LLRF/PLC STATUS FOR THE SPS CRAB CAVITIES AND HL-LHC

L. Arnaudon, P. Baudrenghien, A. Castilla Loeza, B. Kremel, J. Simonin, N. Stapley, *CERN, BE-RF*

T. Mastoridis, *California Polytechnic State University, San Luis Obispo, USA*

E. Yamakawa, *Lancaster University*

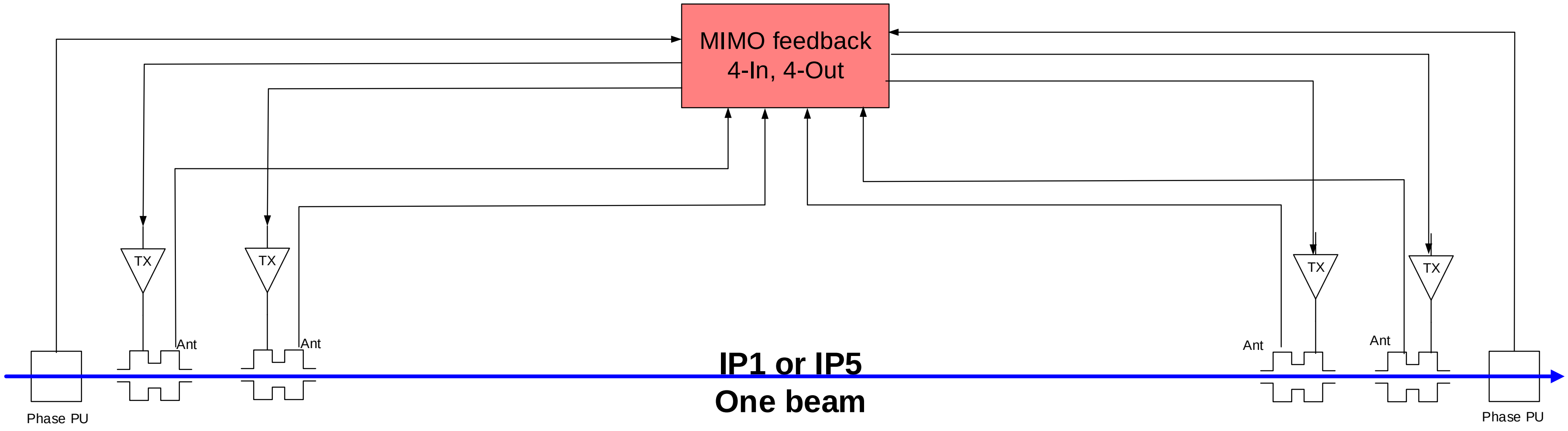
Outline

- LHC and SPS CC LLRF
- SM18 LLRF test results
- PLC
- Left to be done…
- Conclusions

PRESENTATION OF LHC AND SPS CC LLRF

The LHC MIMO LLRF (IP1 and IP5)

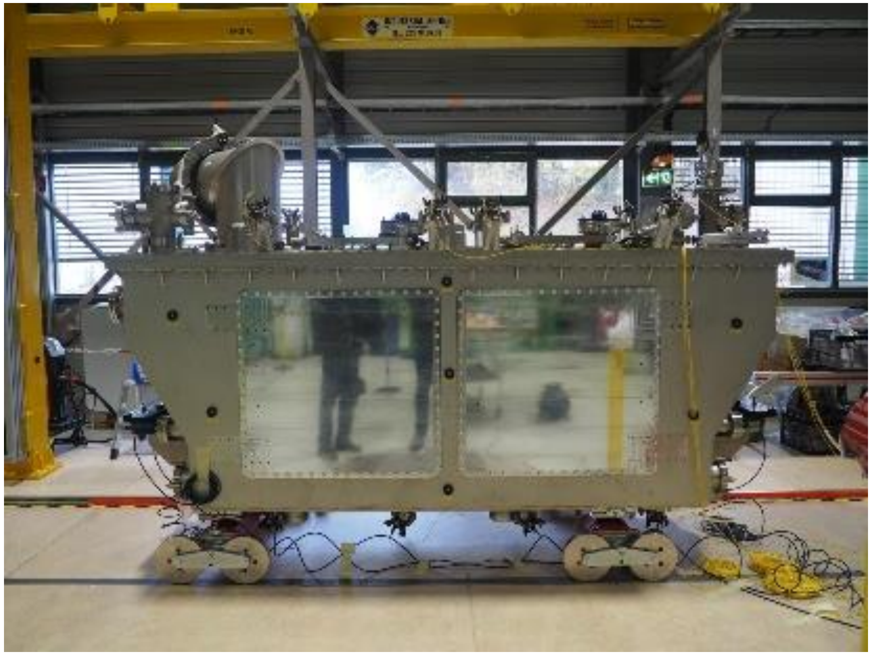
The Multiple inputs- multiple outputs feedback (MIMO) regulates the individual TX drives from a measurement of the field in all four cavities. This allows for better control of the crabbing within the IP zone (that is no crabbing outside) and some compensation in case of one-cavity quench

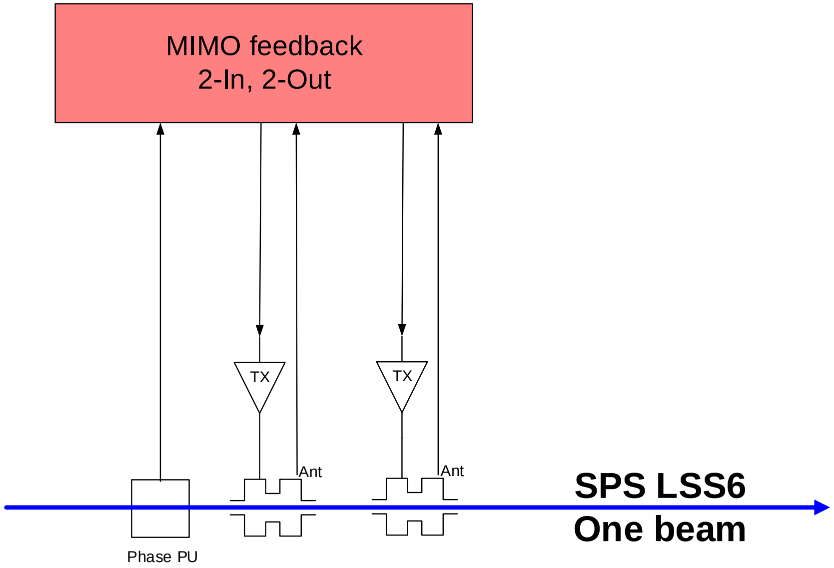


Local PU signals are used to fine-adjust the phase of the CC field with the mean bunch centre

The SPS LLRF (IP1 and IP5)

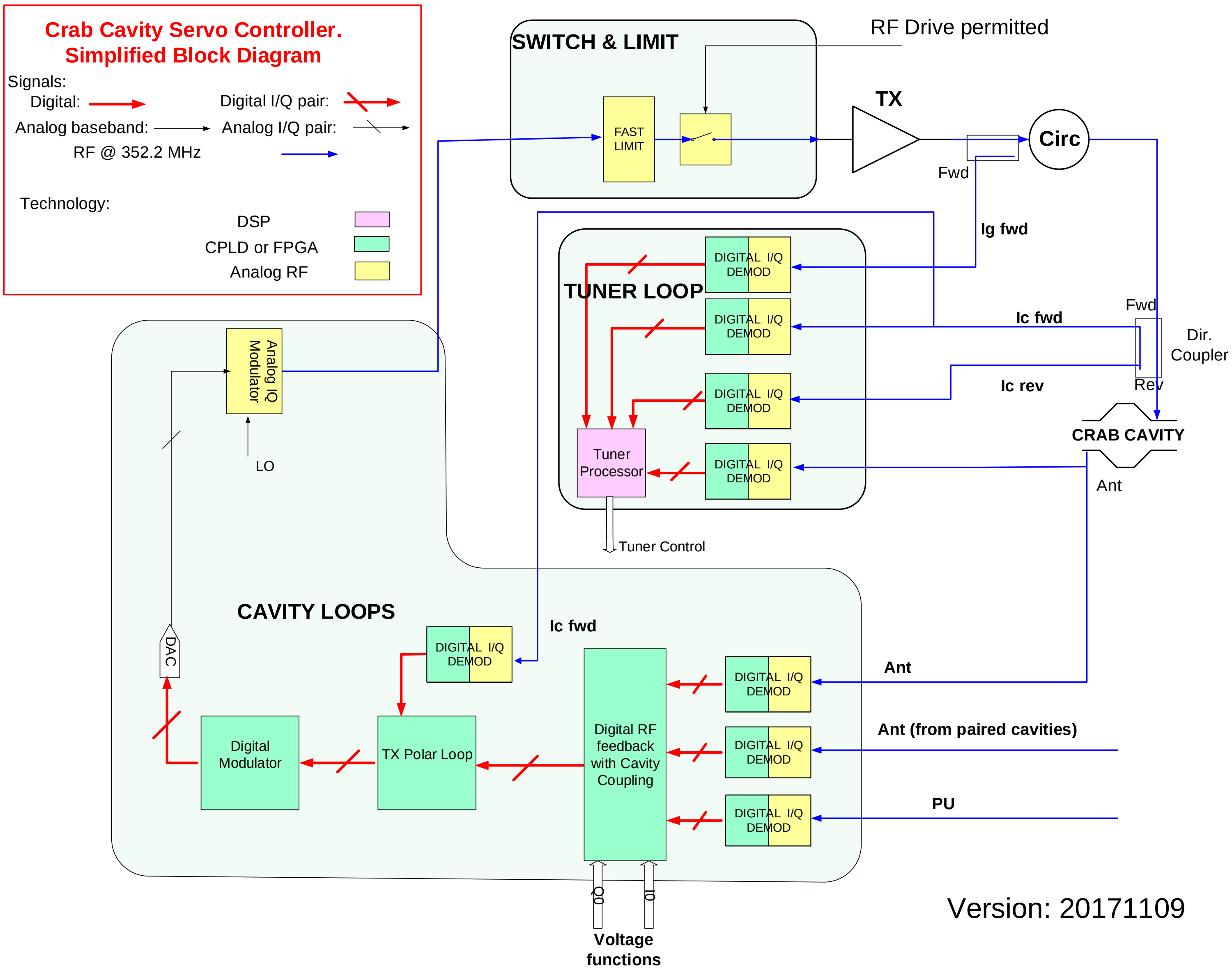
In the SPS we have two cavities in same cryostat. Still we want to commission the MIMO feedback





Local PU signal is used to fine-adjust the phase of the CC field with the mean bunch centre

Block diagram of the SPS CC LLRF



SPS VME crate (1 cav.)

Crate Management module (same as LHC and L4)

Clock Distributor module. Generates the harmonically related LO and ADC clocks. Adapted from L4

Custom-designed RF VME crate (same as LHC and L4)

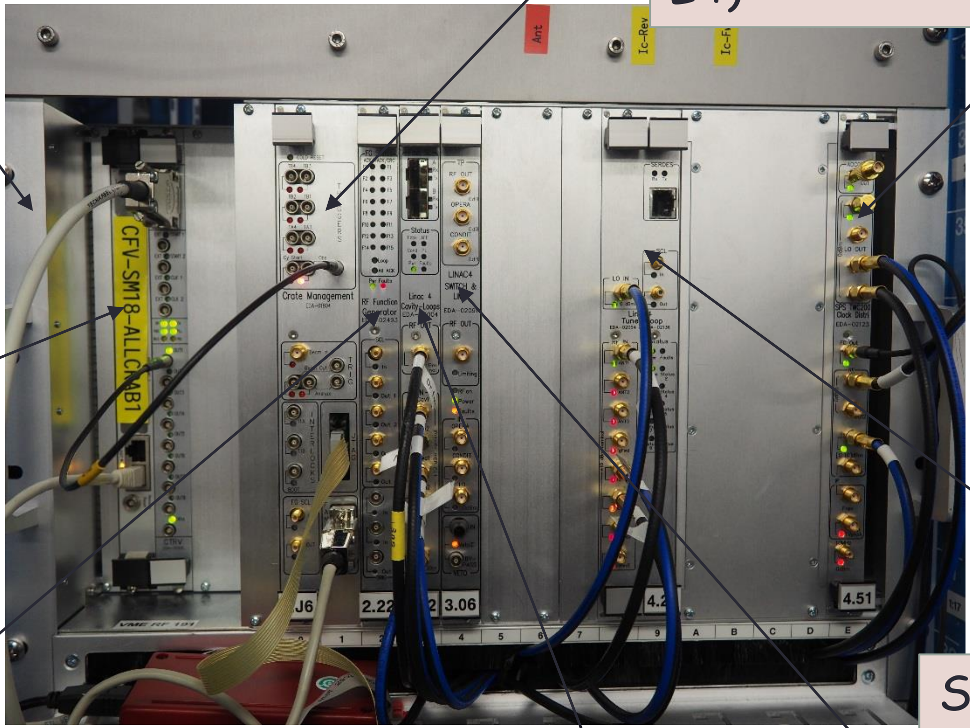
Standard CO-supplied CPU with timing card (CTRV/P)

Function generator (same as SPS LLRF)

Tuner module. Adapted from L4

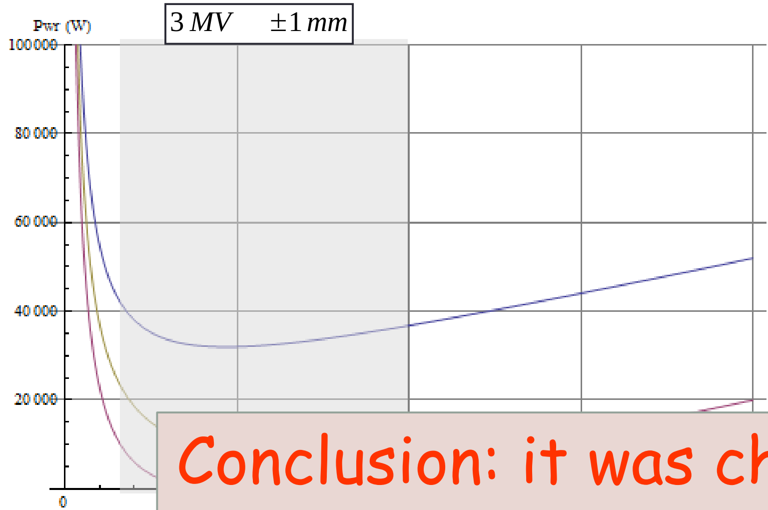
Switch and Limit module. Receives the RF power interlock. (adapted from LHC and L4)

Cavity Loop module (MIMO feedback). Hardware adapted from L4 module (352.2 MHz)



The above VME crate is the SM18 "vertical" test-bench (one cavity). In SPS the modules will be doubled (2 cavities)

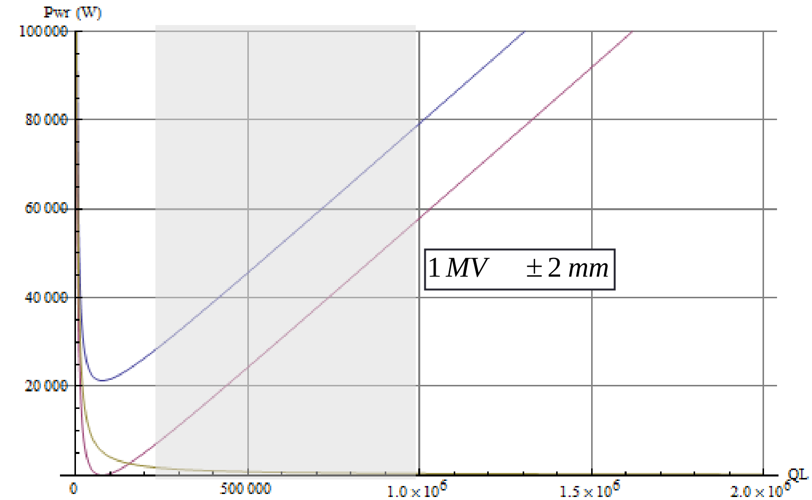
Reminder: RF Power vs. Q_L for various RF voltages and beam offsets



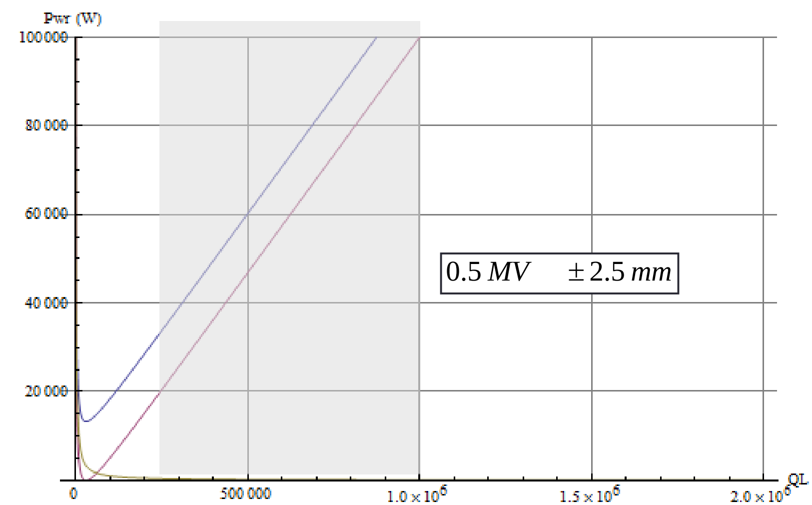
Conclusion: it was chosen to use Q_L=500000

During ...
Assuming a maximum of 1 mm beam offset, the required power is below 40 kW if we choose loaded Q in the 200k-1M range (above).

R/Q = 300 Ω. 1.11 A DC current, 1 ns 4σ bunch length with Cos² longitudinal profile (2 A RF component of beam current). Cavity on tune.



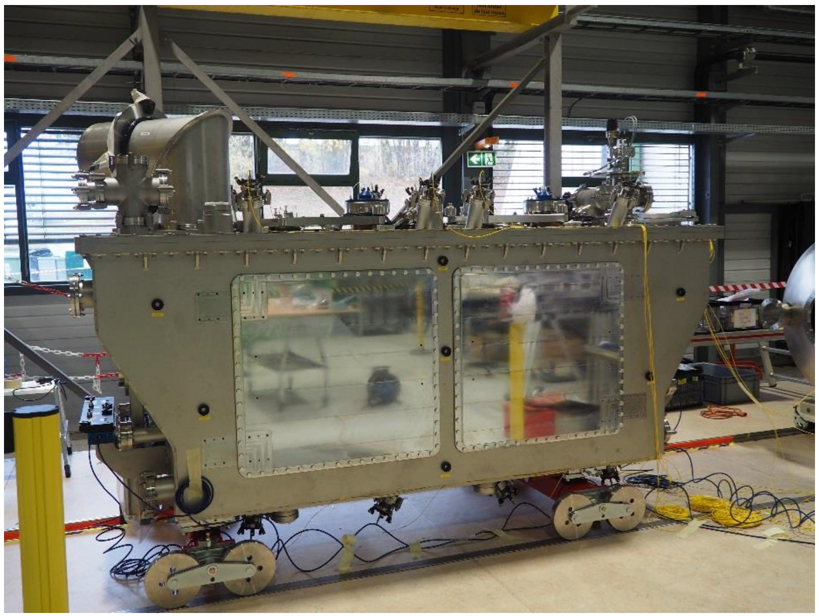
During filling and ramping, we need voltage for tuning only. We would use counter phasing. We can tolerate much larger beam offsets.



SM18 LLRF TESTS

SM18 tests with modified DQW PoP

- Not available before installation in SPS



- Available but not correct Q_L

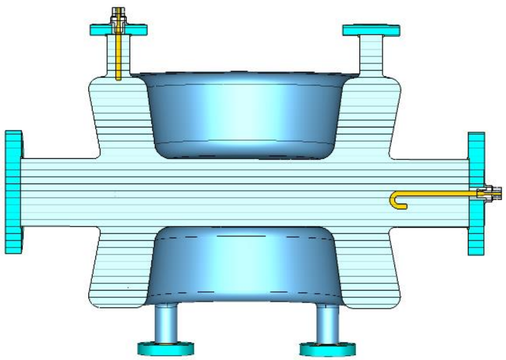
Idea: modify the coupling of the antenna of PoP. Commission LLRF with cavity in the vertical cryostat with 200 W solid-state amplifier.

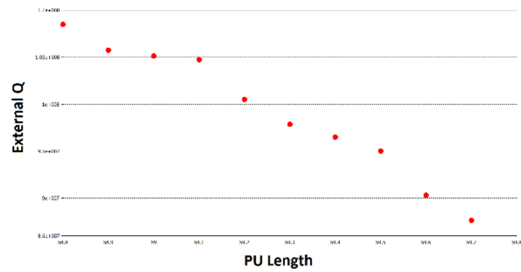
Low Q_L Antenna Design

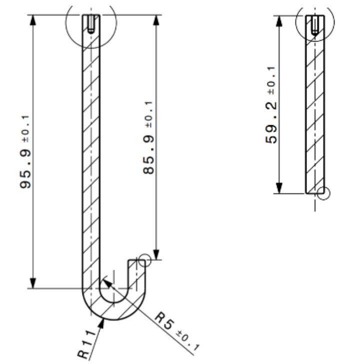
Antennas were designed for the DQW PoP cavity to give a loaded Q of $\approx 10^6$

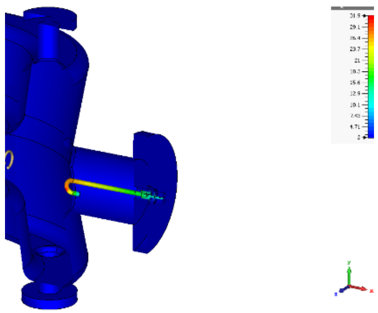
Given the Q_0 and Q_L the external Q of one coupler can be chosen and the other is then determined by the following equation.

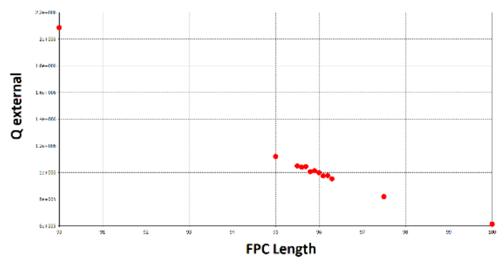
$$Q_{e2} = \frac{Q_0 Q_{e1} Q_L}{Q_{e1} Q_L + Q_0 Q_L - Q_0 Q_{e1}}$$









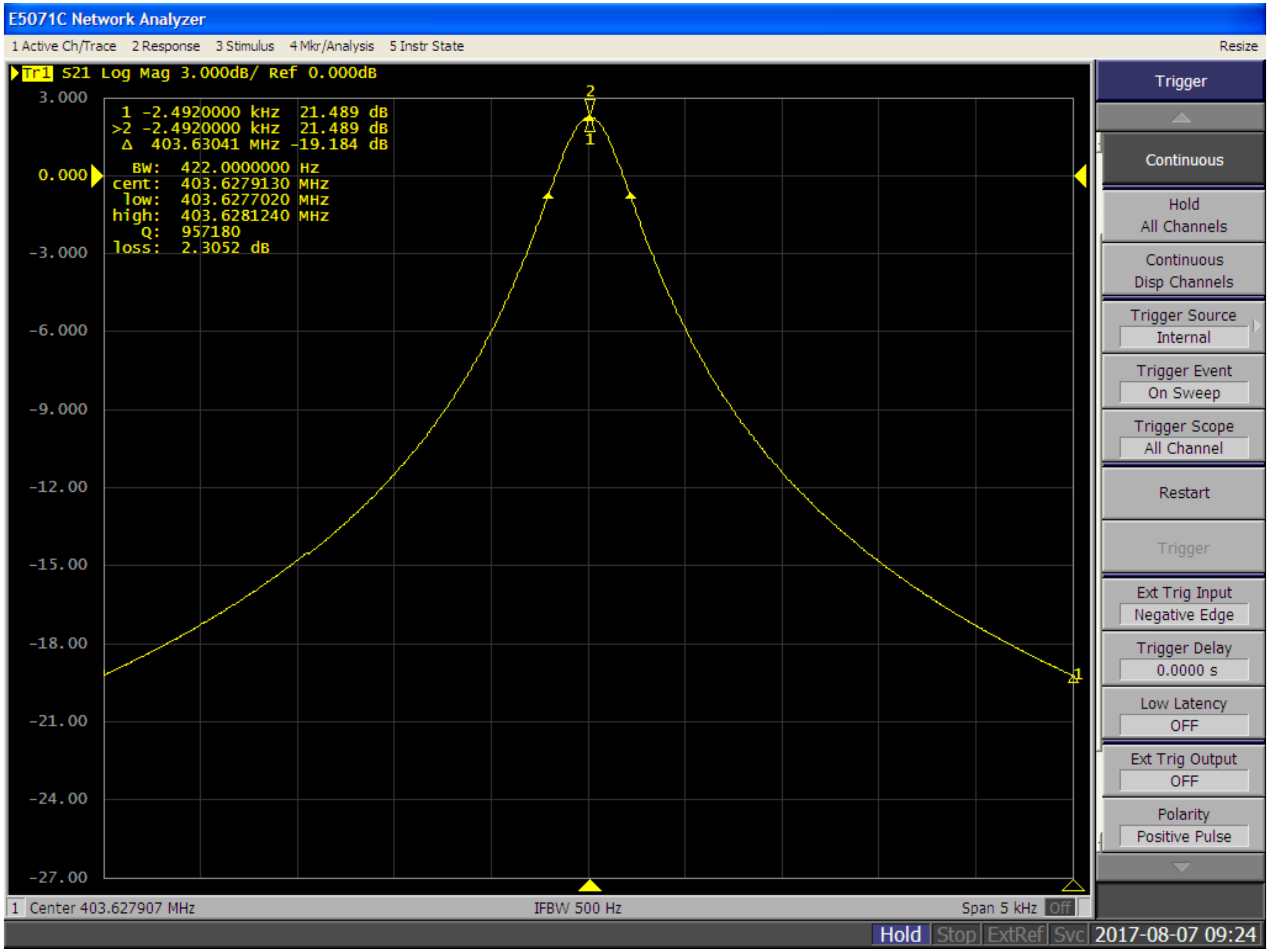


imulations were performed to find the correct geometries of antennas to give the desired external Q values.

Thermal simulations were also performed to ensure the FPC would not heat up too much.

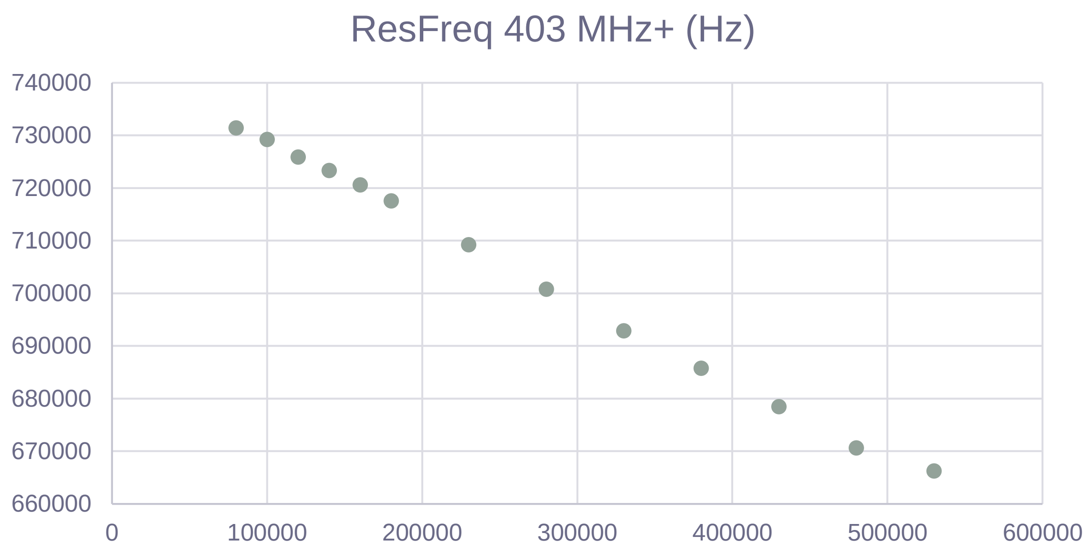
Courtesy: Nicholas Shipman

Cavity response



- Q_L= 960000. OK….

Tuner loop



- The first tests in Aug. 2017 were done at 4 deg K-> large fluctuations of tune. Still tuner loop could lock OK with a loop response of 3-4 s
- In Oct. we worked at 2 deg K -> very stable.

RF feedback (driven mode)

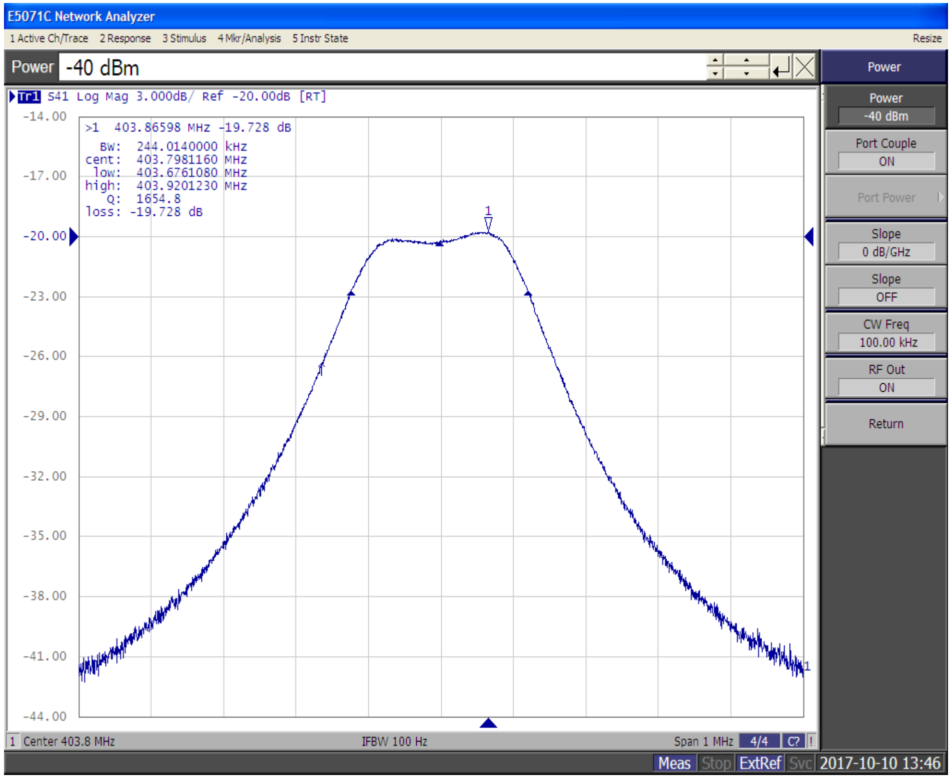
- Reminder: The impedance reduction (and closed-loop BW) scale with the loop delay

$$R_{\min} \approx \frac{R}{Q} \omega_0 T$$

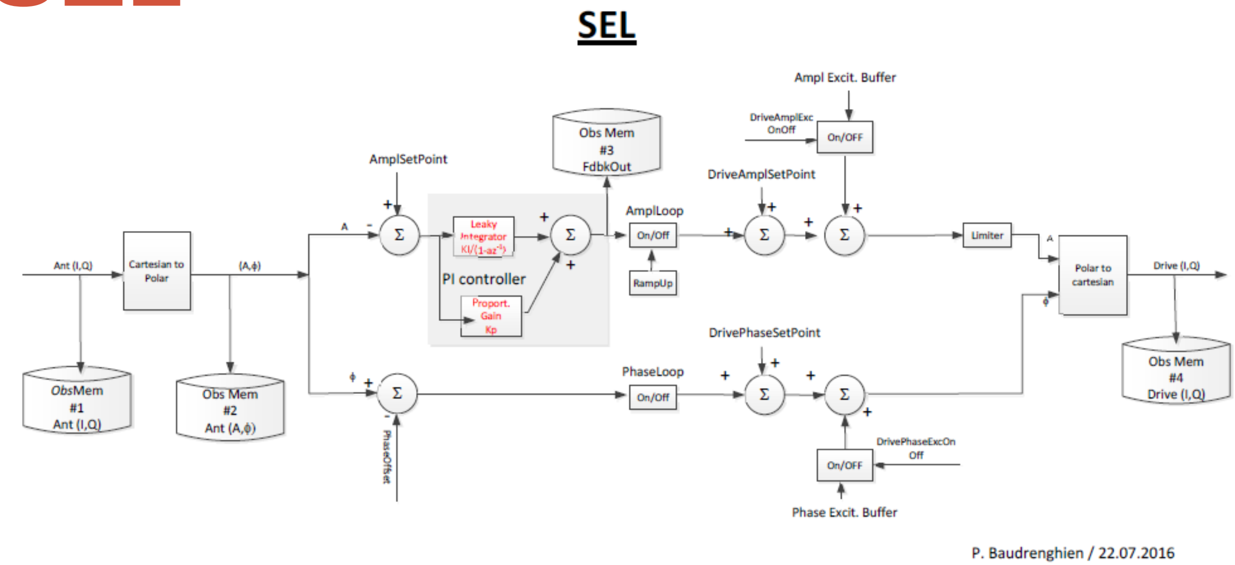
- The resulting 2-sided closed-loop BW is

$$\Delta\omega_{-3} \approx \frac{2.6}{T}$$

- We have 1.3 μs delay, resulting in a closed-loop Q of 1600 (R_{min} around 1 MΩ).

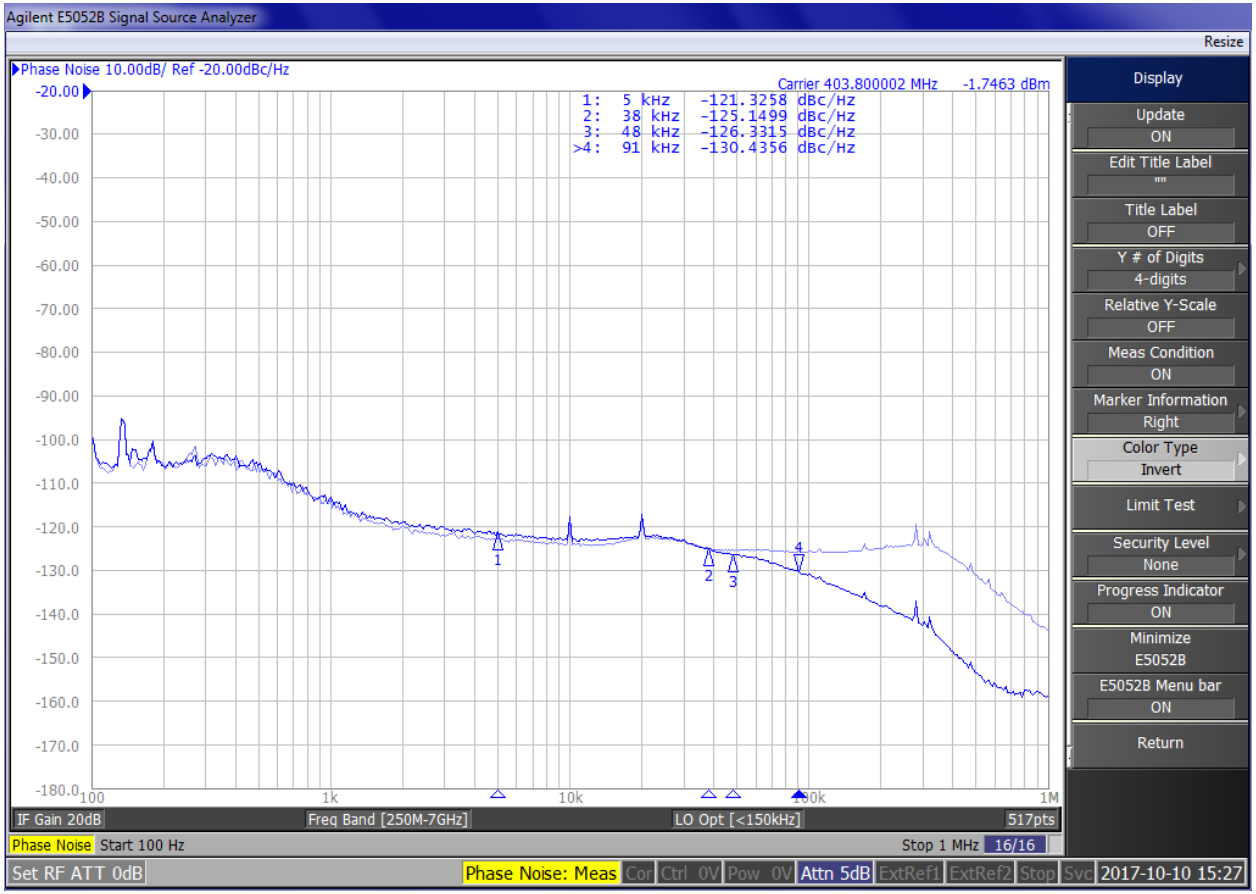


Test SEL



- The Self-Excited Loop (SEL) will be used during the RF ON sequence, when cavity tune is way off
- It worked at first trial.

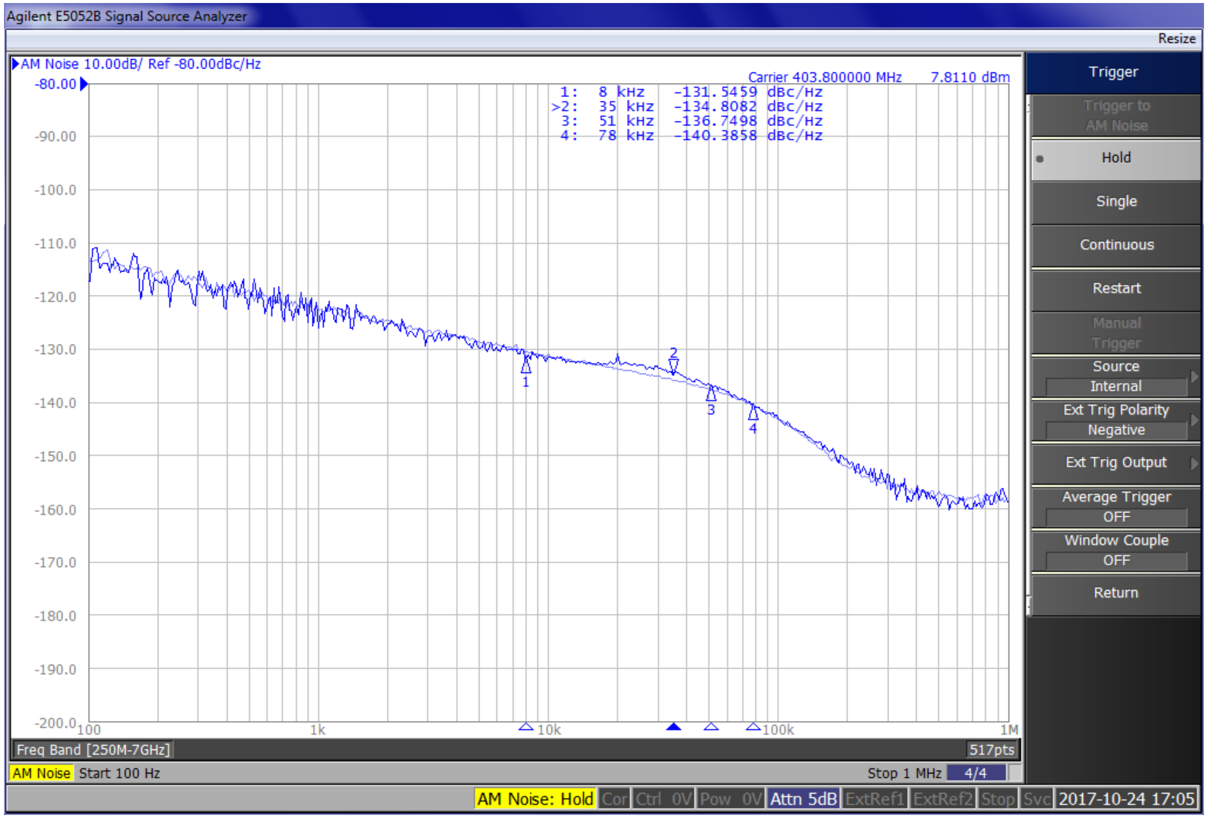
Phase noise measurement



The markers are located on the vertical betatron bands (aliased).

- SSB phase noise of Antenna, compared to phase noise of receiver LO
- In the RF feedback BW (50 kHz), the Antenna noise follows the LO noise
- The Antenna noise drops after 100 kHz as expected.

AM noise measurement

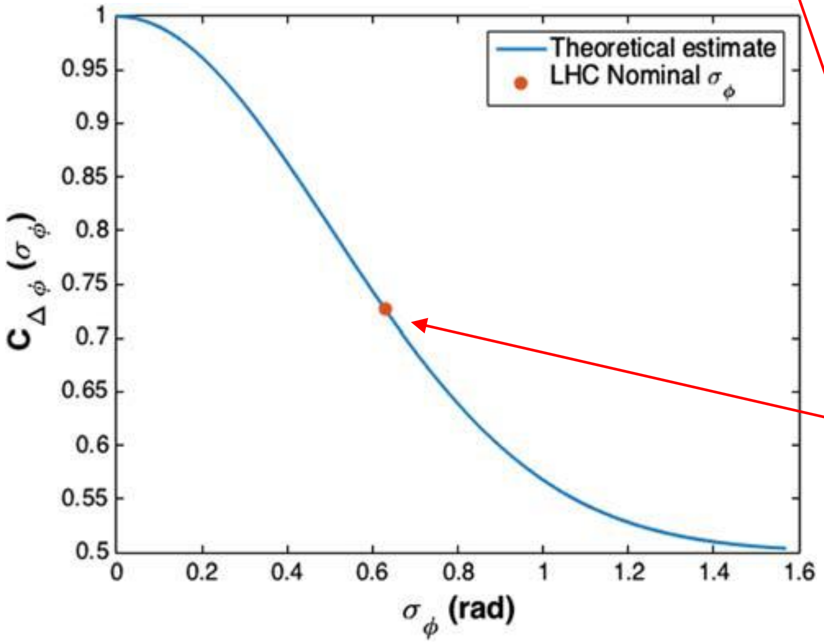


- AM noise of Antenna signal, compared to E5042 sensitivity
- Obviously the instrument sensitivity is not sufficient
- Will be redone in Dec 2017.

Reminder: Phase noise (*)

Machine parameters

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



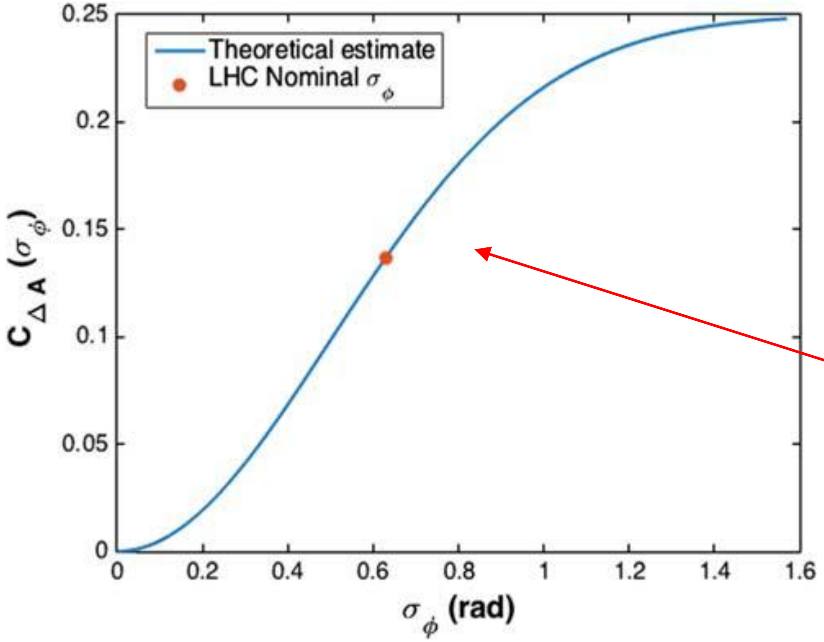
$$C_{\Delta\phi}(\sigma_\phi) = e^{-\sigma_\phi^2}\left[I_0\left[\sigma_\phi^2\right] + 2\sum_{l=1}^{\infty} I_{2l}\left[\sigma_\phi^2\right] \right]$$

- Depends on the overlap between phase noise spectrum and betatron tune distribution
- Phase noise spectrum is aliased at frev
- The "geometric factor" decreases with bunch length

(*) P. Baudrenghien, T. Mastoridis, Transverse emittance growth due to RF noise in the high-luminosity LHC Crab Cavities, PRST AB, 18, 101001 (2015)

Reminder: Amplitude noise (*)

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



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

- Depends on the overlap between phase noise spectrum and betatron tune distribution
- Amplitude noise spectrum is aliased at frev
- The “geometric factor” increases with bunch length

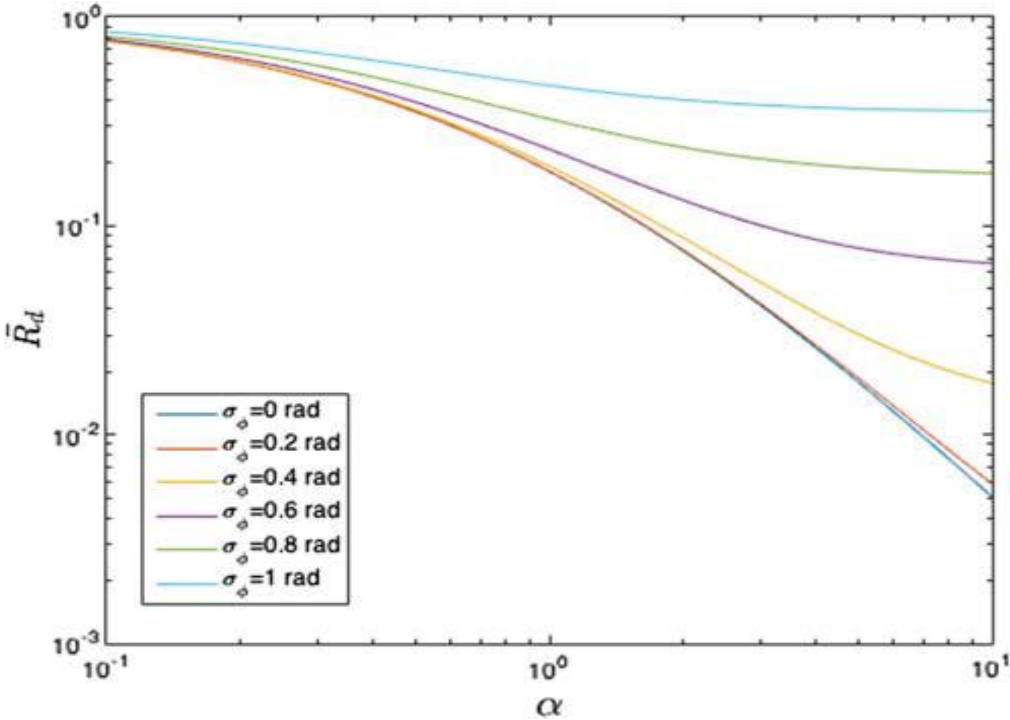
Reminder: Damper reduction factor (*) (phase noise)

$$\bar{R}_d(\sigma_\phi,\alpha)=\frac{1}{\pi}\int_{-\infty}^{\infty} g(u)\left\{1-\frac{e^{-\sigma_\phi^2}}{C_{\Delta\phi}(\sigma_\phi)}\frac{\alpha^2\left[g(u)^2+f(u)^2\right]+2\alpha g(u)}{\left[1+\alpha g(u)\right]^2+\left[\alpha f(u)\right]^2}\right\}du$$

With $\alpha=\frac{G}{2\pi\sigma_\nu}$, $g(u)=\pi\,\sigma_\nu\,\rho(\bar{\nu}-\sigma_\nu u)$, $f(u)=\sigma_\nu\ \mathrm{PV}\int_{-\infty}^{\infty}\frac{\rho(x)}{x-\bar{\nu}+\sigma_\nu u}dx$

f(u),g(u) are scaled versions of the real and imaginary parts of the Beam Transfer Function.

The damper efficiency drops quickly as bunch length increases. The damper kick is uniform along the batch while the effect of phase noise is strong in the core but week in the tails. Increasing the damper kicks therefore excites the tails



Transverse emittance growth in SPS

- SPS conditions: 3.4 MV/cavity, 2 cavities, β_{CC}=72 m, betatron tune spread = 0.001, 4-σ bunch length = 1.1-2 ns, damper gain = 0.2 (10 turns), 270 GeV/c, ε_n=2.0 μm.radian
- For phase noise, the growth rates are very high, caused by the demodulator's LO
  - 400 %/hour
  - 240 %/hour
  - 100 %/hour

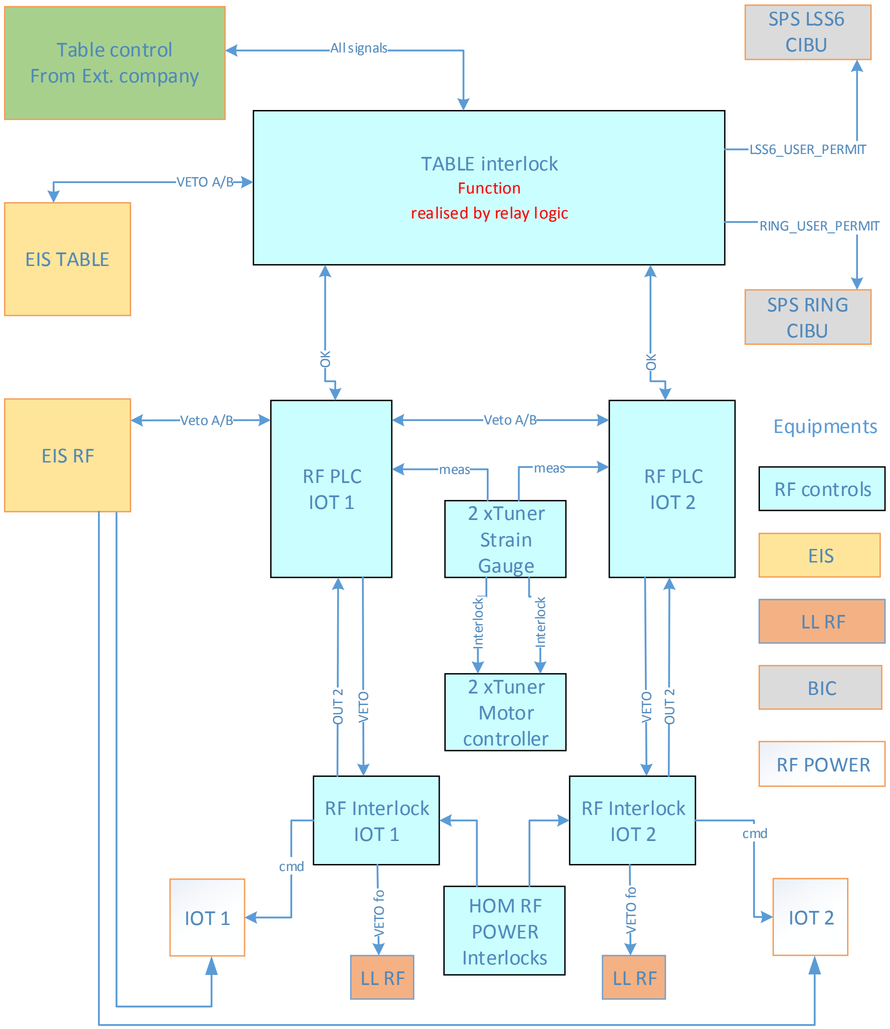
Conclusion: Phase noise must be reduced ….

- For amplitude noise the quoted growth rates are conservative (instrument noise)
  - 70 %/hour for two cavities (2 ns)
  - 62 %/hour for two cavities (1.5 ns)
  - 46 %/hour for two cavities (1.1 ns)

PLC

While VME is used for fast regulation, PLCs are used for slow regulations around amplifiers/cavities.

Interlocks and Automation Controls



Main elements:

- One PLC + one fast interlock to control each IOT / Cavity
- One table interlock relay and PLC monitoring
- One dual RF power interlock for up to 8 HOM signals
- One dual Motor controller for tuner movement
- Dual strain gauge conditioner with interlocks

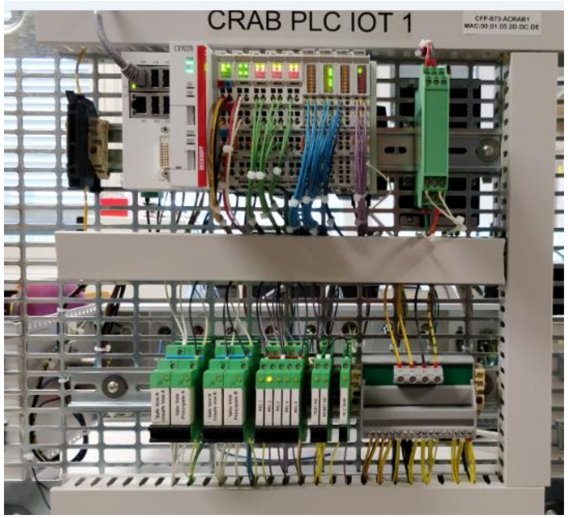
Main external connections:

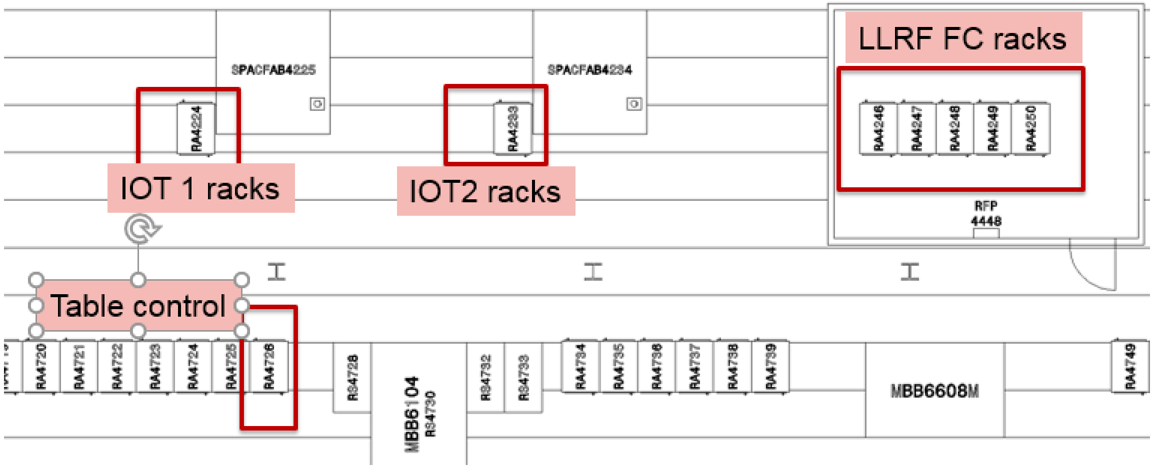
- Table control system with local and tunnel remote control possibility
- Cryogenic control interface for hardware Cryo OK signal
- Separate access system interface for RF controls and for table control
- Dual Beam interlock link for LSS6 and RING
- Low level RF (LLRF) VETO fibre link and extra contact for conditioning RF VETO

L. Arnaudon

Readiness and installation planning

- All elements are ready to be installed in SPS final position
- The very same installation is ongoing in SM18 test place
- The installation is planned to be completed by end 2017, ready to start testing as soon as all the external elements are ready





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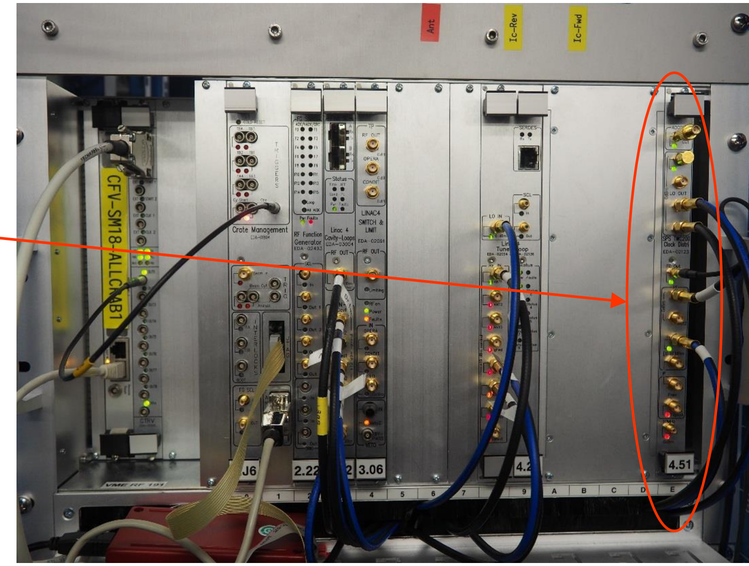
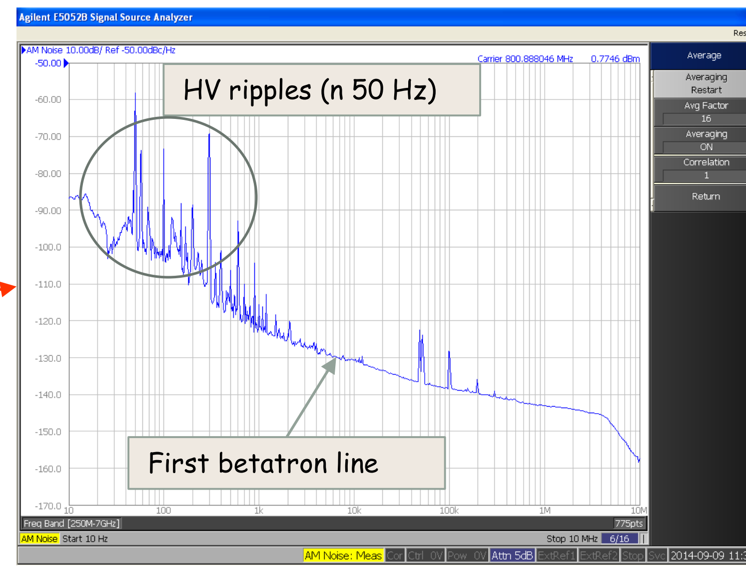
LEFT TO BE DONE…

LLRF

- The phase noise of the Clock Distribution LO must be reduced. A new VCO has been ordered. We hope for a 10 dB reduction of noise floor -> 10 %/h (1.1 ns) to 40%/h (2 ns) transverse emittance growth caused by phase noise
- The Polar Loop should be implemented. It will reduce the TX noise. No big effect expected on emittance growth
- Firmware for the ObsBox (signal monitoring: Antenna , main coupler fwd-rev)





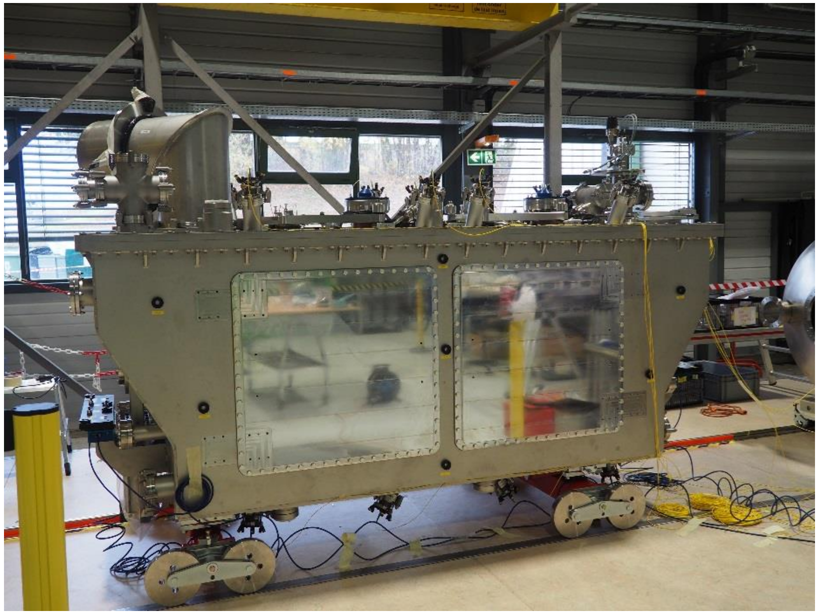
AM noise of an 800 MHz IOT

Controls

- Fesa (Front End Software Architecture) class for CavLoop module
- ObsBox for observation of quench transients (Antenna, Fwd/Rev in power line)
- RF ON Sequence
- Operational properties in LSA (Lhc Software Architecture)
- Functions for cavity voltage during SPS cycle

SPS cryostat

- There will be no time for LLRF test, but the strict minimum is (with cavity cold)
  - Measurement of resonant frequency versus tuner position
  - Measurement of cavity response (Q_L)

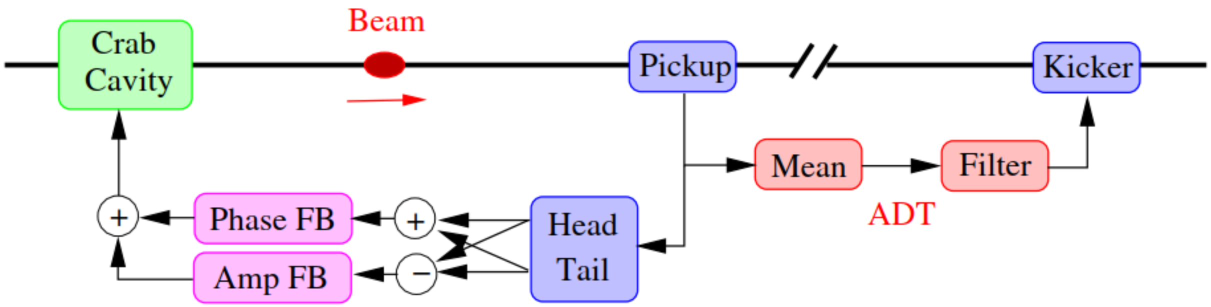


BA6-BA3 link

- The CC will be operated at a constant RF frequency, generated in BA6
- The SPS beam will be accelerated to the corresponding energy plateau. There the SPS beam will be rephased (cogging) to the CC frequency using same method as for SPS-LHC locking
- This calls for the installation of LLRF hdw and controls software. All “classic”…but needs to be deployed/commissioned.

A word on LHC…

- The LHC LLRF will be much different
- We will move away from VME platform (μTCA?)
- The demodulator will be re-designed to reduce phase and amplitude noise
- Feedback on CC voltage/phase is considered as mitigation for damaging RF noise effects (**)



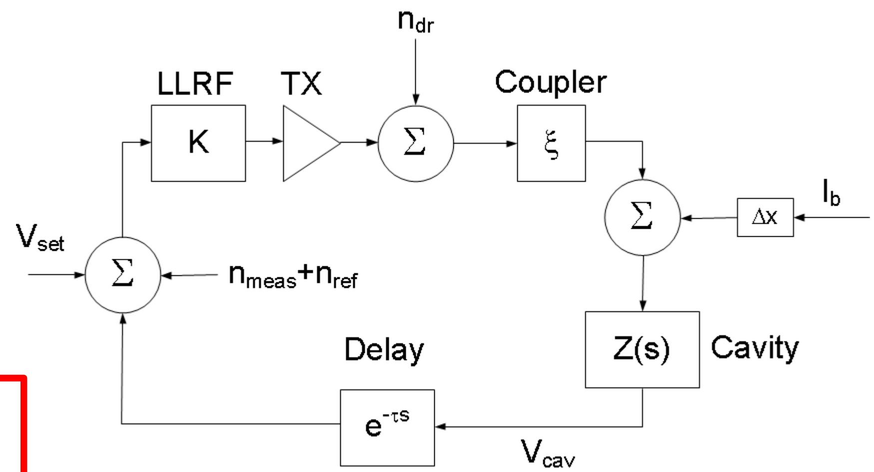
(**) T. Mastoridis, P. Baudrenghien, Estimates of and a Cure for Transverse emittance growth due to RF noise in the High-luminosity LHC Crab Cavities, in preparation (PRAB).

CONCLUSIONS

- LLRF and PLC controls being tested in SM18
- Concern with the RF Phase noise. The source is understood. An upgrade is being assembled for testing in Dec.
- Much work left on the Controls side before the system can be considered “SPS operational”
- So far all tests were done with PoP cavity in vertical cryostat. Differences w.r.t. the operational system
  - TX: 40 kW IOT vs. 200 W solid-state. Not expected to be a major issue for LLRF performances
  - QL (500k vs 1000k)
- LLRF tests on the SPS cavities in SM18 will likely be minimal (tuner range and check of Q_L only).

BACK-UP SLIDES

Cavity RF Noise



- RF feedback noise sources:
  - The RF reference noise n_{ref}
  - The demodulator noise (measurement noise) n_{meas}
  - The TX (driver) noise n_{dr}. It includes also the LLRF noise not related to the demodulator
  - The Beam Loading $I_b\ \Delta x$

$$Z(s) = \frac{\frac{R}{Q} Q_L}{1 + 2 Q_L \frac{s}{\omega_0}}$$

with $s = j\,\Delta\omega$

- We get

Main coupler

$$V_{cav} = \frac{K\ G\ e^{-\tau s} Z(s)}{1 + K\ G\ e^{-\tau s} Z(s)} \left[V_{set} + n_{ref} + n_{meas} \right] + \frac{Z(s)}{1 + K\ G\ e^{-\tau s} Z(s)} \left[\Delta x\ I_b + \sqrt{\frac{Z_0}{\frac{R}{Q} Q_L}}\, n_{dr} \right]$$

Closed Loop response CL(s)
- Equal to ~1 in the CL BW
- Increase of K increases the BW
- Within the BW, reference noise and measurement noise are reproduced in the cavity field

Beam Loading response = effective cavity impedance Zeff(s)
- Equal to ~1/KG in the CL BW
- Increase of K decreases Zeff within the CL BW
- Within the CL BW, TX noise and beam loading are reduced by the Open Loop gain KG