SPS Crab Cavity test
RF Test Program

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Crab Cavity SPS Tests Day II, May 8th 2018

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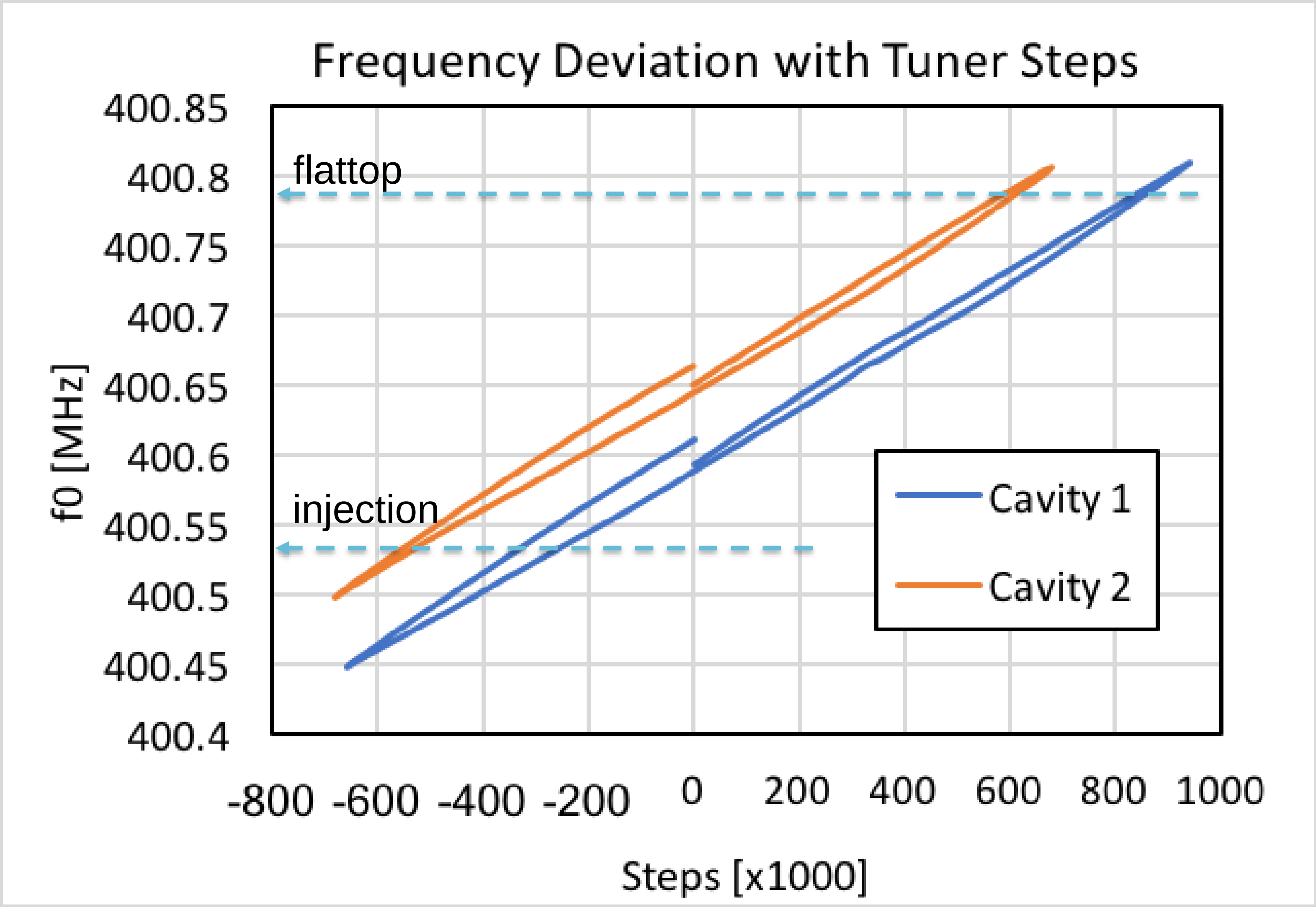
LHC CC Operational scenario

- The RF is ON, with strong RF feedback and tune control at all time. Cavities are on-tune at all time
- During filling, ramping or operation with transparent crab cavities:
  - Small cavity field as required for the active Tuning system
  - We use counter-phasing to make the total field invisible to the beam
  - A strong RF feedback keeps the Beam Induced Voltage zero if the beam is off-centred
- ON flat top:
  - We drive counter-phasing to zero
  - Any adiabatic field manipulation is possible by synchronously changing the voltage or phase in each cavity (luminosity levelling for example).

FREQUENCY SWING

- In the LHC
  - The 400 MHz ramps from 400.788860 MHz (450 GeV/c) to 400.789730 MHz (7 TeV/c)
  - The frequency swing is less than 1 kHz
  - The acceleration ramp lasts for 20 minutes. The max rate is 4 Hz/s
  - Conclusion: **CCs can stay synchronous** with the beam at all time, from prepare filling to dump
- In the SPS
  - The beam synchronous 400 MHz ramps from 400.528890 MHz (26 GeV/c) to 400.787180 MHz (270 GeV/c) to 400.788730 MHz at 450 GeV/c
  - The frequency swing is more than 250 kHz. That is within the tuning range
  - The acceleration ramp lasts ~8 seconds . The max rate is 120 kHz/s (@ 400 MHz) -> tuner cannot follow
  - Conclusion: **CCs cannot stay synchronous** with the beam from injection to flat top.

Frequency Tuning at 2K, SM18

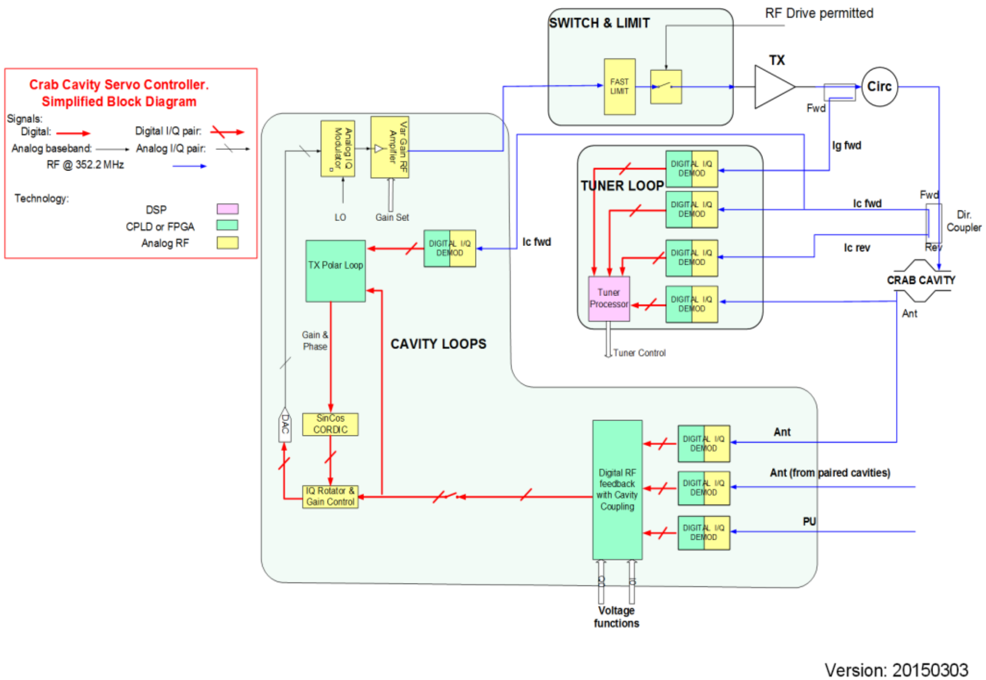


Move the chair or the piano?

- In the SPS, if we wish to accelerate, the CC cannot stay synchronous with the beam (or the 200 MHz RF)
- We have two options
  - Lock the CC on the 200 MHz reference (beam) at flat top. This brings several problems: We need another RF reference for the CC when not locked onto the beam, plus we need a long flat-top to lock the slow CC tuner
  - Lock the beam on the CC at flat top. That is easy for the CC as it can be operated at constant frequency. That is not very complex for the SPS 200 MHz system as it calls for rephasing to an external 400 MHz reference, similar to the gymnastics done before SPS-LHC transfer
- Preferred solution
  - The CC is driven from a stable (non ppm) reference 400 MHz generated in BA6
  - That reference is sent to the BA3 FC
  - The **SPS beam is rephased** to the BA6 reference on the desired energy plateau.

Reminder: CC LLRF functions

- Allows for precise regulation of the cavity field
  - Keep CC field in phase with bunch centre
  - Alignment of the various cavities (counter-phasing)
  - Fast field regulation following a cavity trip (see below)
  - Keep RF noise induced transverse emittance growth compatible with luminosity lifetime



- Reduction of cavity impedance at the fundamental
- Keep cavity on tune

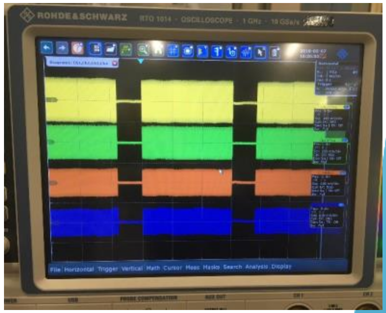
- *The electronics implemented in the LHC CC (commissioned in 2024?) will not be the one used in the SPS test*
- *But the (planned) functionalities are identical*

Hdw commissioning: RF conditioning

- Processing of cavity #1 medium power is done
  - RF conditioning started as usual in pulsed mode, with 20 µs pulses at 52.63 Hz
  - Pulse length and RF power level have been increased up to 15 ms at 52.63 Hz and 10 kW with a FM of +/- 1 MHz around centre frequency
  - We also completed 5 kW CW with a FM of +/- 500 kHz around centre frequency
- Processing of cavity #2 has started the same way Monday. Planned to finish all conditioning by the end of this week.

Top: Charles & Fred preparing and using the stand alone RF processing system in front of the IOT HPRF

Right: Last pulsed length of 15 ms @ 52 Hz before moving to CW



Hardware commissioning: LLRF

- LLRF commissioning
  - To be performed at 4.5 K
  - Tuner loop and RF feedback
  - The 4.5 K temperature makes the tuning more difficult. Impossible to keep the field without tuning loop as the resonant frequency changes quick. But could be stabilized with the tuning loop, with reaction time of 3s, on the SM18 PoP cavity in the vertical test-stand ($Q_L=10^6$) in Aug 2017 -> should be OK…
  - 2 weeks originally planned before beam commissioning
  - Planned cryo stop now after May 30 (2-3 wks ?), this leaves approximately 1.5 weeks of LLRF commissioning before first beam and allows for 2 slots (May 23 & 30) for the beam commissioning.

26 GeV, single (or few) bunch(es)

- One CC driven CW (no timing) from the BA6 400 MHz reference that is set at the same frequency as SPS injection RF (x2)
- During the SPS CC MD cycle
  - Inject
  - Rephase to the BA6 reference (phase only as frequency should be OK. Both systems use same 10 MHz ref)
  - Scan CC phase and amplitude to create crabbing. Measure with Head-Tail monitor plus betatron oscillation
- Same test with the second CC
- Test with both cavities on
  - Adjust respective phases of the two cavities
  - Test counterphasing (vectorial sum of the two cavity voltages)

270 GeV, single (or few) bunch(es)

- During the acceleration ramp the CC frequency will not be synchronous with the bunch. At several points in the 250 kHz+ swing in the ramp, the frequency beat will intersect a betatron line -> expect strong transverse effects!
- Therefore the CC voltage must be programmed (function, timing) and also the counterphasing. The CC must be operated ppm , except for the fixed reference frequency (and tuner)
- SPS rephasing on the desired flat top. BA6 400.8 MHz adjusted close to the corresponding SPS RF (x2)
- Test RF gymnastics: cavities “invisible” during ramp, then active on flat top
- First measurement of transverse emittance growth (?)

270 GeV coast, single (or few) bunch(es)

- Same manipulations as for the 260 GeV cycle test. The main interest is to observe transverse emittance growth
- Validate the calculations/simulations, and mitigation by damper (see HiLumi/Larp annual meeting Oct. 2015)

$$\frac{d\varepsilon}{dt} = \beta_{CC}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta\phi}(\pm f_b - n f_{rev}) + \beta_{CC}\left(\frac{eV_o \sigma_\varphi f_{rev}}{2E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta A}(\pm f_b \pm f_s - n f_{rev})$$

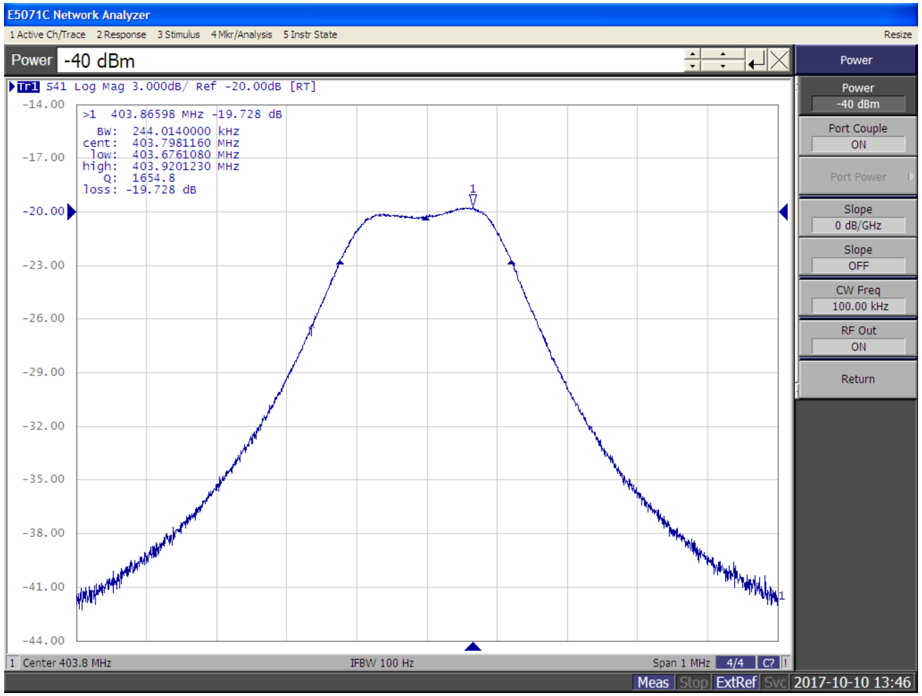
- The SPS CC emittance growth will be much larger than the final LHC system (noisy LLRF, lower energy, smaller f_{rev} but smaller βcc) -> probably no need to boost the noise to see an effect

SM18 tests. Anticipated effect of RF noise

- We consider 2 cavities, 3.4 MV/cavity, 270 GeV/c, β_{cc}=72, TuneSpread ~ 0.001
- Transverse emittance growth from amplitude noise for different bunch length
  - 70 %/hour for two cavities (2 ns)
  - 62 %/hour for two cavities (1.5 ns)
  - 46 %/hour for two cavities (1.1 ns)
  - Conservative figures (limited by the accuracy of the measurement)
- Transverse emittance growth from phase noise
  - 400 %/hour for two cavities (2 ns)
  - 240 %/hour for two cavities (1.5 ns)
  - 100 %/hour for two cavities (1.1 ns)
  - Very large for long bunches (reduced efficiency of transverse damper)
- Attempt to reduce RF noise will be done in fall 2018
- We can also inject noise to confirm our scaling rules

Batch (1/2)

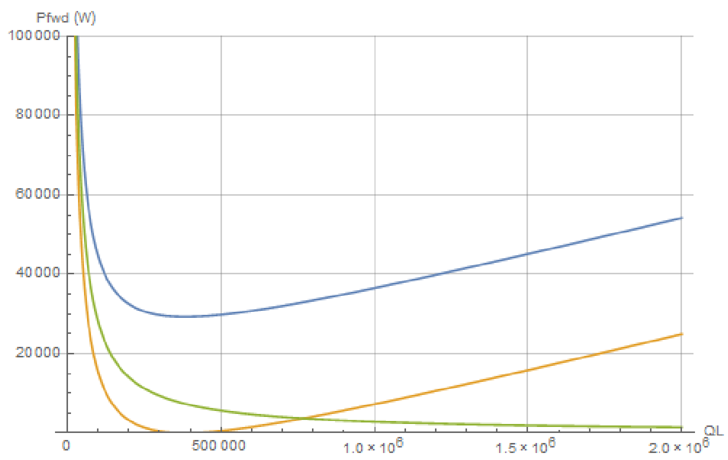
- High intensity single bunch up to 4x72 trains
- Compensation of transient beam loading
- In the SM18 test stand the RF feedback reduced the cavity impedance at the fundamental by ~300 linear
- Expect a bit less in the SPS due to longer loop delay.

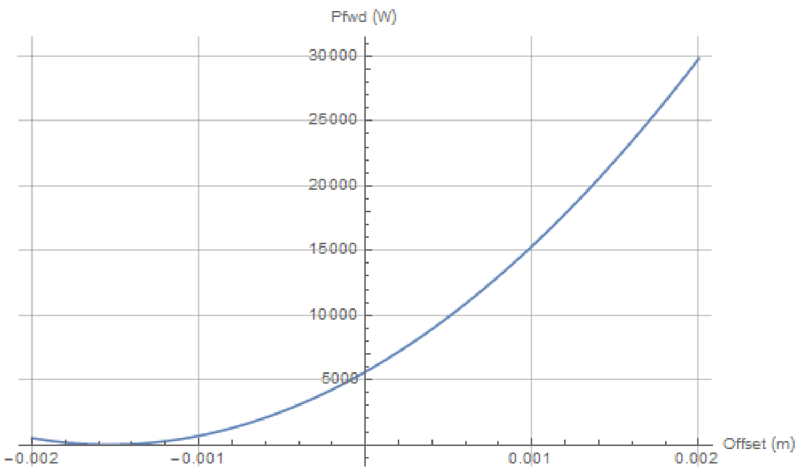


- SM18 test
- Closed-Loop response (with RF feedback)
- The Q is reduced to 1600, from an original value of 500000

Batch (2/2)

- Required TX power vs. beam displacement
  - Use this measurement to centre the beam





- Required TX power vs. QL for beam offset of -2 mm, 0 mm and +2 mm. 3 MV. 1.4E11 p/bunch. 2 ns long bunch (left)
- Required power vs beam offset (right)

- Measurement of HOM spectra/power
- Stability of the crabbing RF w.r.t. the beam (using the PUs)

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Field evolution following a fast failure

- **Case 1**: A problem with power hardware supplying one cavity (such as TX trip, arcing in waveguide, circulator or load,…) resulting in switching off the TX. The cavity stored energy will flow out, through the waveguide and circulator, and will be dissipated into the circulator's load. The cavity field will decay to zero with a time constant τ

$$\tau = \frac{2\,Q_L}{\omega_{RF}}$$

With a Q_L equal to 500000, the time constant is 400 μs.

- **Case 2:** In the case of a quench, the stored energy is dissipated in the cavity walls and the He evaporation. The main coupling (Q_L) has no effect on the field evolution. Lessons can be learnt from the SPS tests.
- **Case 3:** In the case of an arc in the main coupler, the stored energy will be dissipated through the arc. Again lessons must be learnt from the SPS tests.

- A fast acquisition system (25 Msps) will monitor cavity and waveguide signals to give signatures from quenches and arcs (Q4 2018)

Questions?
Comments?

Back-up slides

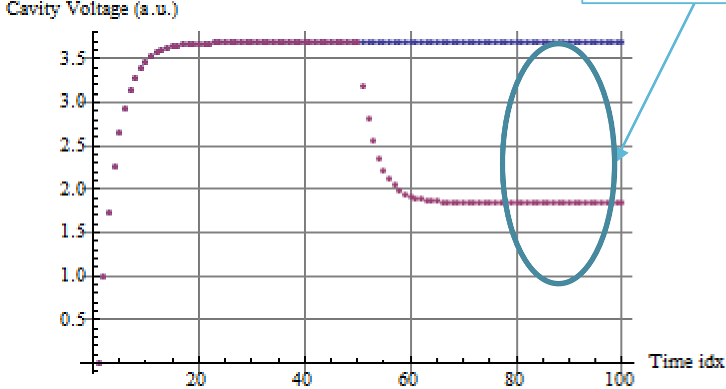
Coupled feedback

- For perfect closure of the orbit and to minimize the overall effect of one-cavity fault, we look at the possibility of coupled feedback
- Taking the two sets of cavities on each side of a given IP (crabbing and un-crabbing), we wish to keep the two total voltages equal
- That can be done if the FDBK for a given TX considers also the voltage measured in all other cavities

SPS two-cavities case

Independent feedbacks

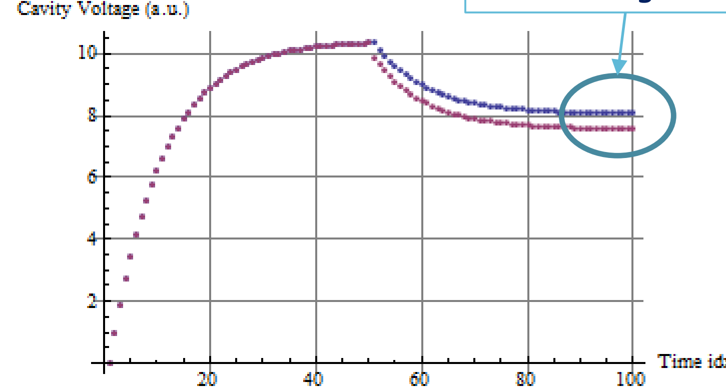
Kly1 ignores Cav2 voltage drop



Cavity 1
Cavity2

Coupled feedbacks

Kly1 tries to track Cav2 voltage drop



Cavity voltage following a unit step of both klystrons at time zero, and a half-unit step reduction of klystron 2 alone at time 50.
When observing one loop at the time, the regulation with independent klystrons is better: It is 3 times faster and the static error is three times smaller.
When the transient is on one klystron only (kly2, red), there is no compensation on cavity 1 for the independent feedbacks, resulting in a static error of ~2. With the coupled feedbacks, kly1 (blue) reacts to the drop in cavity 2 voltage and the final voltage difference is ~ 0.5.

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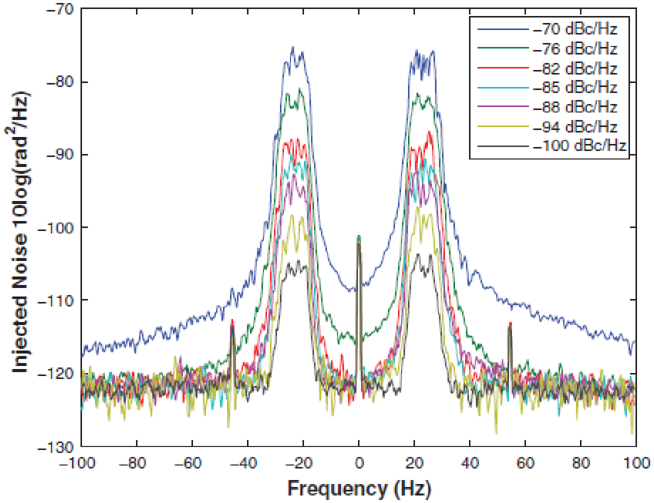
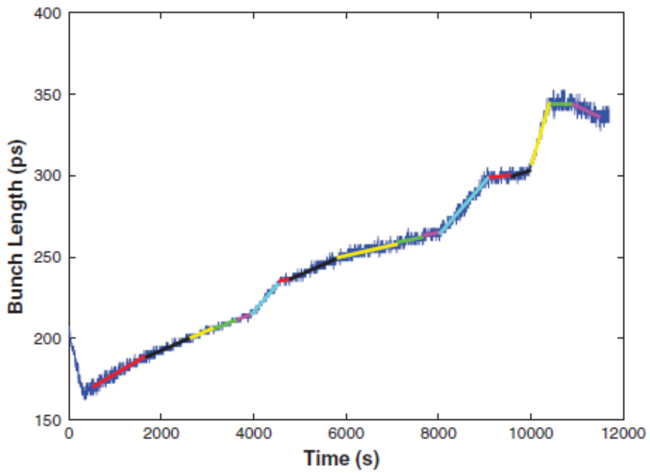
Test Program Summary (3)

- **Long-term behavior** of coasting beams
  - *Study the effects of RF noise on transverse emittance*
  - *Inject excess noise and observe growth*
  - *Although there are many sources of transverse emittance growth in the SPS, we can benchmark our calculations by increasing the CC RF noise to the point where it becomes dominant (> 30%/hr?)*





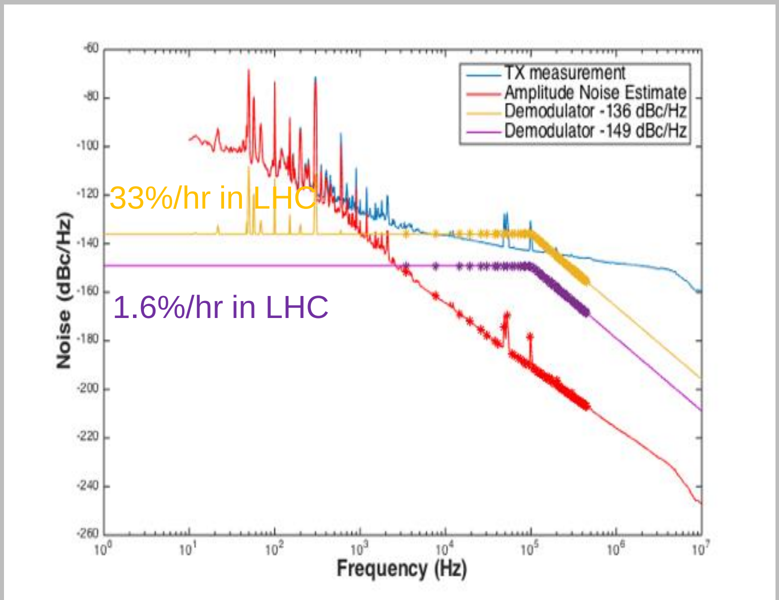
Measurement of the LHC longitudinal emittance growth vs. RF noise
- Power Spectral density of RF phase noise injected (top)
- Evolution of the bunch length (bottom)

Test Program Summary (4)

- **Long-term behavior** of coasting beams
  - *Validate the calculations/simulations, and mitigation by damper* (see HiLumi/Larp annual meeting Oct. 2015)

$$\frac{d\varepsilon}{dt} = \beta_{CC}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta\phi}(\pm f_b - n f_{rev}) + \beta_{CC}\left(\frac{eV_o \sigma_\varphi f_{rev}}{2E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta A}(\pm f_b \pm f_s - n f_{rev})$$

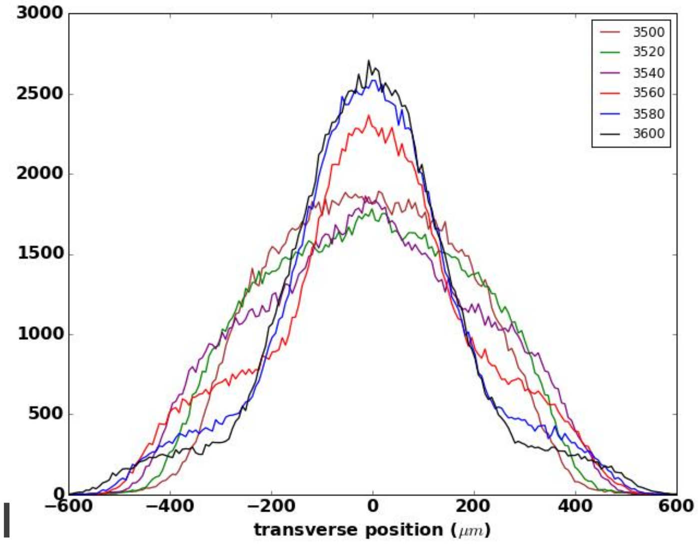
- The goal is to confirm the specs on the LHC CC RF noise



- Calculated and simulated transverse emittance growth vs. CC RF phase noise (left)
- Calculated and simulated mitigation of the RF phase noise with the transverse damper vs. damper gain for different bunch lengths (right)

Test Program Summary (5)

- **Long-term behavior** of coasting beams (cont'd)
  - *Mitigation of the CC Voltage noise by feedback using the Head-Tail monitor signal (available to SPS CC LLRF?) and modulating the CC voltage. Study and simulations on-going.*
  - *Active noise shaping:*
    - ❑ *We inject noise whose spectrum overlaps with the tails of the betatron distribution, and does not affect the core*
    - ❑ *This noise will excite the tails of transverse distribution and make these particles diffuse out of the bunch*
    - ❑ *Such a transverse distribution is beneficial for Machine Protection as it would limit the losses following a CC trip*

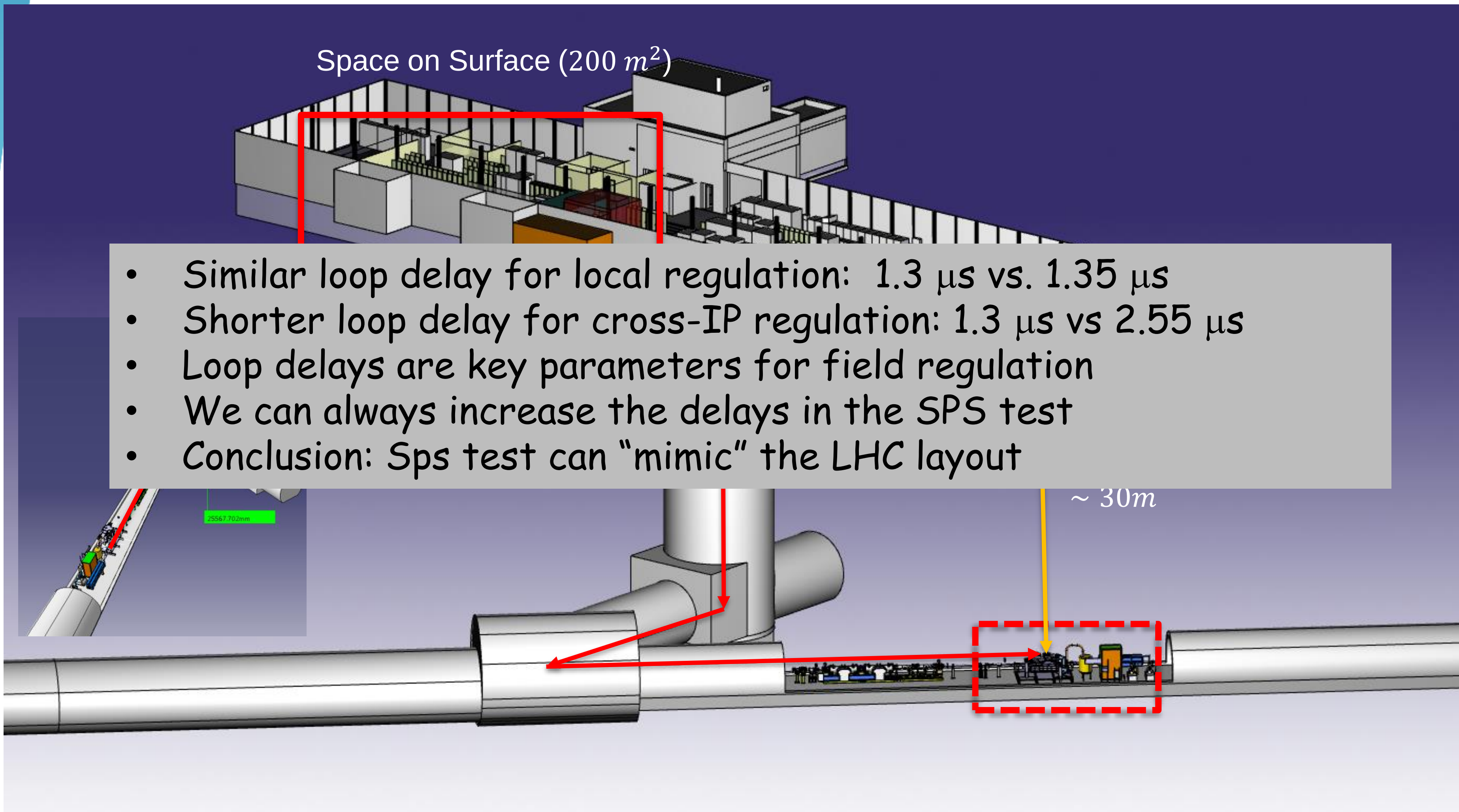


- Distribution of particles after 100,000 turns in the presence of CC RF noise with a 6 Hz BW, centred at various frequencies within the tune
- Bunch core at 3500 Hz
- Damper off

- **I** … **ity:** stability of the tune and HOM spectra/power

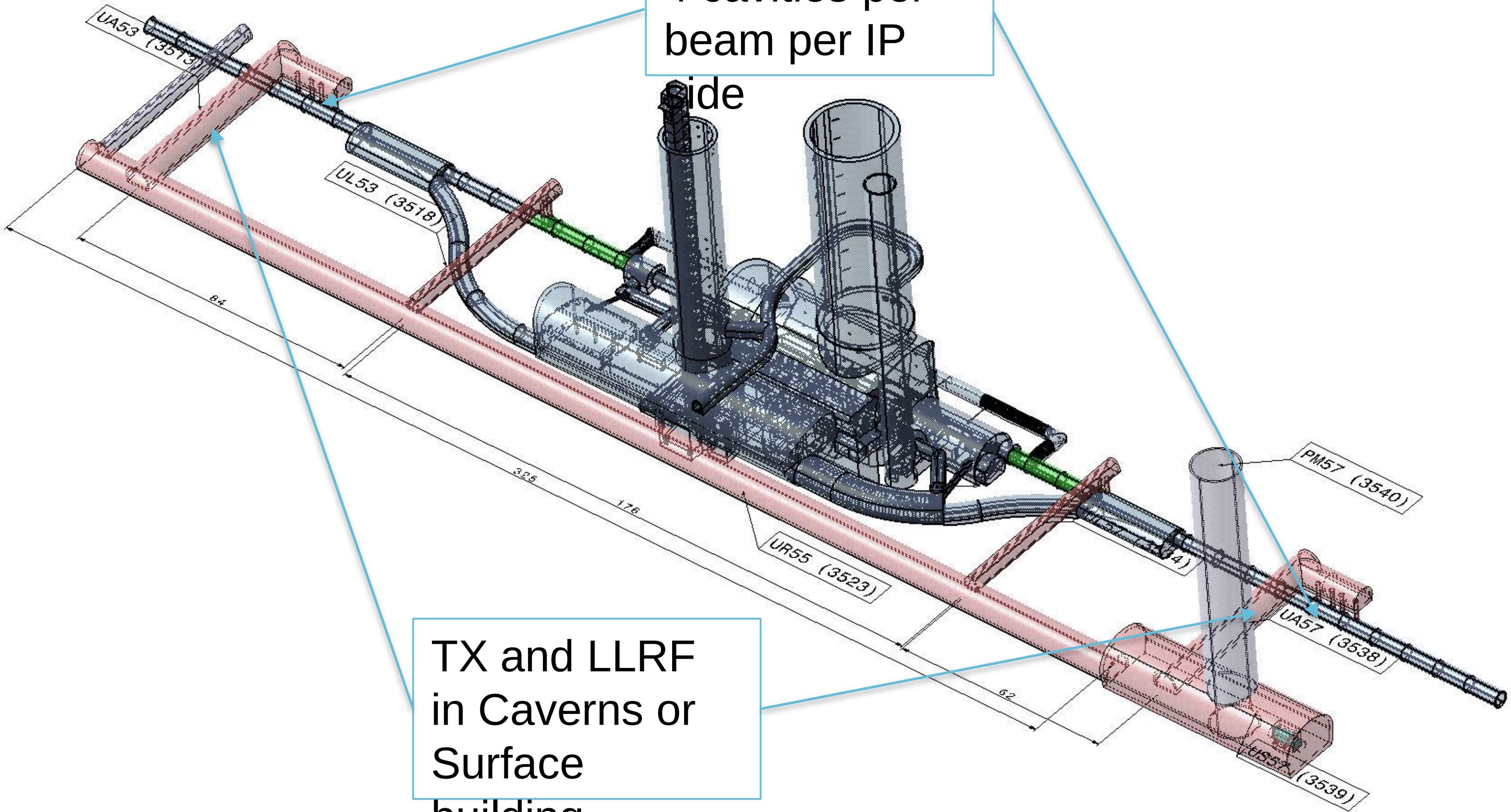
SPS @ LSS6, preliminary

Courtesy EN-MEF-INT



- Similar loop delay for local regulation: 1.3 μs vs. 1.35 μs
- Shorter loop delay for cross-IP regulation: 1.3 μs vs 2.55 μs
- Loop delays are key parameters for field regulation
- We can always increase the delays in the SPS test
- Conclusion: Sps test can “mimic” the LHC layout

LHC: Cavern or Surface Buildings. Baseline

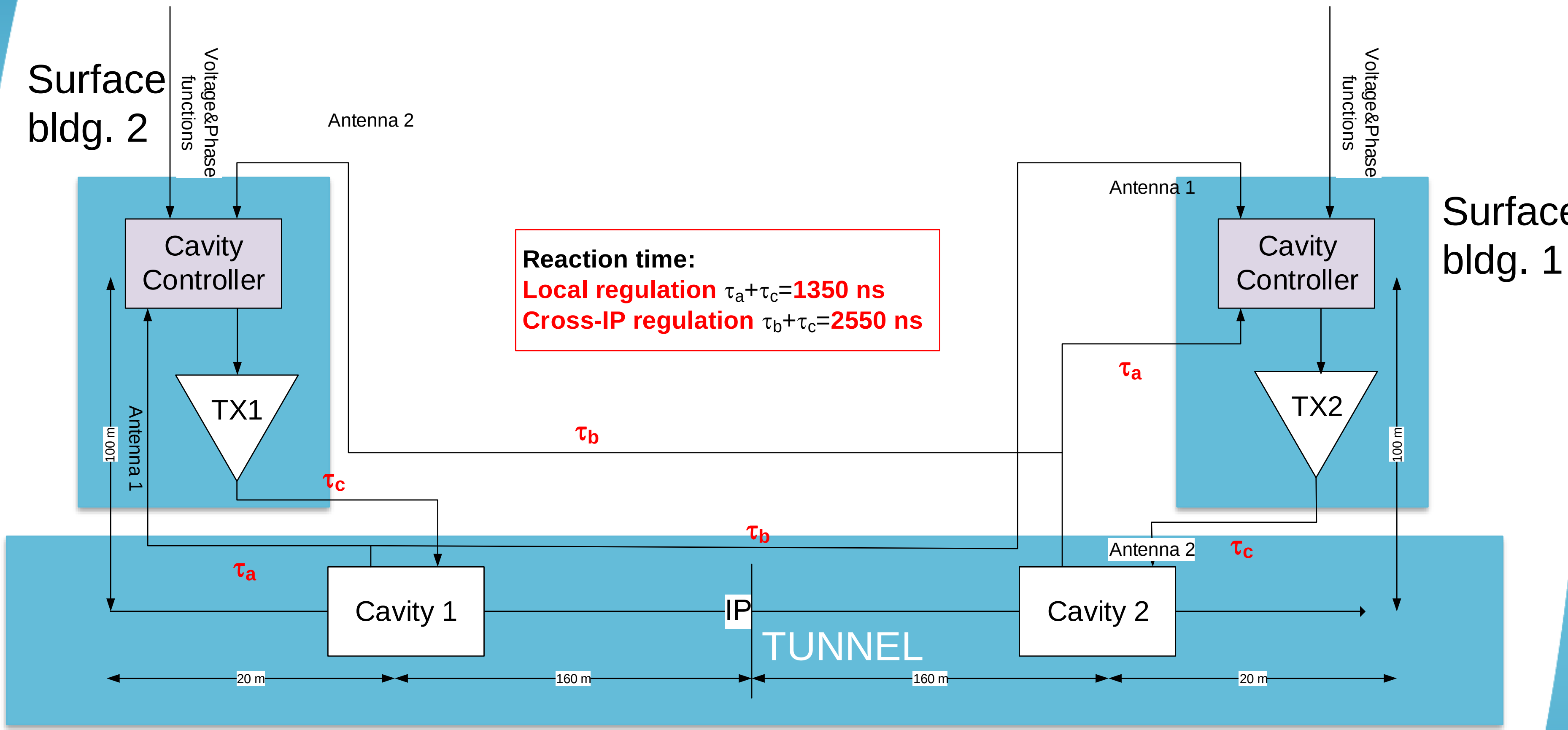


4 cavities per beam per IP side

TX and LLRF in Caverns or Surface building

John Osborne GS/SE/FAS

LHC: TX and LLRF in Surface Buildings. Baseline



surface architecture:

τ_a is the delay of the local antenna signal (20+100) x 3.7 ns = 444 ns rounded to **450 ns**

τ_b is the delay of the opposite antenna signal (320+100+20) x 3.7 ns = 1628 ns rounded to **1650 ns**

τ_c is the drive path delay, including LLRF, TX, circulator and coax = 300 ns + 100 ns + 50 ns + (20+100) x 3.7 ns = 894 ns rounded to **900 ns**