SPS LLRF
Measurements and lessons learned

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Outline

- Transverse emittance growth results
- Hardware issues
  - Historical recap
  - TX (non) linearity
  - Coupling of ANT signal to beam
  - Problems with Tuning
  - Performances of the regulation: spectral purity with/without feedback
- Conclusions

Transverse 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)
- 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 measured with Signal analyser
- ADT off

Calculations. Unnormalized Emittance

Phase noise

Beam parameters

Geometric factor (bunch length)

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

- 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

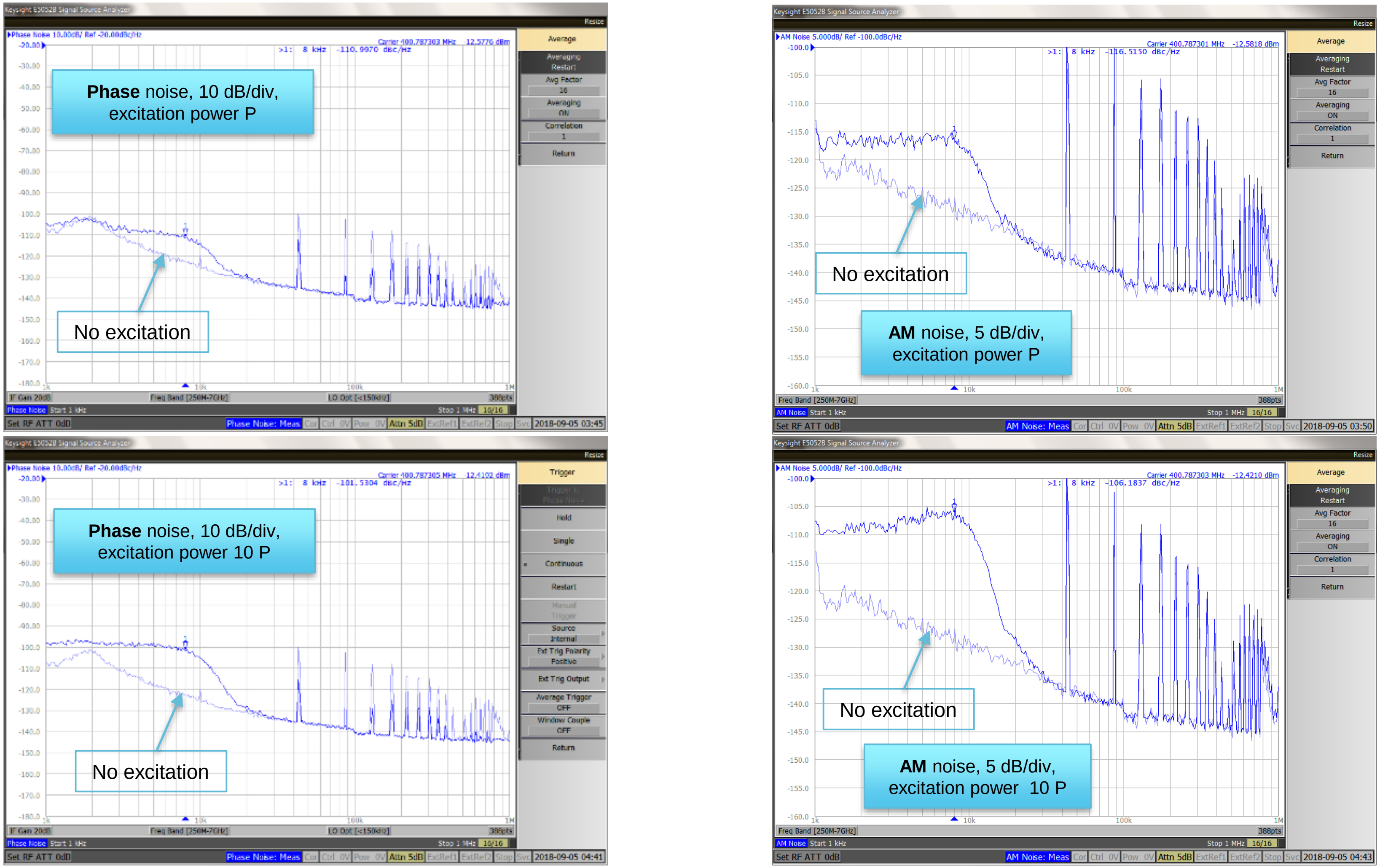
Amplitude noise

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

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

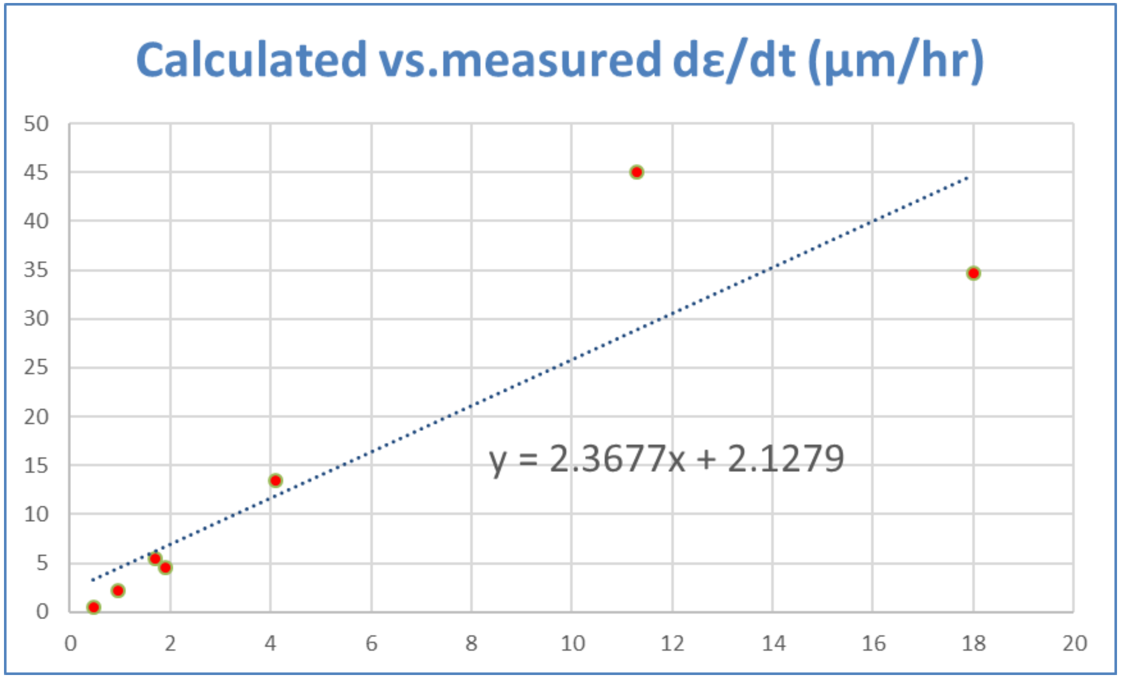
See P. Baudrenghien and T. Mastoridis, “Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities,” Phys. Rev. Accel. Beams 18, 101001 (2015).https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.101001

Noise spectra measured in Ant CC2



Left: Phase noise PSD. Right: AM PSD. 1 kHz – 1 MHz
Top: -10 dBm excitation, bottom: 0 dBm excitation (10 times more power)
Background trace shows PSD without noise injected. The marker is on the betatron line (8 kHz)
The frev lines are generated by the beam

Results

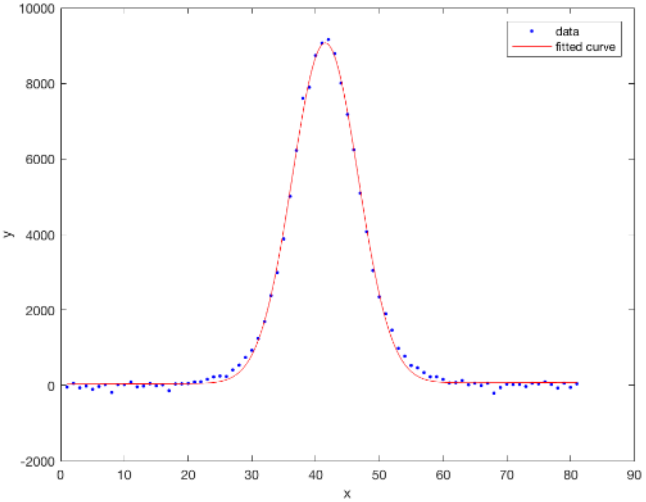


Calculated (eq. slide 5 using measured spectra) vs. measured (Wire Scan) during the coasts with different noise levels. The calculations over-estimate the growth by factor 2-3. With CC off the growth rate is around 0.4 μm/hr. Wire scan measurements by L. Carver.

Possible reasons for the difference

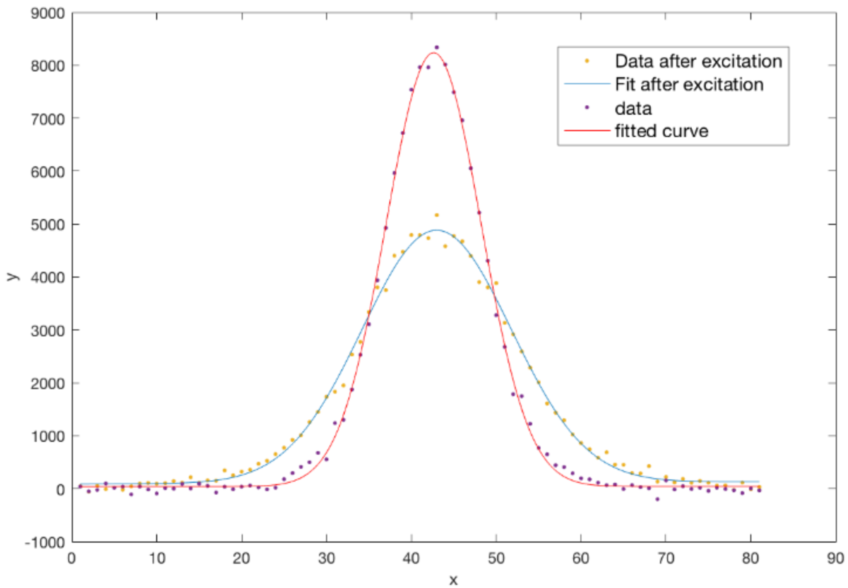
- The ***Calculated*** computes the rms value of the transverse distribution from beam parameters and measured noise spectrum (formulas on slide 4)
- The ***Measured*** emittance is estimated by fitting a Gaussian model (*A*,*b*) plus baseline offset (*o*) and tilt (*d*) to the pickup data

$$\frac{A}{\sqrt{2\pi c}} e^{-(y-b)^2/2c^2} + d\,y + o$$

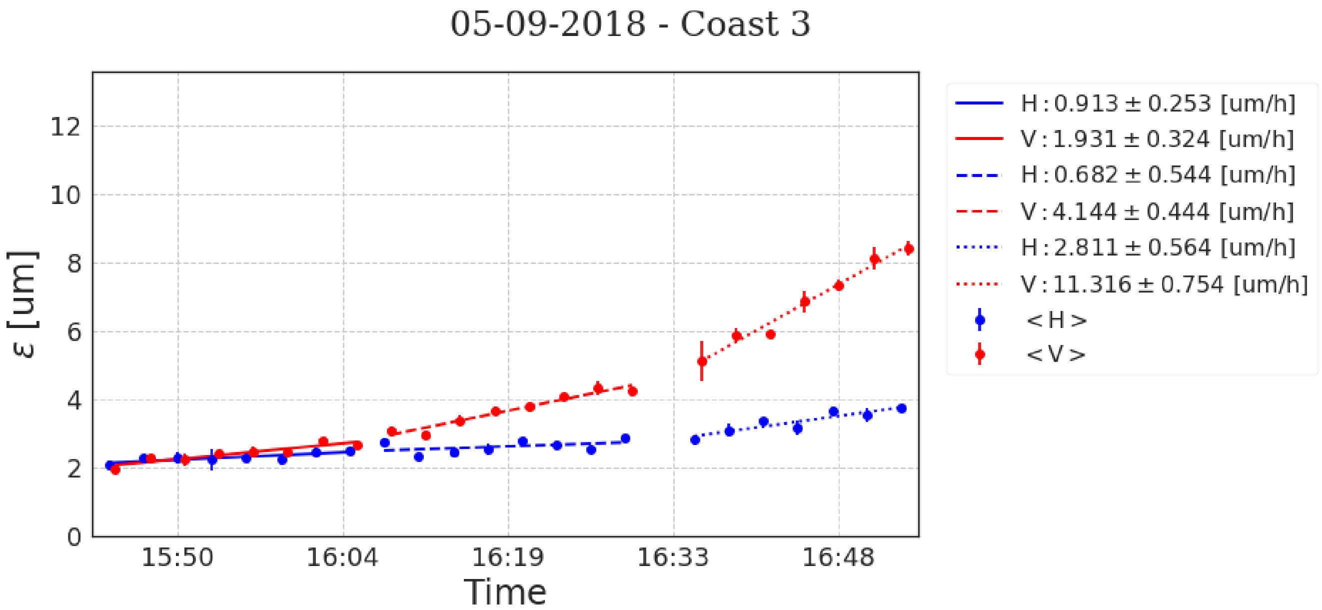


- Then calculating the emittance from the estimated σ (model parameter *c*)

- The measured emittance does not include **Beam Losses**: The bunch population is estimated by the model parameter *A*, that decreases by 8-11% during the excitation record. This can either be real loss or population in the tails that is below the pickup noise threshold. This loss has a really large effect on rms estimates
- The baseline term *o* in the previous equation is 5-6% HIGHER after noise injection. It is not expected that the baseline of the scan would change, suggesting a **growing tail population** that is discarded from the emittance measurement.



- An additional source of error is the apparent **coupling between the horizontal and vertical planes**, which is not included in the calculations
- The horizontal emittance growth rate is clearly increasing as we inject noise on the vertical plane.



Measured growth of the horizontal emittance in blue (up to 2.8 μm/h for the largest excitation, to be compared to the vertical 11.3 μm/h in red) while the CC kicks are strictly vertical.

Emittance Growth Summary

- The first measurements of emittance growth show a factor of 2 difference between calculated (higher) and measured
- The result is conservative (measured below calculated)
- Several factors suggest that the measured data are under-estimated
- The factor 2 is not very important though as the noise level must be reduced by factor 100-1000 (in power) for the HL-LHC target if calculations are trusted
- This confirms that a very **significant effort in RF noise reduction must be achieved for HL-LHC**.

Hardware issues

Historical recap

Quick SM18 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)
- We commissioned the tuning loop, the Self Excited Loop (SEL) and the RF feedback (driven mode)
- Very promising. But recall….low field (100 kV) and solid-state amplifier.

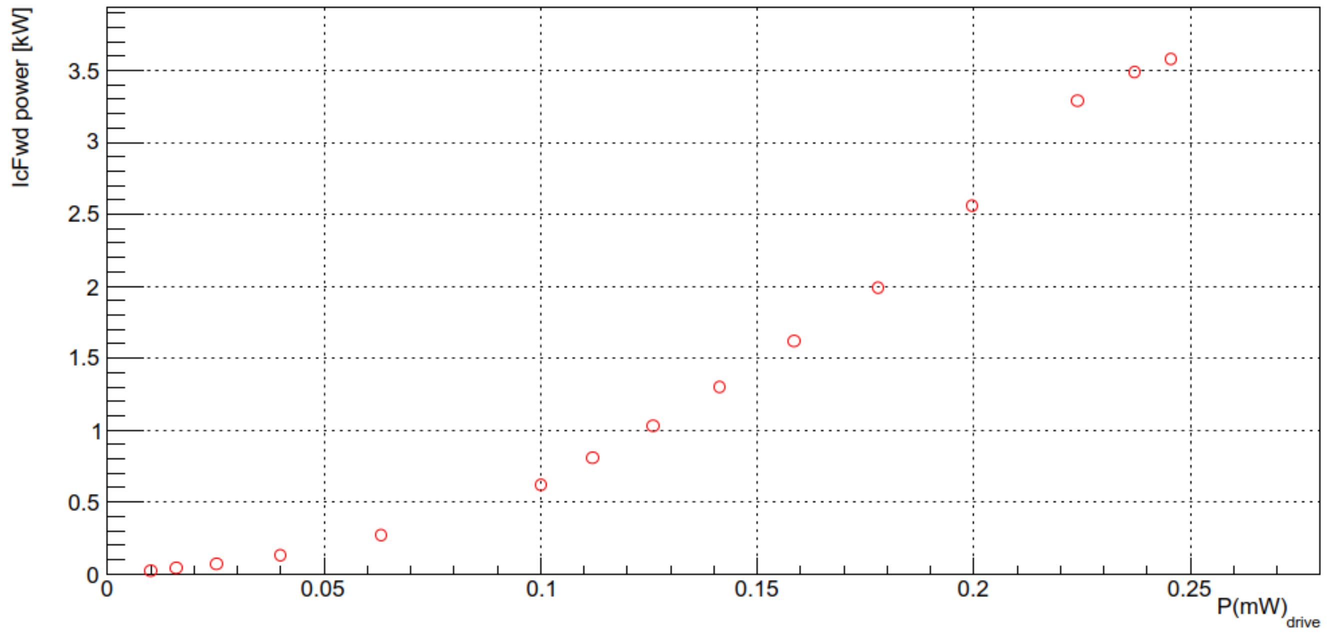
… then SPS tunnel

- Cryomodule was then installed in LSS6 in Jan. 2018
- We were promised time to set-up LLRF between MDs, with cavities out of beam line…but that came begin Oct 2018 only. Till then the cavities were passed to LLRF at best the evening before the MD
- For comparison: We had a full scale test bench of the ACS system in SM18 from begin 2005 on. First LHC beam in Sept. 2008….
- Compared to the SM18 Dec 2017 tests, the SPS presents 3 main differences: The amplifier (50 kW IOT), the higher field and…the beam.

TX (non) linearity

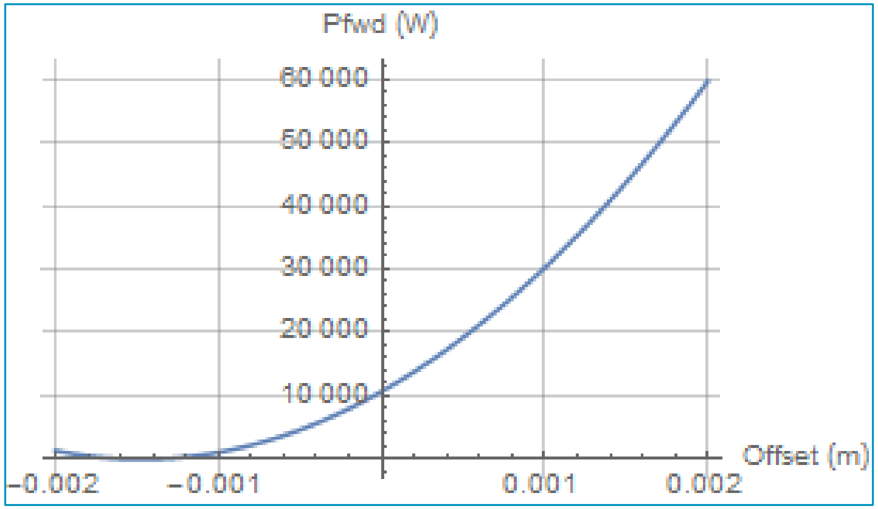
SPS CC TX

- 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.

- 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 -1.5 mm offset the power actually goes to zero, as the beam-induced crabbing voltage equals the demanded 3 MV. If the offset is +1.5 mm we need about 45 kW.

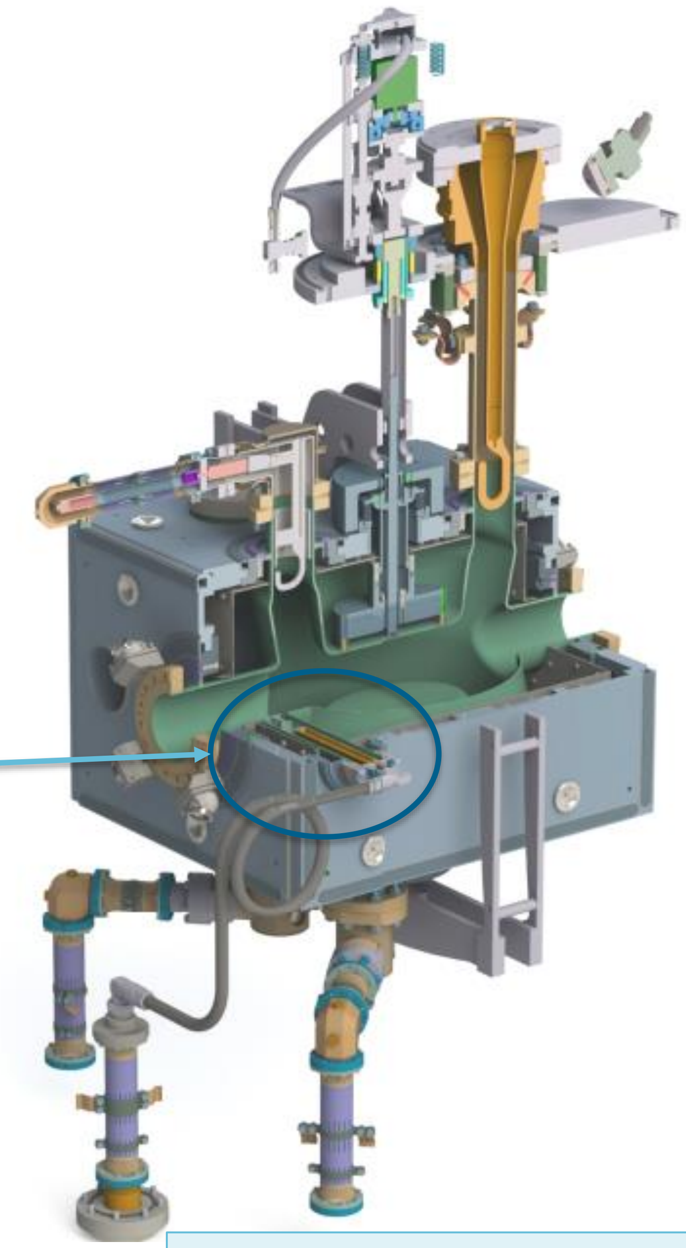
- It is therefore important to have **a system that can deal with a large range of TX power, including very low drive.**

Actions

- On the LLRF side we will include a Polar Loop to linearize the TX gain (as in the LHC). But at very low gain this solution is noisy
- Effort on the power side welcome…Being discussed with Eric.

Direct coupling of ANTENNA signal to the Beam

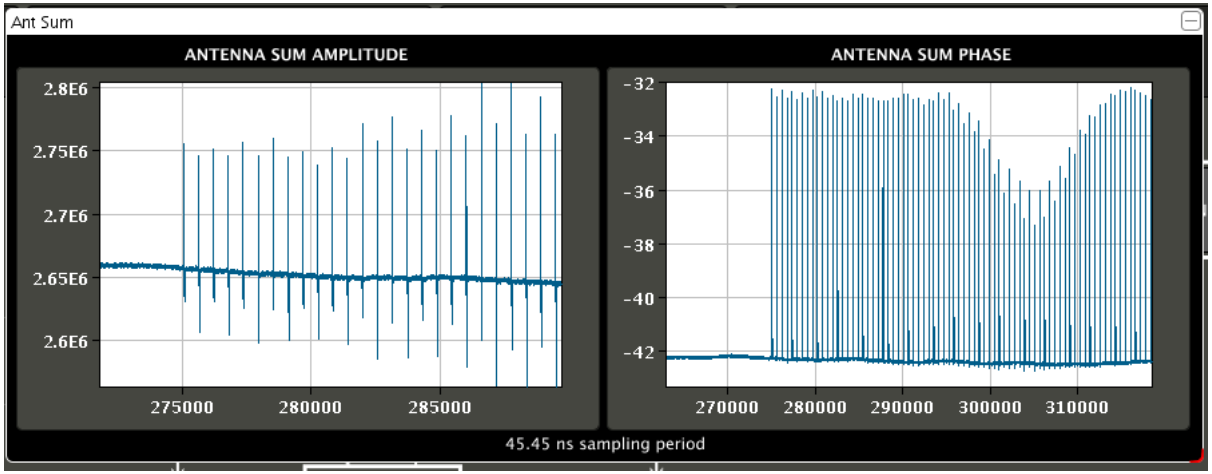
- The LLRF measures the field in the cavity and corrects the TX drive to keep the measured field equal to the voltage set point
- In the CC the location of the ANT creates a direct coupling to the beam. The ANT probe is not in the cavity, but in the adjacent beam pipe
- Its shape was designed to couple to some HOM
- So the cavity field measurement is corrupted by the direct measurement of beam passage.



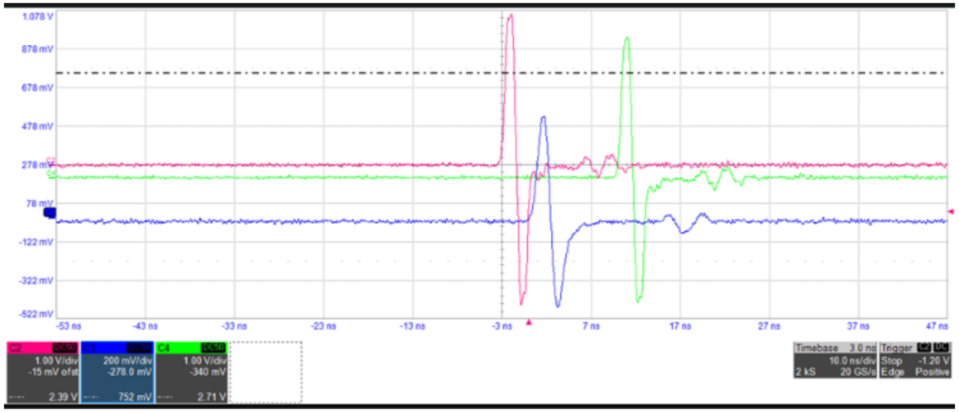
Reproduced from [Zanoni]

Direct coupling to beam. Measurements 1/2

- The ANT signal with single bunch (May 30th, uncalibrated)

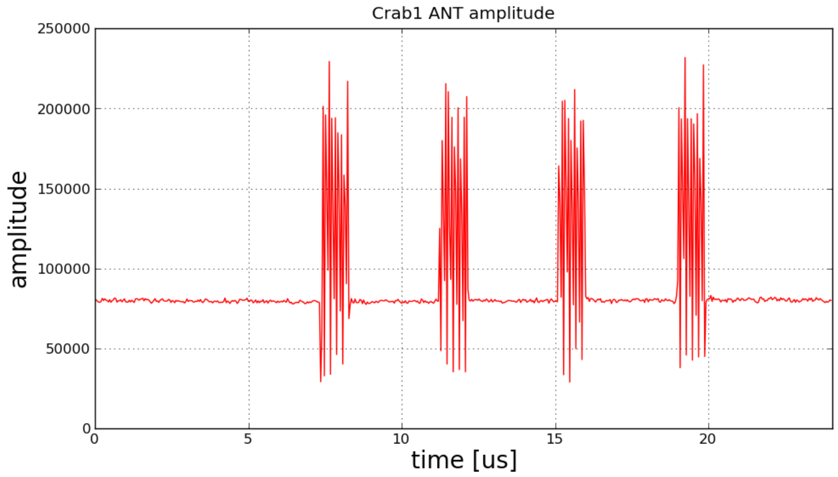


- ANT1, ANT2 and PU (blue) during bunch passage (10 ns/div)



Direct coupling to beam. Measurements 2/2

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



- 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**.

Actions

- We have added some filtering in the LLRF processing for SPS
- For the LHC, the Antenna shape will be modified to couple less at high frequency. Being discussed.

Problems with tuning

- We could easily lock the tuner loop at low field (as done in SM18 in Dec 15th- 17th, 2017)
- But when we tried to exceed 700 kV, the tune measurement became very noisy and the loop would drive the cavity way out of tune
- We have recently understood that we suffer from **ponderomotive oscillations** (Emi's talk). The phenomenon is common with high Q_L superconducting cavities [Ceperley], [Delayen]. It was a problem in LEP [Boussard] and is present with the HIE-Isolde QWRs as well
- It happens, at a threshold field, when the RF frequency is above the cavity tune. As the LFD is negative, instability happens when increasing the drive without acting on the tuning plate motor. Our SPS experience…
- The LFD is large (- 350 Hz/MV^2) compared to the 400 Hz Single sided BW)
- When **RF fdbk is ON**, the field is stabilized and the **oscillations cannot develop**
- But…to close the RF feedback we need to adjust the LLRF phase with cavity on tune -> **a setting-up nightmare….**

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Actions

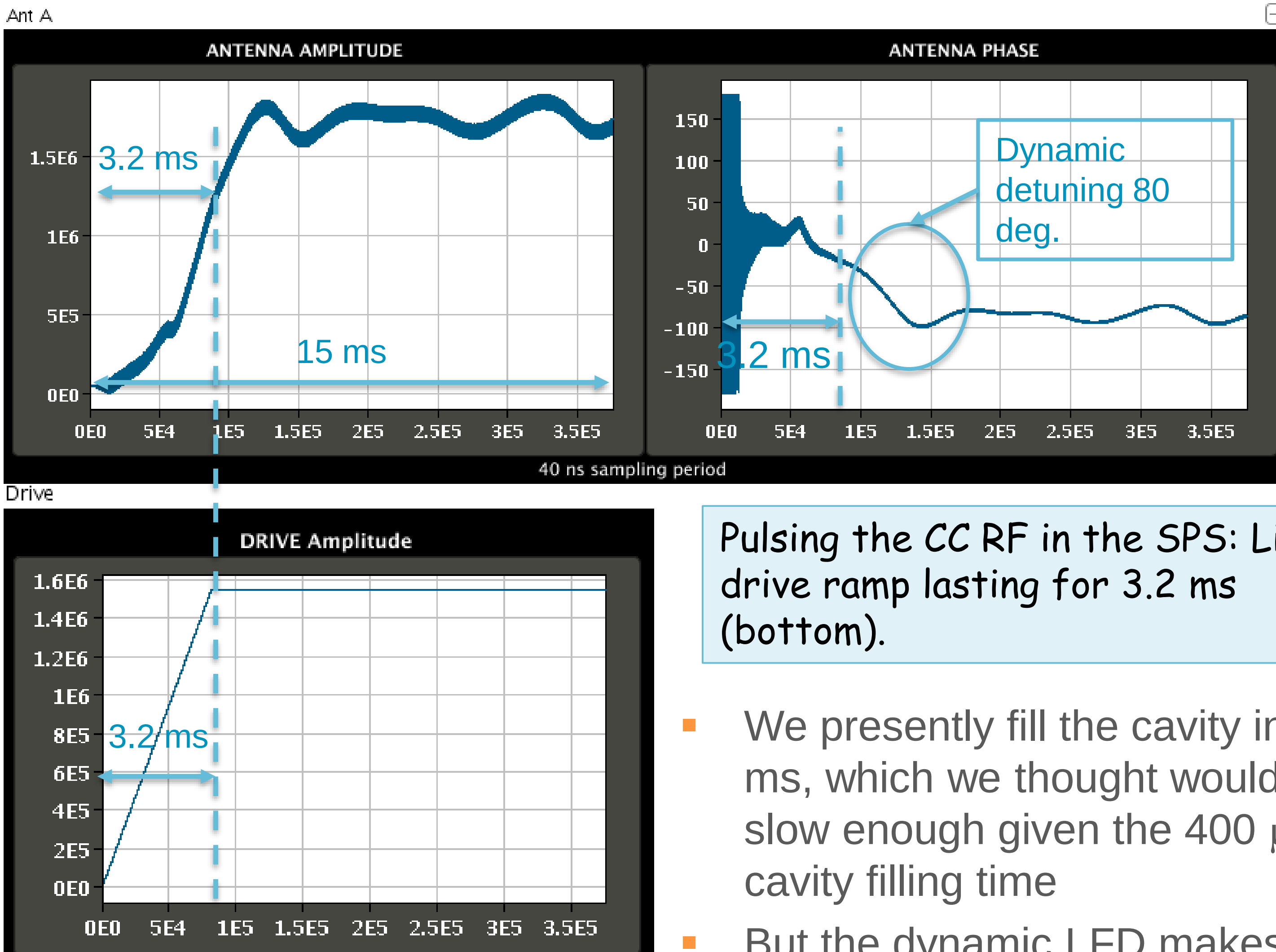
- Now that we have understood the issue, it is not "fundamental", it just makes the setting-up tricky
- Plans:
  - Use **SEL (with amplitude loop ON) to find the tune**, then switch to Driven Loop (as done in HIE-Isolde)
  - To be implemented during LS2

Performances of the regulation: spectral purity with/without feedback

- Within its regulation BW (~10 kHz at present) the RF feedback regulates the cavity field as it should

Spectrum of ANT (centre freq. 400.528800 MHz, 26 GeV, 10 kHz span).
Left: fdbk OFF
Right: fdbk ON

- But our cavity filling is way too fast…

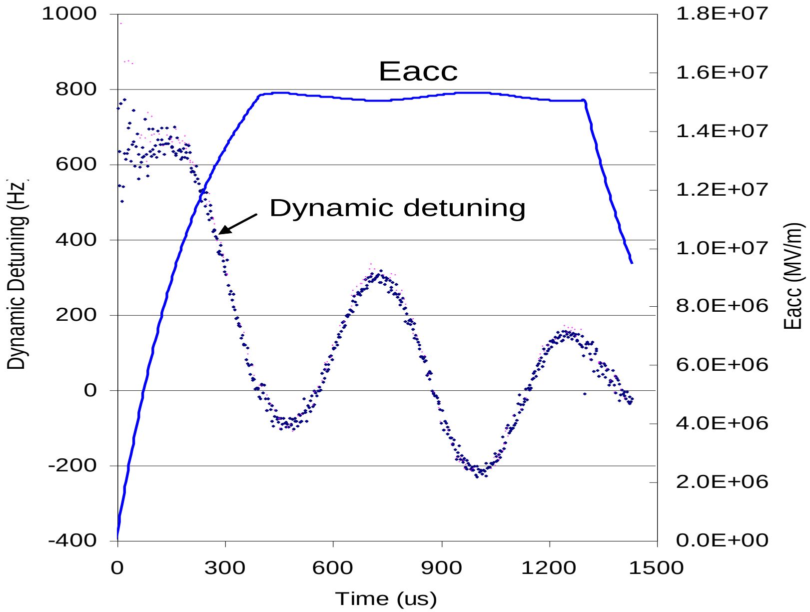


Pulsing the CC RF in the SPS: Linear drive ramp lasting for 3.2 ms (bottom).

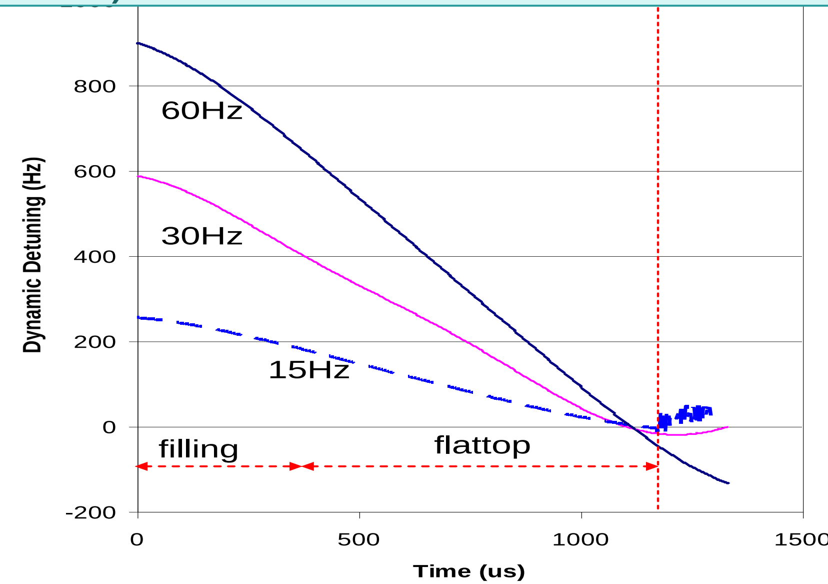
- We presently fill the cavity in 3.2 ms, which we thought would be slow enough given the 400 μs cavity filling time
- But the dynamic LFD makes the cavity phase shift ring for > 10 ms.

Lorentz Force Detunin

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.

Actions

- We must be more gentle with the RF ON sequencing
  - Make the cavity filling last longer
  - Let the mechanical oscillation damp before closing the RF feedback.

Conclusions

- The first measurements of emittance growth show reasonable agreement with expectations and reaffirm the **need for significantly lower noise levels for HL-LHC**
- From the first tests of tuner and feedback loop, several problems have been identified, but we have potential solutions for them:
  - The non-linearity of the TX at low power must absolutely be reduced thanks to a LLRF Polar Loop and amplifier upgrade
  - The Antenna signal must not couple directly to the beam passage. Redesign of the coupler
  - The SEL loop will be used to set the cavity on tune before closure of the RF feedback. Ponderomotive oscillations should not be a problem anymore
  - The RF feedback has shown capable to clean the cavity field. We just need to treat the RF ON sequence much more gently
- We have cavity available (without beam) till end Nov. 2018 and will implement part of the above LLRF upgrades by then
- Work on the LLRF **must continue during LS2** (Polar loop and SEL).

Thank you for your attention!

References

[Zanoni] The crab cavities cryomodule for SPS tests, C. Zanoni et al., 2017, J. Phys. Conf. Ser. 874 012092

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

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

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

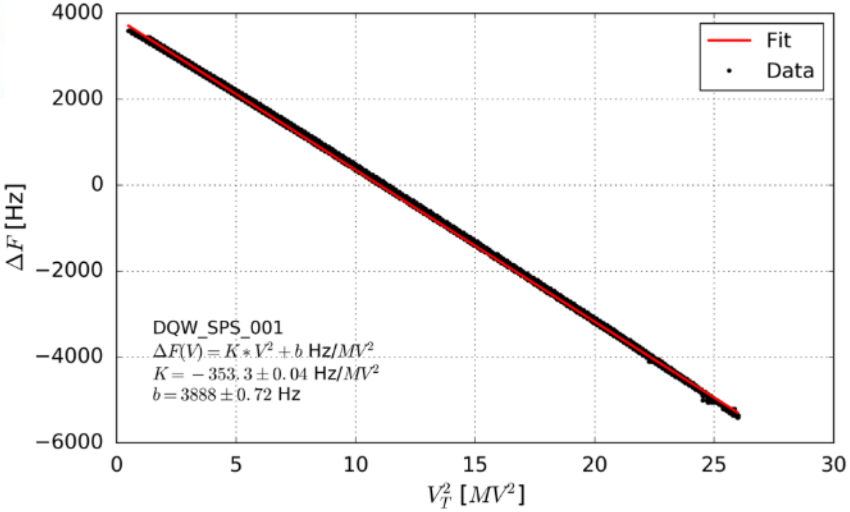
[SangHo] Sang-Ho Kim, Status of the SNS Superconducting Linac and Future Plan, 11th International Workshop on Accelerator and Beam Utilization, Gyeungju, Korea, September 13, 2007

Additional material

Other Measurements

DQW_SPS_001

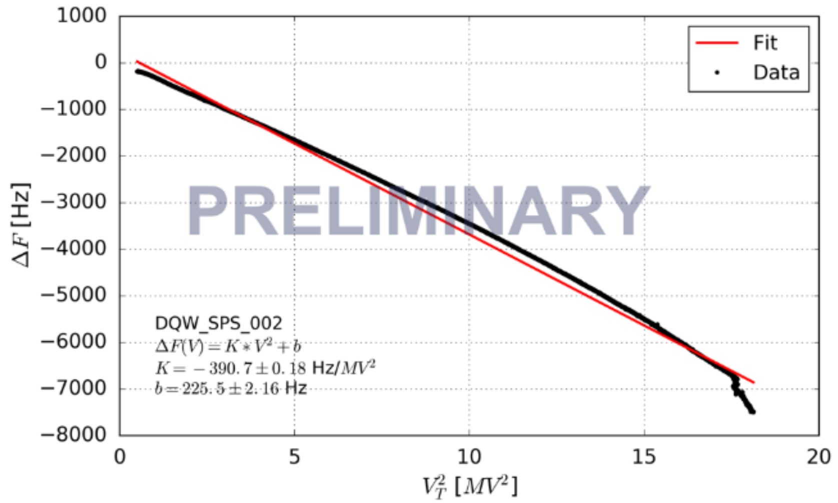
Lorentz Force Detuning



DQW_SPS_002

Lorentz Force Detuning,

Non-Linear = measurement problem



K. Hernandez-Chahin, UGto/CERN-BE-RF-SRF