CERN SPS LowLevel RF Architecture & Implementation

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SPS RF Upgrade project (LIU)

LHC Injector Upgrade project (LIU)

Protons: doubling pre-LIU intensity [1, 2]

- 2.3e11 p+/bunch at extraction
- 25ns spacing, 72 bunches/batch, 4 batches

Lead ions: 50ns spacing (100ns pre-LIU) [3]

- 2.5e10 charges/bunch at extraction, 56 bunches
- Fixed-frequency Acceleration (FFA)
- Slip-stacking for 50ns bunch spacing
- Low RF noise (long injection plateau)

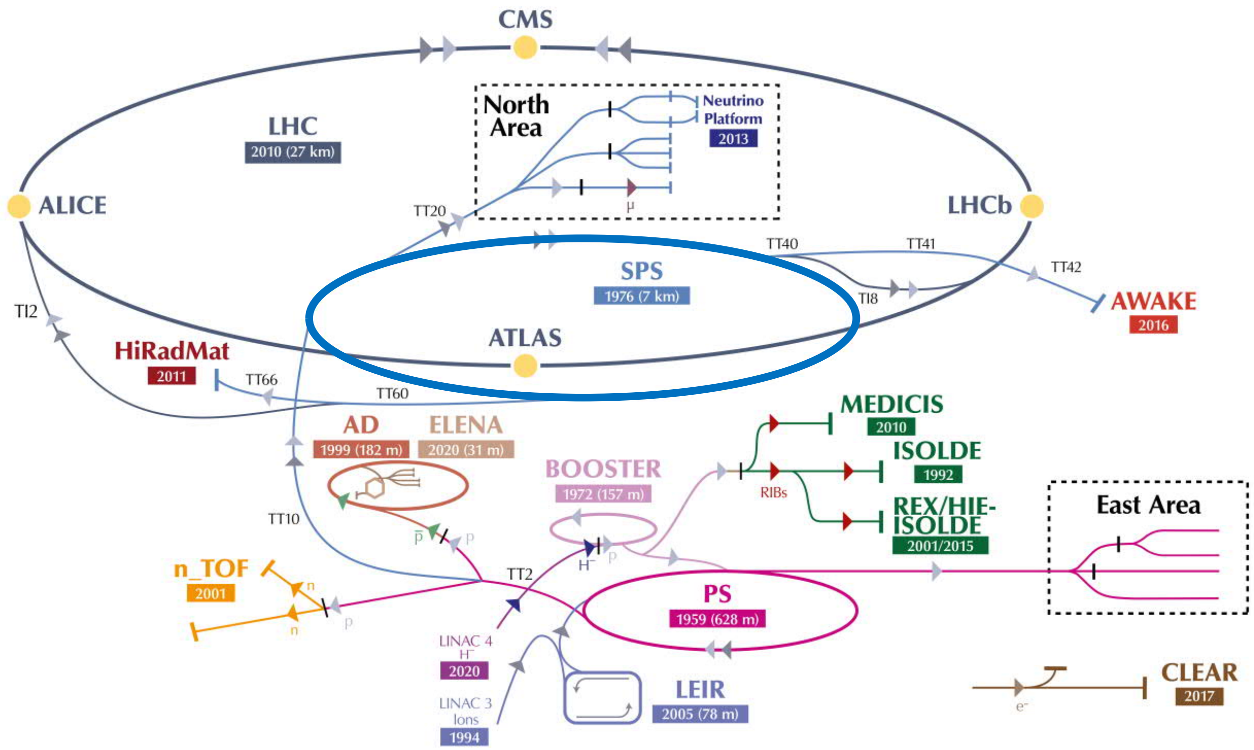


Fig1 – CERN accelerator complex

SPS RF Upgrade project

Completely new RF system

- From 6 to 8 200MHz Cavities
- New 1.6MW solid-state amplifier systems (2x)

New digital LLRF

- MTCA for 200MHz Cavity-Controllers (RF feedback) [4]
- MTCA for Beam control (beam based loops) [5]

Infrastructure

- Huge decabling/recabling campaign
- Integration of legacy HW

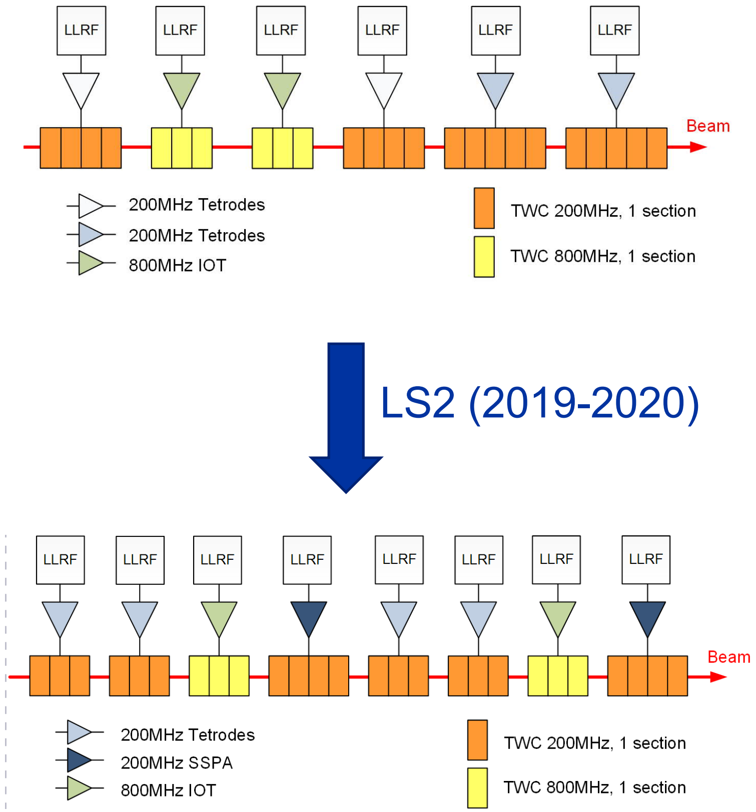


Fig3 – SPS RF Upgrade in Long-shutdown 2 (LS2)

Fig3 – SPS Solid-state amplifier systems (32 towers of 140kW!)

Fig4 – SPS low-level RF system (MTCA)

SPS RF Upgrade project

SPS RF cavities

- **Four → Six 200MHz travelling wave cavities (LS2)**
- **Two 800MHz travelling wave cavities (LS1)**

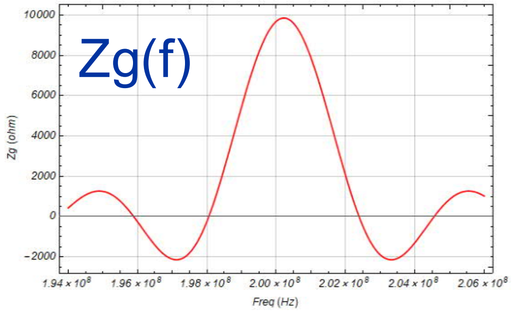


Fig5 – 200MHz 3-sections cavity, Zg(f)

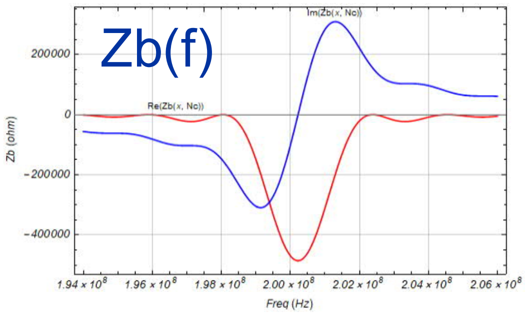


Fig6 – 200MHz 3-sections cavity, Zb(f) real(red), imaginary (blue)

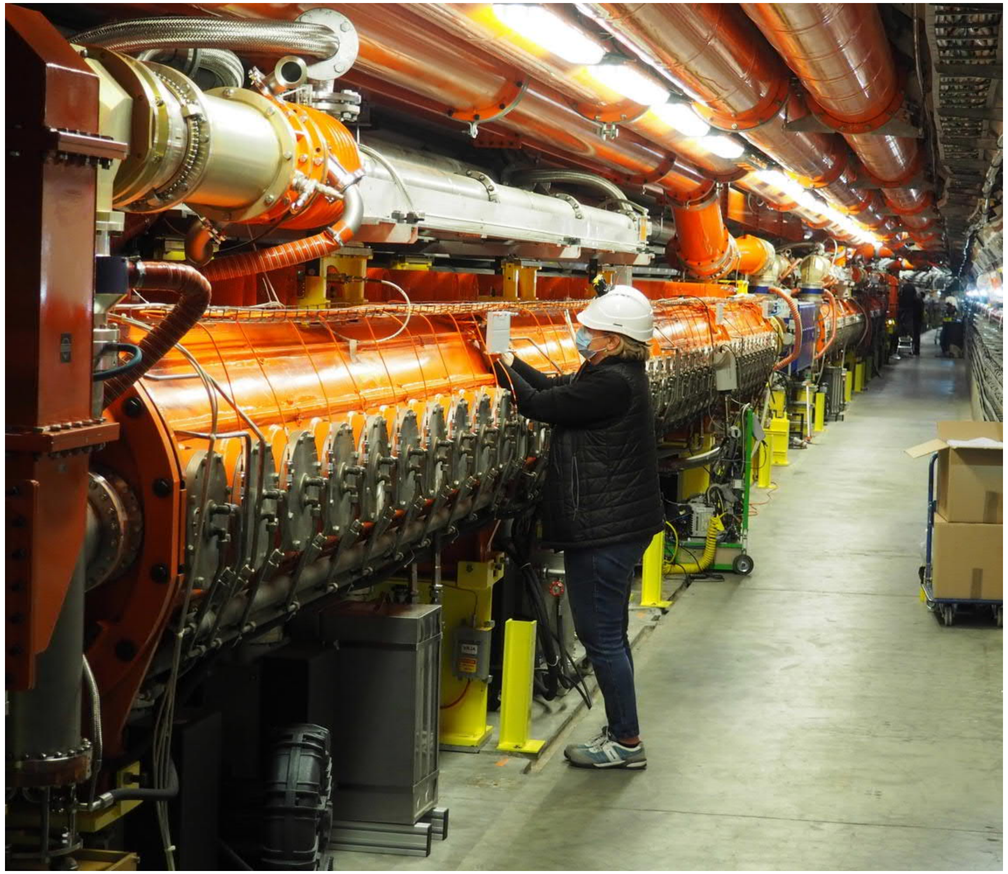


Fig7 – 200MHz travelling wave cavity

$$Z_g(f) = R_1 \left\{ \operatorname{sinc}\left[\tau(f - f_0)\right] e^{-j\pi\tau(f-f_0)} + \operatorname{sinc}\left[\tau(f+f_0)\right] e^{-j\pi\tau(f+f_0)} \right\}$$

$$Z_b(f) = -R_2 \left\{ \begin{array}{l} \operatorname{sinc}^2\left[\tau(f-f_0)\right] + \operatorname{sinc}^2\left[\tau(f+f_0)\right] \\ -j\dfrac{1-\operatorname{sinc}\left[2\tau(f-f_0)\right]}{\pi\tau(f-f_0)} - j\dfrac{1-\operatorname{sinc}\left[2\tau(f+f_0)\right]}{\pi\tau(f+f_0)} \end{array} \right\}$$

Zg(f) ≠ Zb(f)

Parameter	3-sections	4-sections
Cavity filling time t (ns)	462	621
Resistance driven by generator R_1 (Ω)	9851	13237
Resistance driven by beam R_2 (Ω)	485202	876112

SPS LLRF Architecture

Architecture based on White-Rabbit

- White-Rabbit B-Train: Bending field
- White-Rabbit RF-train:
  - RF frequency (FTWs) @ frev
  - Voltage setpoints
- Locked on low noise 10MHz Master clock (GPS receiver)
- Fixed latency, link stabilization [6, 7]
- Sampling clock re-construction from WR data stream in all RF station/crate (1 fiber link for clock & data)

Direct sampling at 125Msps of 200MHz RF

- **Fixed frequency sampling & processing clock** (Predictable, low noise clocks, easier for HW)
- Higher complexity for DSP (Resampler, variable fractional delay - VFD)

10Gbits links

- Cavity voltages → Beam-Control (200MSPS)
- Long Damper → Cavity-Controllers (20MSPS)

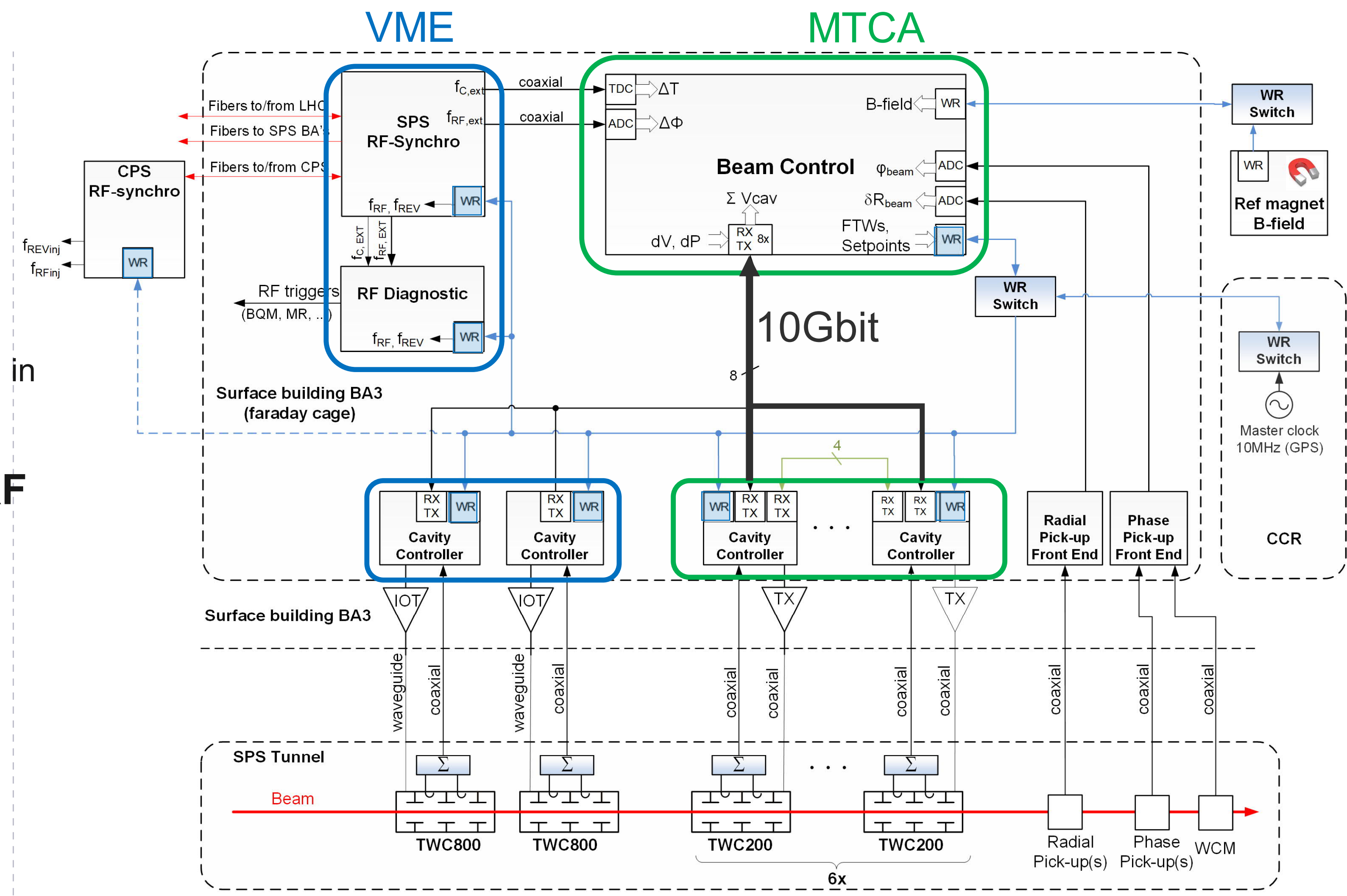


Fig8 – SPS low-level Architecture - platforms

SPS LLRF Architecture

Distributed NCO's

- Every node has its own NCO (RFNCO)
- Running on fixed frequency clock (125MHz)
- Synchronous reset through White-Rabbit (WR) (fixed latency)

RF frequency

- Revolution frequency (FTW) computed in Beam-Control (master)
- FTWs distributed over WR (fixed latency)

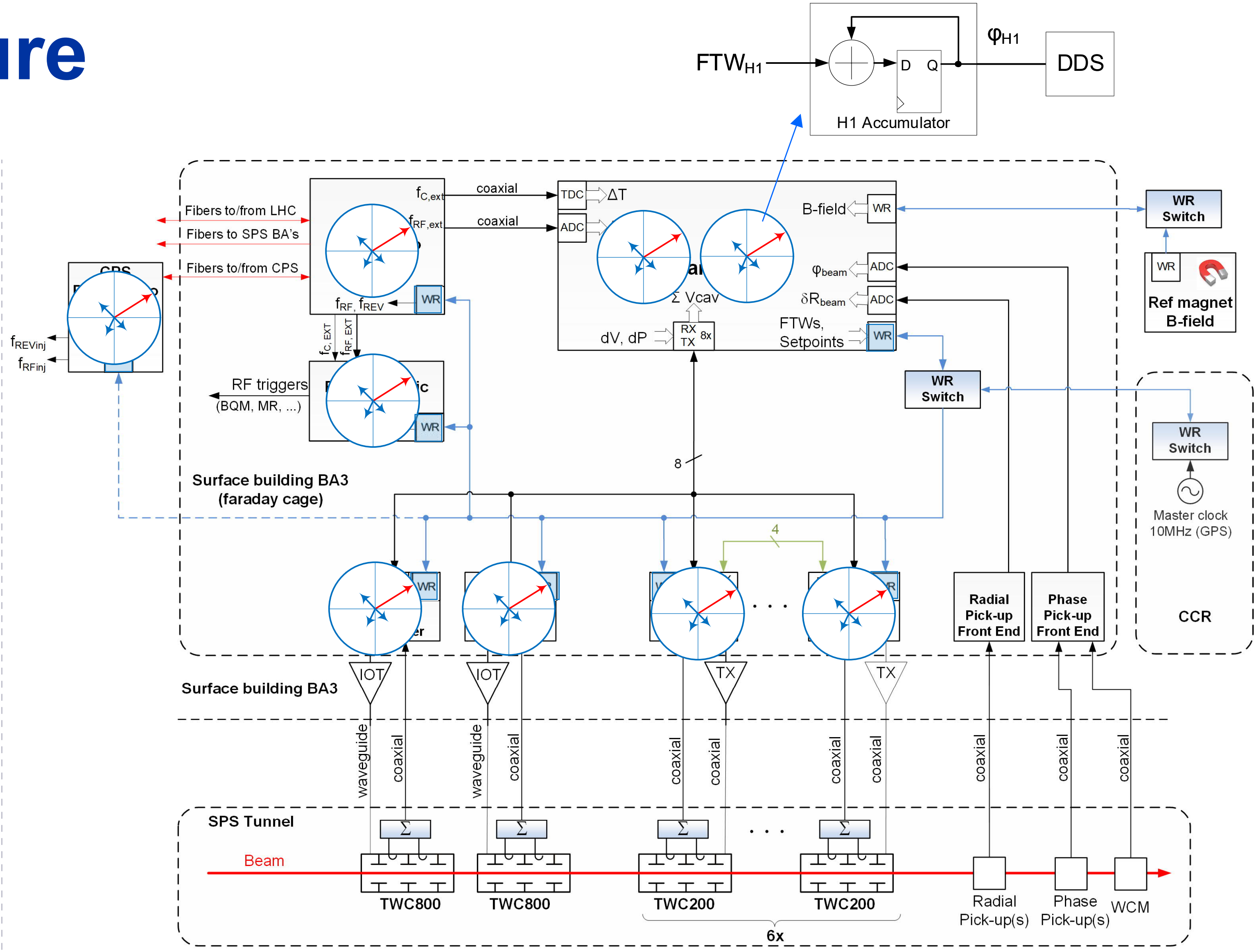


Fig9 – SPS low-level Architecture – distributed NCOs

SPS LLRF Architecture

Numerical Control Oscillator (NCO)

- IP Core in all RF stations
- Reference for RF synchronization
- Allow complex RF gymnastics required for ions acceleration:
  - Amplitude & Frequency modulation used for fixed-frequency acceleration, slip-stacking [8]
- 5 Phase accumulators & 5 FTW's
  - Revolution phase
  - Slippage phase (ions slip-stacking)
  - Frequency modulation
  - Demodulation LO
  - Modulation LO

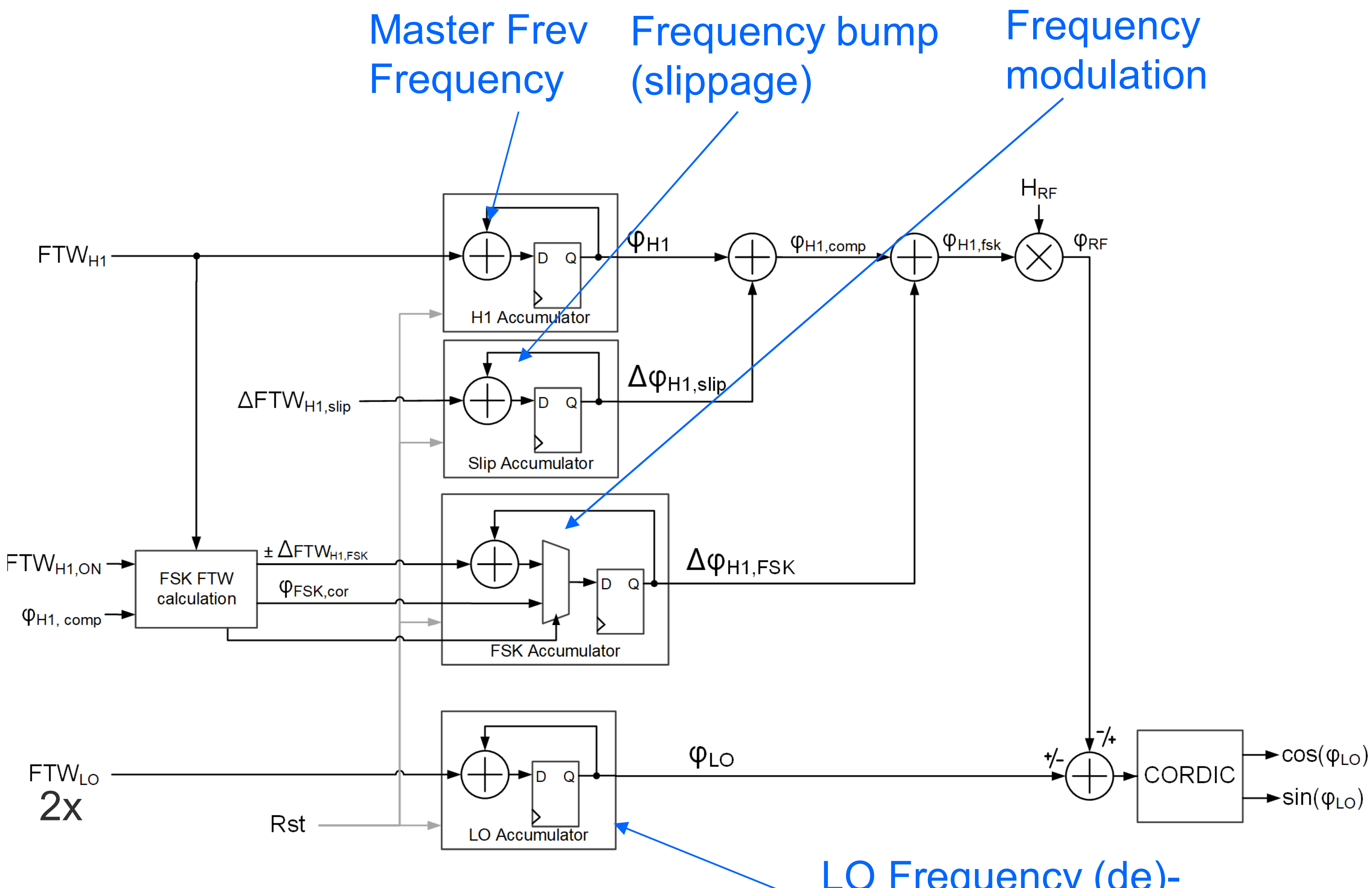


Fig10 – Numerically Controlled Oscillator diagram

SPS LLRF Signal processing

Re-sampler

- Required for bunch-per-bunch signal processing
- Change **from clock-synchronous** data rate (125MHz) **to bunch-per-bunch** data rate (200Msps), and vice-versa
- Synchronized to the NCO
- Phase, radial loops are bunch synchronous
- Farrow based Variable Fractional Delay (VFD) filter with Horner-architecture polynomial interpolation [9]

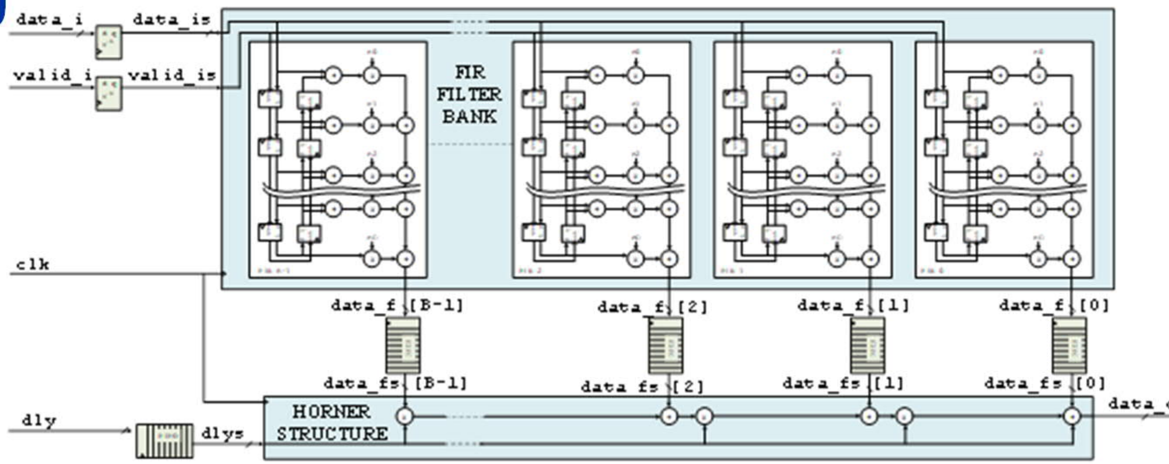
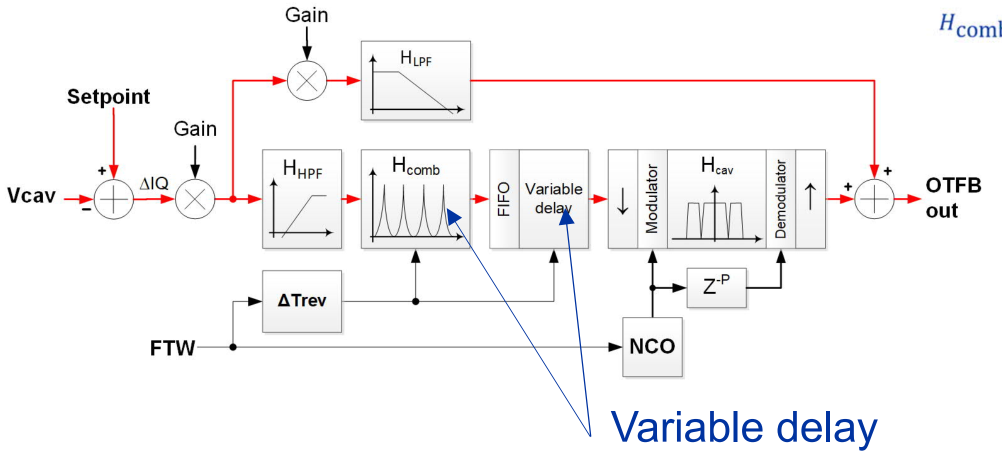


Fig11 – Resampler, Farrow VFD with Horner architecture polynomial interpolation

Variable delay

- Some loops need an exact one-turn delay
  - One-Turn delay Feedback, One-Turn delay Feed-Forward [4, 10]
- Variable integer+fractional delay
  - Integer delay: addressable shift register
  - Variable delay: FIR, 4th order Lagrange polynomial interpolation
- No data rate change (125Msps)
- Delay computed from FTW (NCO)



$$H_{comb} = \frac{b_0 + b_1 \cdot z^{-(N+n)} + b_2 \cdot z^{-2(N+n)}}{1 + a_0 \cdot z^{-(N+n)} + a_1 \cdot z^{-2(N+n)}}$$

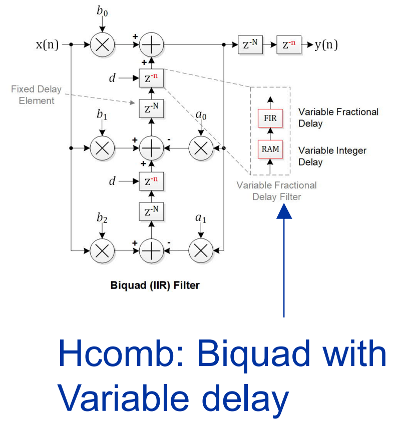


Fig12 – 200MHz RF feedback - Variable delay, Comb filter biquad

SPS 200MHz Cavity-controller - Hardware

WR switch

MTCA crate

RF front-end (1 cavity)

RF front-end (1 cavity)

Fig13 – 200MHz Cavity-Controller MTCA crate + Analog Front-end

FTCI (CERN, EDA-04141)

RTM card [12]

AMC card [11]

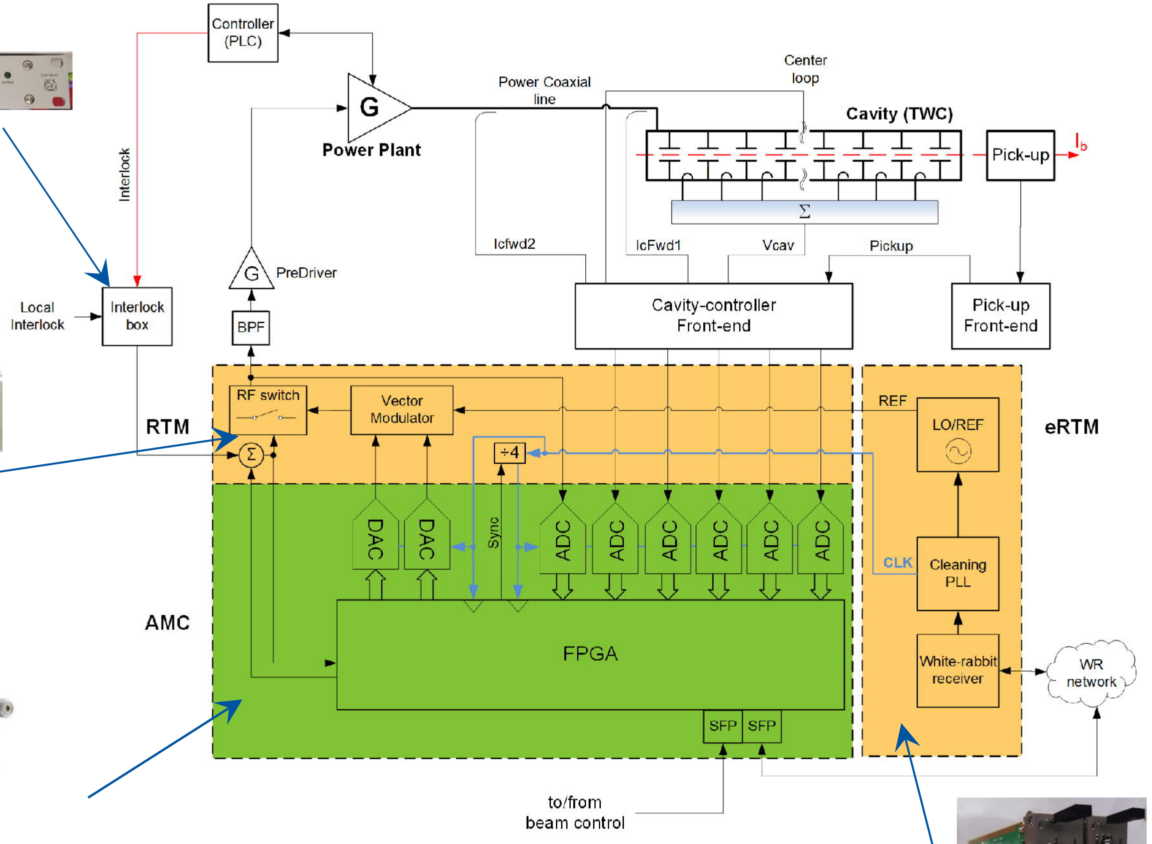


Fig14 – 200MHz Cavity-Controller diagram & hardware [4]

LO/REF : 223.5MHz
CLK: 125/500MHz

eRTM14-15 [13] (CERN, EDA-03849/50)

SPS 200MHz Cavity-controller - Feedback loops

1. **Polar-loop**
   1. Gain & phase loop
   2. 20us response time (CL)
   3. Reduce amplifier noise
   4. Compensate amplifier gain/phase drifts
2. **RF feedback (OTFB)**
   1. One-Turn Delay Fdbk, BW ≈ 4MHz
   2. Reduce transient beam loading
3. **One-Turn FeedForward (OTFF)**
   1. Measure beam current
   2. Reduce transient beam loading
4. **Longitudinal Damper**
   1. Dipole mode (phase modulation)

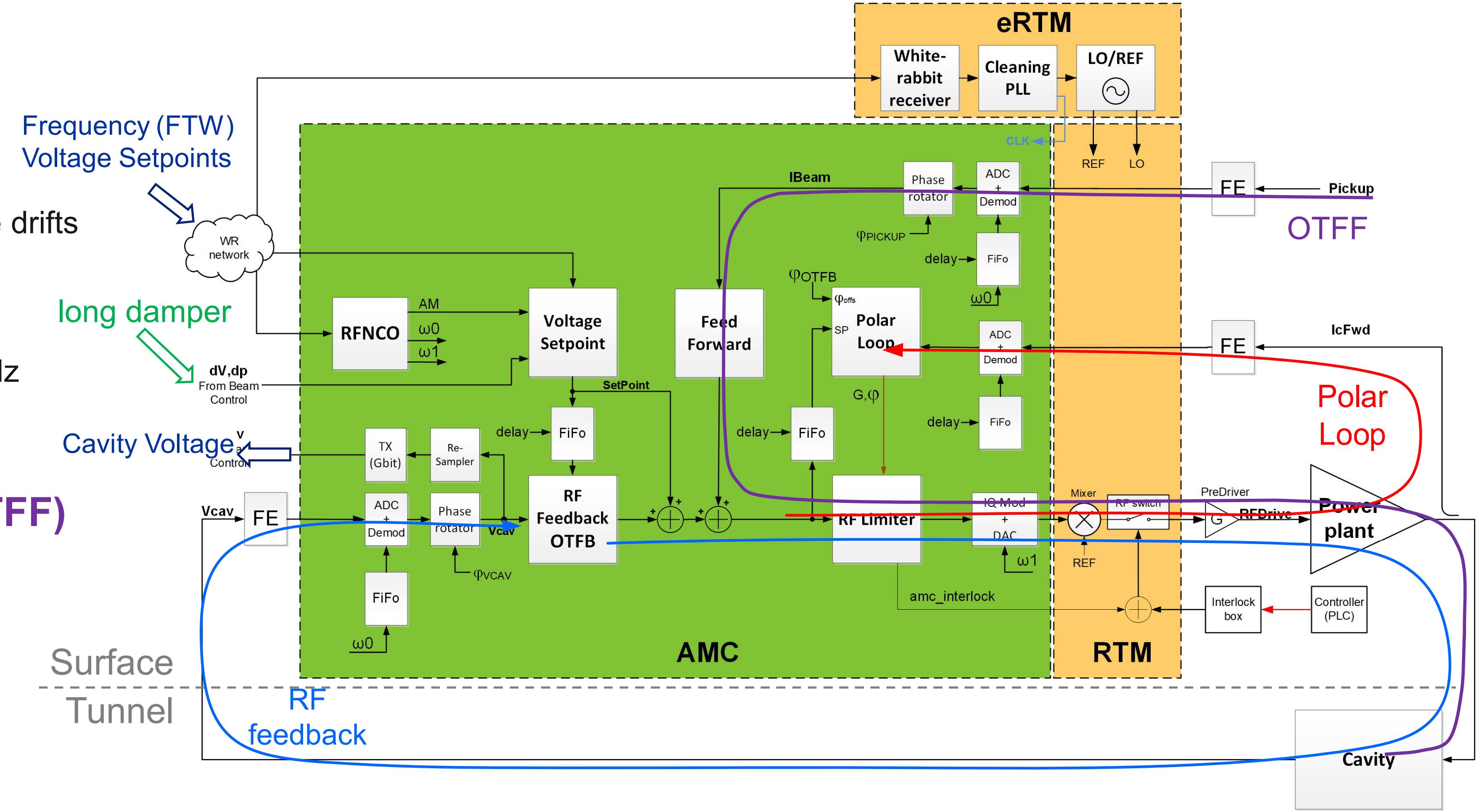


Fig15 – 200MHtz Cavity-Controller feedback loops [4]

Cable + amplifier delay ≈ 3us

RF Frequency and RF (de)-modulation

Synchrotron → RF ramp

- Sweeping RF (avg) = 200+/-2 MHz, BW ≈ 4 MHz
- AM & FM modulation for ions accelerations

RF demodulation (input)

- Direct sampling of 200MHz RF at 125MSPS (fixed frequency)
- Alternative with down-mixing with LO at ~223.5MHz (LO fixed freq, optimized for IF harmonics aliasing)

RF modulation (output)

- Single-side band transmitter scheme
- REF=LO at ~223.5MHz, IF at ~23.5MHz +/-2MHz
- External BPF on VM output to remove LO leakage and image frequencies

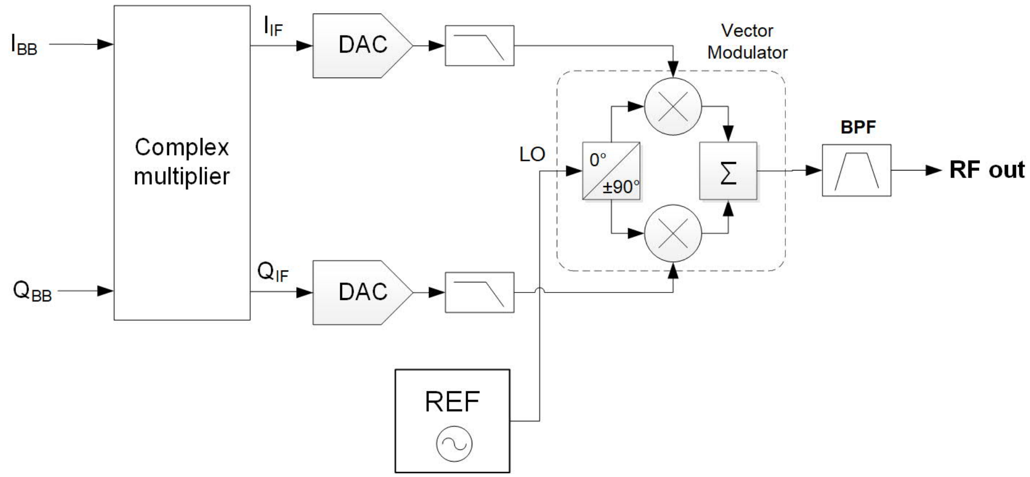


Fig16 – 200MHtz Cavity-Controller Vector modulator

Fig17 – 200MHtz Cavity-Controller vector modulator spectrum

SPS 200MHz Cavity-controller - Phase noise

RF Phase noise is critical for ions acceleration

- Long injection plateau (>20s)
- injection synchrotron frequency ~1kHz
- Goal: fs=300Hz to 2kHz, <-120dBc/Hz

LO/REF (223.5MHz)

- -127dBc/Hz @ 1kHz
- 63fs (100Hz to 10MHz)

Voltage Sum of 6 cavities (close loop)

- -128dBc/Hz @ 1kHz
- 140fs (100Hz to 10MHz)

HL-LHC requirements are ~20dB lower @8kHz

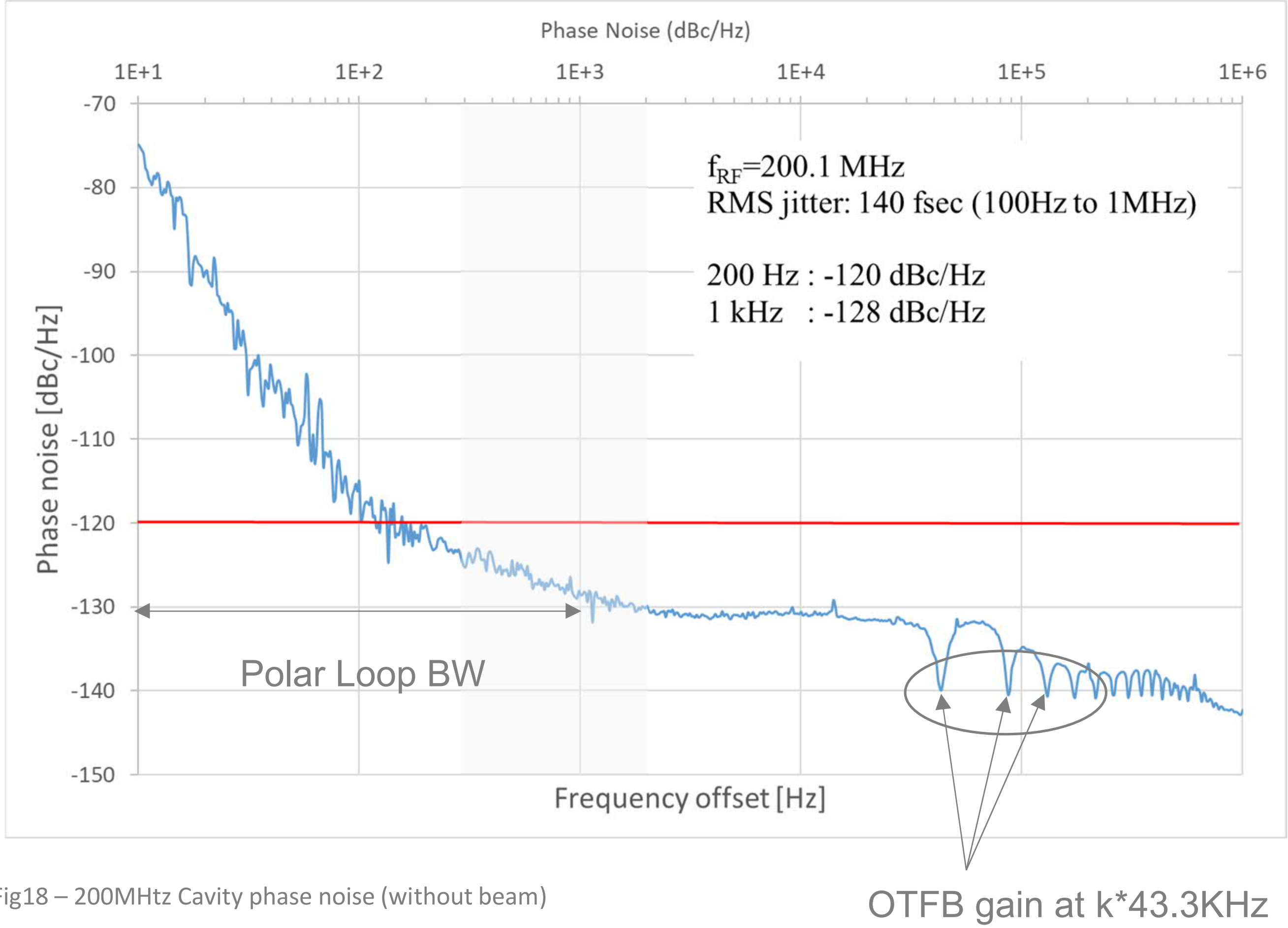


Fig18 – 200MHz Cavity phase noise (without beam)

SPS Beam-Control - Hardware

Fig19 – SPS Beam control crate

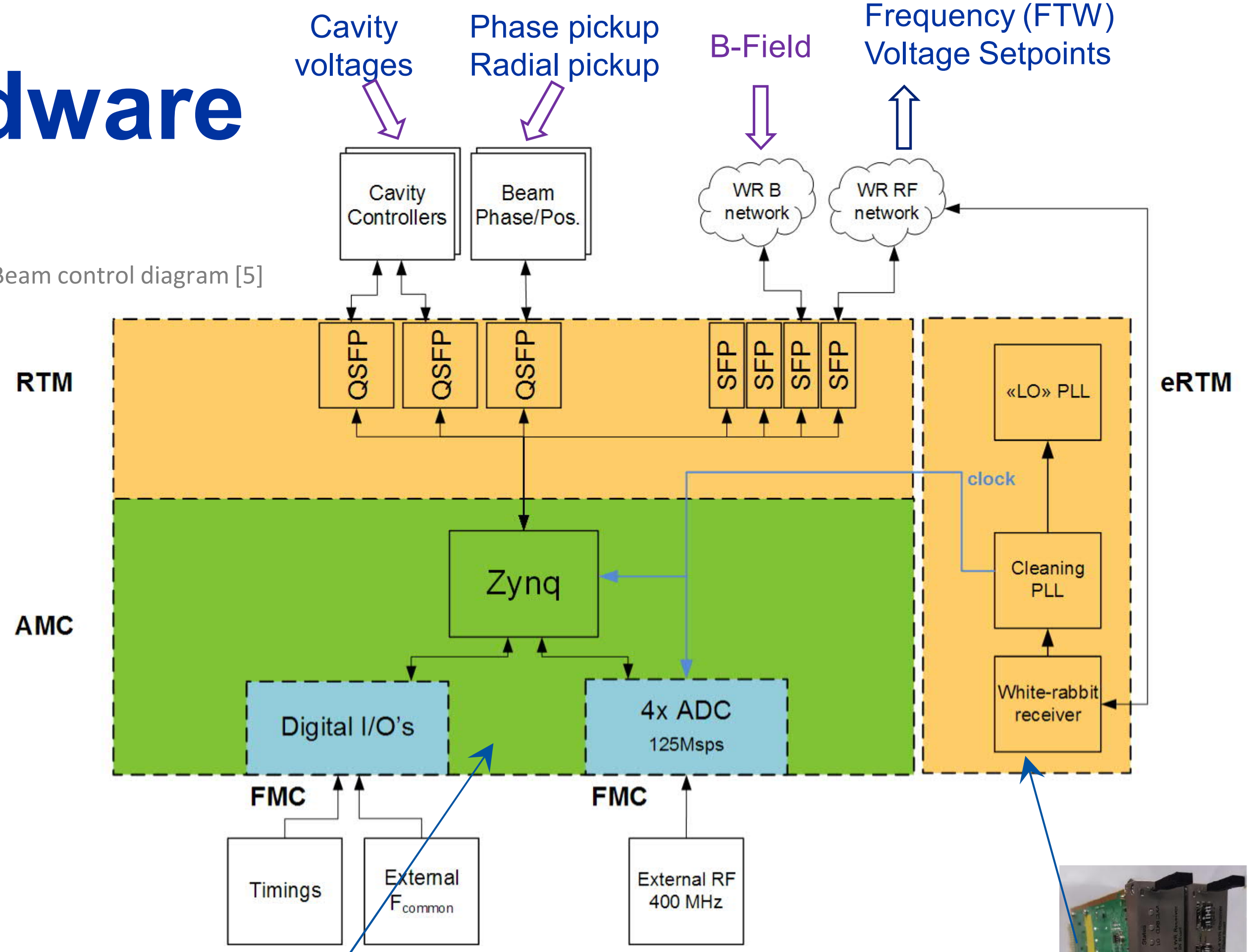


Fig20 – SPS Beam control diagram [5]

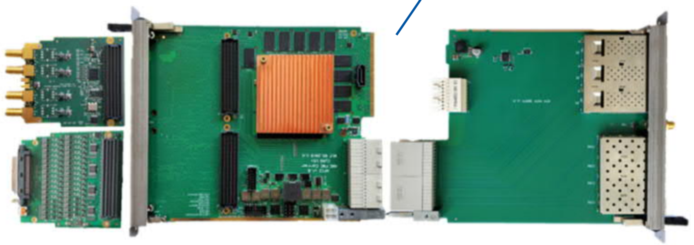
1. MicroTCA Advanced Mezzanine Carrier (AMC) with a Zynq UltraScale+ (AFCZ)

2. Beam-based loops

3. Frequency program

4-channel ADC
125 Msps, 14 bits

32 Digital I/O interface [16]



AFCZ MicroTCA carrier [14] *QSFP-SFP RTM[15]*

LO/REF : 223.5MHz
CLK: 125/500MHz

eRTM14-15 [13]
(CERN, EDA-03849/50)

SPS Beam & results

Protons

- Intensity achieved for LHC beam:
  - 1.84e11 p/bunch, 72bunches, 25ns spacing
  - 1.4e11 p/bunch, 4x 72bunches, , 25ns spacing
- **HL-LHC target:** 2.3e11 p/bunch
- 100% Amplitude modulation with OTFB

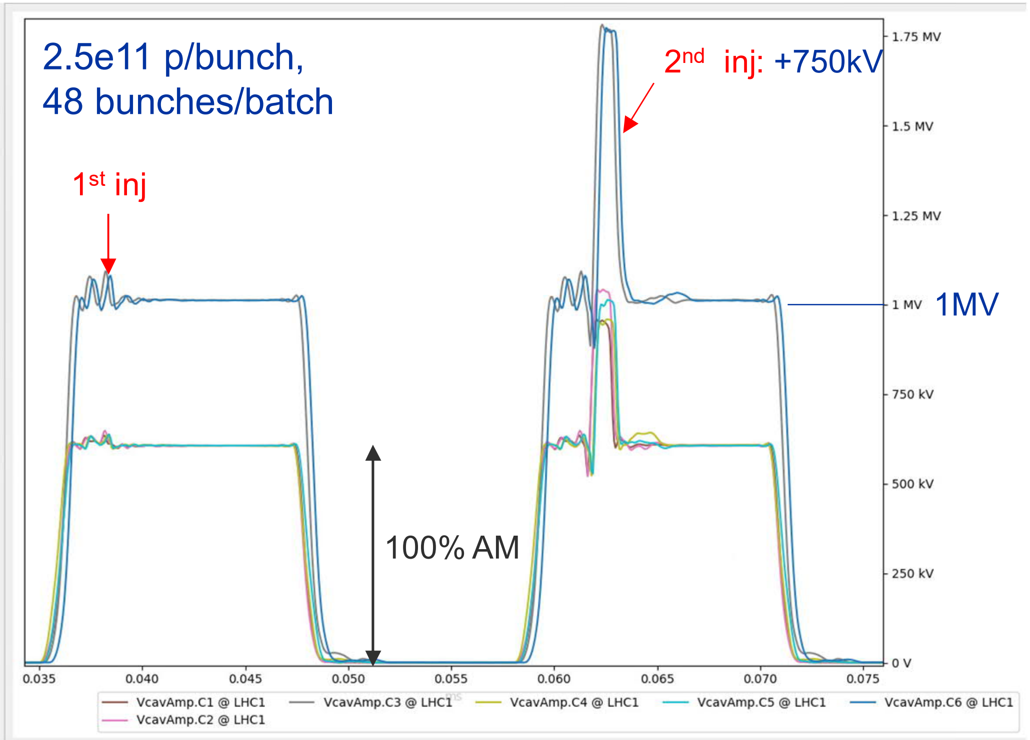


Fig21 – Cavity voltage with Beam loading, 100% AM

SPS Beam & results

Ions

- Cavities splitted into two groups (2 RF frequencies)
- Fixed-frequency acceleration with OTFB
  - 100% Amplitude & Frequency modulation
- slip-stacking from 100ns to 50ns bunch spacing [8]
- Beam commissioning on-going

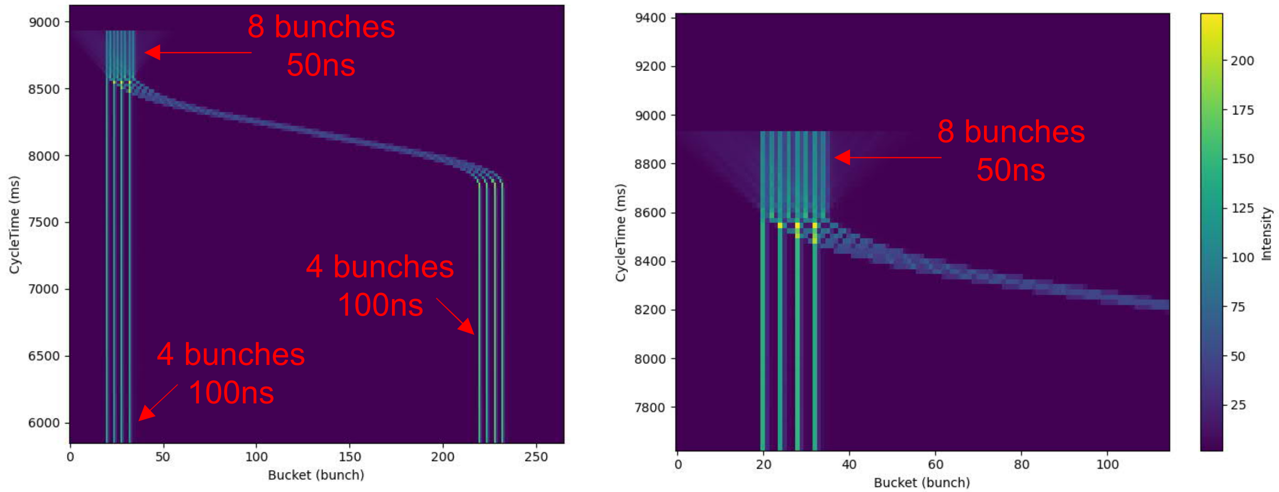


Fig22 – Fast BCT during slip-stacking, 2 batches of 4 bunches

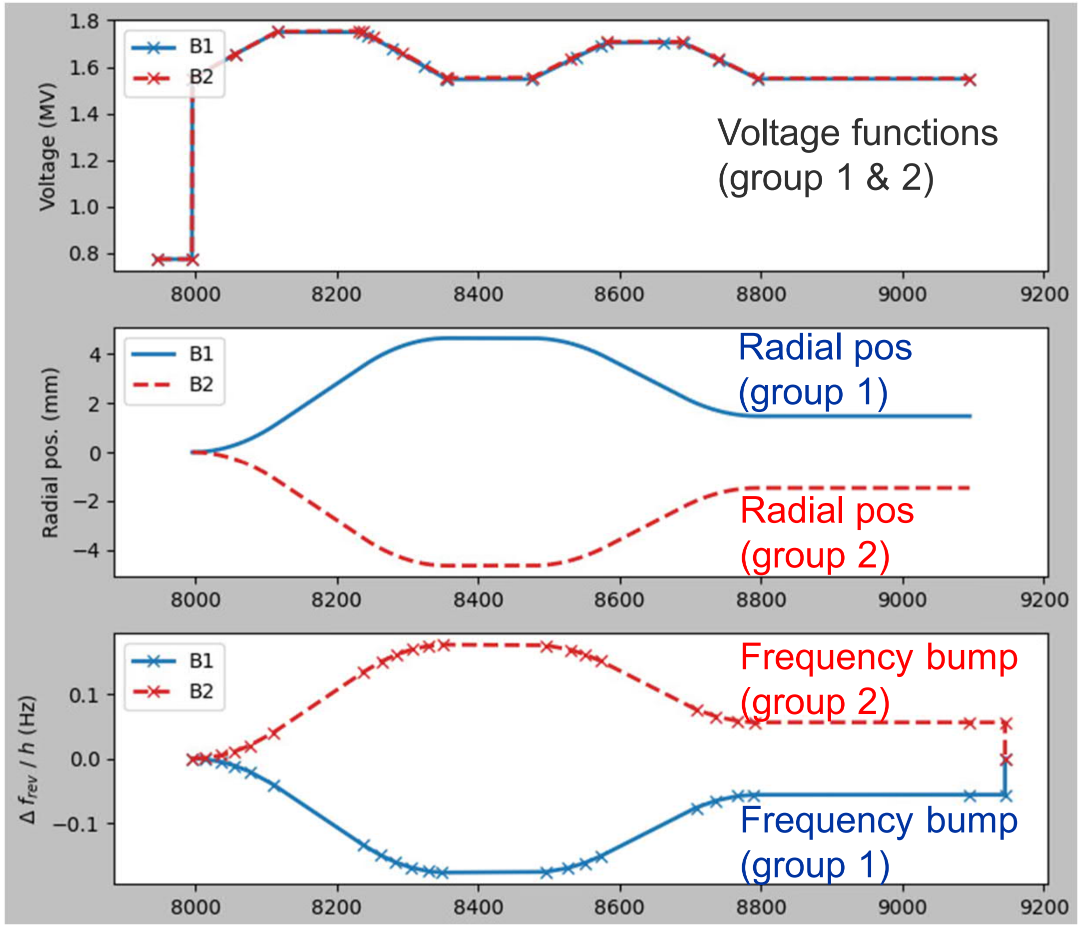


Fig23 – Frequency & voltage functions for slip-stacking

Conclusion

Steep learning curve

- MTCA platform
- Fixed sampling & processing clock
- Resampler, fractional variable delay

Good architecture choices

- Fixed frequency clock, RFNCO flexibility
- White-rabbit for clock and data transmission

We benefit from MTCA (PCIe)

- Fast bus bandwidth (Long acquisition buffer for troubleshooting)
- Compactness, diagnostics, HW hot-swap, Redundancy (PM)
- Use of COTS (Home-made HW in LHC or L4)

Almost two years of operation

- Pre-upgrade performance exceeded
- Ramping up towards HL-LHC intensity

Future CERN LLRF projects on MTCA

- High-Lumi LHC (crab-cavities)
  => much high RF noise requirements
- PS 200MHz Cavity-Controllers
- AWAKE2 (S and X-band linacs)

White-rabbit

- Much improvements to achieved the clock phase reproducibility, target < 13ps (1deg @ 200MHz)
  Achieved: σ=16ps, and few erratic jumps of 75ps under investigation (GTXE2, Kintex), but none with GTXE1 (spartan 6)
- In depth WR/clock performances under characterization

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References

[1] LHC Injector Upgrade, Technical Design Report, Vol. I: Protons, edited by J. Coupard et al, CERN-ACC-2014-0337 (CERN, Geneva, 2014).

[2] E. Metral et al., “Update of the HL-LHC operational scenarios for proton operation”, Jan 19th, 2018, pp. 11-12, CERN-ACC-NOTE-2018-0002

[3] LHC Injector Upgrade, Technical Design Report, Vol. II: Ions, edited by J. Coupard et al., CERN-ACC-2016-0041 (CERN, Geneva, 2016).

[4] G. Hagmann, P. Baudrenghien, J. Egli, A. Spierer, M. Sumi, and T. W, “The CERN SPS Low level RF: The Cavity-Controller”, in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 903-906. doi:10.18429/JACoW-IPAC2022-TUPOST023

[5] A. Spierer et al., “The CERN SPS Low Level RF: The Beam-Control”, in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 895-898. doi:10.18429/JACoW-IPAC2022-TUPOST021

[6] J. Serrano et al., “The White Rabbit Project”, in Proc. 2nd Int. Beam Instrumentation Conf. (IBIC'13), Oxford, UK, Sep. 2013, paper THBL2, pp. 936-942.

[7] P. Boven, “DWDM stabilized optics for white rabbit WR link stabilization link”, in Proc. 2018 European Frequency and Time Forum (EFTF), Torino, Italy, April 10-12, 2018, pp. 213-216. doi:10.1109/EFTF.2018.8409035

[8] P. Baudrenghien, J. Egli, G. Hagmann, A. Spierer, and T. W, “The CERN SPS Low Level RF: Lead Ions Acceleration”, in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 899-902. doi:10.18429/JACoW-IPAC2022-TUPOST022

[9] J. Galindo Guarch, P. Baudrenghien, J. M. Moreno Arostegui, “An Architecture for Real-Time Arbitrary and Variable Sampling Rate Conversion With Application to the Processing of Harmonic Signals”, IEEE Trans. Circuits Theor. 67 (2020) 1653-1666, doi: 10.1109/TCSI.2019.2960686

[10] L. Schmid et al., “Implementation of a One-Turn Delay Feedback with a Fractional Delay Filter (PDF)”, LLRF17, workshop, Barcelona, Spain, Oct. 16-19, 2017, Poster P-77.

[11] MicroTCA AMC card SIS8300-KU, SIS8300 µTCA for Physics Digitizer, Struck Innovative Systeme GmbH, https://www.struck.de/sis8300-ku.html

[12] MicroTCA RTM card DS8VM1, DS8VM1 MTCA.4 Direct Sampling/Vector Modulator RTM, Struck Innovative Systeme GmbH, https://www.struck.de/ds8vm1.html

[13] eRTM14/15 - High Performance White Rabbit Timing Receiver in MTCA.4 format, OHWR, CERN, https://ohwr.org/project/ertm15-llrf-wr/wikis/home

[14] MicroTCA AMC FMC CARRIER – AFCZ, OHWR, Creotech Instruments S.A. https://creotech.pl/product/amc-fmc-afcz/

[15] MicroTCA RTM RTM_4SFP_3QSFP, OHWR, Creotech Instruments S.A., https://creotech.pl/product/qsfp-rtm/

[16] FMC DIO 32ch lvds a, OHWR, CERN, https://ohwr.org/project/fmc-dio-32chlvdsa

Spare slides

Cavity voltage in AM (3-sections, no beam)

Amplitude:

Phase:

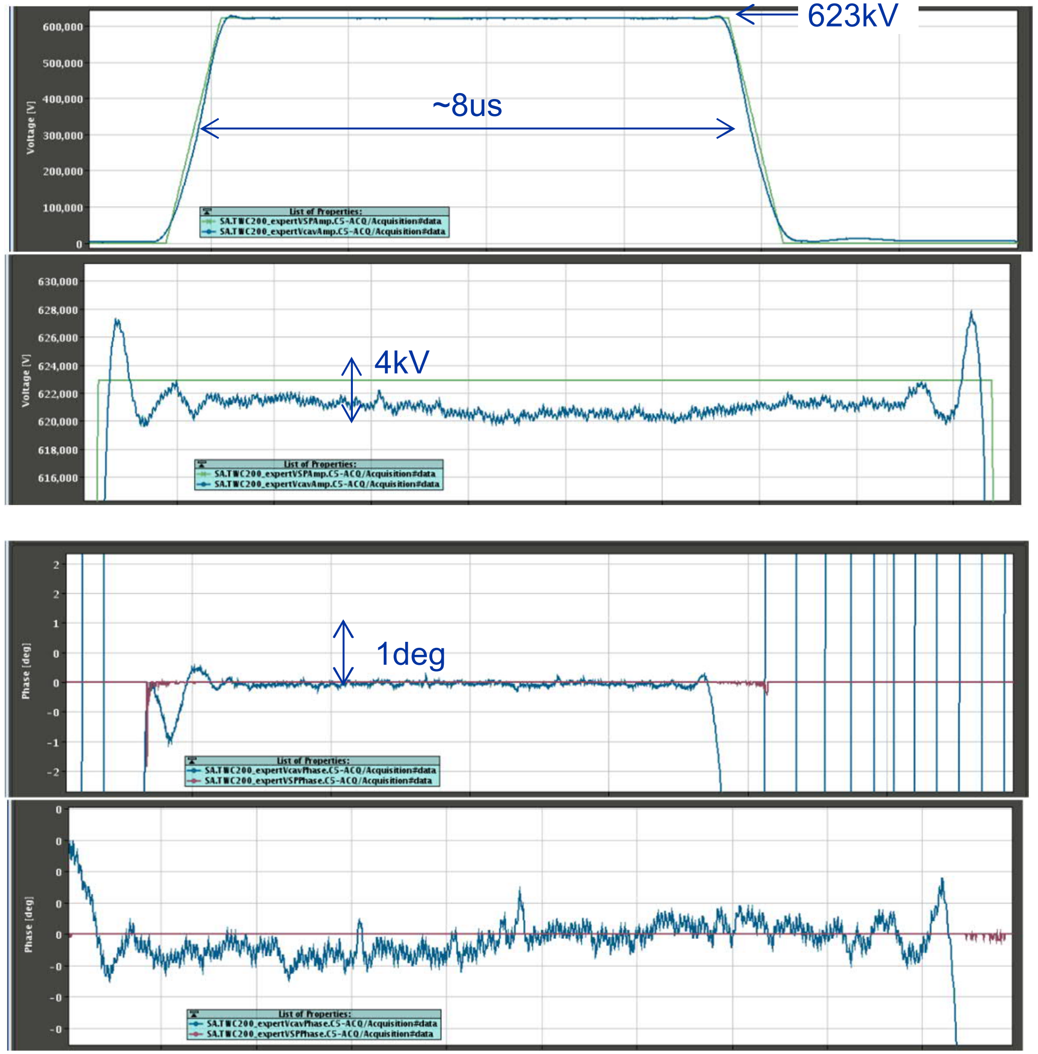

Fig24 – Cavity voltage in Amplitude modulation, no beam, 3-sections cavity

- Frf_inj = ~198.5MHz
- Frf_on = 200.2MHz

- RF ramp on/off 1us
- Modulation at 1*Frev
- Pulse ~11us
- Polar loop + OTFB closed