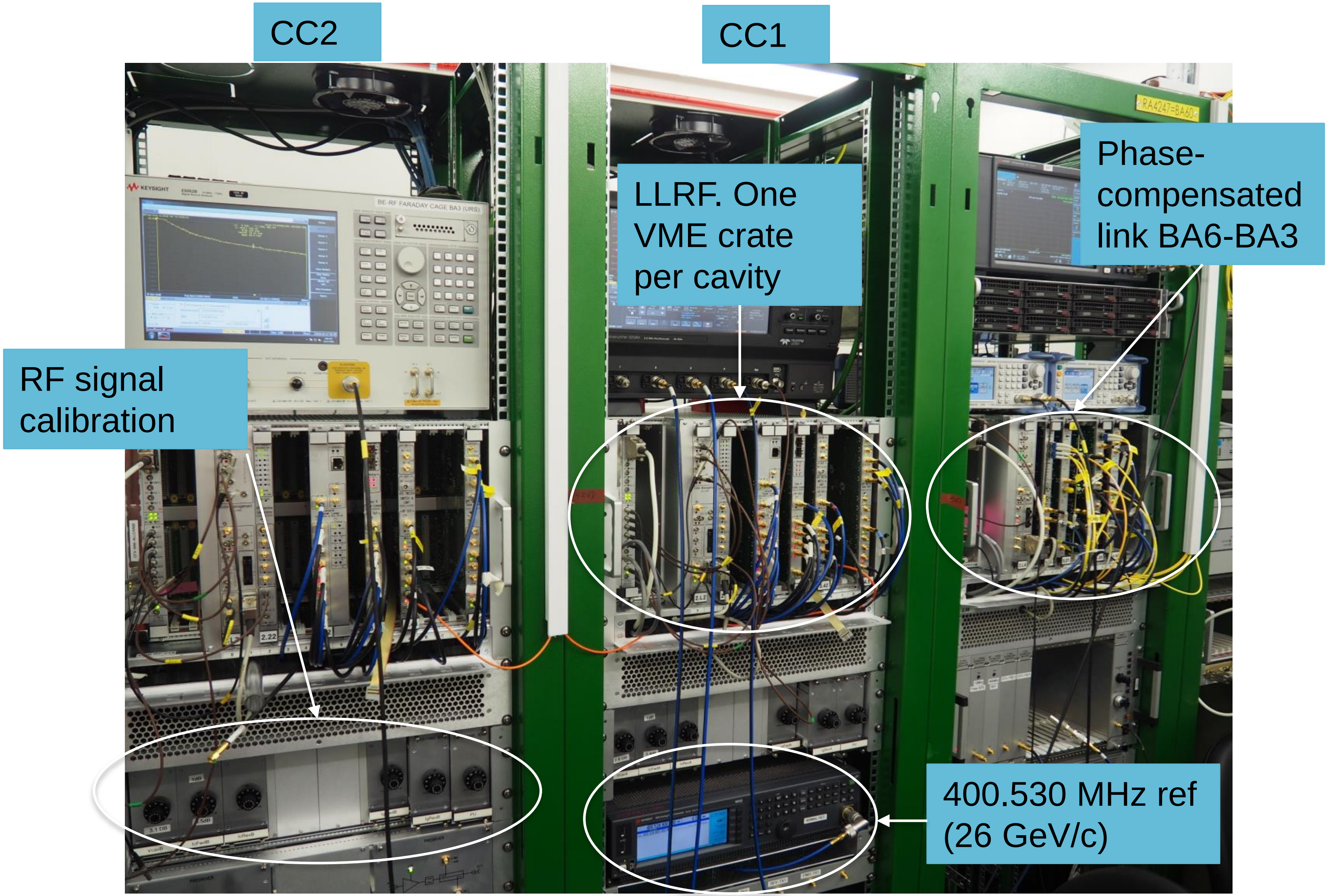
Outline

- SPS 2018 tests
  - LLRF hardware
  - Ponderomotive Instabilities
  - Microphonics and TX noise
  - TX non-linearity
  - Coupling of Antenna signal to beam
  - Transverse emittance growth
- Plans SPS 2020-2023
- Plans HL-LHC
- Conclusions

SPS tests

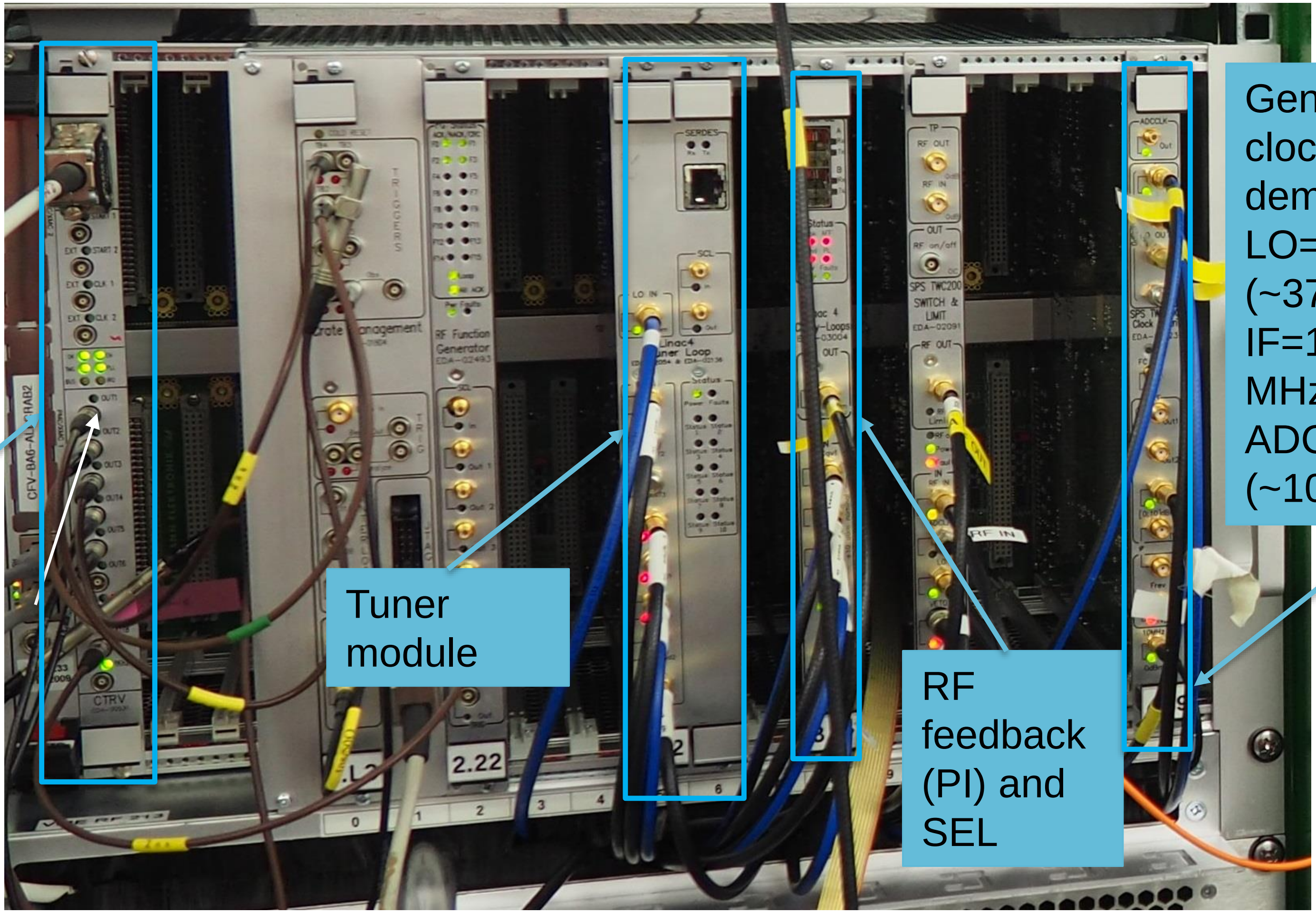
- For the SPS tests the energy range is 26-270 GeV/c. The 2 x 4620 harmonic of the SPS revolution frequency is therefore 400.530 MHz - 400.787 MHz
- Fits in the tuning range
- But the CC tuning system is very slow -> cannot track the SPS acceleration ramp
- Solution:
  - We drive the CC with a fixed frequency (adjusted to the energy, 400.5288 MHz @ 26 GeV/c, 400.7873 MHz @ 270 GeV/c)
  - We rephase the SPS beam to that frequency on a corresponding plateau in the SPS cycle
  - RF manipulation similar to the cogging done before SPS-LHC transfer.
- CC RF is switched ON after the rephasing of beam to CC
- Note: The CCs are in LSS6 and driven from equipment in surface building BA6. The accelerating cavities are in LSS3, driven from BA3.

SPS LLRF hardware (1/2)



SPS LLRF hardware (2/2)

Linac4 system adapted for the Crab Cavity frequency (400 MHz vs. 352.2 MHz).



Front End Computer (FEC)

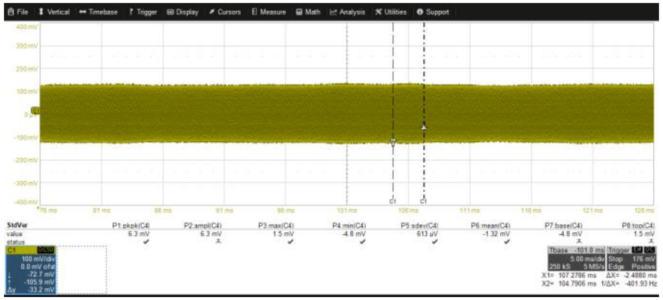
Tuner module

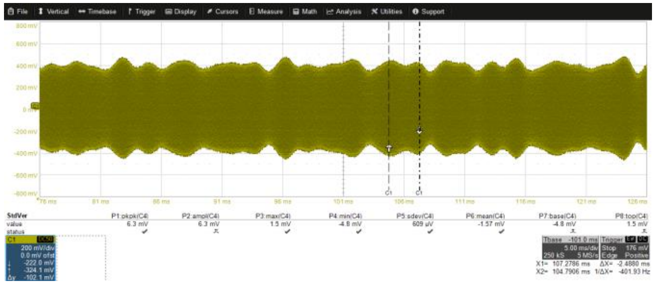
RF feedback (PI) and SEL

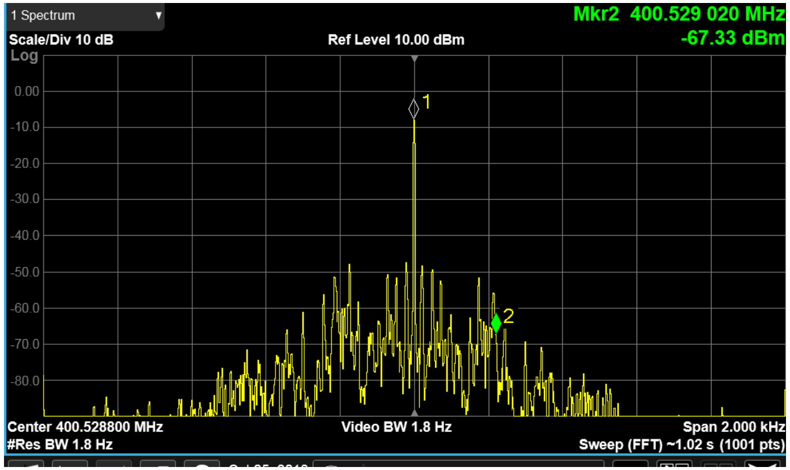
Generation of clocks for I/Q demod/mod
LO= 15/16 RF (~375 MHz)
IF=1/16 RF (~25 MHz)
ADC CK=1/4 RF (~100 MHz)

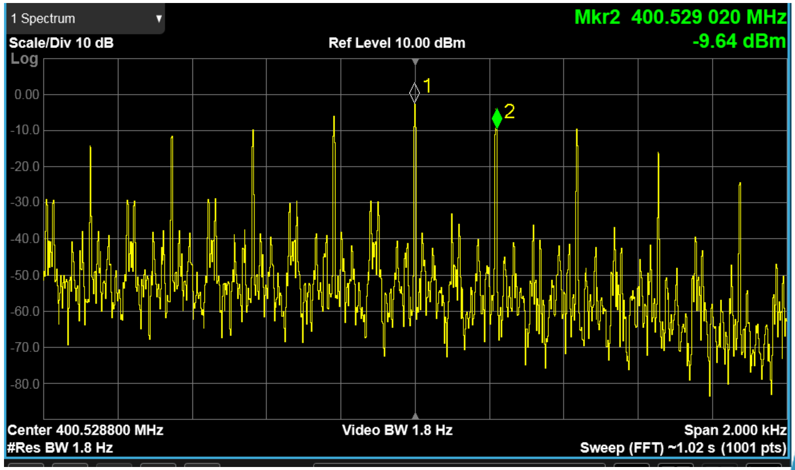
Ponderomotive instabilities [1]-[3] (1/2)

- The oscillation is not seen in the Antenna when the cavity field is below 1 MV. (FDBK is OFF).
- When the cavity voltage is above 1 MV, we observe huge oscillations (210 Hz) in the Antenna. (FDBK is OFF).



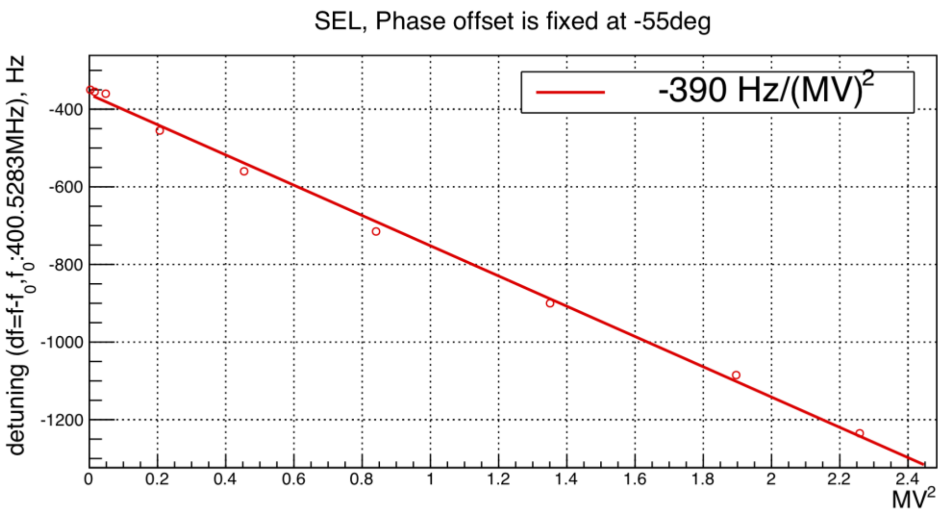


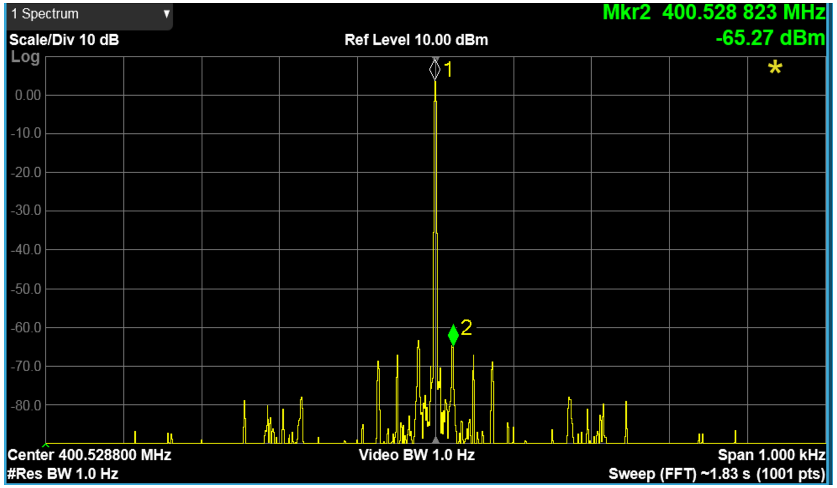




Ponderomotive instabilities (2/2)

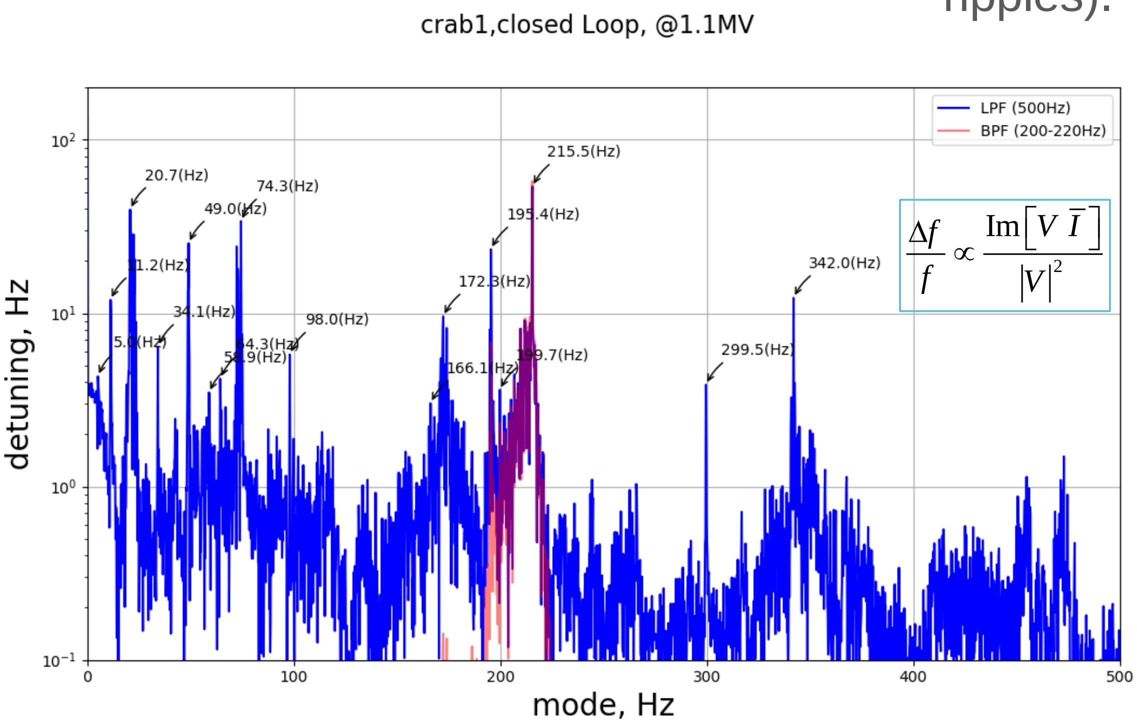
- Lorentz Force Detuning is -350 Hz/MV^2 (CC1), -390 Hz/MV^2 (CC2)
- When the cavity field is close to 1 MV, the detuning frequency is about one cavity bandwidth (-400 Hz, Q_L=500000), that is the worst case for ponderomotive oscillation
- When the RF FDBK is closed, it stabilises the cavity field. No more problem of ponderomotive oscillation. Remain small 20 Hz sidebands (cryo pumps). (Antenna, 1.6 MV).

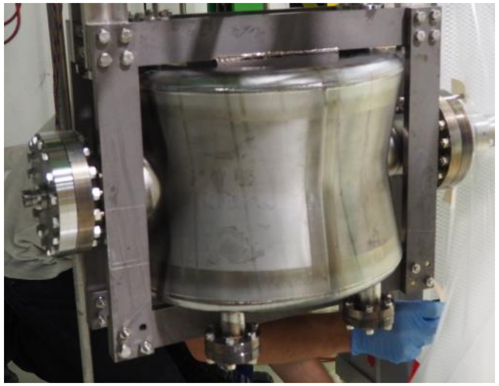




Microphonics and TX noise [6]

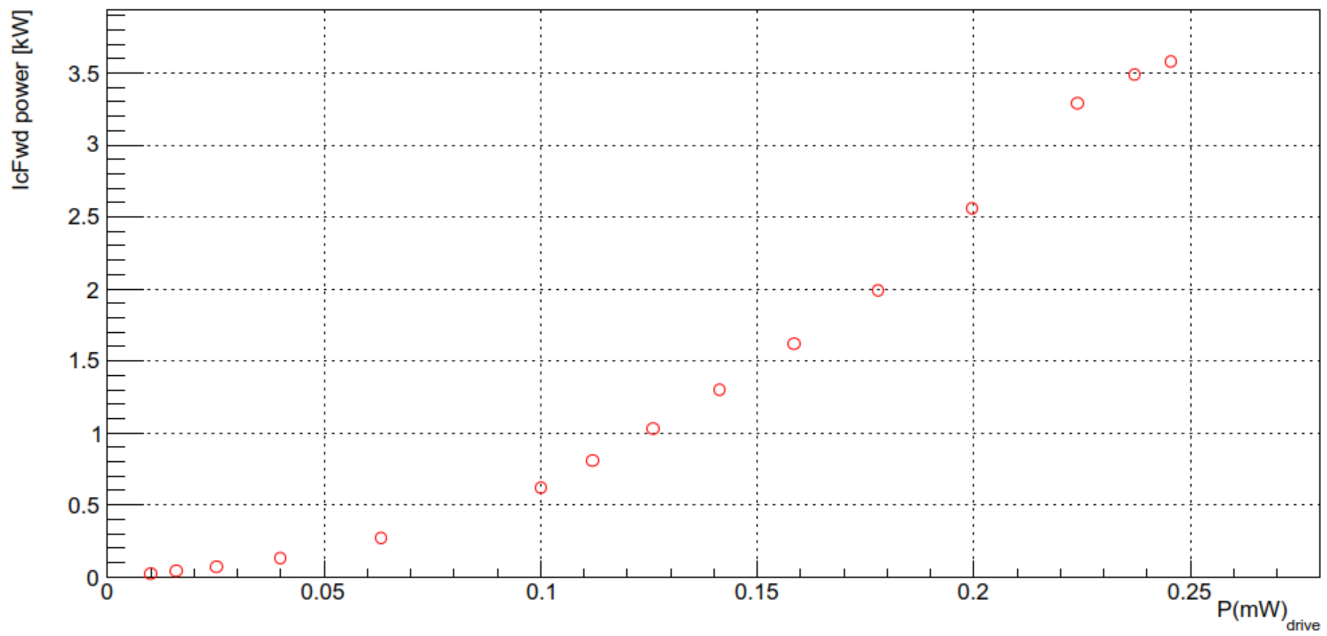
- 20-30 Hz: Cryo-pump
- 49 Hz: TX high voltage ripples (50Hz)+ Tuner mode (Mechanical 47.7Hz)
- 74.3 Hz: Mechanical mode
- 98 Hz: Harmonics of TX ripple
- 172.3 Hz: Not identified
- 215.5 Hz: Mechanical mode. EM to mechanical coupling source of the ponderomotive oscillation
- 199.7 Hz, 299.5 Hz, 342 Hz: Not identified (could be TX high voltage ripples).





SPS CC TX

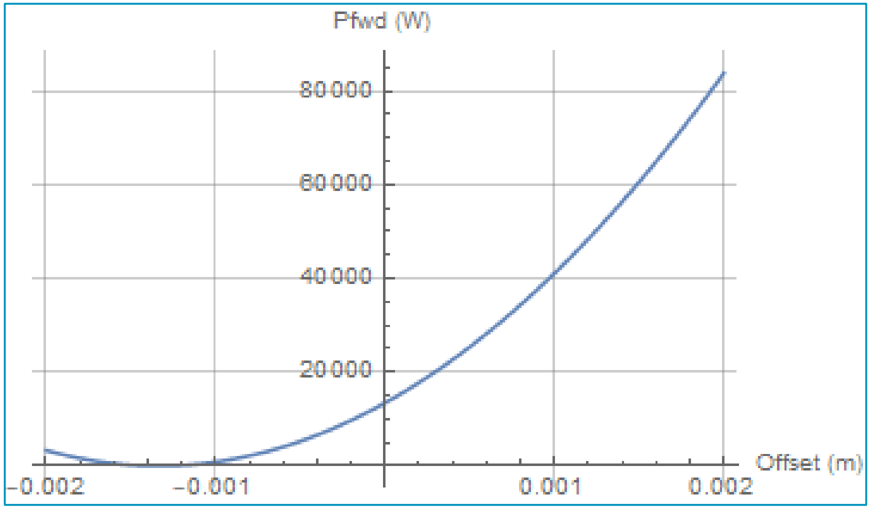
- The power needed depends on the beam displacement. The HL-LHC system is designed to accept ±2 mm beam offset in the CC
- In the SPS we have a 50 kW TX that has been used in the 0-5 kW range during the MDs
- We have observed very small gain at low drive level



Amplifier output power (kW) vs. LLRF drive power (mW). The gain is very low below 1 kW.

LHC CC TX

- In operation we will need the full dynamic range from 0 to 50 kW, including very low power
- The power needed depends mainly on the beam centering

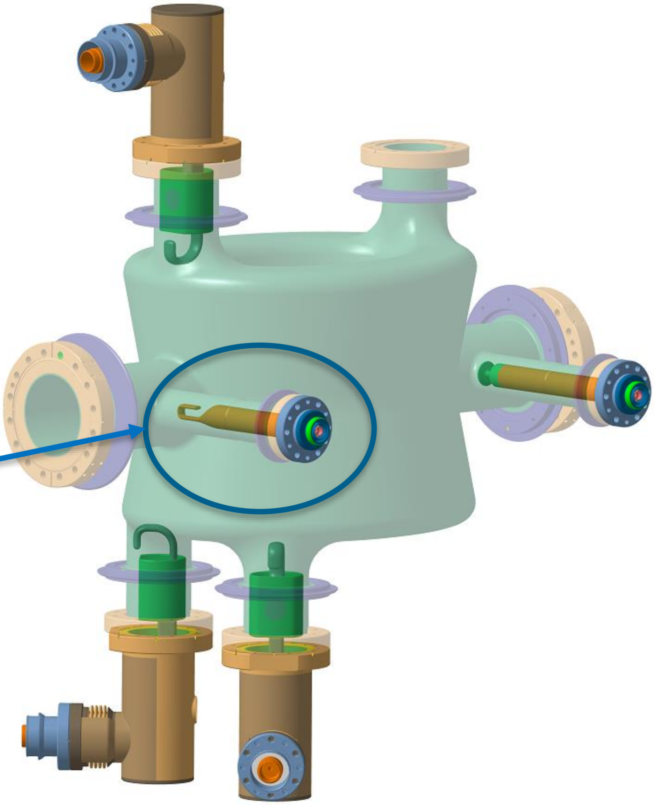


HL-LHC case. Power required with 3 MV/cavity. With -1.3 mm offset the power actually goes to zero, as the beam-induced crabbing voltage equals the demanded 3 MV. If the offset is +1 mm we need about 40 kW. Full compensation of transient beam loading.

- It is therefore important to have **a system that can deal with a large range of TX power, including very low drive** [7]**.**

Direct coupling of ANTENNA signal to the BEAM

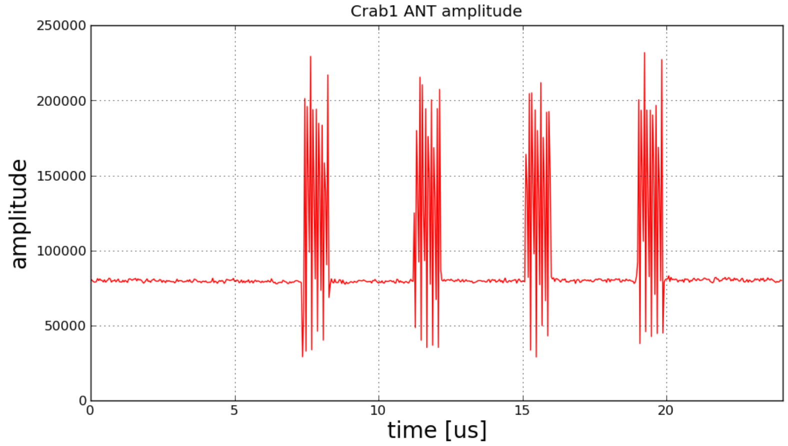
- The LLRF measures the field in the cavity and corrects the TX drive to keep the measured field equal to the voltage set point
- In the CC the location of the Antenna creates a direct coupling to the beam. The Antenna probe is not in the cavity, but in the adjacent beam pipe
- Its shape was designed to couple to HOMs in 1.7 GHz range (*mushroom* shape)
- So the cavity field measurement is corrupted by the direct measurement of beam passage.



Upgraded design with antennas on both sides: *hook* for the LLRF and *mushroom* for HOM.

Direct coupling to beam. Measurements

- The Antenna signal with 4 batches of 36 bunches, nominal intensity. Cavity idling (Oct 12th, 2018)



- The “direct beam coupling” is a problem. It generates ripples at the revolution frequency (43 kHz in SPS, 11 kHz in HL-LHC)
- We can filter it a bit in the SPS but, as we want fast (10+ kHz) regulation BW, **filtering will not be possible in the LHC**
- The Antenna shape will be modified to couple less at high frequency. A 20 dB improvement is expected for both DQW and RFD [5]
- In addition the LLRF will use the PU signals (on both sides of the CCs) for Adaptive Noise Cancelling: We will remove from the Antenna the part of the signal that is correlated with the PU.

Emittance growth. Calculations [4]

Phase noise

Beam parameters

Geometric factor (bunch length)

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

- 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

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

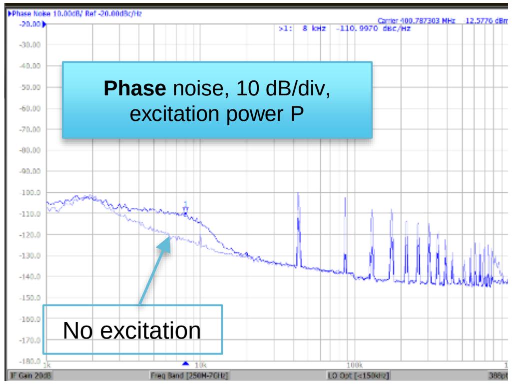
- Depends on the **overlap** between phase noise spectrum and synchro-betatron tune distribution
- The “amplitude-noise geometric factor” **increases** with bunch length.

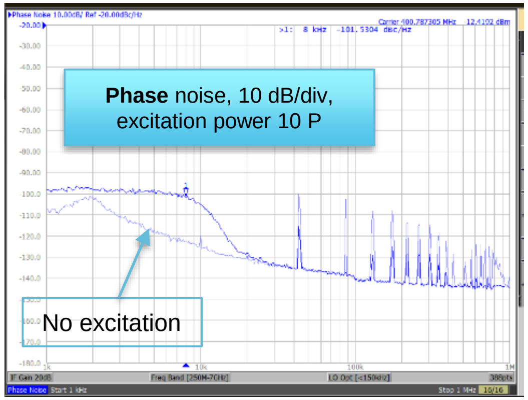
Emittance growth. Data taking

- SPS CC MD5, Sept 4th, 2018
- Coasts at 270 GeV/c
- 4 bunches, low intensity, ~2 ns long
- CC1 idling (no RF), CC2 field at ~1 MV
- 4 coasts, with first one with CC RF off
- Transverse emittance measured with Wire Scanners (Lee Carver, [8])
- RF noise added vectorially -> always a mixture of phase and amplitude noise. Tried to minimize amplitude noise. Phase noise was always dominant
- RF noise (PM and AM) covered a band from DC to 10 kHz only -> excites the first betatron band only (around 8 kHz)
- CC2 phase and amplitude noise Power Spectral Density (PSD) measured with Signal analyser
- Transverse Damper (ADT) off.

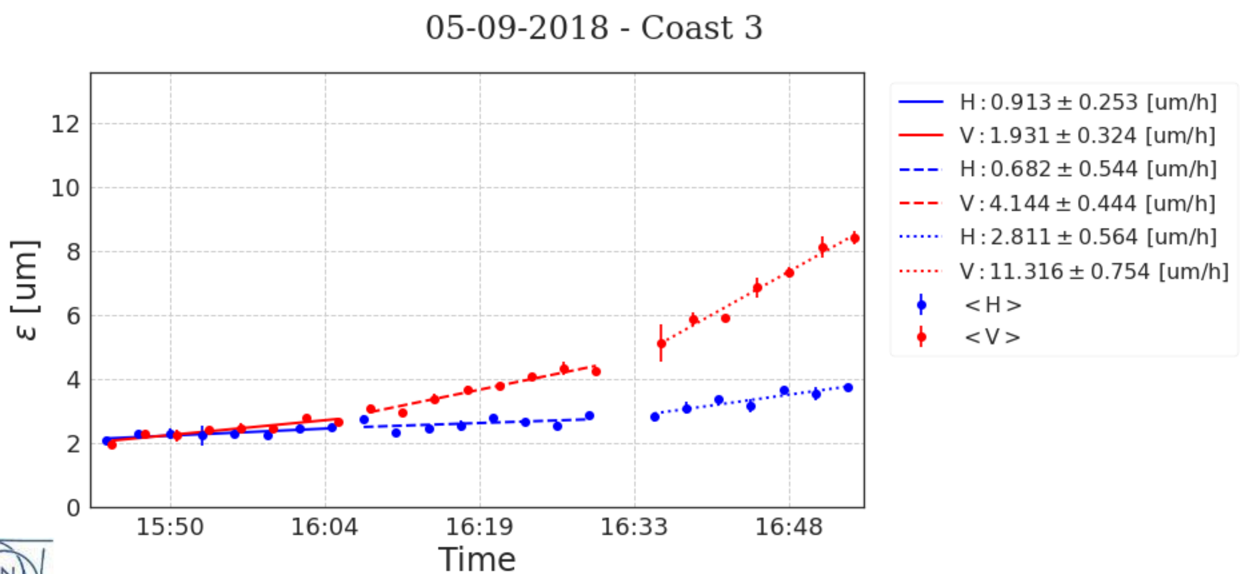
Measurements

- We inject RF noise and measure its PSD in the Antenna signal





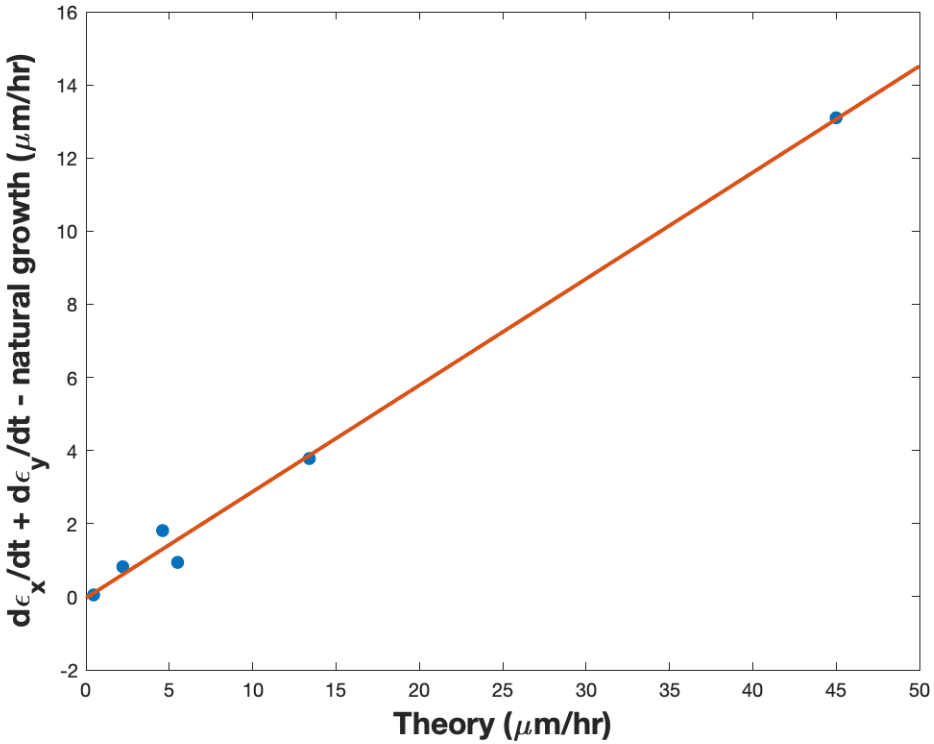
- We measure the x-y emittance evolution



Corrections

- Although the CC gives vertical kicks, we observe some emittance growth in x
- The relevant measurement should be the $\varepsilon_x + \varepsilon_y$. That was confirmed by running simulations with pyHeadTail, injecting CC RF noise in one plane, with coupling by skew quadrupoles
- We observe emittance growth in z-plane as well, but no relation with CC RF noise. Again simulations with pyHeadTail including chromaticity confirmed: No significant effect on transverse emittance growth
- The background growth (0.55 μm/h in x, 0.45 μm/h in y, measured with CC RF Off) was removed
- One measurement point was discarded as the noise level had been modified during the corresponding data taking.

Emittance growth. Results



Measured (Wire Scan) vs. Theory (eq. slide 13 using measured spectra) during the coasts with different noise levels. The **calculations over-estimate the growth by a factor 3.45**. Wire scan measurements by L. Carver.

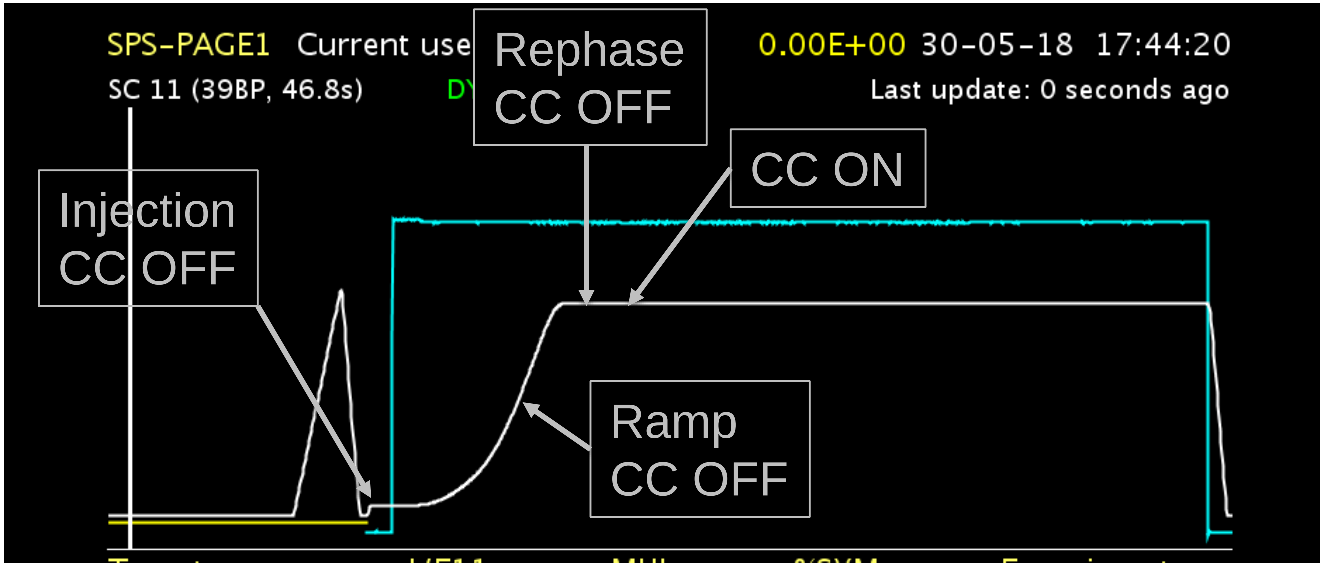
- Very good correlation between measured and calculated
- The **factor 3.45 suggests a systematic error**: *V (1 MV),* β_{cc} *(75.85),* Noise Power,…?
- Investigations on-going.

Plans SPS

- SM18, 2021
  - Measurements of the RFD at higher voltage (> 1 MV). Use “linearized” IOT or Solid State amplifier.
  - Check ponderomotive oscillations with RFD
  - Check RF feedback with “linear” TX
  - Optimize RF ON sequence.
- SPS, 2021
  - Restore end-2018 situation for both cavities
  - Measurements of DQW with “linearized” IOT amplifiers at higher voltage (>2 MV) and beam
  - Investigations of Transverse Emittance Growth.
- SPS, 2022-2023
  - Test RFD in SPS.

Plans LHC

- Review the operational scenario?
  - The operational scenario was to have the CC ON from injection, with low field and using counter-phasing to make them invisible -> not favourable from RF noise point of view
  - At 2 deg K the CC tune is very stable
  - Can the cavities be left "parked" during filling/ramping and switched ON when needed in physics?



- CC LLRF
  - Design prototype uTCA (?) system in 2022-2023. Synergy with SPS LLRF upgrade (on-going) and possible LHC LLRF upgrade (LS3?).

Conclusions

- SM18 2017 tests:
  - The cavities in the cryomodule were driven from the LLRF on Dec. 15th-18th 2017, just before installation in the tunnel during YETS 2017-2018
  - They were powered from a solid-state 200 W amplifier (not the SPS 50 kW IOT)
  - We could not exceed 100 kV due to poor conditioning (to be compared to the nominal 3 MV).
- SPS 2018 tests:
  - 2 deg K from end-August only. At 4.5 deg K tune is unstable (He ebullition)
  - Work at low field-> big problems with TX non-linearity
  - Tune oscillation above 1 MV (ponderomotive oscillations) understood in October
  - Measured emittance growth a factor 3 below calculations
  - "Rocky" learning but we have solutions for all identified issues.
- LHC operational scenario:
  - To achieve 1% integrated lumi reduction during fill, the RF noise power must be reduced by 100 (-20 dB) compared to LHC ACS design (calculated) or 30 (-15 dB) extrapolated from 2018 SPS measurements
  - Cavity tune very stable at 2 deg K
  - Study the possible filling/ramping with parked CC?

Thank you for your attention!

References

[1] Ponderomotive Oscillations in a Superconducting Helical resonator, IEEE Trans. On N.Sc., Vol 19, April 1972

[2] Ponderomotive Instabilities and Microphonics- a Tutorial, J.R. Delayen, 12th Intl. Workshop on RF Superconductivity, 2005

[3] Electroacoustic Instabilities in the LEP2 Superconducting Cavities, D. Boussard et al., CERN-SP-95-81 RF, 1995

[4] 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

[5] S. Verdu-Andres, Evaluation of RF pickup antennas

for crab cavity (DQW and RFD) LHC-series, 8th HL-LHC meeting, Oct. 2018, https://indico.cern.ch/event/742082/contributions/3085085/attachments/1735409/2806683/181018_HiLumiCERN2018_PickupsForLHC-series.pdf

[6] E. Yamakawa, Transient beam loading in crab cavities

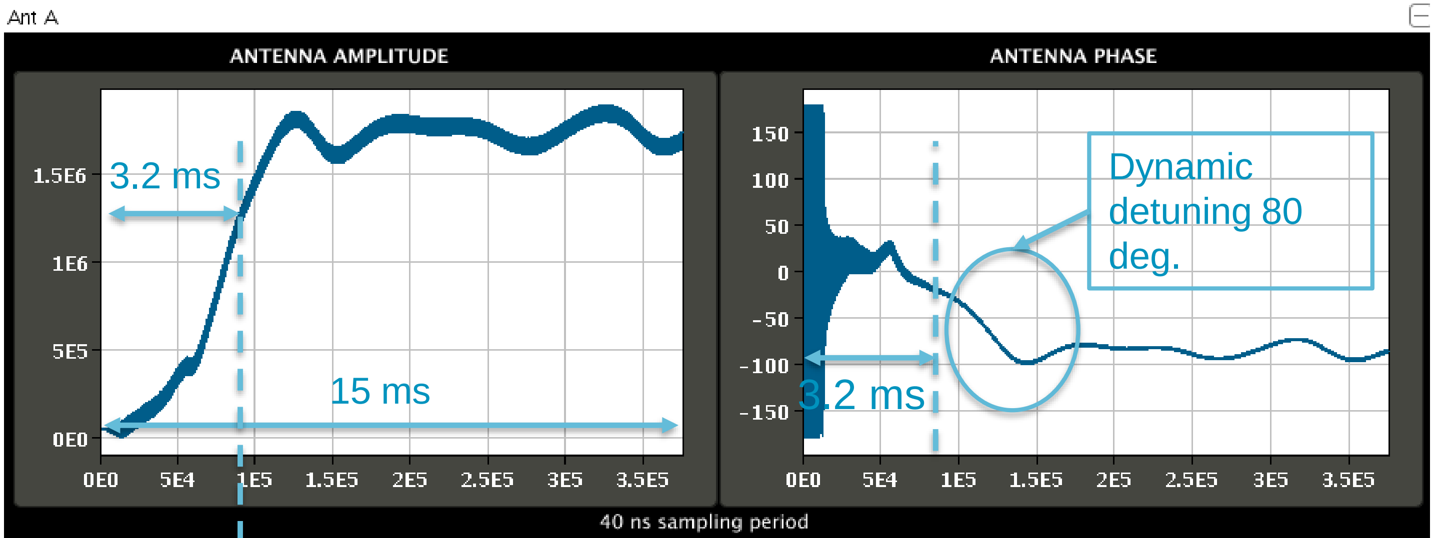
Experience from SPS & predictions for HL-LHC, 8th HL-LHC meeting, Oct. 2018, https://indico.cern.ch/event/742082/contributions/3084841/attachments/1734391/2805146/HLLHC_2018_Eyamakawa.pdf

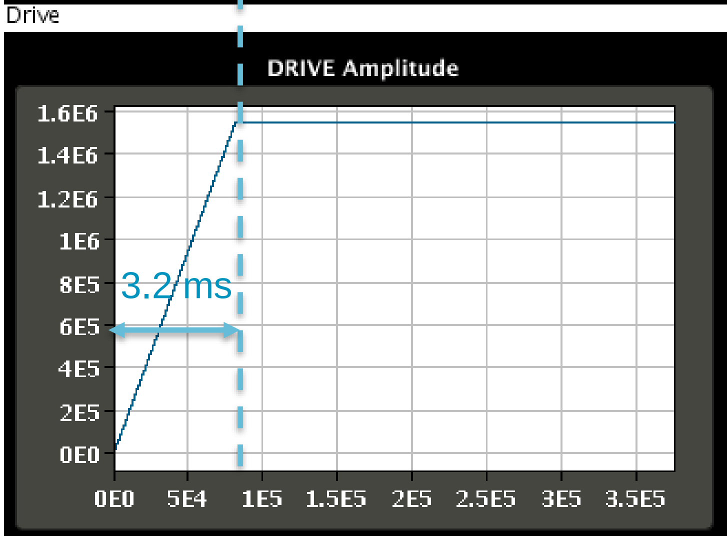
[7] E. Montesinos, WP4 Strategy for RF System , this Review, https://indico.cern.ch/event/787363/contributions/3365401/attachments/1865131/3066511/20190619_RF_power_strategy.pdf

[8] R. Calaga, SPS beam measurements & Operational challenges, this Review https://indico.cern.ch/event/787363/contributions/3367295/attachments/1865083/3066410/HLLHC_Review_Challenges_17062019_Calaga.pdf

Back-up slides

But our cavity filling is way too fast…



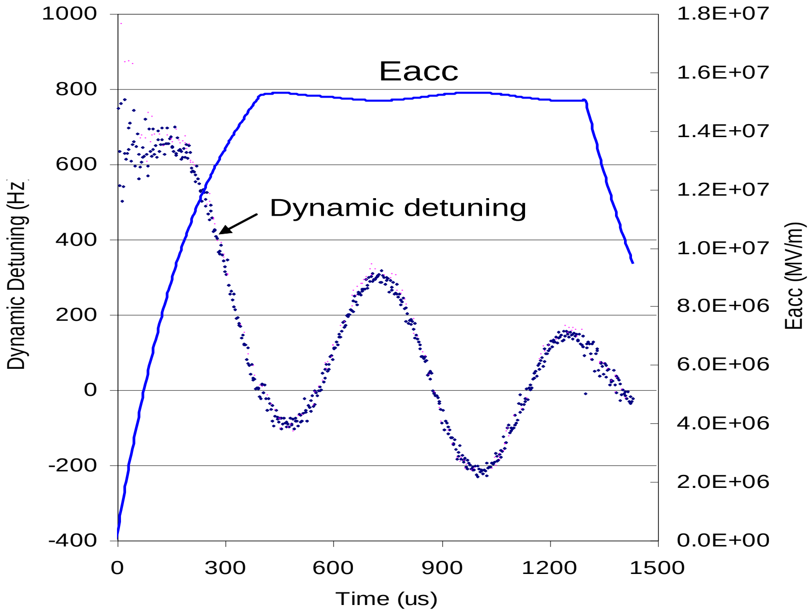


Pulsing the CC RF in the SPS: Linear drive ramp lasting for 3.2 ms (bottom).

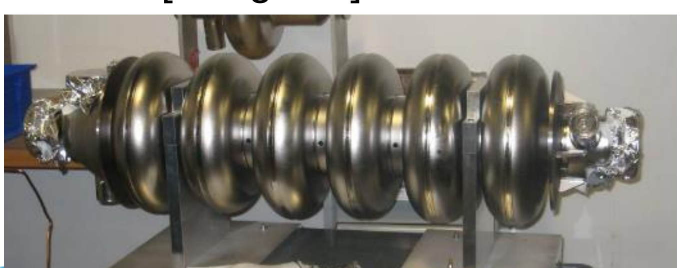
- We presently fill the cavity in 3.2 ms, which we thought would be slow enough given the 400 μs cavity filling time
- But the dynamic LFD makes the cavity phase shift ring for > 10 ms.

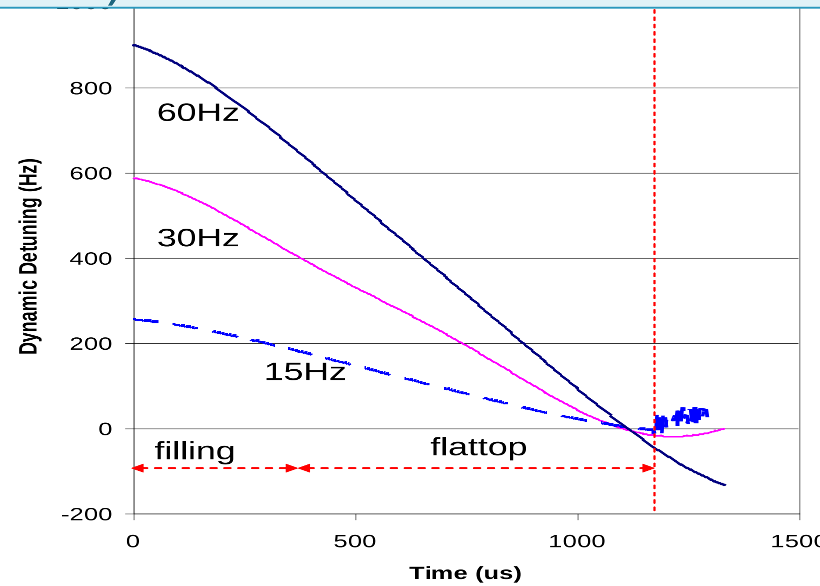
Lorentz For

That is nothing new… Similar observations in the SNS multi-cell cavities (Q_L= 7 10^5 @ 805 MHz) in 2009…



2 kHz resonance in medium beta cavities [SangHo1].





High beta cavity at 12.7 MV/m for various rep rates [SangHo].

Fast piezzo tuners were installed but are NOT used anymore. The ~1 kHz detuning can be dealt with by the RF feedback.