LHC Injectors Upgrade

# BE OP shutdown lectures 2023
# The SPS LLRF Cavity-Controllers

G. Hagmann on behalf of the SPS LLRF Team (LIU-SPS WP 4.4.1)

**Hardware & Firmware**: P. Baudrenghien, J. Bento, R. Borner, J. Egli, G. Hagmann, G. Kotzian, P. Kuzmanovic, C. Lombard, A. Spierer, I. Stachon, J. Galindo, L. Schmid

**Software:** K. Adrianek, J. Betz, A. Butterworth, D.A. Dglugosz, S.N. Gonzalez, B. Przemyslaw, A. Rey, M. Suminski

And the strong support of our colleagues from BE-CEM

J.R. Gill, D. Lampridis, T. Wlostowski, M. Rizzi, T. Gingold, J. Serrano

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  - Embedded signal acquisition
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- Troubleshooting
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  - Low level RF loops  (Remote, on-site)

# The SPS Low Level RF architecture (LIU-SPS)

# Cavities & amplifiers layout

- **Six 200MHz Cavities**
  - four 3-section cavities
  - two 4-section cavities
- **Two 800MHz cavities**
  - two 3-section cavities

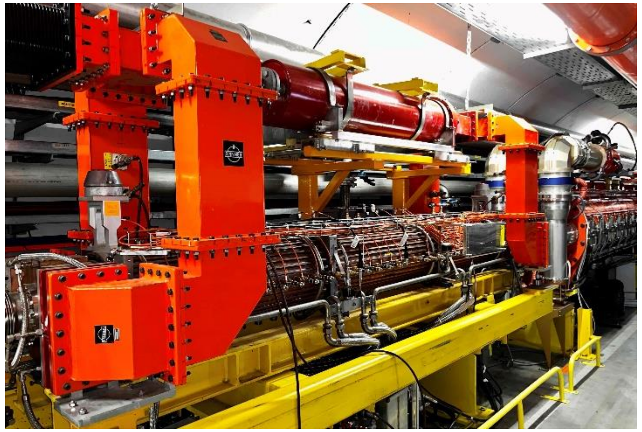


Fig – TWC 800MHz Cavity

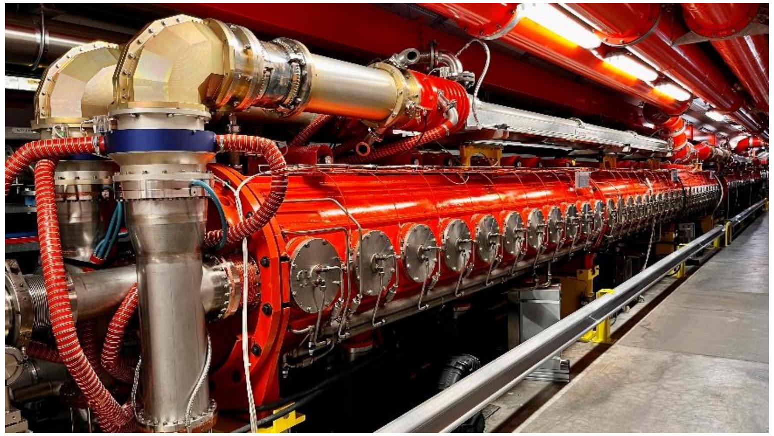


Fig – TWC 200MHz Cavity

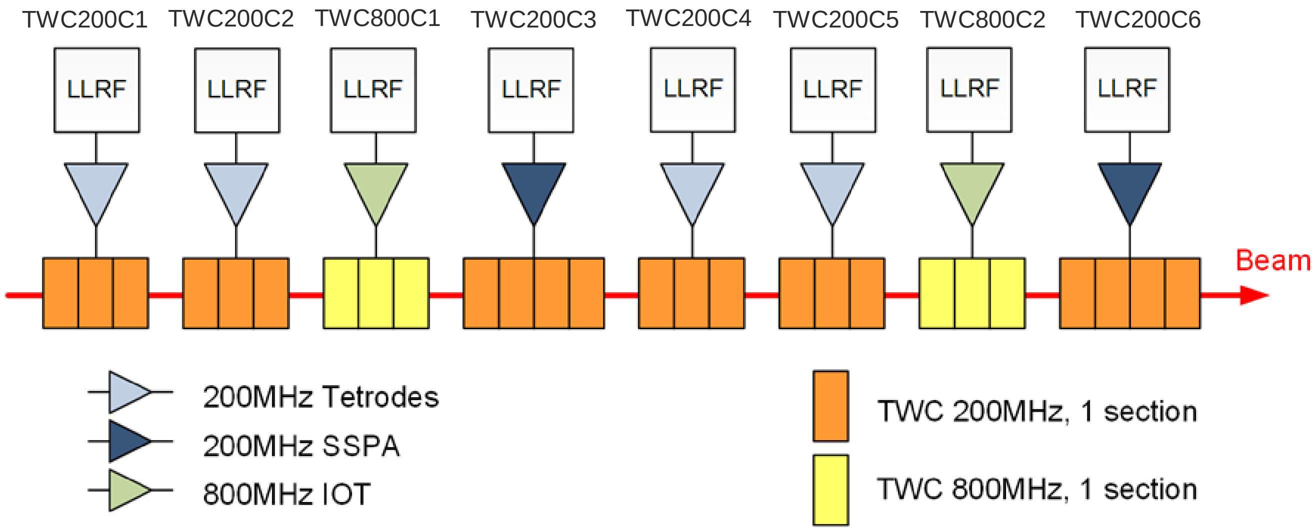



Fig – SPS Cavity arrangement

| 200 Cavity | Type | Pnom | Vnom | Vmin |
|---|---|---|---|---|
| 1 | 3-section | 1MW | 1.97MV | 500kV |
| 2 | 3-section | 1MW | 1.97MV | 500kV |
| 3 | 4-section | 1.6MW | 3.35MV | 500kV |
| 4 | 3-section | 1MW | 1.97MV | 500kV |
| 5 | 3-section | 1MW | 1.97MV | 500kV |
| 6 | 4-section | 1.6MW | 3.35MV | 500kV |
| **800 Cavity** | **Type** | **Pnom** | **Vnom** | **Vmin** |
| 1 | 3-section | 200kW | 1.2MV | 200kV |
| 2 | 3-section | 200kW | 1.2MV | 200kV |

Fig – SPS RF power and RF voltage (max peak)

More details on the SPS-LIU project in the 2020 OP shutdown lecture "The new SPS LLRF" [1]

# LLRF architecture

- **White-rabbit (WR) network**
  - B-train (Magnetic bending field)
  - RF train (digital Frev: FTWH1)
- **Fixed clock (Beam-Control, TWC200)**
  - Re-constructed from WR network
- **Beam Control**
  - Beam based loops (phase, synchro, radial loop,…)
- **Cavity-controllers**
  - Cavity voltage field regulation
- **8x Pickup front-ends (PUAFE)**
  - 2x phase narrow band, 1x phase wide band
  - 2x Radial narrow band, 2x Radial wide band
  - 1x Wall Current Monitor (Feedforward)
- **RF-Synchro & RF distribution**
  - Inj/ext pulses, External References

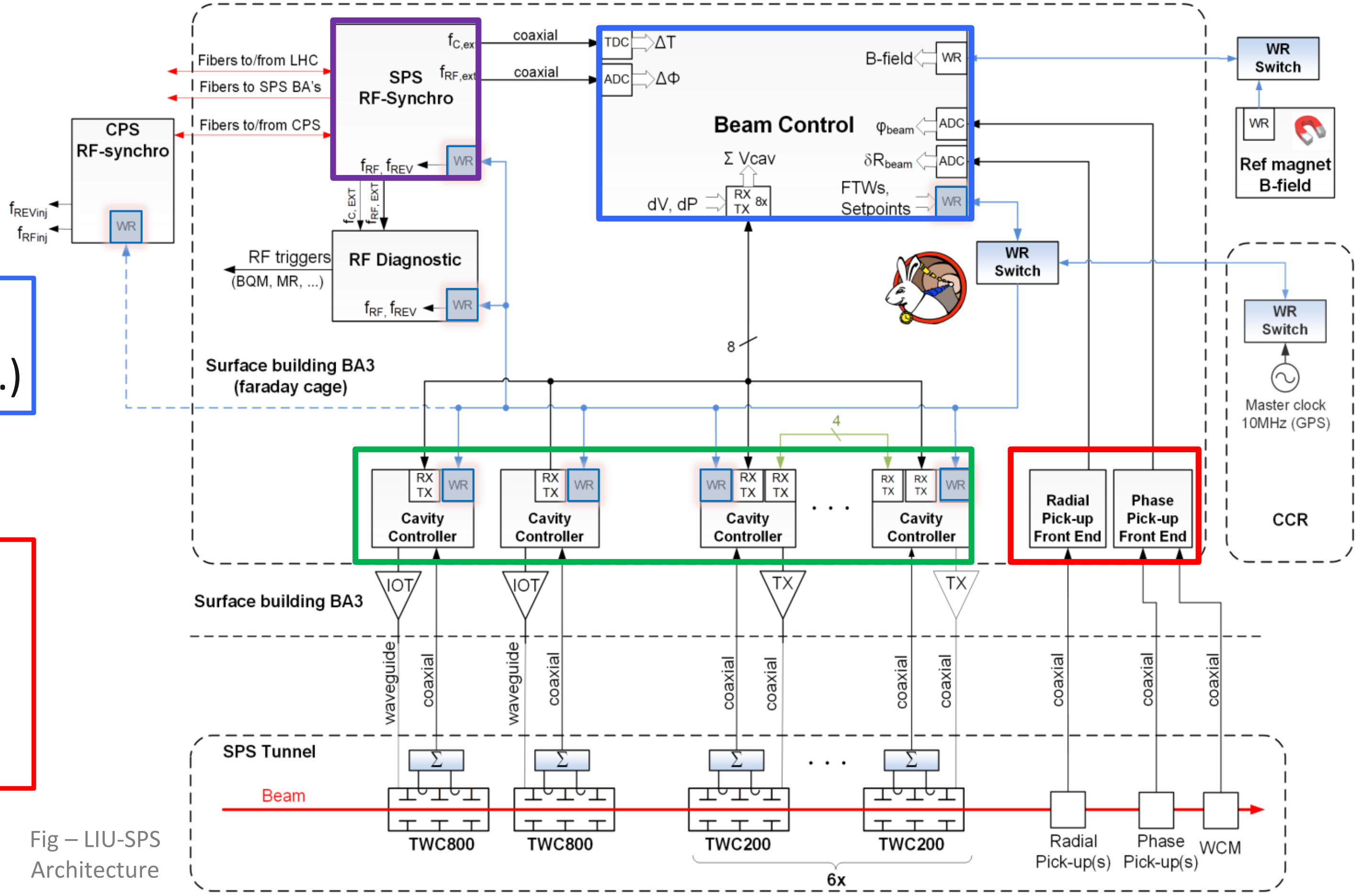



Fig – LIU-SPS Architecture

More details on the SPS-LIU project in the 2020 OP shutdown lecture "The new SPS LLRF" [1]

# White-Rabbit RF-train principle

- **Ethernet network with precision timing protocol**
- **Improved WR network/switch for RF train (low jitter, phase reproducibility)**
- **Distributed Numerically Controlled Oscillators (NCO)**
  - Accumulator adds Frequency Tuning Word (FTW)
  - Accumulator output = RF phase
  - LUT (or Cordic) computes sin/cos
- **Fixed latency Ethernet links**
  - Deterministic reset for NCO (absolute phase reference)
  - Deterministic FTW update
- **Link stabilisation from WR**
  - reduces phase drifts
- **Scalable**

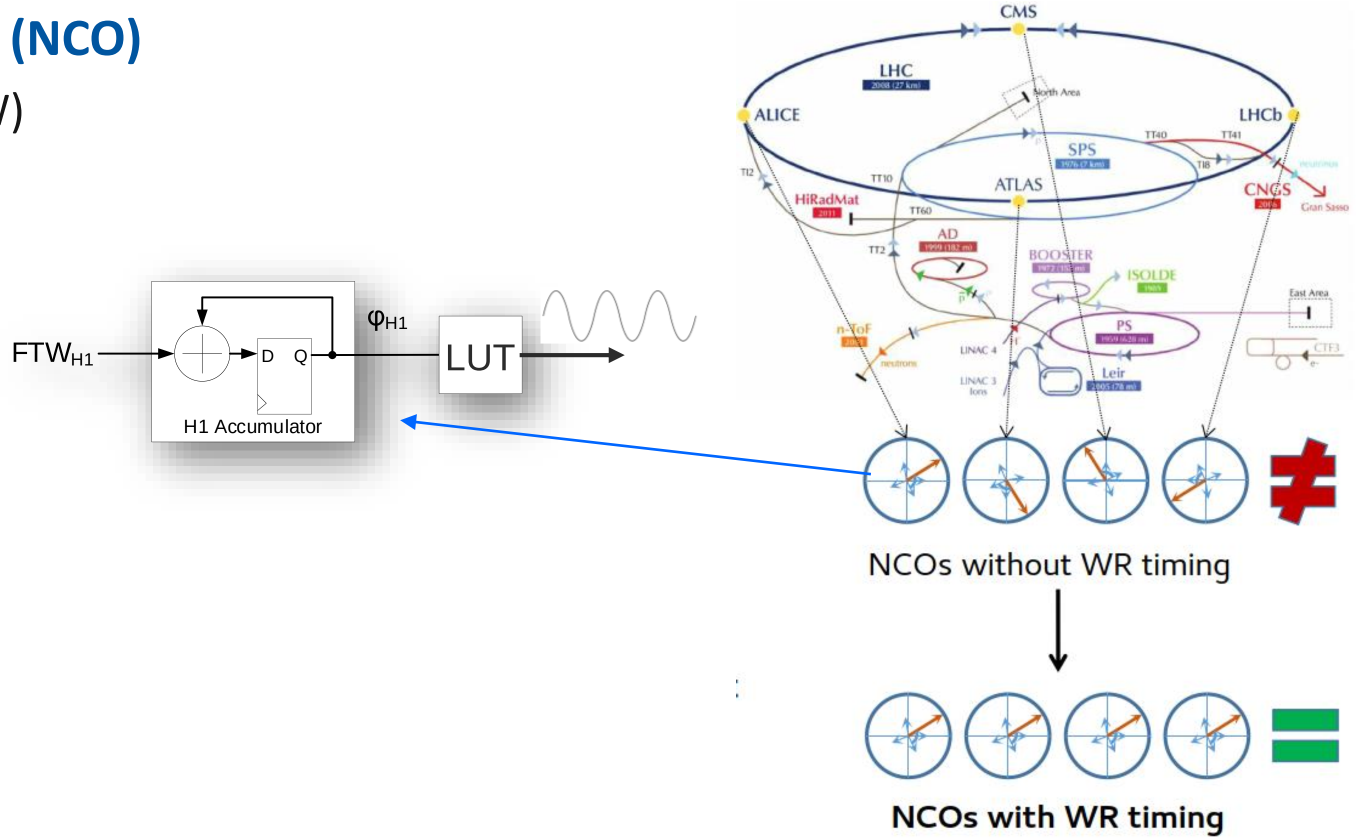



Fig John R. Gill, RF Signal Distribution over WR, J. Gill, Nov. 2019, BE

# White-Rabbit RF-train in SPS LLRF

- **Digital RF frequency distribution**
  - FTW's (frev, frev_on)
  - Two ΔFTW (slip-stacking)
- **NCO reset distribution**
- **Cavity voltage setpoints distribution**
- **Absolute time**
  - timestamps
- **Beam-Control is the Master**
- **Reconstruction of the RF anywhere in the accelerator, even with fixed-frequency acceleration**

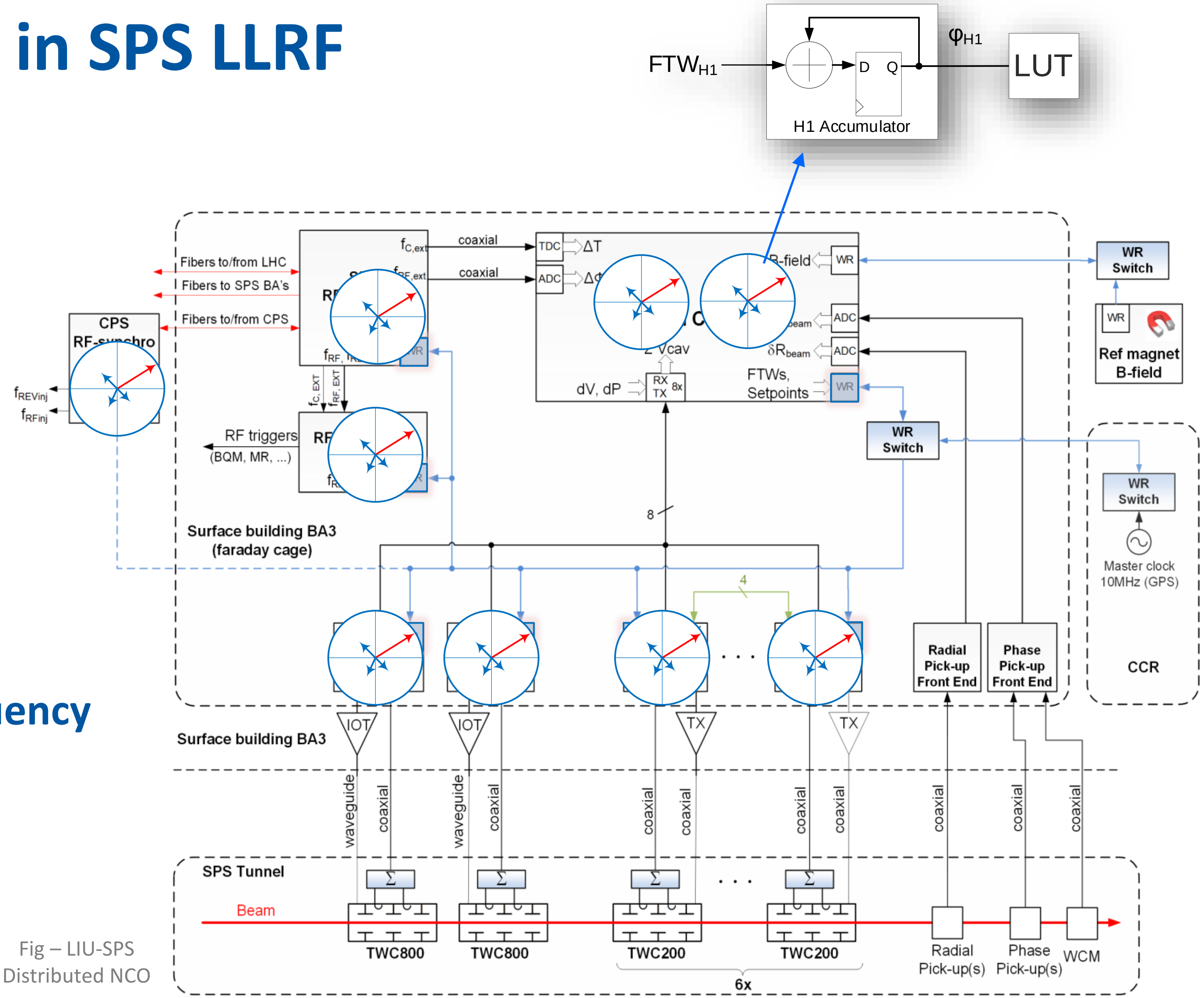
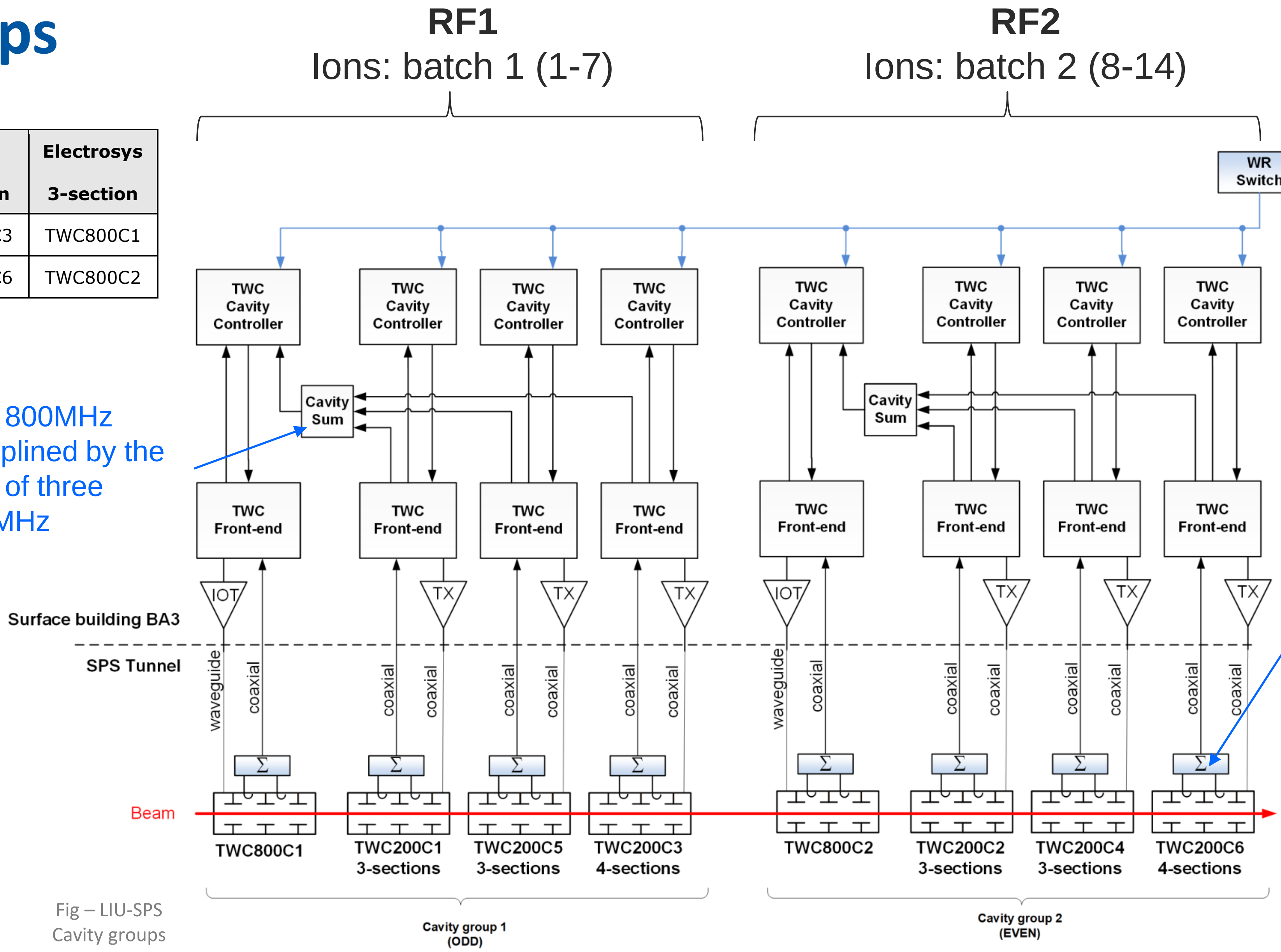



Fig – LIU-SPS Distributed NCO

# Cavity groups

| Group | Siemens A 3-section | Philips B 3-section | Thale C 4-section | Electrosys 3-section |
|---|---|---|---|---|
| **1 (odd)** | TWC200C1 | TWC200C5 | TWC200C3 | TWC800C1 |
| **2 (even)** | TWC200C2 | TWC200C4 | TWC200C6 | TWC800C2 |

One 800MHz disciplined by the sum of three 200MHz




All Vcav cables have identical length

Fig – LIU-SPS Cavity groups

# Layout

# LLRF localization

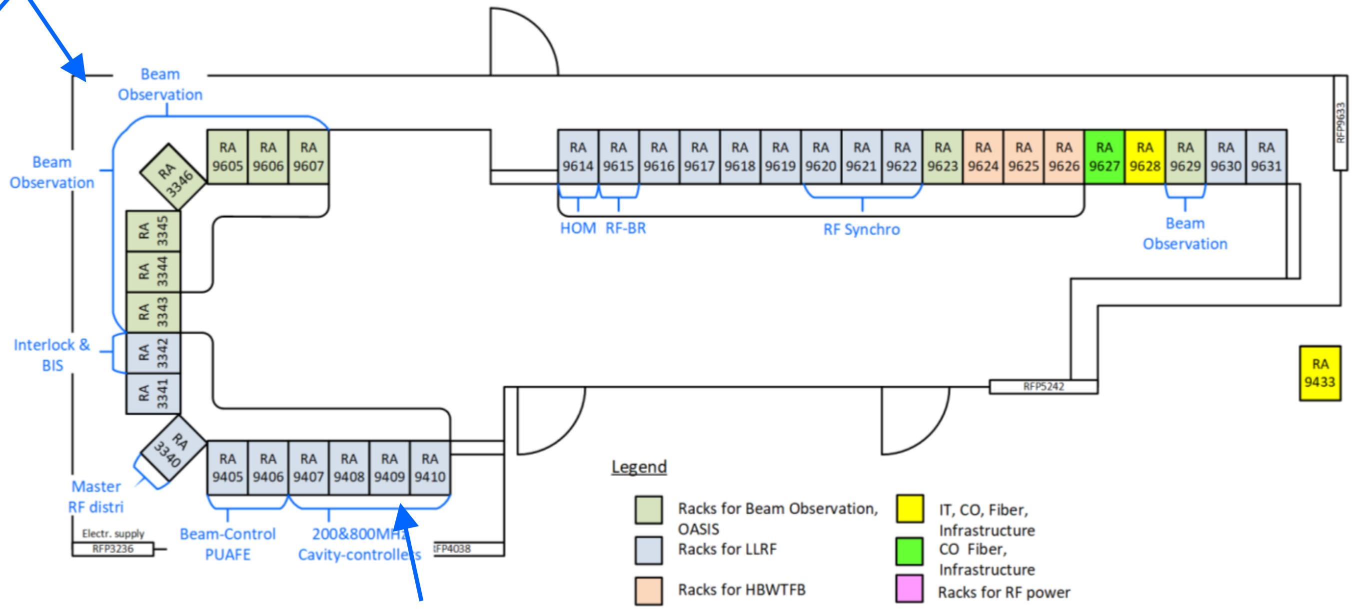
- Beam-Control, Cavity controllers, RF-Synchro, RF distribution: **870-R-002 (BA3, Faraday cage)**
- RF distribution: **874-R-012 (CCR, Rack 0612)**
- Transverse Damper **(BA2):**

BA3, Faraday Cage

CCC

CCR


Fig – SPS BA3




200&800MHz Cavity-Controllers

Fig – SPS BA3 – Faraday cage

# 200 & 800 MHz Cavity-Controllers crates

Analog 200MHz Cavity Vector Sum (2x 3 cavities)

200MHz Interlock crate (FTCI)

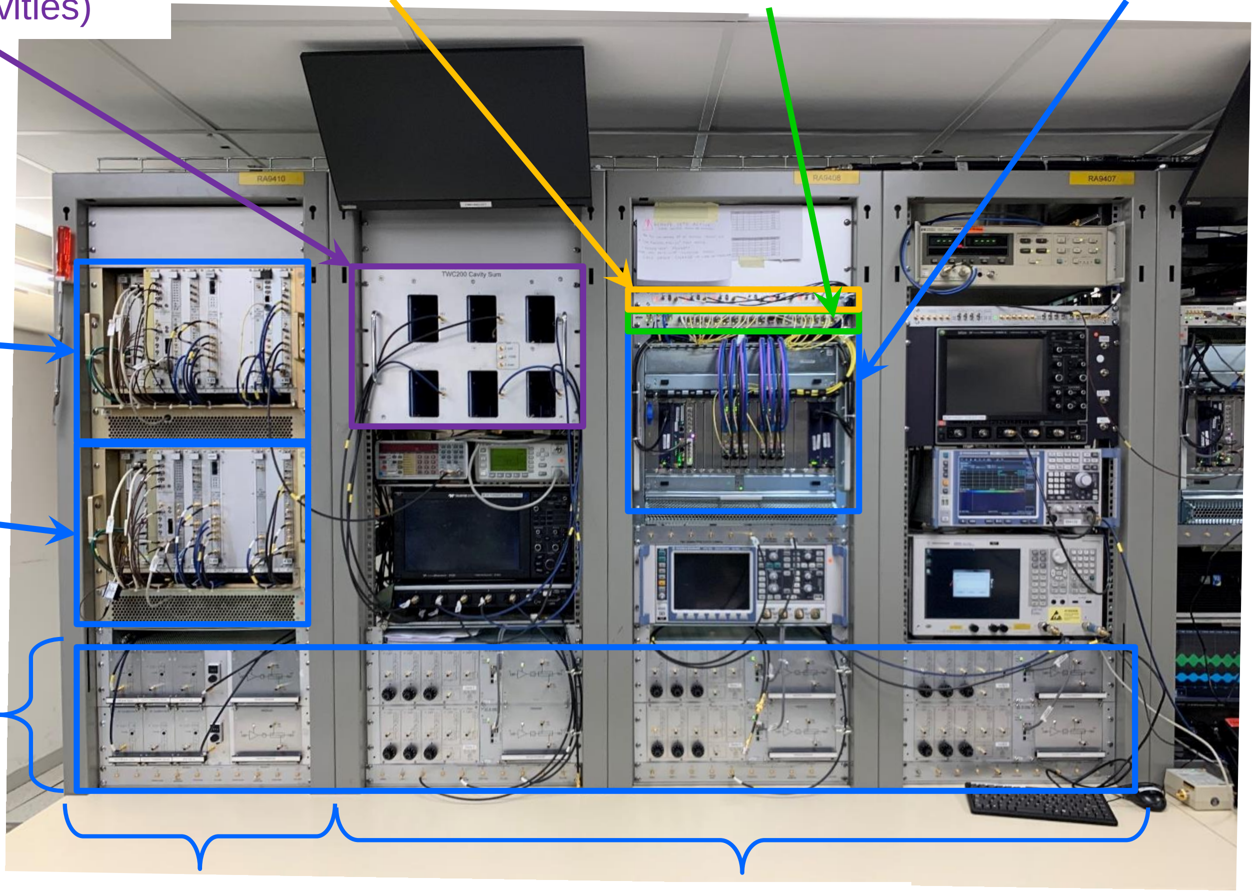
200MHz White-Rabbit switch (RF-Train)

200MHz LLRF MicroTCA

800MHz C1 LLRF VME crate

800MHz C2 LLRF VME crate

3U Analog front-ends (1 per cavity)



800MHz Cavity-Controllers

200MHz Cavity-Controllers

Fig – 200 & 800MHz Cavity-controllers racks

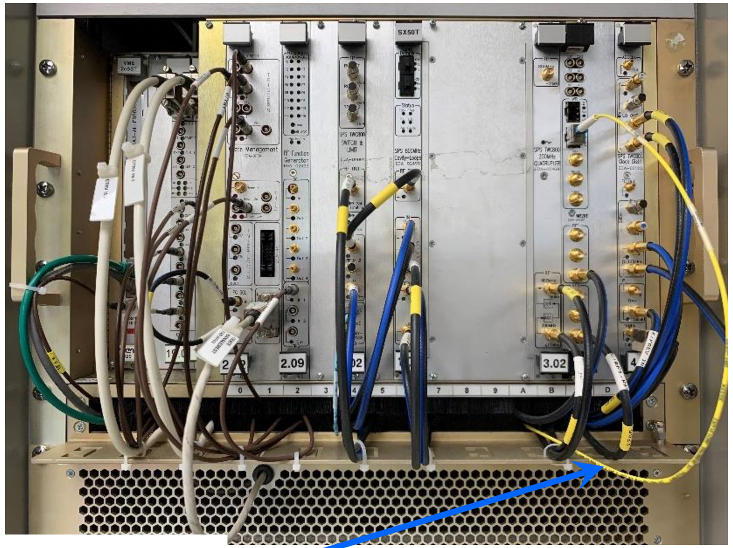



Fig – 800MHz C1 LLRF, VME crate

Yellow Fibers: White-rabbit RF-train

Fig – 200MHz LLRF, MicroTCA crate

# Cavities’ location

- **SPS point 3 (LSS3)**

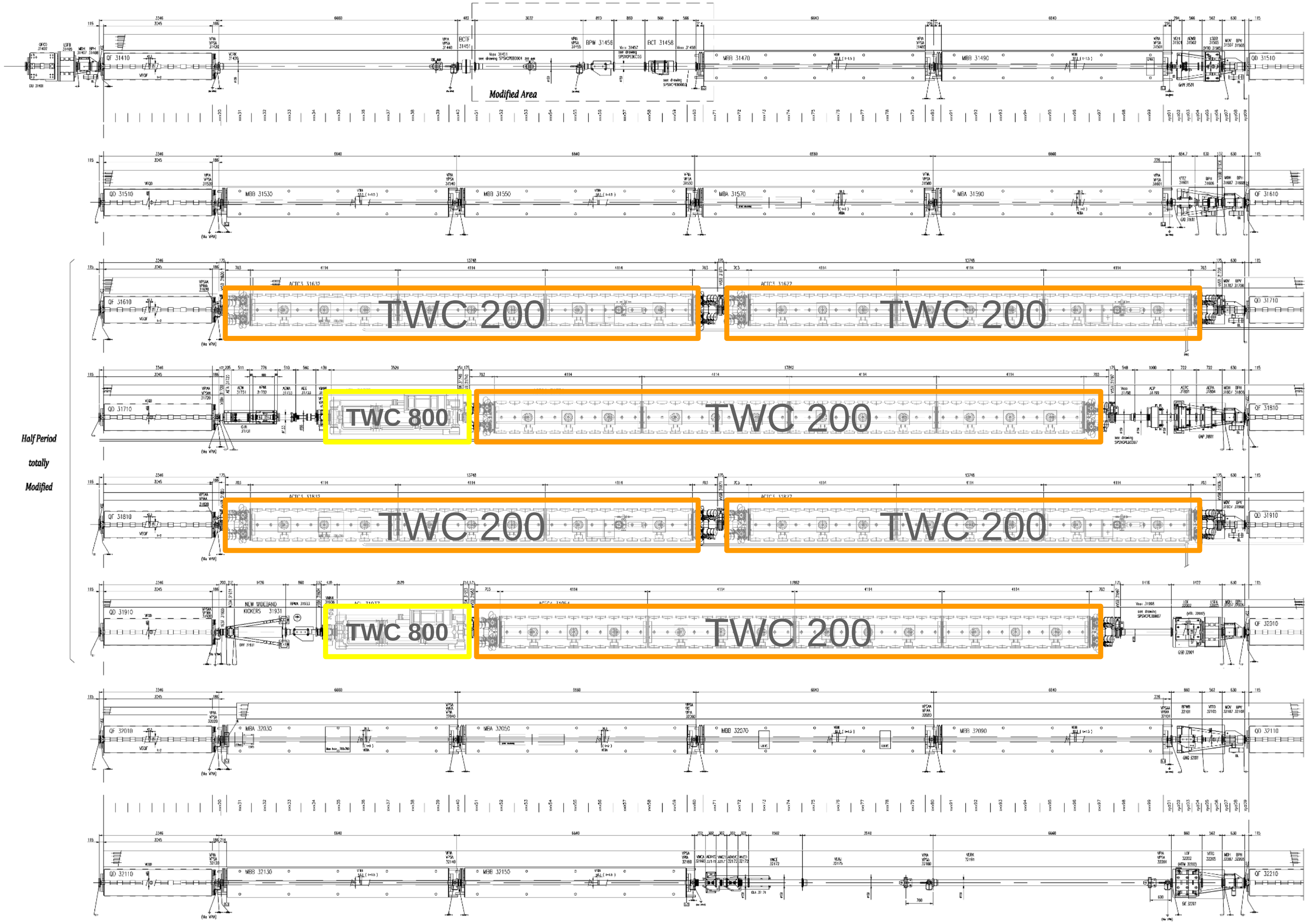



Fig – LSS3 arrangement
edms.cern.ch/ui/file/1155058/AB/spslnins0106-vAB.pdf

# Controls loops

# 200MHz Cavity-controller - Overview

White-rabbit switch
(CERN, BE-CEM-EDL)

eRTM14+eRTM15
(CERN, BE-CEM-EDL)

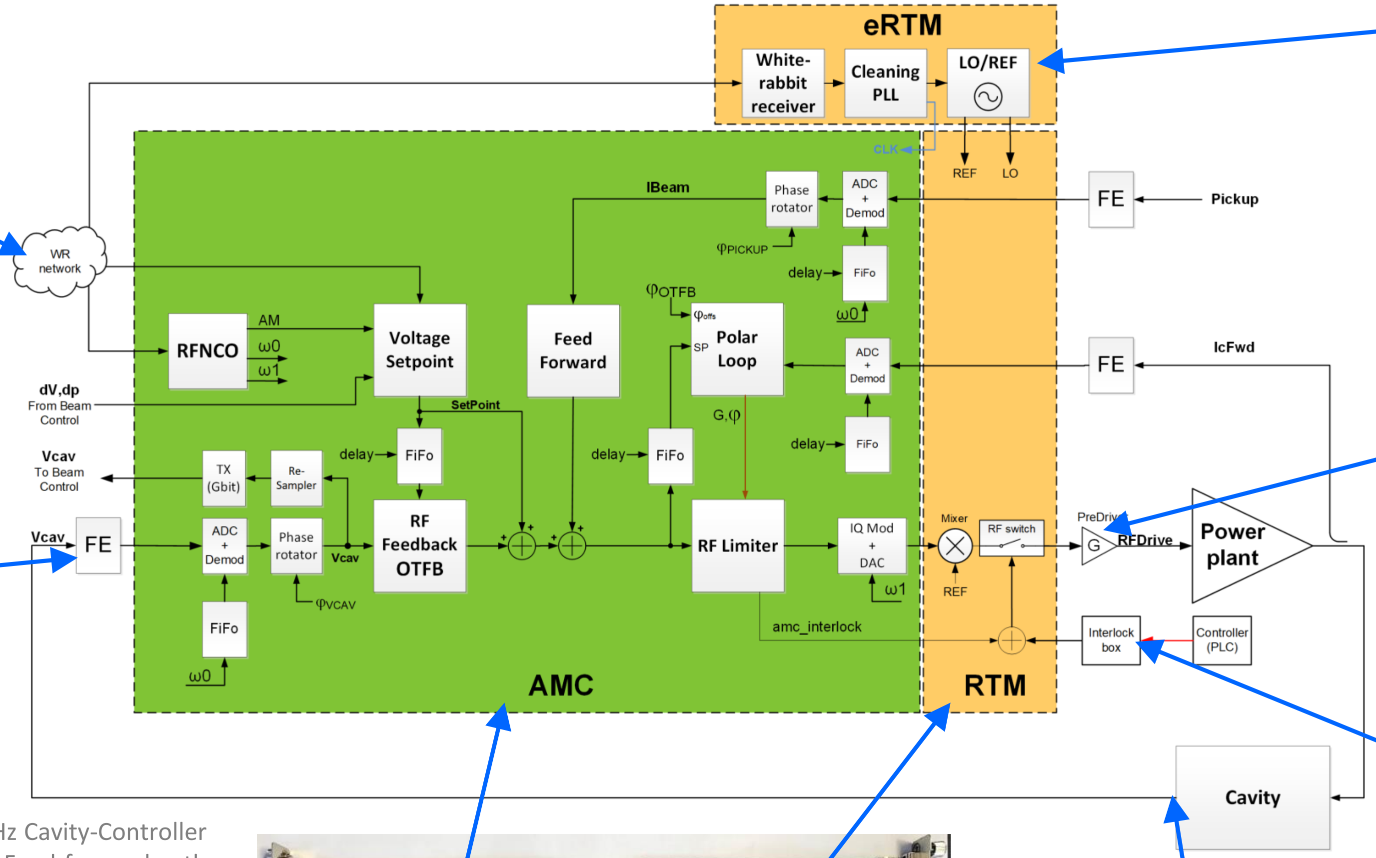
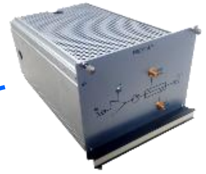
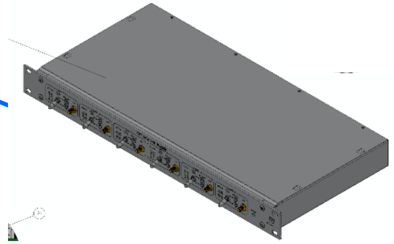



Fig – SPS 200MHz Cavity-Controller diagram: Feed-forward path



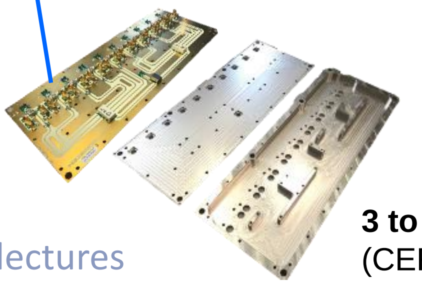
PreDriver
(CERN, SY-RF-FB)

RF calibration front-end
(CERN, SY-RF-FB)



Interlock
(CERN, SY-RF-FB)

SIS8300-KU, DS8VM1
(Desy, Struck)



3 to 4 RF combiners
(CERN, SY-RF-FB)

# 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)

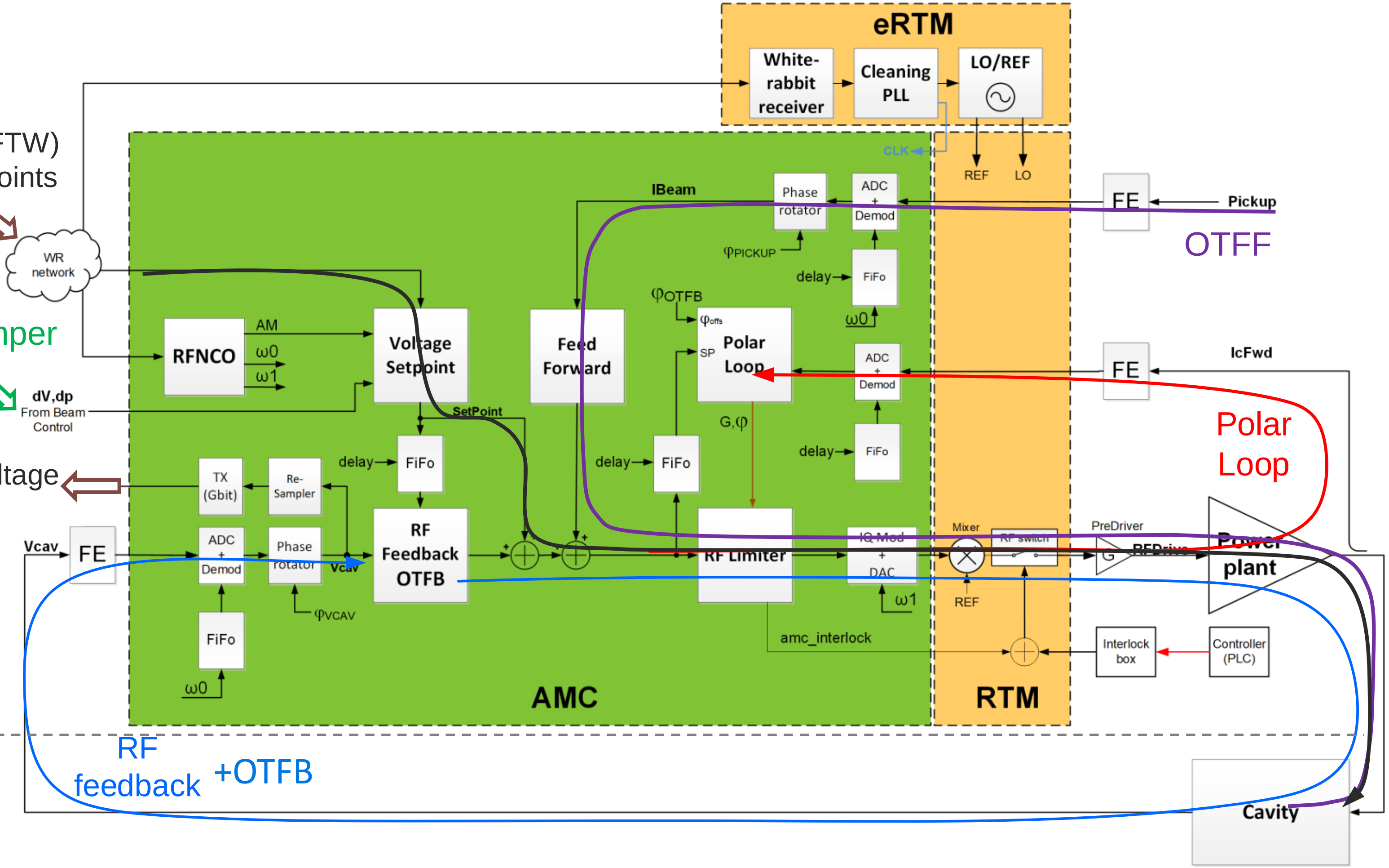



Fig – 200MHz Cavity-Controller feedback loops [4]

Cable + amplifier delay ≈ 3us

# Voltage Setpoint & longitudinal Damper

- **Two functions per cavity for Voltage setpoint**
  - amplitude, phase
  - update rate: frev
  - Function resolution > 1ms (few exception <1ms)
- **Functions generators in the Beam-Control for all 200MHz cavities**
  - Setpoints send over White-Rabbit to the Cavity-Controllers
  - Allow the Beam control to by-pass the functions (RF gymnastics)
- **Static setpoint (scalars) selectable in the Cavity-Controllers for setting-up, troubleshooting.**
- **Beam-Control sends phase kicks (dp) for Longitudinal damper, this is added to the setpoint phase**
  - update rate: 20 MHz
  - Individual gain per cavity (non-multiplex)
- **Voltage interlock if below an amplitude threshold (400kV) → RF off**
- **Amplitude Modulation controlled (on/off) by the Beam-Control**
  - AM rate: Frev, 4xfrev
  - AM shaper (trapezoidal RF on pulse)

More details on the Cavity-Controllers functions specifications [4,5]

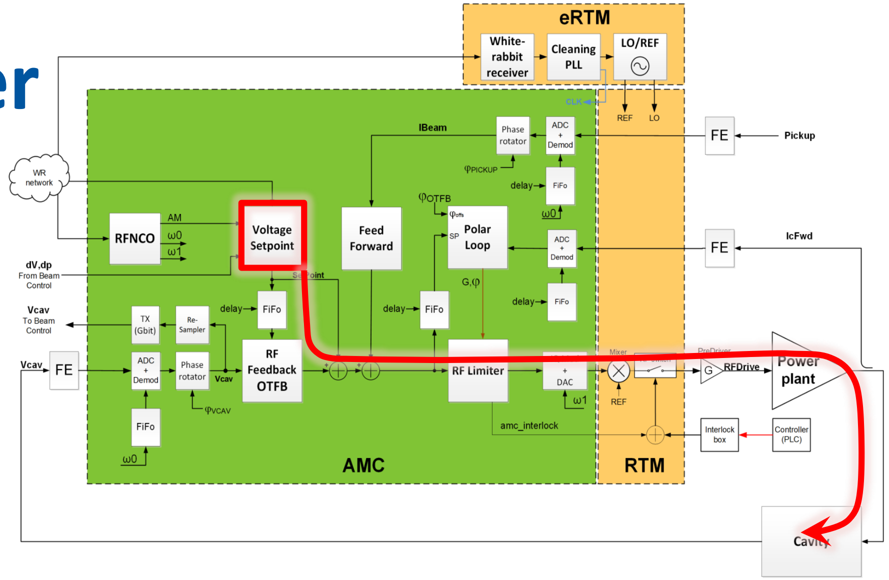



Fig – SPS 200MHz Cavity-Controller diagram: Voltage setpoint path

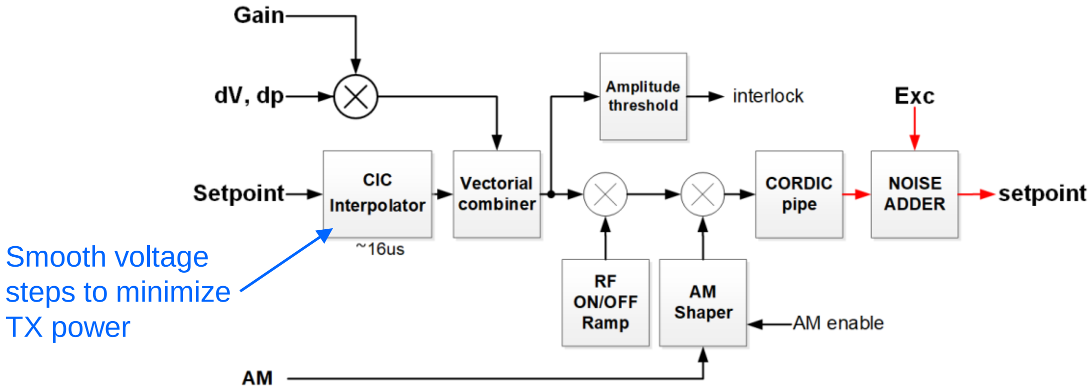



Fig – SPS 200MHz Voltage setpoint diagram (firmware)

# Voltage Setpoint & longitudinal Damper

- **Expert settings only**
- **for troubleshooting**
  - Use Static setpoint (functions on/off)
  - This separates the Cavity-Controller from BC
- **Voltage interlock**
  - Interlock (RF off) if setpoint below **amplitudeThreshold** (400kV)

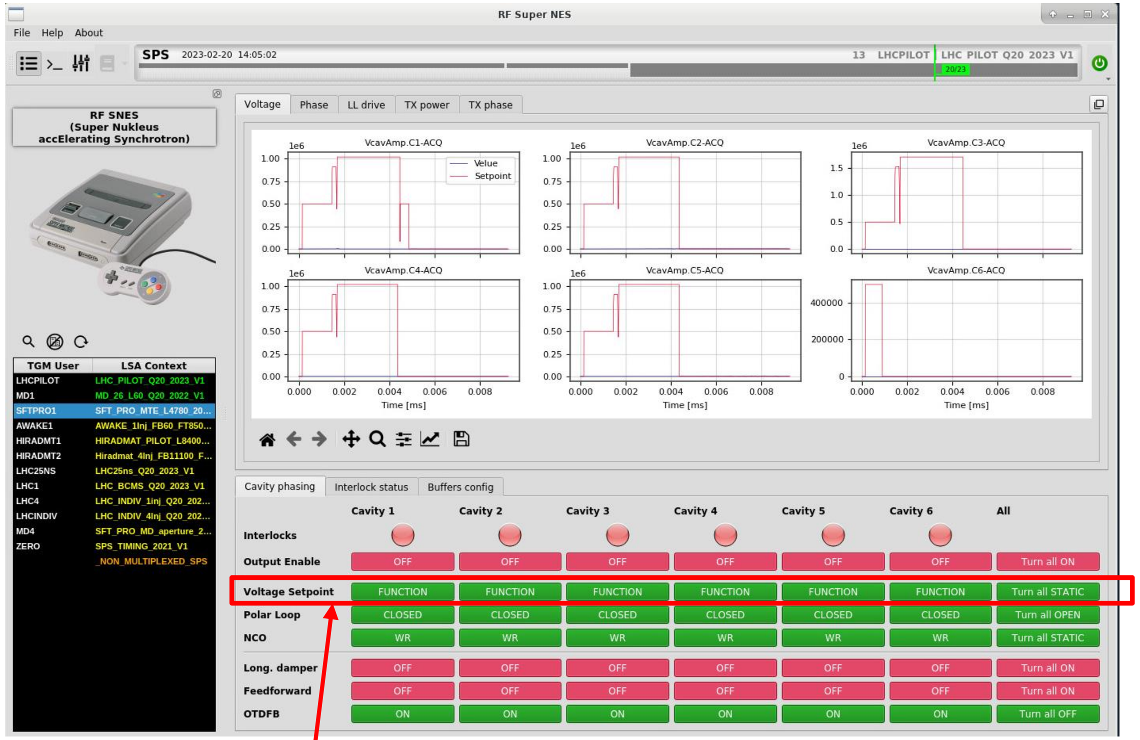



Fig – 200MHz Control, SNES – Static Setpoint

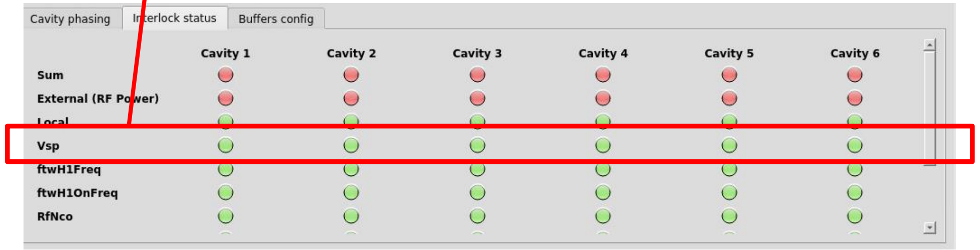



Fig – 200MHz Control, SNES – voltage interlock

# Polar loop of the 200MHz cavities

- **Restore open-loop phase for the Feedback**
- **First loop ON at RF on! (essential for feedback stability)**
- **Reduce TX amplitude/phase noise and drifts**
- **Compensate for the TX non-linearity**
- **Two loops:**
  - Gain loop
  - Phase loop

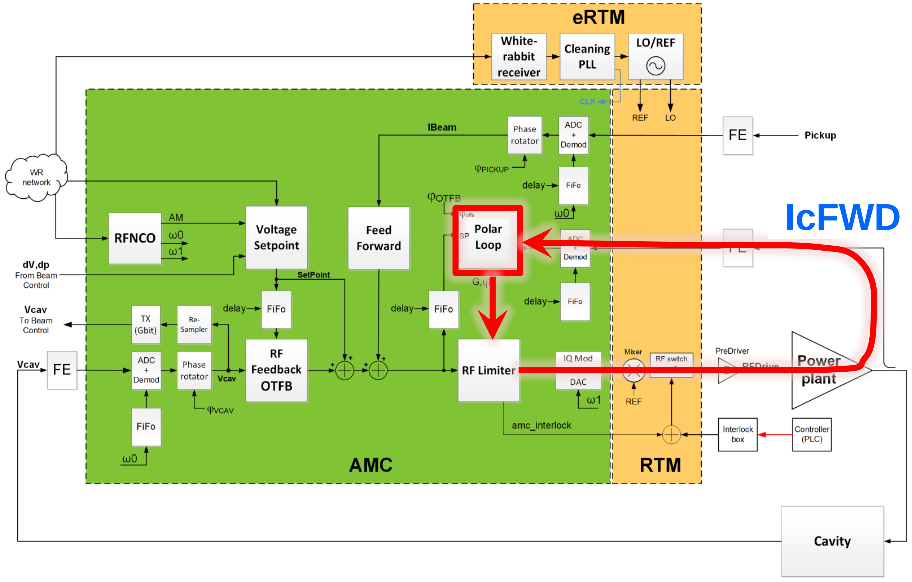



Fig – SPS 200MHz Cavity-Controller diagram: Polar-Loop path

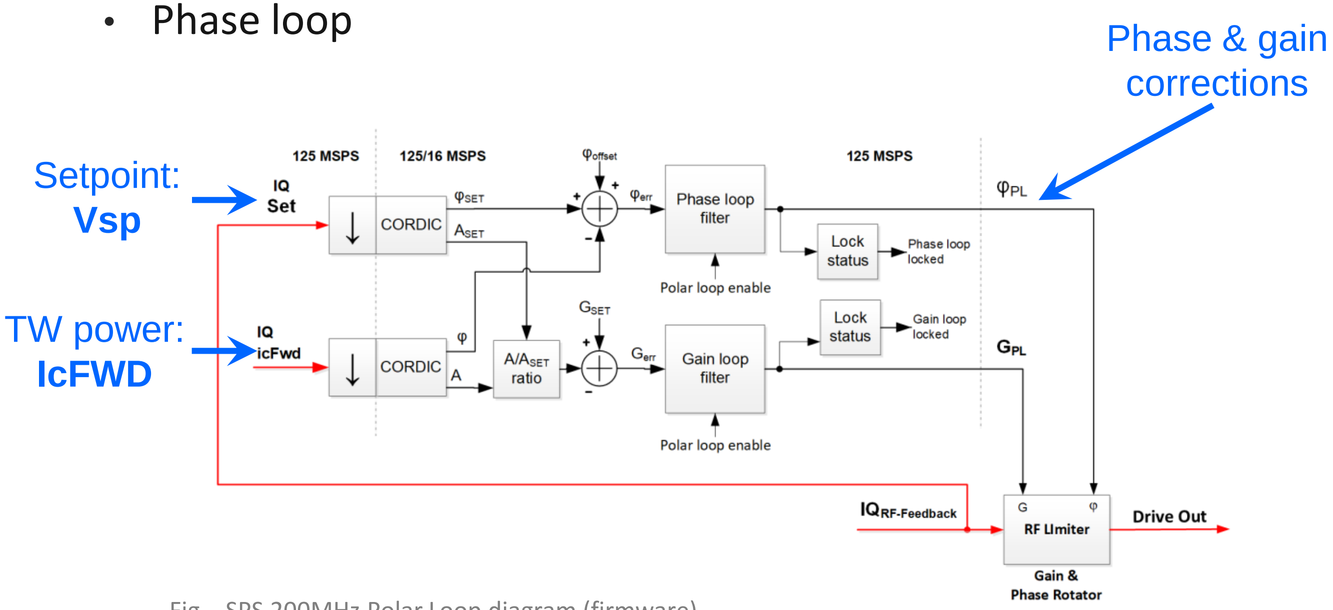



Fig – SPS 200MHz Polar Loop diagram (firmware)

# Polar loop of the 200MHz cavities

- **Polar loop switches ON automatically if :**
  - TX power (IcFWD) above **icFWDMin** threshold (3-section: 15kW, 4-section: 5kW)
  - Voltage setpoint (Vsp) above **setMin** threshold (350kV)
- **Polar loop freezes if IcFWD or Vsp below the thresholds**
- **Two loops:**
  - Gain loop
  - Phase loop
- **Troubleshooting**
  - Possibility to disable Polar-loop only if RF feedback is disabled (OTFB)
  - Check acquisition signals

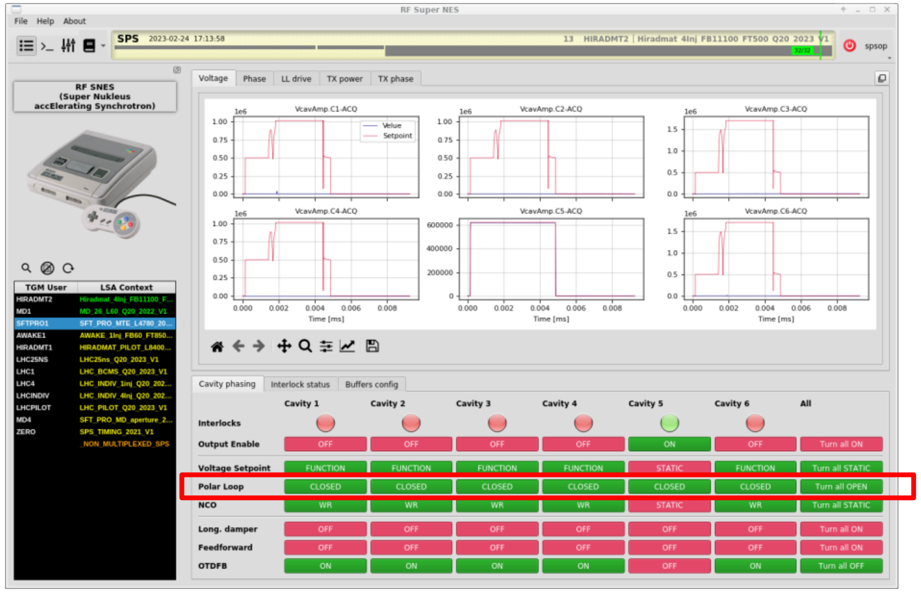



Fig – SPS SNES – Polar loop enable

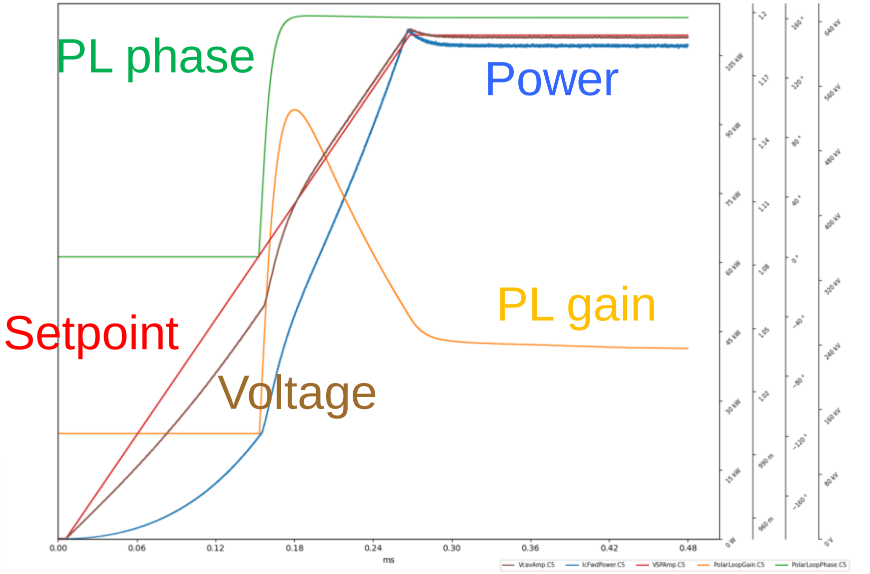



Fig – RF On ramp with polar loop closure (fdbk off)

later on you will see how to diagnose the polar loop Acquisition signals

# RF Feedback of the 200MHz cavities

- **Reduce beam-induced voltage at the fundamental ($f_{RF}$) and on the revolution frequency sidebands ($f_{rev}$)**
- **To counteract coupled-bunch instabilities, gain on the synchrotron sidebands (fs) of the revolution frequency lines (m=1 for dipole mode)** $f_{\mathrm{RF}} \pm (k \cdot f_{\mathrm{rev}} \pm m \cdot f_s), \quad k, m \in \mathbb{N}.$
- **Bandwidth 4 MHz**
- **Two branches**
  - Low pass branch (fundamental RF)
  - One-Turn Delay Feeback, Gain at the harmonic at the best compensate for the beam induced voltage

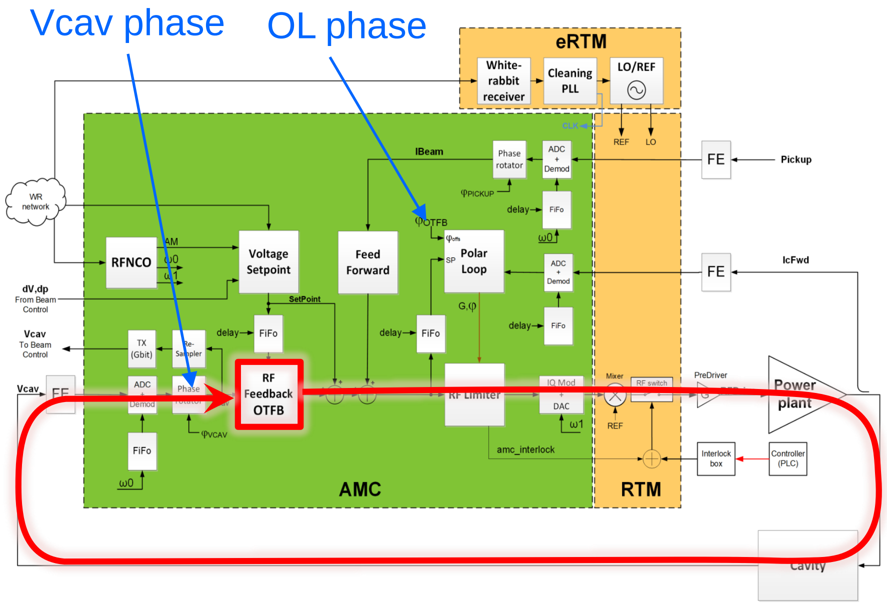



Fig – SPS 200MHz Cavity-Controller diagram: RF Feedback

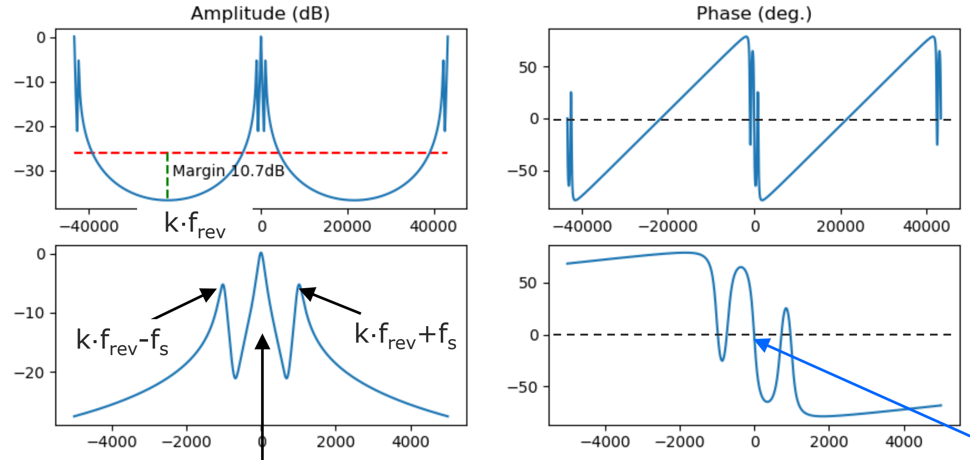



Fig – 1T-Fdbk Gain at revolution and synchrotron frequencies sidebands

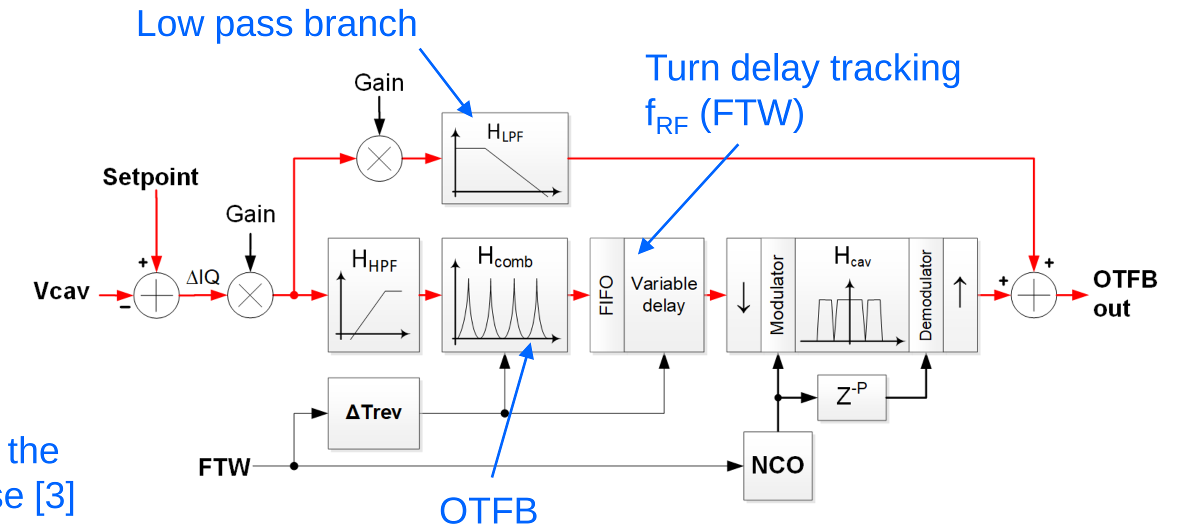



Fig – SPS 200MHz RF Feedback diagram (firmware)

# RF Feedback of the 200MHz cavities

- **RF Feedback closes at then end of RF ramp**
- **Expert settings only**
- **Troubleshooting**
  - Disable/enable the RF feedback
  - Switch to Static setpoint, Static frequency
  - Check acquisition signals

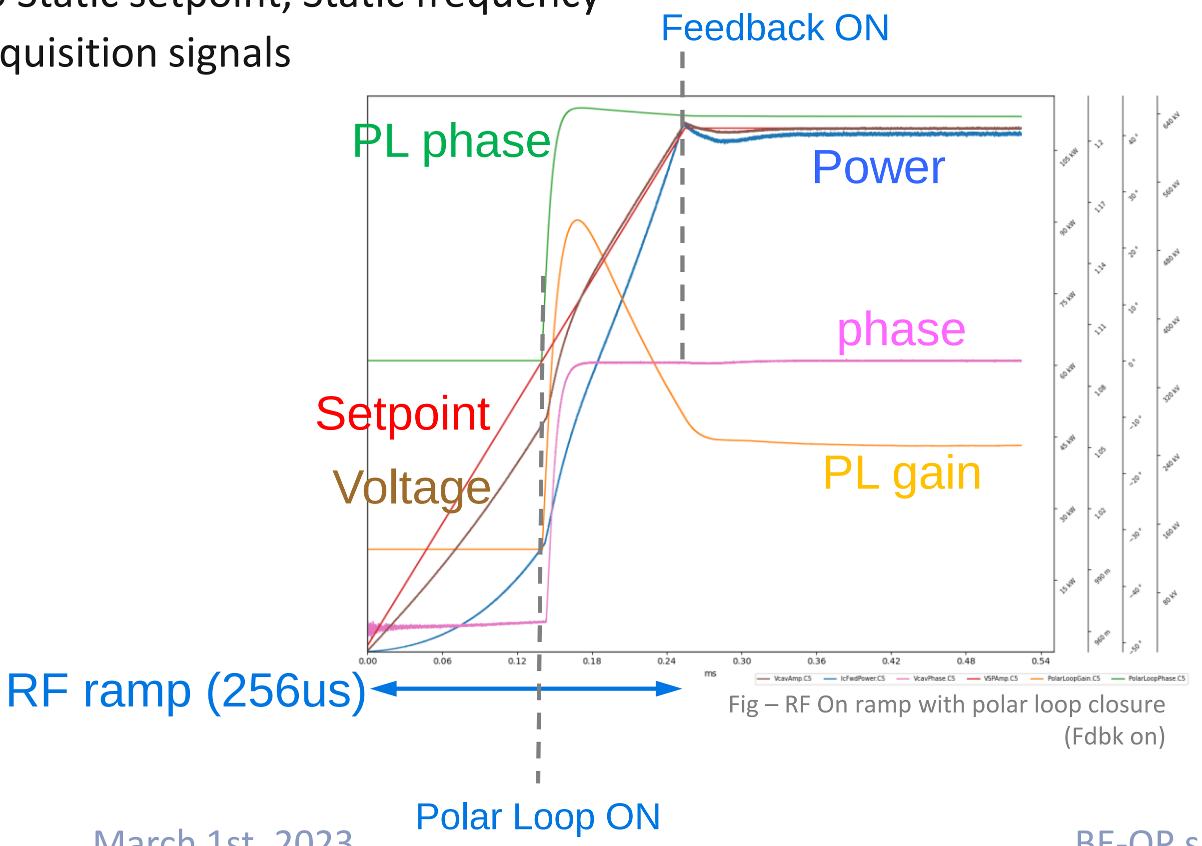



Fig – RF On ramp with polar loop closure (Fdbk on)


Fig – SPS SNES – Polar loop enable, Feedback enable

# Feedforward via (only) 200MHz cavities

- Measure beam current from wideband Pick-up
- Processed by a digital filter ($H_{FFWD}$) to generate a drive that will best compensate for the beam induced voltage
- Reduce transient beam loading already the 2nd turn
- Improve transient beam loading compensation at head & tail of the batch

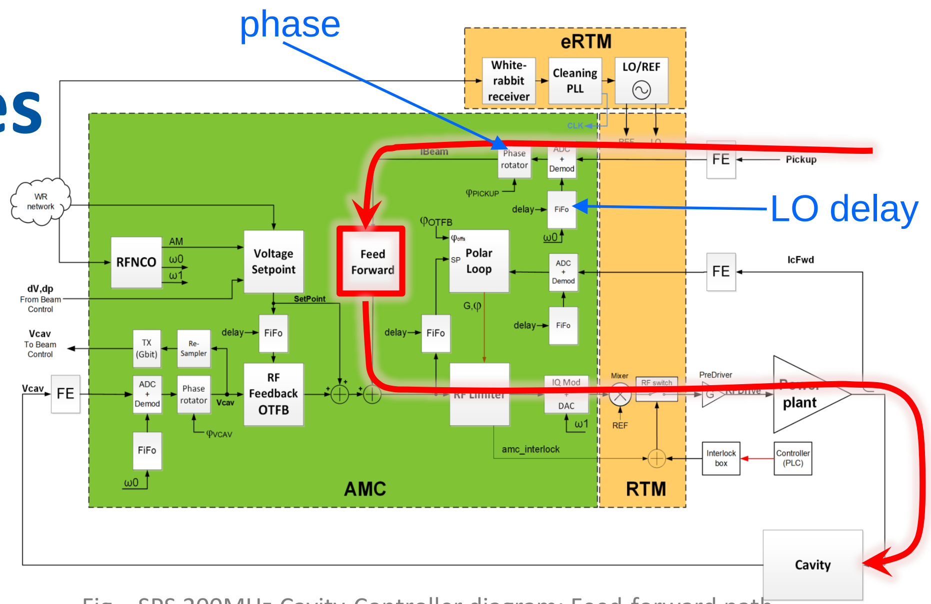



Fig – SPS 200MHz Cavity-Controller diagram: Feed-forward path

Fig – SPS PUAFE FeedForward (RA9405)

**Pickup** signal

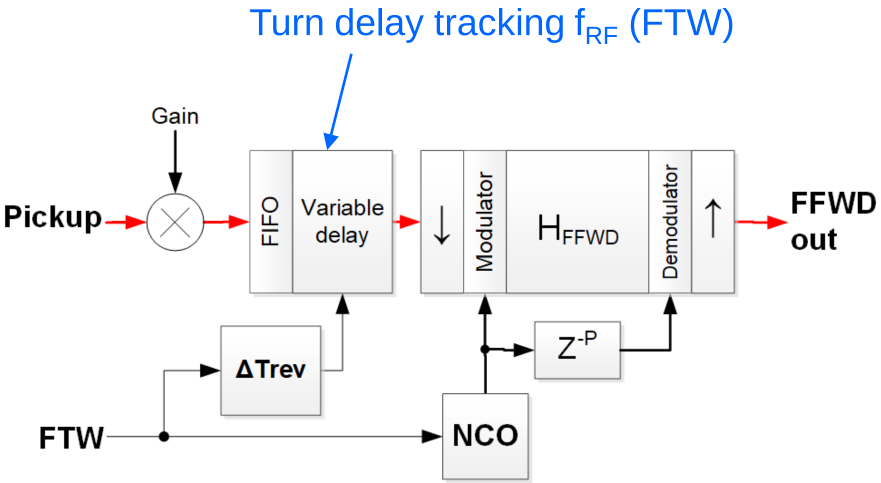



Fig – SPS 200MHz Feed-Forward diagram (firmware)

# Feedforward via 200MHz cavities

- FFWD ON before injection, first action on 2nd turn
- For pLHC cycles
- Feedback low pass ON before injection
- OTFB ON only after the second turn → Timing! (avoid double compensation)
- Optional (MD) FFWD on/off timings, OTFB off timings

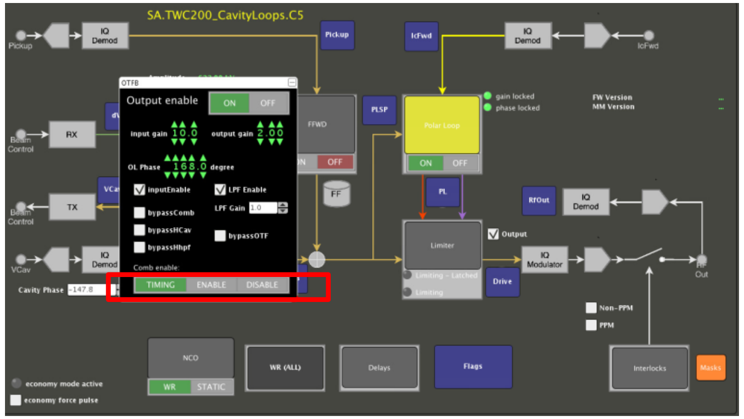



Fig – Inspector, – Cavity Control 200MHz, OTFB

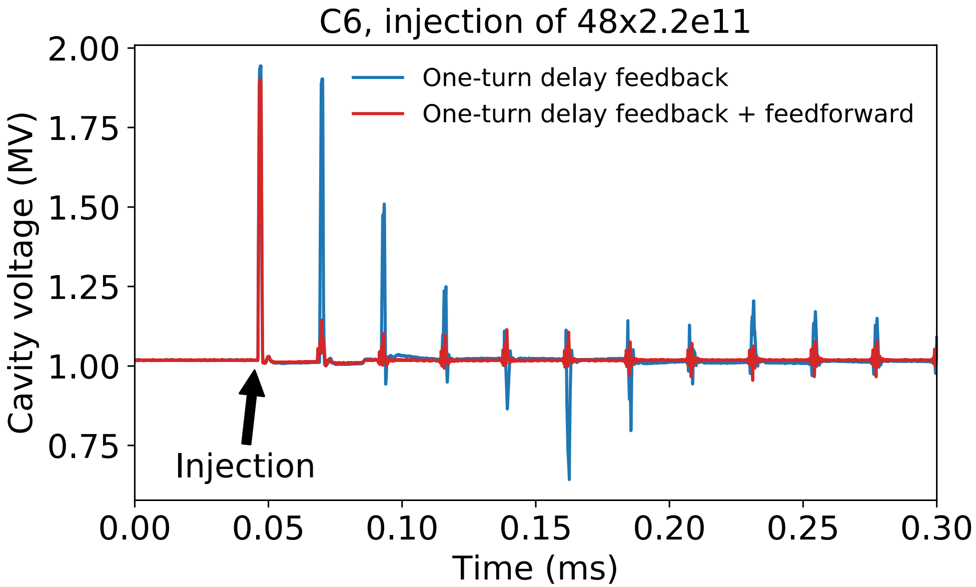
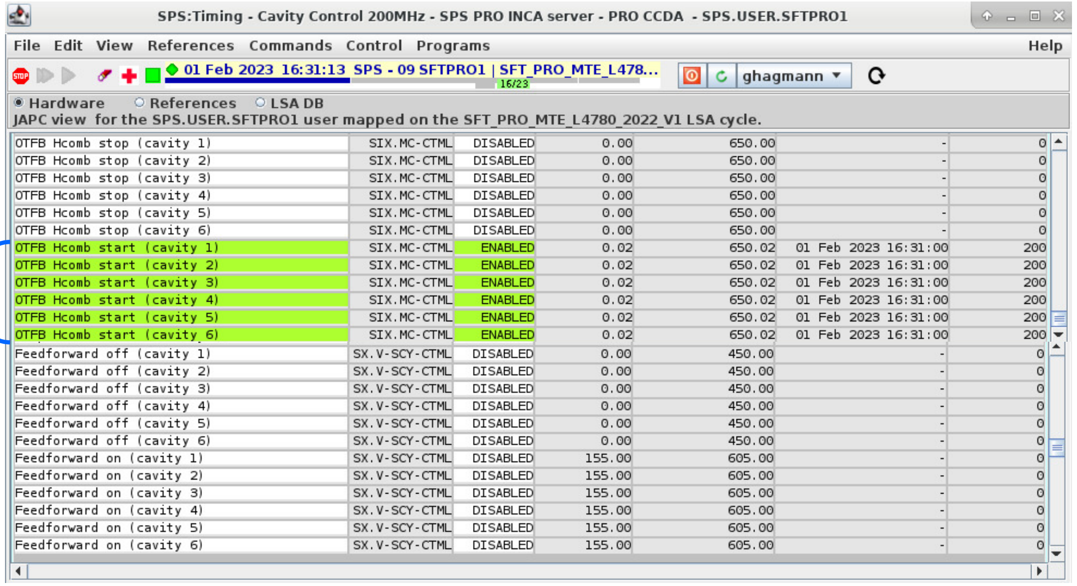



Fig – 200MHz Cavity 6 voltage – Feedforward on (red) and off (blue), courtesy of I. Karpov [2]

OTFB timings




| | | | | | | |
|---|---|---|---|---|---|---|
| OTFB Hcomb stop (cavity 1) | SIX.MC-CTML | DISABLED | 0.00 | 650.00 | - | 0 |
| OTFB Hcomb stop (cavity 2) | SIX.MC-CTML | DISABLED | 0.00 | 650.00 | - | 0 |
| OTFB Hcomb stop (cavity 3) | SIX.MC-CTML | DISABLED | 0.00 | 650.00 | - | 0 |
| OTFB Hcomb stop (cavity 4) | SIX.MC-CTML | DISABLED | 0.00 | 650.00 | - | 0 |
| OTFB Hcomb stop (cavity 5) | SIX.MC-CTML | DISABLED | 0.00 | 650.00 | - | 0 |
| OTFB Hcomb stop (cavity 6) | SIX.MC-CTML | DISABLED | 0.00 | 650.00 | - | 0 |
| OTFB Hcomb start (cavity 1) | SIX.MC-CTML | ENABLED | 0.02 | 650.02 | 01 Feb 2023 16:31:00 | 200 |
| OTFB Hcomb start (cavity 2) | SIX.MC-CTML | ENABLED | 0.02 | 650.02 | 01 Feb 2023 16:31:00 | 200 |
| OTFB Hcomb start (cavity 3) | SIX.MC-CTML | ENABLED | 0.02 | 650.02 | 01 Feb 2023 16:31:00 | 200 |
| OTFB Hcomb start (cavity 4) | SIX.MC-CTML | ENABLED | 0.02 | 650.02 | 01 Feb 2023 16:31:00 | 200 |
| OTFB Hcomb start (cavity 5) | SIX.MC-CTML | ENABLED | 0.02 | 650.02 | 01 Feb 2023 16:31:00 | 200 |
| OTFB Hcomb start (cavity 6) | SIX.MC-CTML | ENABLED | 0.02 | 650.02 | 01 Feb 2023 16:31:00 | 200 |
| Feedforward off (cavity 1) | SX.V-SCY-CTML | DISABLED | 0.00 | 450.00 | - | 0 |
| Feedforward off (cavity 2) | SX.V-SCY-CTML | DISABLED | 0.00 | 450.00 | - | 0 |
| Feedforward off (cavity 3) | SX.V-SCY-CTML | DISABLED | 0.00 | 450.00 | - | 0 |
| Feedforward off (cavity 4) | SX.V-SCY-CTML | DISABLED | 0.00 | 450.00 | - | 0 |
| Feedforward off (cavity 5) | SX.V-SCY-CTML | DISABLED | 0.00 | 450.00 | - | 0 |
| Feedforward off (cavity 6) | SX.V-SCY-CTML | DISABLED | 0.00 | 450.00 | - | 0 |
| Feedforward on (cavity 1) | SX.V-SCY-CTML | DISABLED | 155.00 | 605.00 | - | 0 |
| Feedforward on (cavity 2) | SX.V-SCY-CTML | DISABLED | 155.00 | 605.00 | - | 0 |
| Feedforward on (cavity 3) | SX.V-SCY-CTML | DISABLED | 155.00 | 605.00 | - | 0 |
| Feedforward on (cavity 4) | SX.V-SCY-CTML | DISABLED | 155.00 | 605.00 | - | 0 |
| Feedforward on (cavity 5) | SX.V-SCY-CTML | DISABLED | 155.00 | 605.00 | - | 0 |
| Feedforward on (cavity 6) | SX.V-SCY-CTML | DISABLED | 155.00 | 605.00 | - | 0 |

Fig – WorkingSet: Timing – Cavity Control 200MHz, nominal configuration

# Feedforward via 200MHz cavities

- **Expert settings only**
- **Except FFWD enable (output)**
- **Troubleshooting**
  - Disable/enable the Feedforward
  - Disable/enable the RF Feedback
  - Check acquisition signals
    - Vcav at injection (first turns)
    - Phase loop error at injection (first turns)

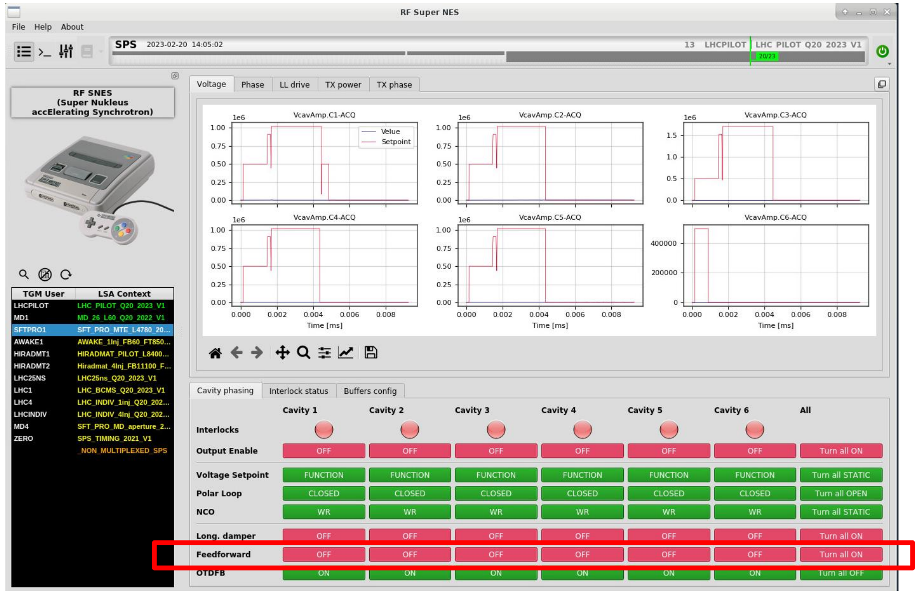



Fig – SPS SNES – FeedForward control

# Cavity Voltage Setpoint (Vsp)

# Voltage functions & hierarchies

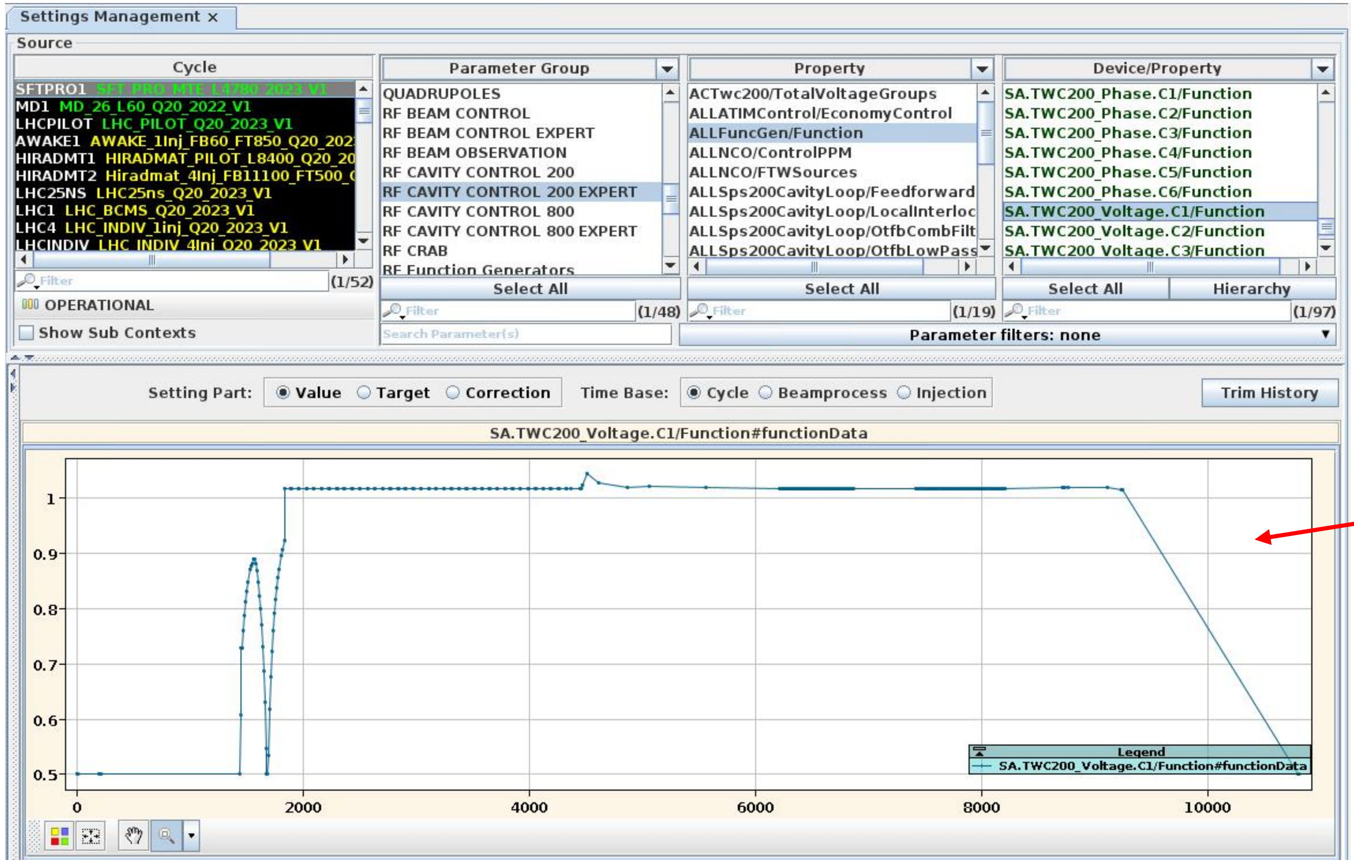



Fig – 200MHz Voltage setpoint function, cavity 1


Fig – 200MHz Voltage partitioning hierarchies [6]

More details on the SPS parameter Model [6]

# Counter-phasing & Vector diagrams

- **Minimum voltage setpoint (Vmin=500kV)**
  - Required to operated normally the RF feedback
- **If a lower voltage setpoint required:**
  - 0 < Voltage Setpoint < 3·Vmin (1.5MV)
  - Counter-phasing **between 3 cavities** (1 group)
    - two 3-section cavities
    - one 4-section cavity
  - 800MHz not phase locked to 200MHz if vector sum to low (~500 kV)
  - Automatized: Make rule in LSA

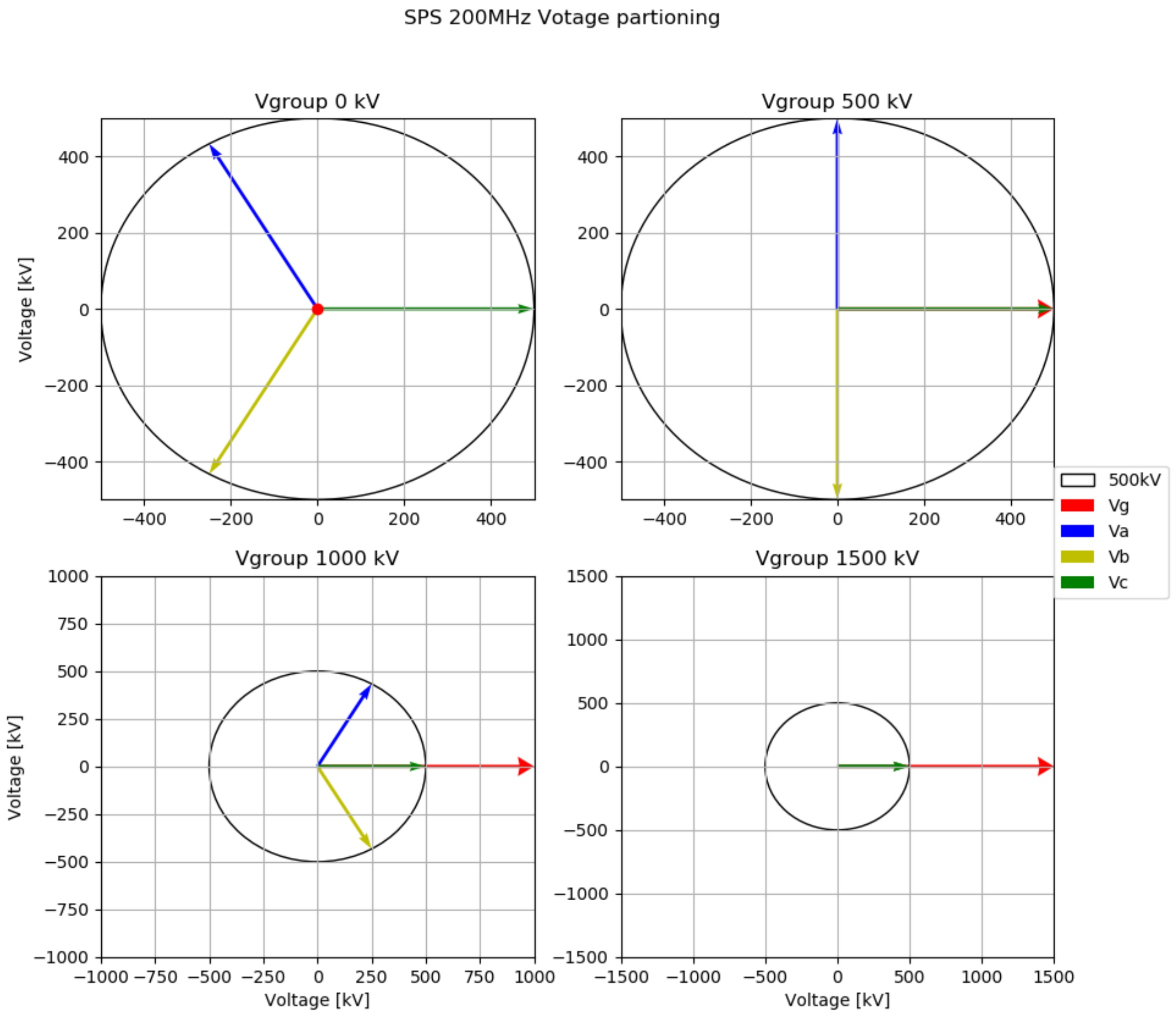



Fig – 200MHz Conter-phasing vector for 1 group of 3 cavities

More details on the Cavity-Controllers functions specifications [4,5]

# Voltage partitioning

- **Total voltage from bucket area [6]**
- **Total voltage distributed equally to two voltage groups**
- **One function Vmax per cavity**
- **One scalar Vmin for all cavities (500kV)**
- **3 régimes**
  - Regime 1: counter-phasing, Vcav=Vmin
  - Regime 2: interpolation between regime 1 & 3
  - Regime 3: partitioning with Vmax
    - $\widehat{V_A}, \widehat{V_B}$ : 3-section cavities
    - $\widehat{V_C}$ : 4-section cavity

$$r_A = \frac{\hat{V}_A}{\hat{V}_A+\hat{V}_B+\hat{V}_C} \qquad V_A = r_A \cdot V_g$$

$$r_B = \frac{\hat{V}_B}{\hat{V}_A+\hat{V}_B+\hat{V}_C} \qquad V_B = r_B \cdot V_g$$

$$r_C = \frac{\hat{V}_C}{\hat{V}_A+\hat{V}_B+\hat{V}_C} \qquad V_C = r_C \cdot V_g$$

$$\varphi_A = \varphi_B = \varphi_C = 0$$

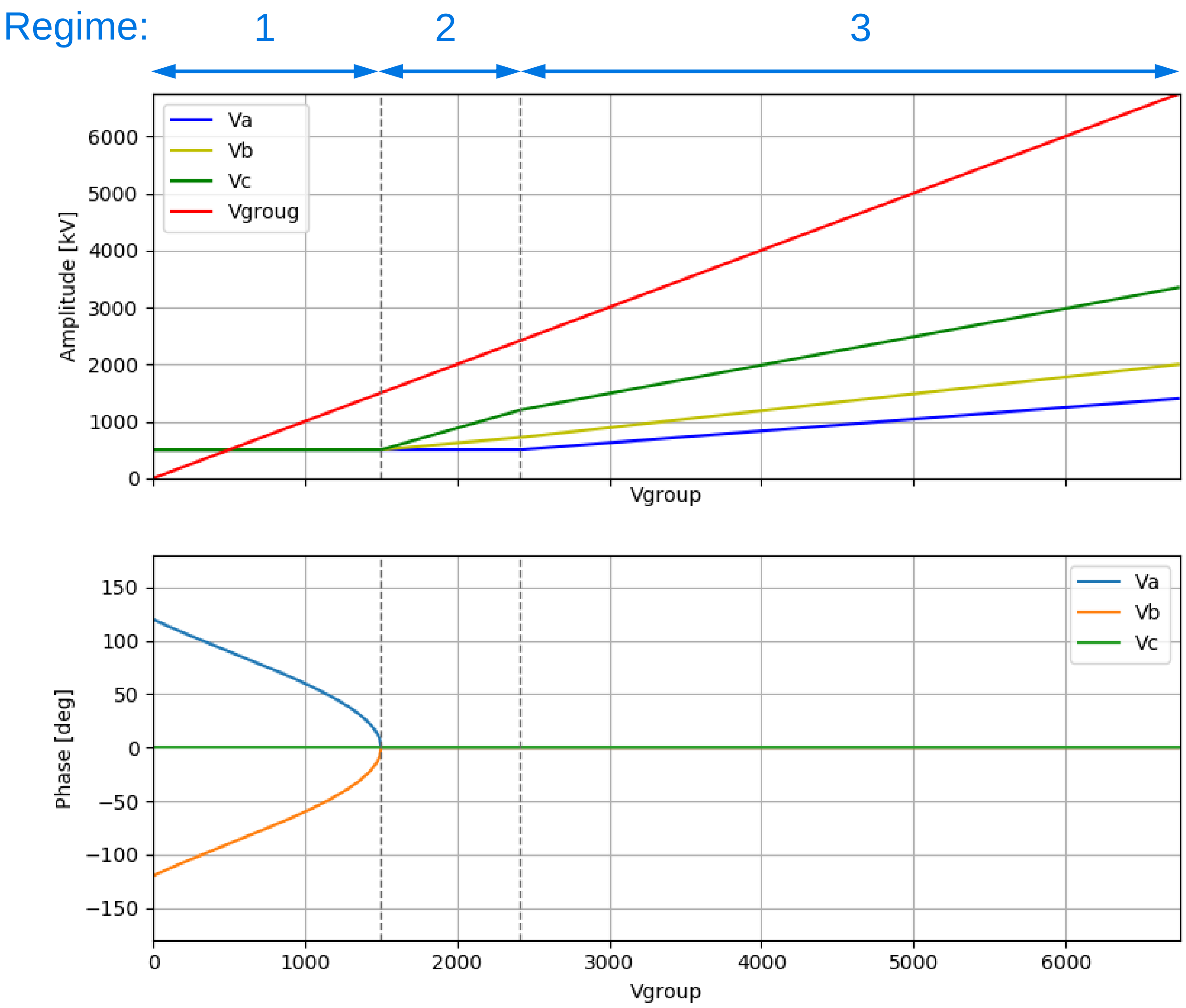



Fig – 200MHz Voltage partitioning for 1 group of 3 cavities

# Voltage for RF gymnastics

- Voltage jump scalar values (not visible in LSA functions)
- Sent from Beam-Control to Cavity-controllers (White-Rabbit)
- Triggered by timing or external pulse (Awake)
- Setpoint acquisition in embedded acquisition (⚠ decimation)

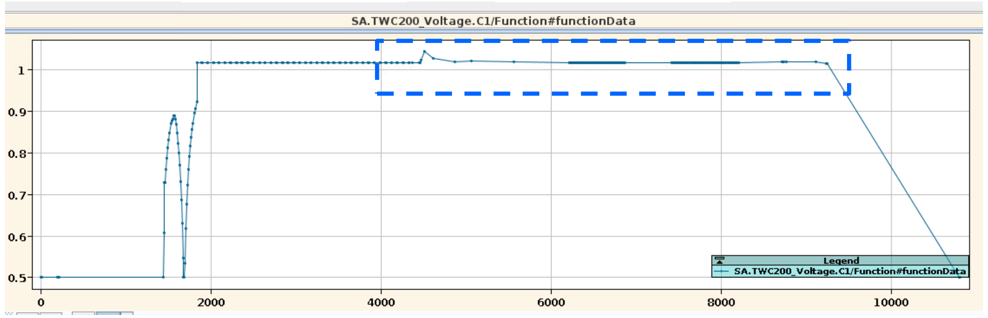



Fig – 200MHz C1 Voltage setpoint function

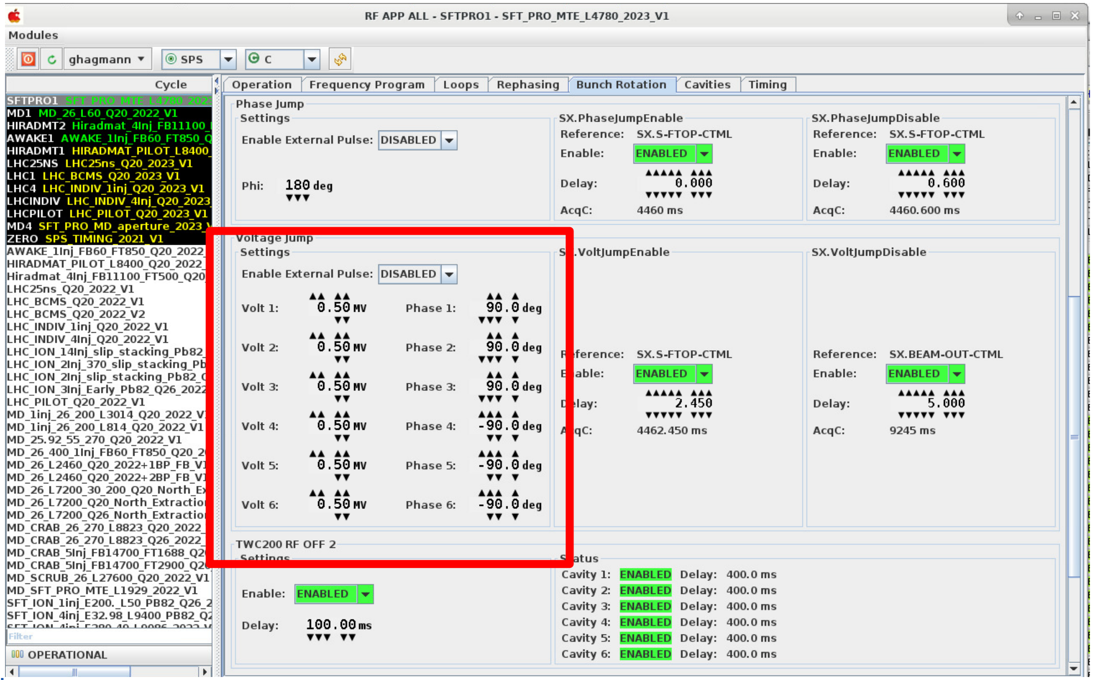



Fig – RF APP ALL – Voltage jump settings for SFTPRO1

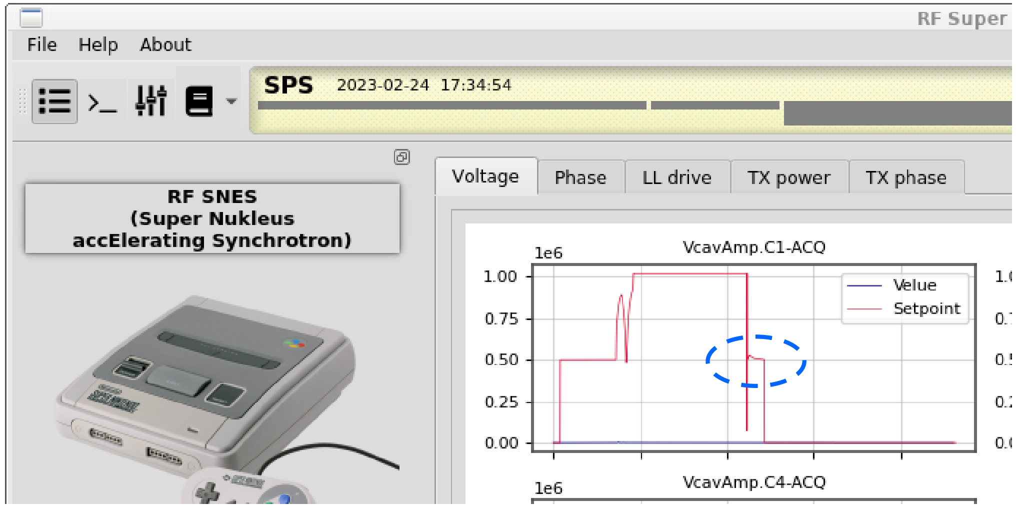
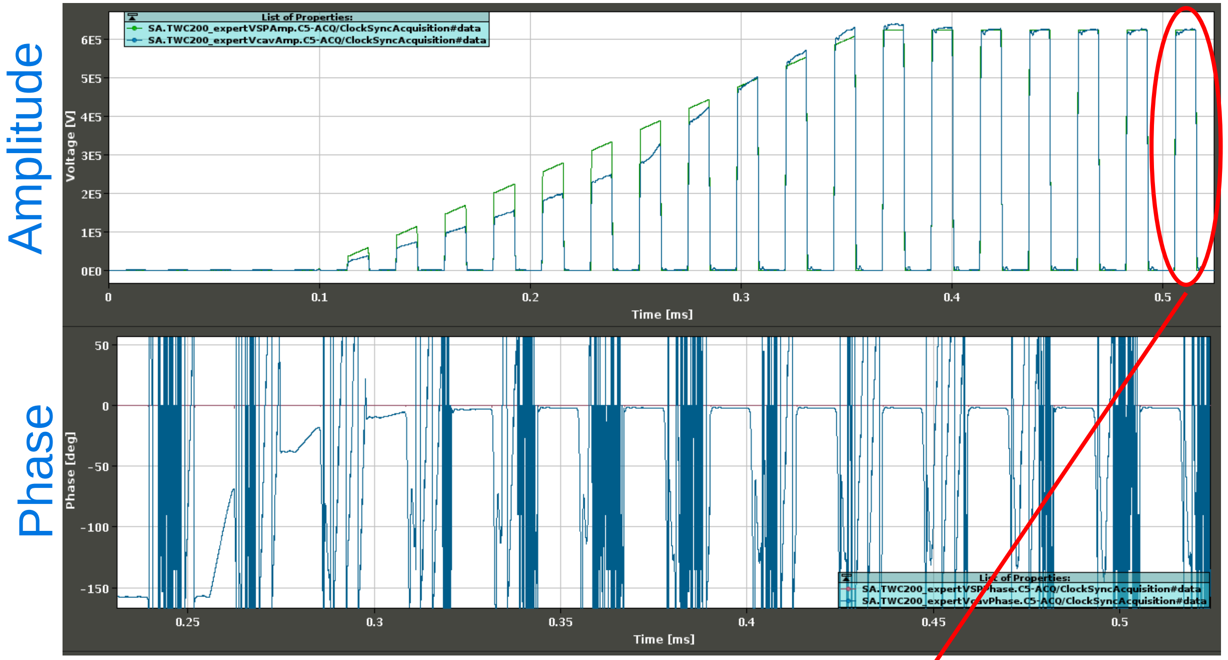


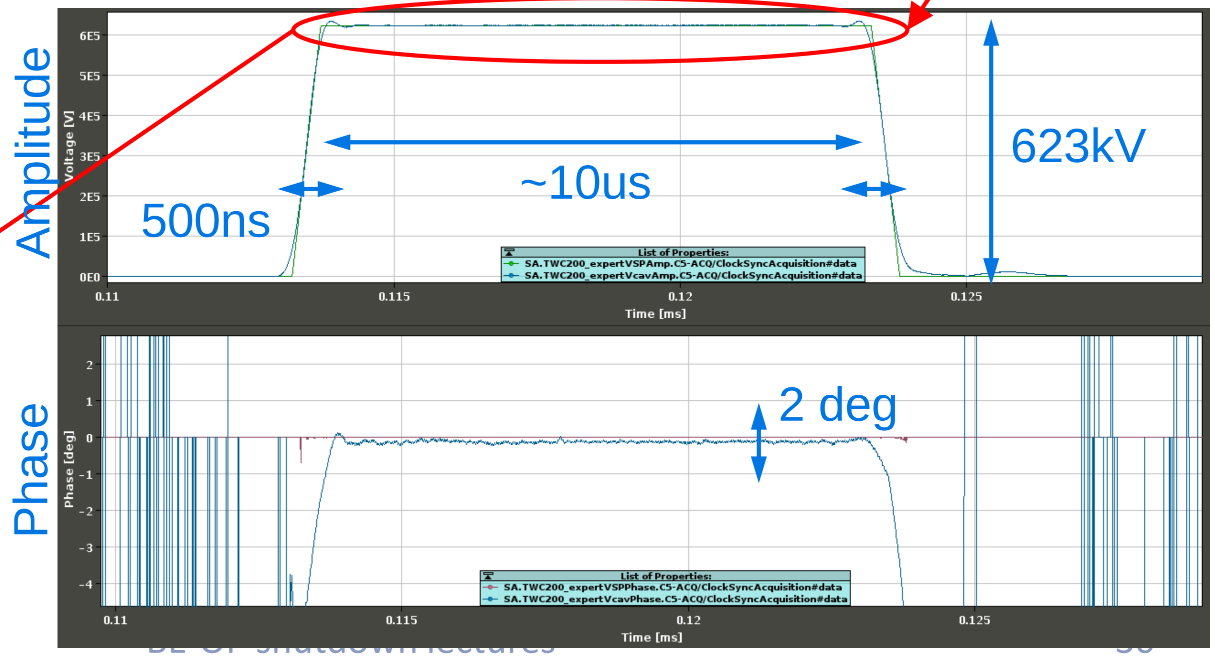

Fig – 200MHz Control, SNES , C1 Voltage setpoint acquisition

# Amplitude & Frequency modulation

# Amplitude modulation

- **Proton cycles**
  - Reduce average RF power
    - Power coaxial lines: ≤750kW CW
    - Exploit max RF peak power/voltage
  - Rate: frev or 4xfrev
  - Ramp: 500ns
- **Ions cycles**
  - FM for Fixed-Frequency acceleration
  - Frequencies outside amplifier/cavity range → RF off



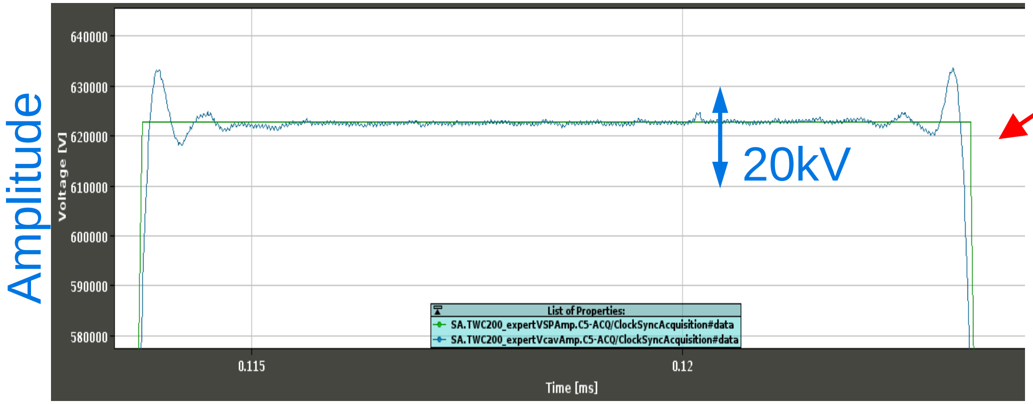




Fig – Cavity voltage (C5) at RF on

# Frequency Modulation for LHC Ions

- **Fixed frequency acceleration (FFA)**
- **Frequency while the cavity is**
  - ON : $F_{RF\ ON}$
  - OFF: $F_{RF\ OFF}$
- **Injection:**
  - $F_{RF\ ON} = 4653 \cdot frev \approx 199.93$ MHz
  - $F_{RF\ AVG} = 4620 \cdot frev \approx 198.51$ MHz
- **Before ramp**
  - $F_{RF\ ON}$ = 200.1MHz
  - Optimised for RF power
- **Interlock if frequencies out of range**

| FTW | | Rf frequency | Description |
|---|---|---|---|
| $f_{RF\_avg}$ | min | 198.400123 MHz | Minimum RF average frequency (ions FFA) |
| | max | 200.399942 MHz | Maximum RF frequency (450GeV) |
| $f_{RF\_on}$ | Min | 199.560106 MHz | Minimum RF on frequency |
| | Max | 200.399942 MHz | Maximum RF frequency (450GeV) |

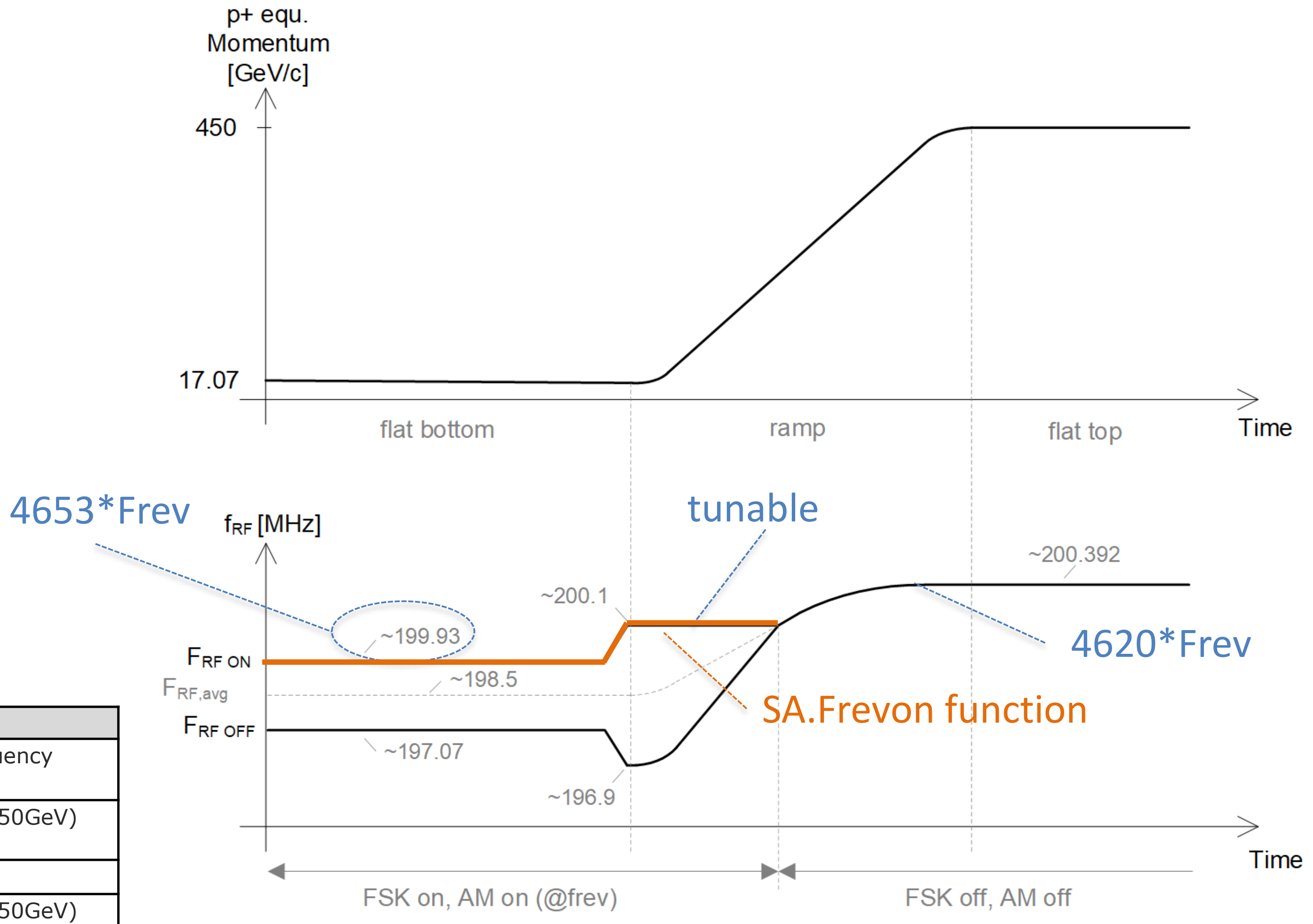



Fig – LHC Ions cycle – RF frequencies

# Frequency Modulation for Fixed target Ions

- **Fixed frequency acceleration (FFA)**
- **Debunching on intermediate plateau: 26GeV/c**
  - Cavities switched OFF
- **Lowest RF frequency**
  - Re-capture $F_{RF\ ON} \approx 199.57$ MHz

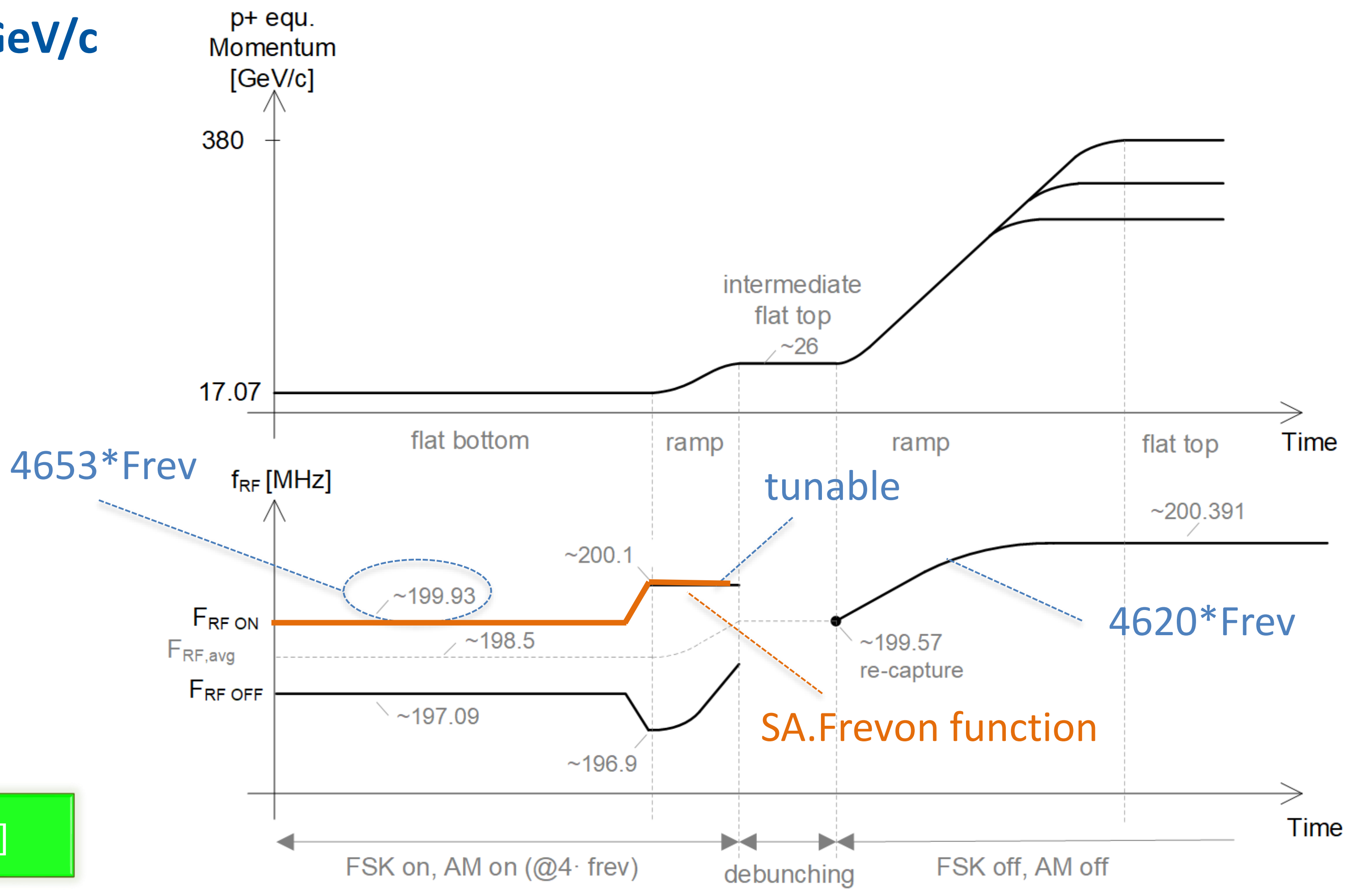


Fig – LHC Ions cycle – RF frequencies

More details on the Beam-Control OP shutdown lecture [9]

# Ions slip-stacking

- **Doubling** of the total Pb beam intensity for HL-LHC [X] by reducing **bunch spacing to 50 ns**
- This spacing cannot be produced in the PSB-PS chain
- The idea is therefore to [3]
  1. Inject 2 to 7 batches with 100 ns bunch spacing
  2. On an intermediate plateau, apply a frequency difference between the two batches (3 cavities/batch) so that they slip in position
  3. Let them drift until we get the 50 ns interleaving
  4. Then move both RF to identical frequency (collapse the buckets), increase voltage and let filamentation create identical 50 ns spaced bunches.

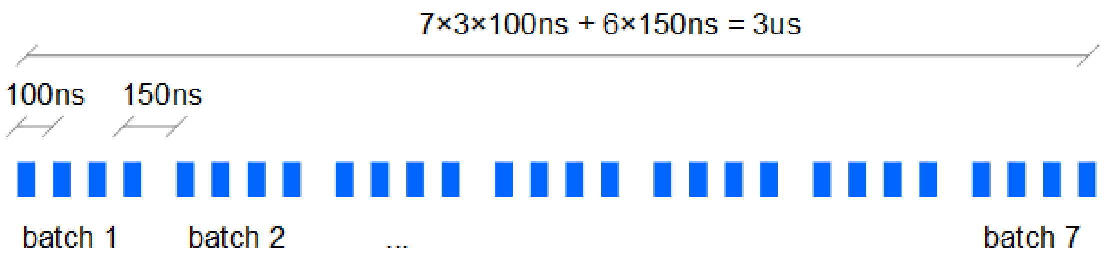



Fig – LHCION bunch pattern (2x 7 injections of 4 bunches)

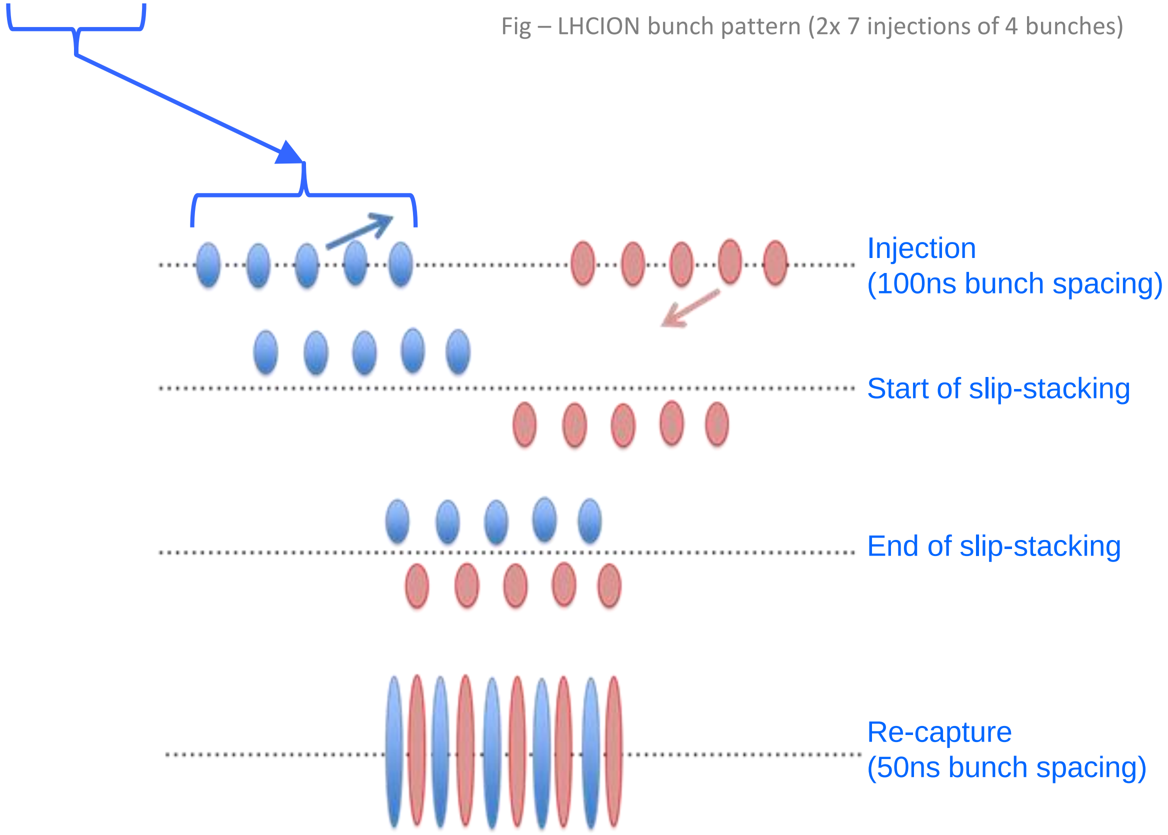



Fig – Ions slip-stacking principle

# Ions slip-stacking – Amplitude modulation

- **LHCION cycles**
- **AM & FM Modulation at 1xFrev**
- **9us RF on pulse (top),**
- **4us/group for slip-stacking (intermediate plateau)**
- **Up to 14 injections, 4 bunches/inj, 100ns spacing**

- 2 groups of cavities (≠$f_{rf}$) during slip-stacking
- 2 phase loops
- Real time bunch mask

More details on the Beam-Control OP shutdown lecture [9]

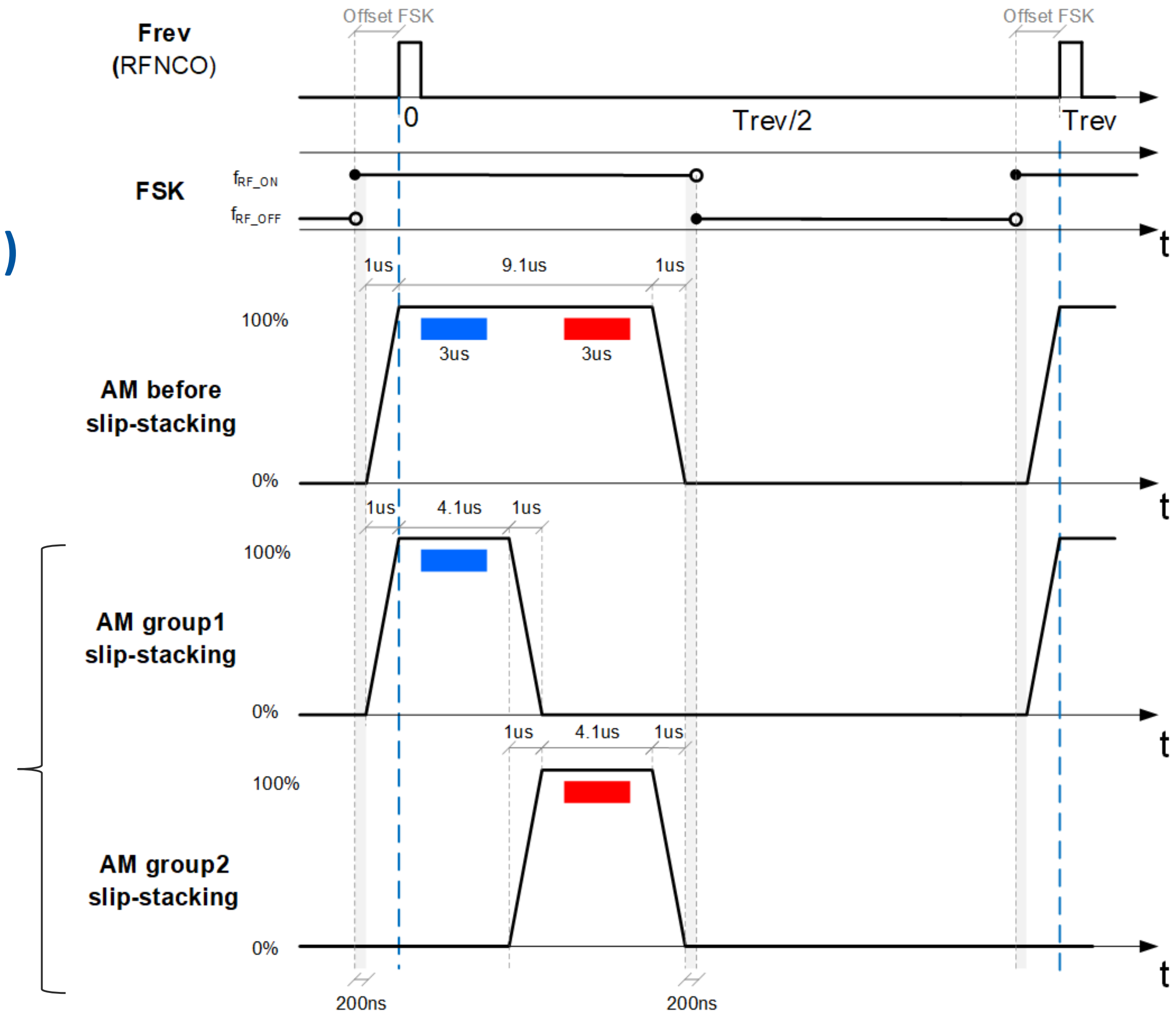



Fig – AM for Ions slip-stacking

# Ions slip-stacking - Cycle

- **Correction dV on the voltage groups function from slip-stacking APP Slippyry**
- **Two *dFrev* functions for slip-stacking frequency**

- **Performances in 2022 with two batches only.**
- **2x 7 batches to be commissioned for LHC ions in 2023**

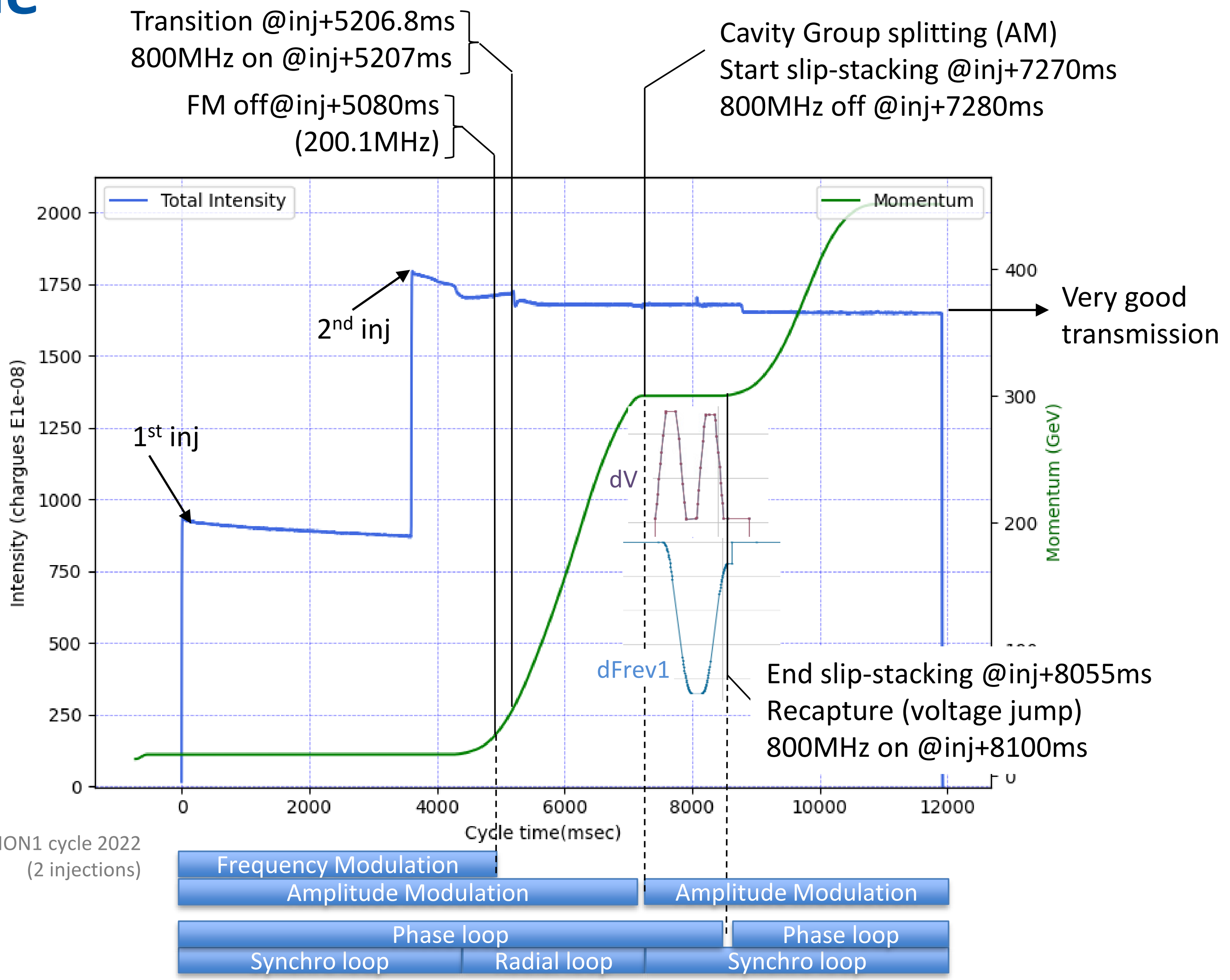



Fig – BCT, LHCION1 cycle 2022 (2 injections)

# Ions slip-stacking – Beam parameters

- **2 injections cycle**
- **Bunch length ok without bunch rotation**
- **Bunch rotation available if needed**

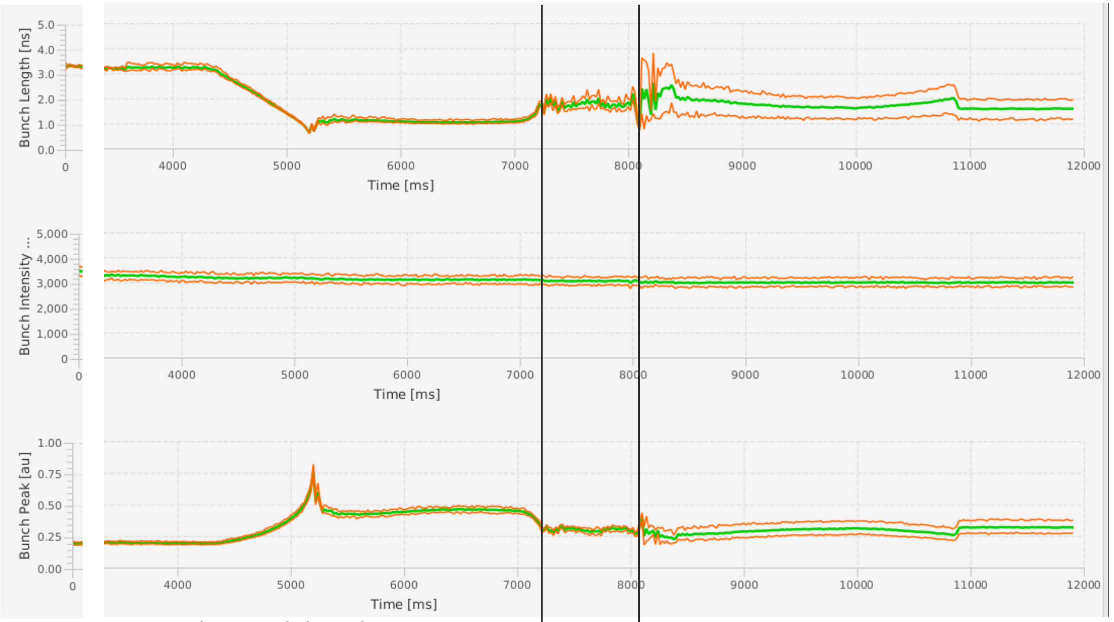



Fig – LHCION1 cycle, Bunch length measurement

bunch length:
1.3 to 1.8ns
avg: 1.6ns

25ns bucket

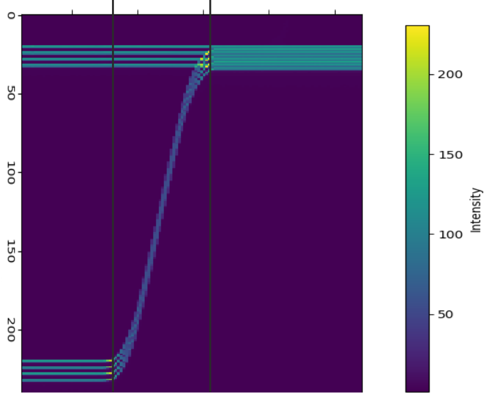



Fig – Fast BCT, LHCION1 cycle

# LHC Ions, Slip-stacking - BCT

- **LLRF beyond the Faraday cage – RF to BI over White-Rabbit**
  - Azimuthal compensation
  - Delay compensation

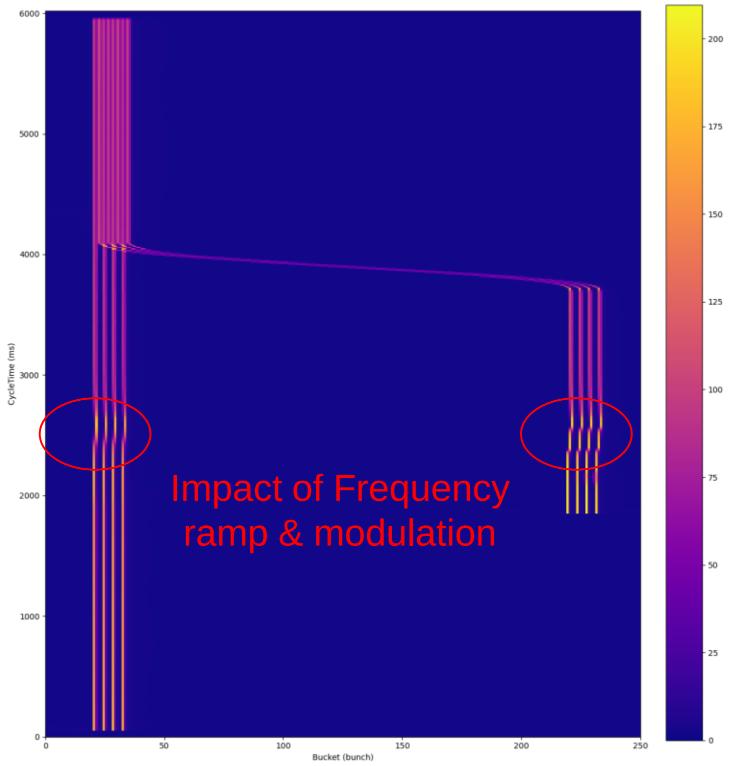



Fig – LHCION1 cycle, Fact BCT
(Courtesy of Tom Levens)

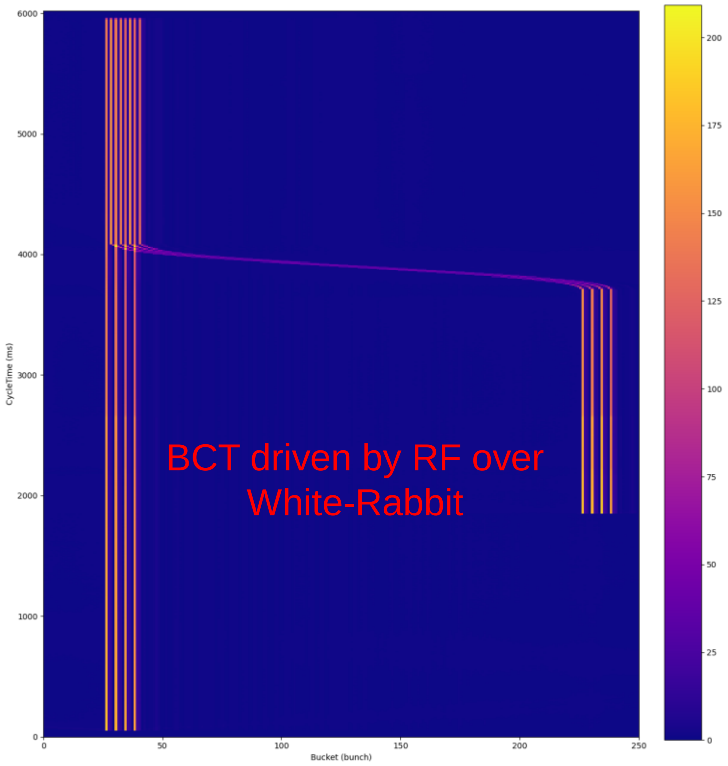
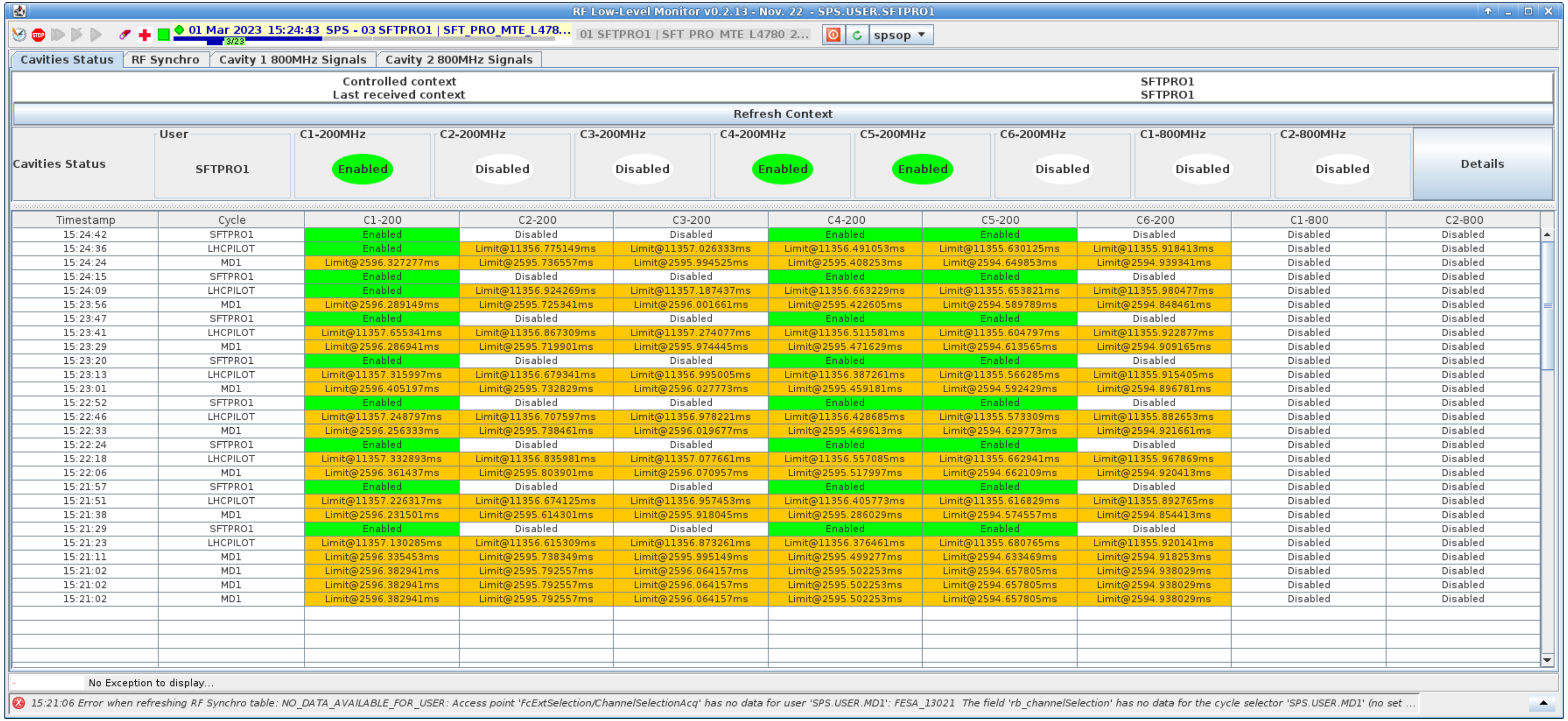



Fig – LHCION1 cycle, Fact BCT with RF over White-Rabbit (WR2RF)
(Courtesy of Tom Levens)

# Controls & Observation

# Fixed display : RF Low level status

- **Status with cycles history**




| Timestamp | Cycle | C1-200 | C2-200 | C3-200 | C4-200 | C5-200 | C6-200 | C1-800 | C2-800 |
|---|---|---|---|---|---|---|---|---|---|
| 15:24:42 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:24:36 | LHCPILOT | Enabled | Limit@11356.775149ms | Limit@11357.026333ms | Limit@11356.491053ms | Limit@11355.630125ms | Limit@11355.918413ms | Disabled | Disabled |
| 15:24:24 | MD1 | Limit@2596.327277ms | Limit@2595.736557ms | Limit@2595.994525ms | Limit@2595.408253ms | Limit@2594.649853ms | Limit@2594.939341ms | Disabled | Disabled |
| 15:24:15 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:24:09 | LHCPILOT | Enabled | Limit@11356.924269ms | Limit@11357.187437ms | Limit@11356.663229ms | Limit@11355.653821ms | Limit@11355.980477ms | Disabled | Disabled |
| 15:23:56 | MD1 | Limit@2596.289149ms | Limit@2595.725341ms | Limit@2596.001661ms | Limit@2595.422605ms | Limit@2594.589789ms | Limit@2594.848461ms | Disabled | Disabled |
| 15:23:47 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:23:41 | LHCPILOT | Limit@11357.655341ms | Limit@11356.867309ms | Limit@11357.274077ms | Limit@11356.511581ms | Limit@11355.604797ms | Limit@11355.922877ms | Disabled | Disabled |
| 15:23:29 | MD1 | Limit@2596.286941ms | Limit@2595.719901ms | Limit@2595.974445ms | Limit@2595.471629ms | Limit@2594.613565ms | Limit@2594.909165ms | Disabled | Disabled |
| 15:23:20 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:23:13 | LHCPILOT | Limit@11357.315997ms | Limit@11356.679341ms | Limit@11356.995005ms | Limit@11356.387261ms | Limit@11355.566285ms | Limit@11355.915405ms | Disabled | Disabled |
| 15:23:01 | MD1 | Limit@2596.405197ms | Limit@2595.732829ms | Limit@2596.027773ms | Limit@2595.459181ms | Limit@2594.592429ms | Limit@2594.896781ms | Disabled | Disabled |
| 15:22:52 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:22:46 | LHCPILOT | Limit@11357.248797ms | Limit@11356.707597ms | Limit@11356.978221ms | Limit@11356.428685ms | Limit@11355.573309ms | Limit@11355.882653ms | Disabled | Disabled |
| 15:22:33 | MD1 | Limit@2596.256333ms | Limit@2595.738461ms | Limit@2596.019677ms | Limit@2595.469613ms | Limit@2594.629773ms | Limit@2594.921661ms | Disabled | Disabled |
| 15:22:24 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:22:18 | LHCPILOT | Limit@11357.332893ms | Limit@11356.835981ms | Limit@11357.077661ms | Limit@11356.557085ms | Limit@11355.662941ms | Limit@11355.967869ms | Disabled | Disabled |
| 15:22:06 | MD1 | Limit@2596.361437ms | Limit@2595.803901ms | Limit@2596.070957ms | Limit@2595.517997ms | Limit@2594.662109ms | Limit@2594.920413ms | Disabled | Disabled |
| 15:21:57 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:21:51 | LHCPILOT | Limit@11357.226317ms | Limit@11356.674125ms | Limit@11356.957453ms | Limit@11356.405773ms | Limit@11355.616829ms | Limit@11355.892765ms | Disabled | Disabled |
| 15:21:38 | MD1 | Limit@2596.231501ms | Limit@2595.614301ms | Limit@2595.918045ms | Limit@2595.286029ms | Limit@2594.574557ms | Limit@2594.854413ms | Disabled | Disabled |
| 15:21:29 | SFTPRO1 | Enabled | Disabled | Disabled | Enabled | Enabled | Disabled | Disabled | Disabled |
| 15:21:23 | LHCPILOT | Limit@11357.130285ms | Limit@11356.615309ms | Limit@11356.873261ms | Limit@11356.376461ms | Limit@11355.680765ms | Limit@11355.920141ms | Disabled | Disabled |
| 15:21:11 | MD1 | Limit@2596.335453ms | Limit@2595.738349ms | Limit@2595.995149ms | Limit@2595.499277ms | Limit@2594.633469ms | Limit@2594.918253ms | Disabled | Disabled |
| 15:21:02 | MD1 | Limit@2596.382941ms | Limit@2595.792557ms | Limit@2596.064157ms | Limit@2595.502253ms | Limit@2594.657805ms | Limit@2594.938029ms | Disabled | Disabled |
| 15:21:02 | MD1 | Limit@2596.382941ms | Limit@2595.792557ms | Limit@2596.064157ms | Limit@2595.502253ms | Limit@2594.657805ms | Limit@2594.938029ms | Disabled | Disabled |
| 15:21:02 | MD1 | Limit@2596.382941ms | Limit@2595.792557ms | Limit@2596.064157ms | Limit@2595.502253ms | Limit@2594.657805ms | Limit@2594.938029ms | Disabled | Disabled |

Fig – RF low level Fixed display, 200 & 800MHz cavities

# Embedded signal acquisition

Expert tools

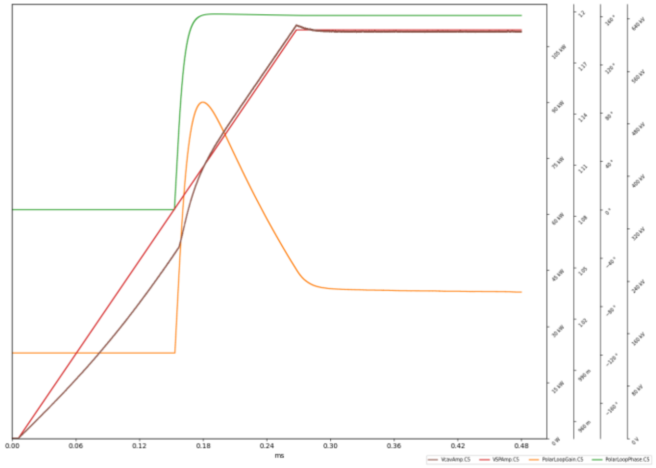


Fig – Pegasus, signals acquisition at RF on

| Expert Acquisition | OP Acquisition |
|---|---|
| 12 signals | 6 signals |
| 32 Flags | 32Flags |
| ≤ 4M pts | ≤ 2048 pts |
| Adjustable rate | “Fixed” rate |
| Individual configuration | Common configuration |

Fixed displays

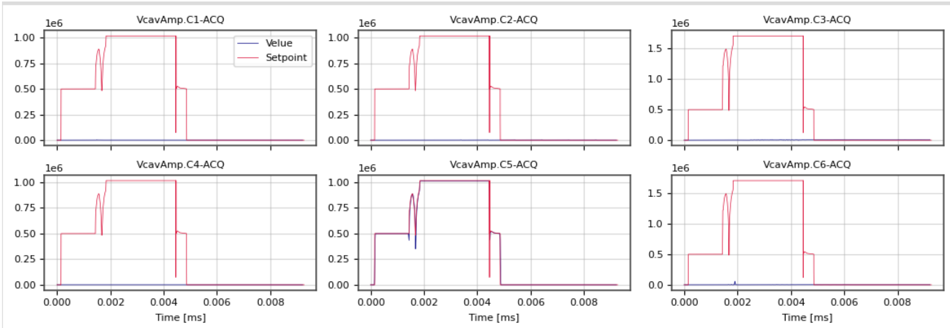



Fig – SNES, Vcav acquisition for 200MHz cavities, full cycle (SFTPRO1)

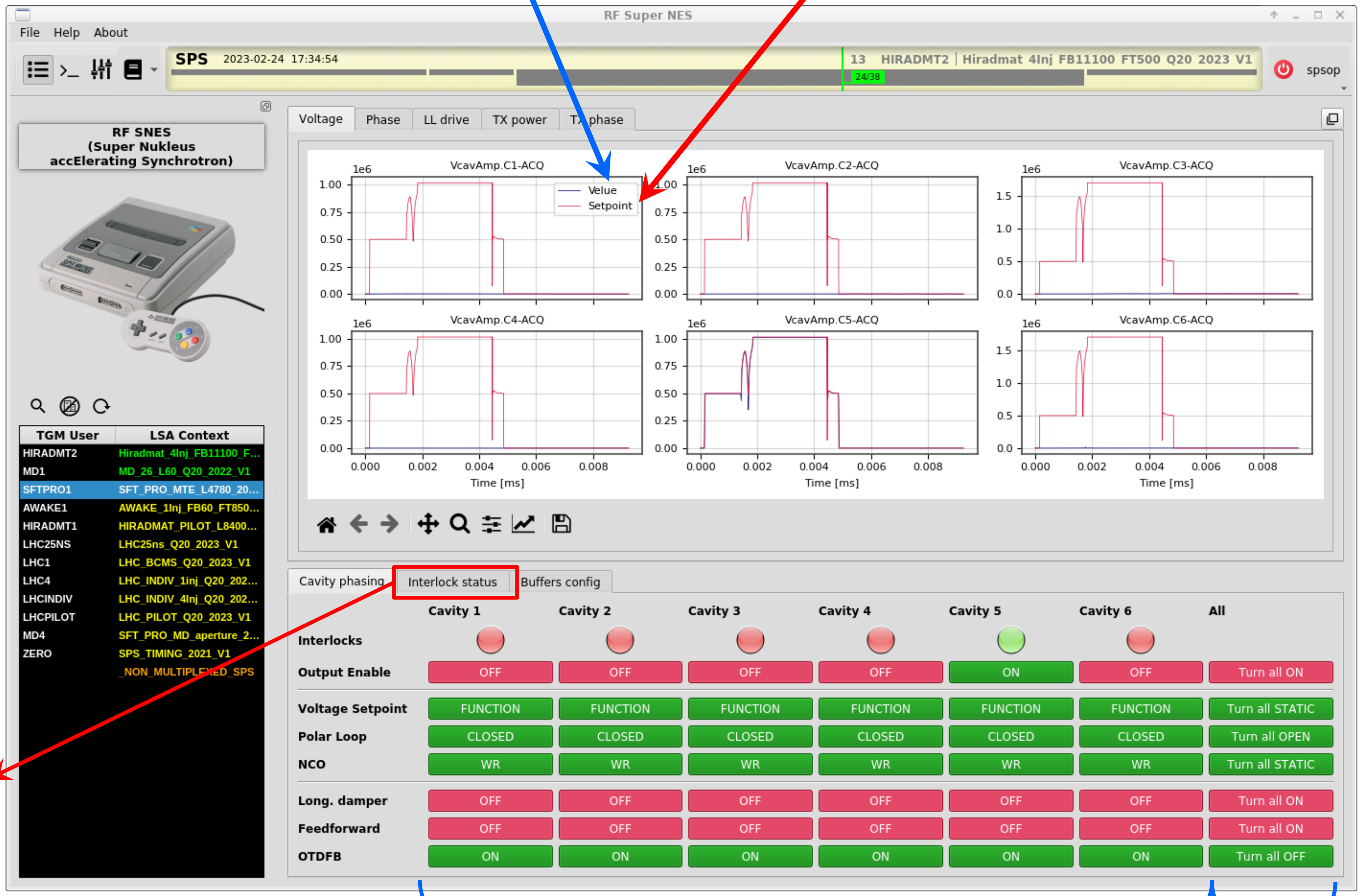
More details on the Cavity-Controllers acquisition specifications [8]

# OP high-level application (SNES) OP Acquisitions

- **OP acquisition**
- **Signals**
  - Cavity voltage & phase
  - LLRF drive (sent to TX)
  - TX power and phase
- **High-level control of the loops**
- **Interlock status**

Cavity voltage acquisition

Cavity voltage **setpoint** acquisition



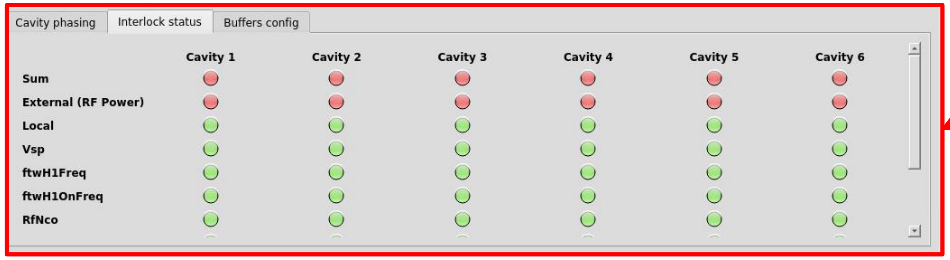




Fig – 200MHz Control, SNES

Individual control

global control

# OP high-level application (SPS RF Power Control)

OP Acquisitions

- **OP acquisition**
- **Signals**
  - Cavity voltage & phase
  - TX power and phase
  - Flags


Fig – SPS RF Power Control, 200MHz signals acquisition

# Expert high-level application

- **Status on all cavities**
- **Main settings**
- **Signals acquisition**
- **Advanced subpanels**
  - Cavity-Controllers
  - White-Rabbit
  - GBLinks
  - Clock distri (eRTM)
  - Acquisition settings
  - etc.

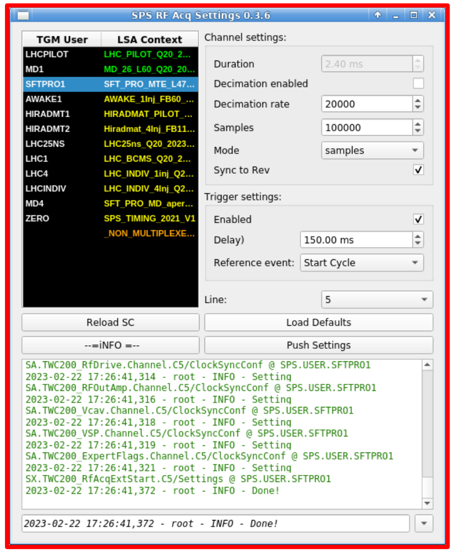




Fig – Expert Acquisition settings

$$Data\ rate = \frac{Decimation\ rate}{Clock\ rate} = \frac{Decimation\ rate}{8ns}$$

Nb Samples:

- Inspector ≤ 100’000 pts
- Pegasus ≤ 4Mpts (max)

# Expert high-level application

Expert acquisition

- **Cavity-Controller**

SPS LLRF Main Expert Panel

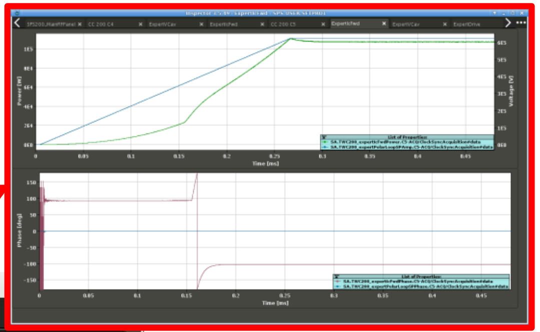


Fig – IcFwd acquisition at RF on (no decimation)

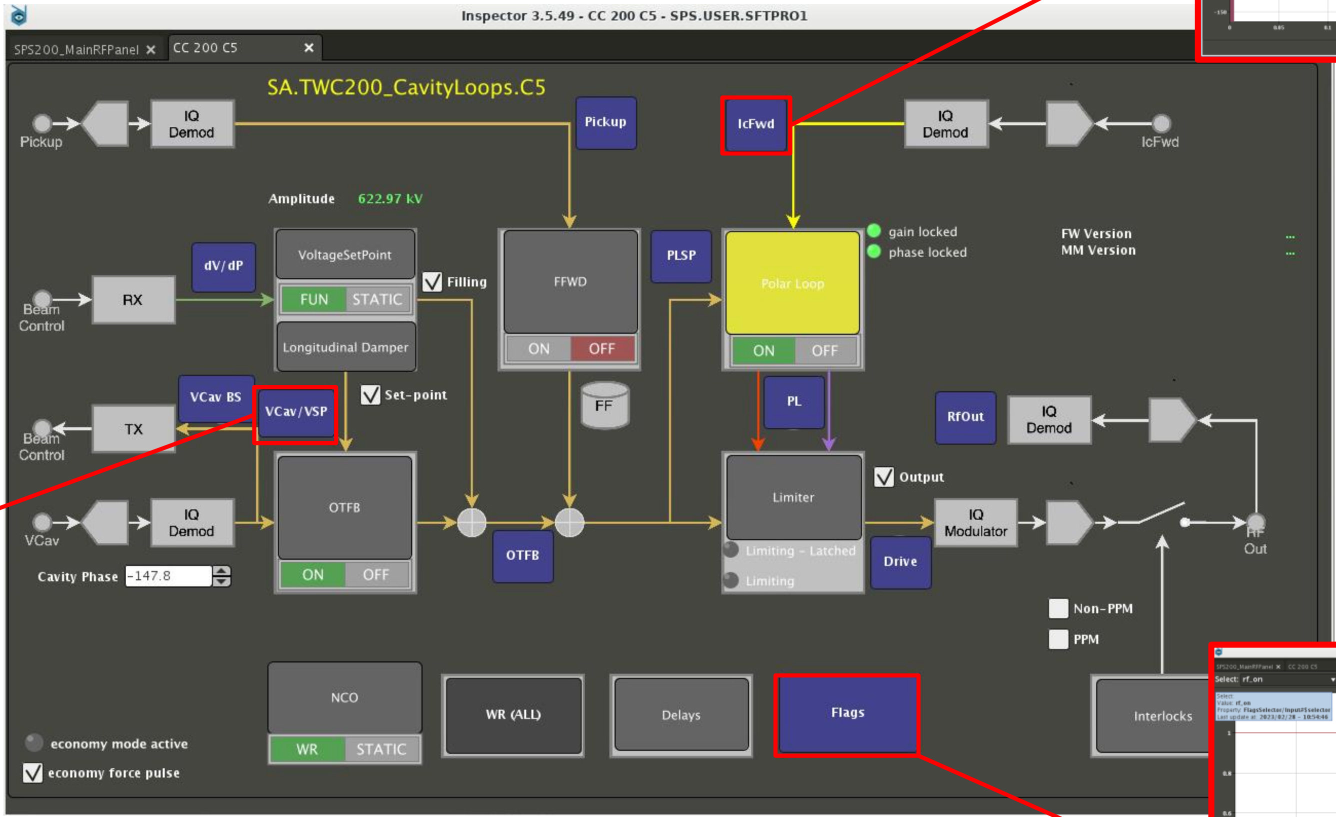



Fig – TWC200 Cavity-Controller application

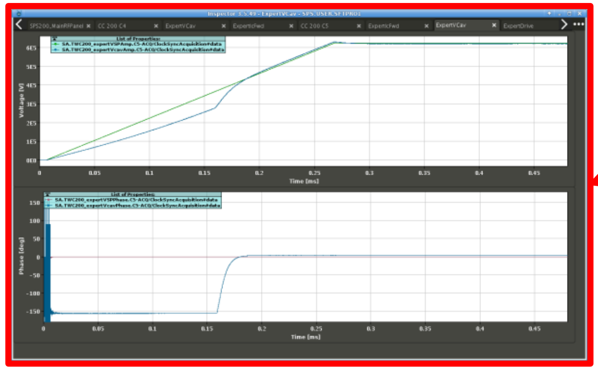
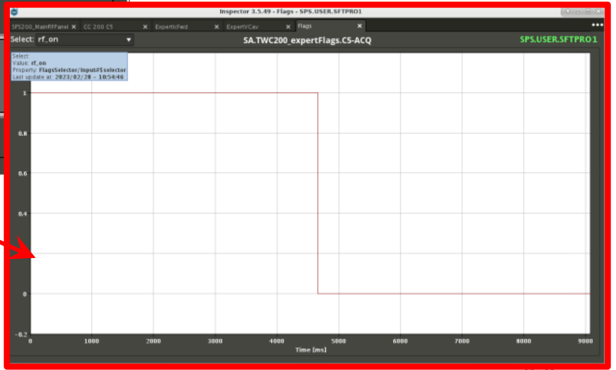


Fig – Vcav acquisition at RF on (no decimation)



# Expert acquisition - Pegasus

Expert acquisition

- **All 200MHz signals in one plot**
  - All signals (included flags)
  - Comparison between cavities
  - Higher number of points
  - Data saving (.csv)
  - Plot saving (.png)
- **Available in CCM**
  - RF Pegasus (Acq App)
  - Close the app if not used (subscription)
- **Acquisition settings**
  - Configure only active channels
  - Use SPS Acq Settings to configure all channel at once

SPS LLRF Acq Settings

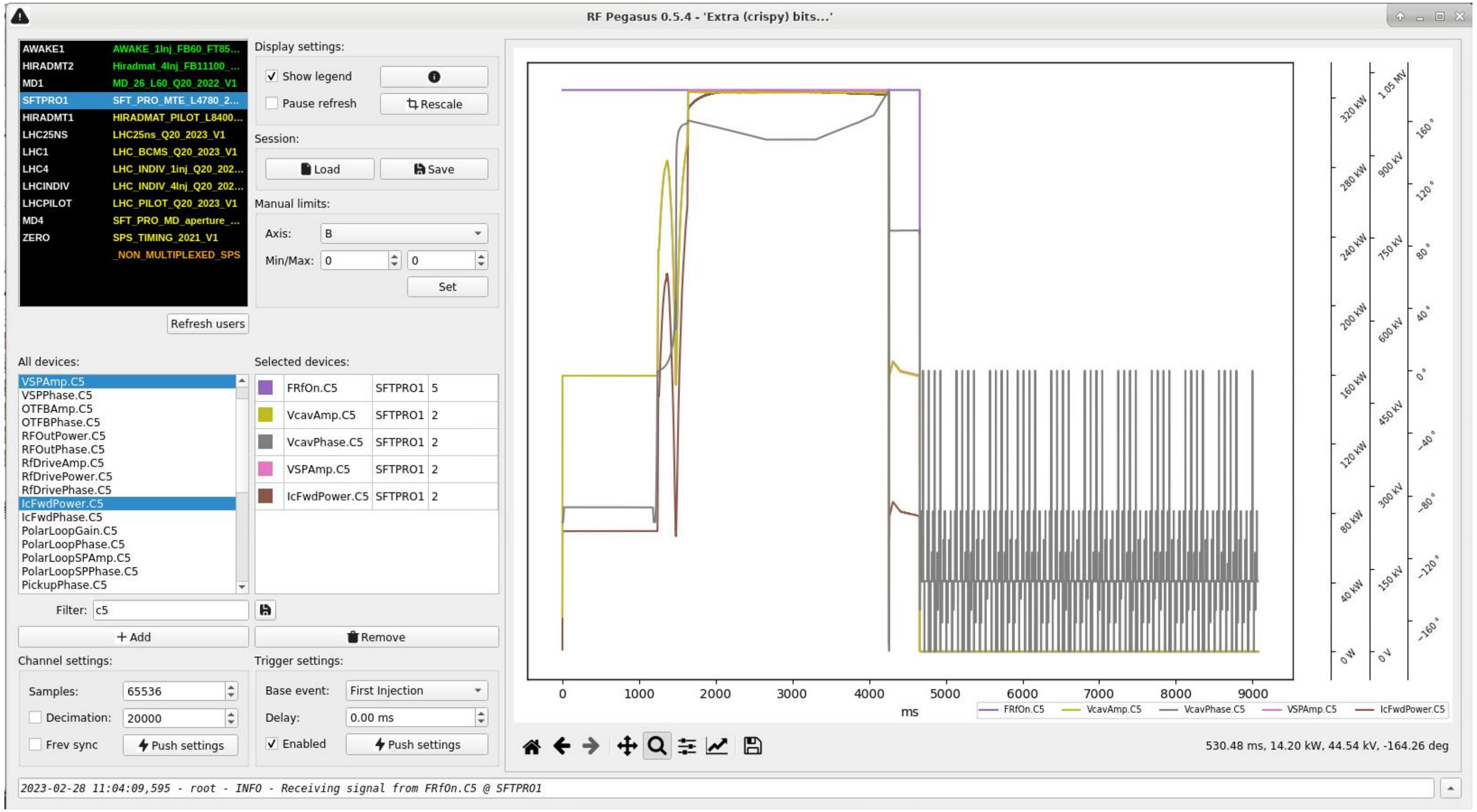
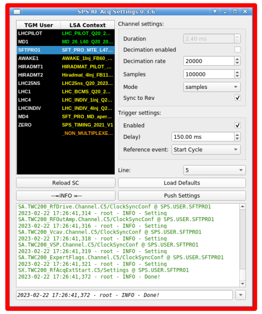


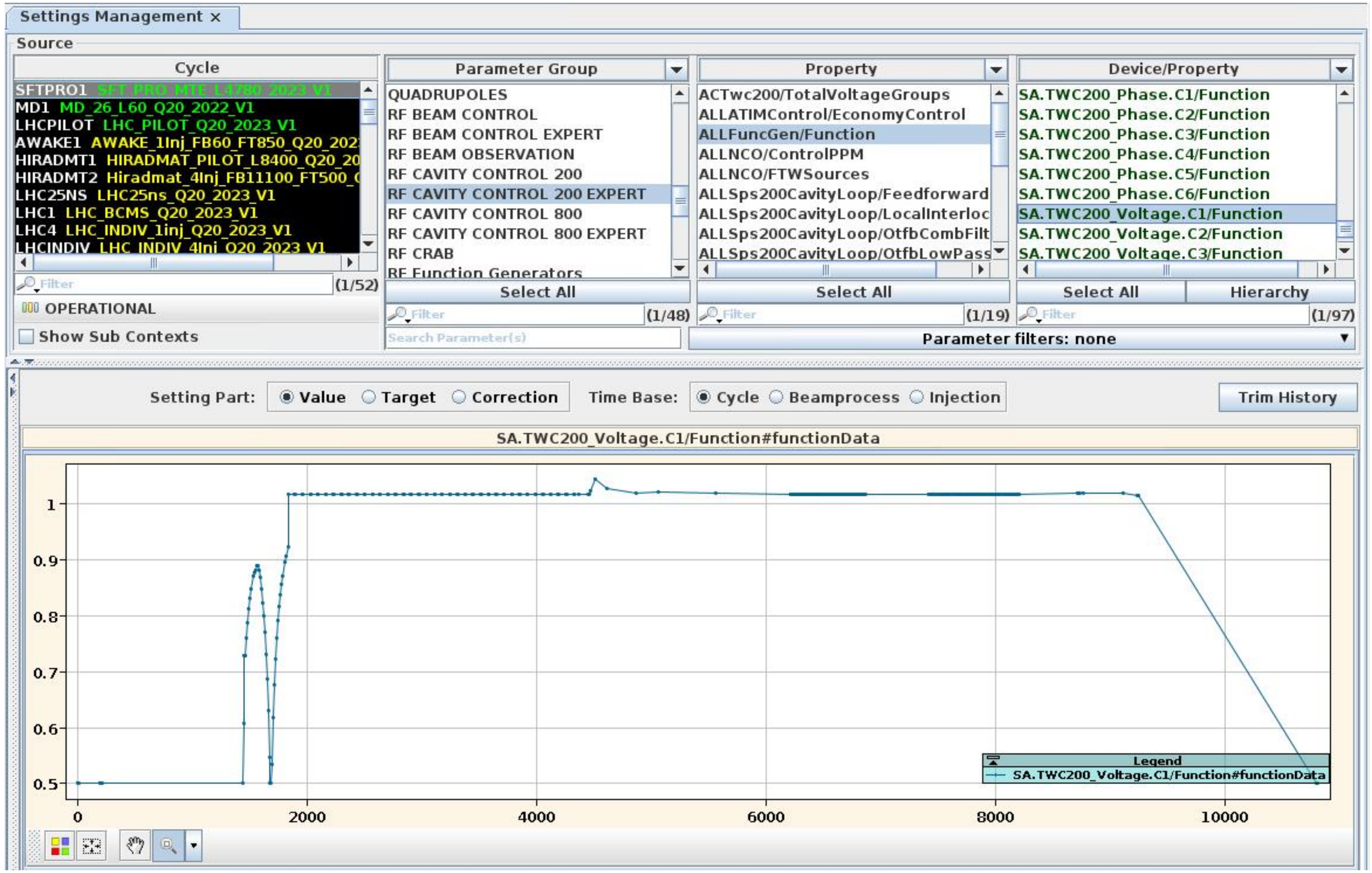

Fig – Pegasus, 200MHz signals acquisition



Do no subscribe to all signals at once!
1G Ethernet bandwidth limit

# Guru application

- **LSA trim editor**
- **All settings in LSA**
  - Value generator
  - Make rules
  - Particle type dependant
  - Specs: https://wikis.cern.ch/x/yZ9WCg
- **Only tool for functions**
- **No copy of the settings**
  - Except voltage functions
  - Rely on settings generation
  - By default: RF off (output enable)
- **Missing:**
  - settings for AM on protons cycle
  - few settings for Slip-stacking



# Troubleshooting

# Basic system checks

- **Remote checks**
  - FEC connection? (ping, ssh or DIAMON)
  - FESA classes running? (ssh or DIAMON)
  - Power supplies ok?
  - White-Rabbit network
  - Grafana, Inspector
- **On-site checks**
  - Power supplies (LEDs)
  - Board failure (LEDs)
  - Local Veto  (FTCI)
  - WR network switch

# Basic system checks – Remote

1. **FECs for the Cavity-Controllers**
   - cfu-ba3-allfb1
   - cfv-ba3-allfb800c1, cfv-ba3-allfb800c1
   - cfc-ba3-allgpsps2
2. **FEC connection**
   - DIAMON (from CCM)
   - try **ping** or **ssh** connection
3. **FESA classes running**
   - DIAMON services all green?
   - logged on the FEC (advanced boot state)
     - **~$ lumensctl list**
   - Power supplies status
     - CCM [SPS Crates Monitoring]
   - Grafana (FEC, network, history, …)
     - CCM [Micro TCA LLRF Monitoring]

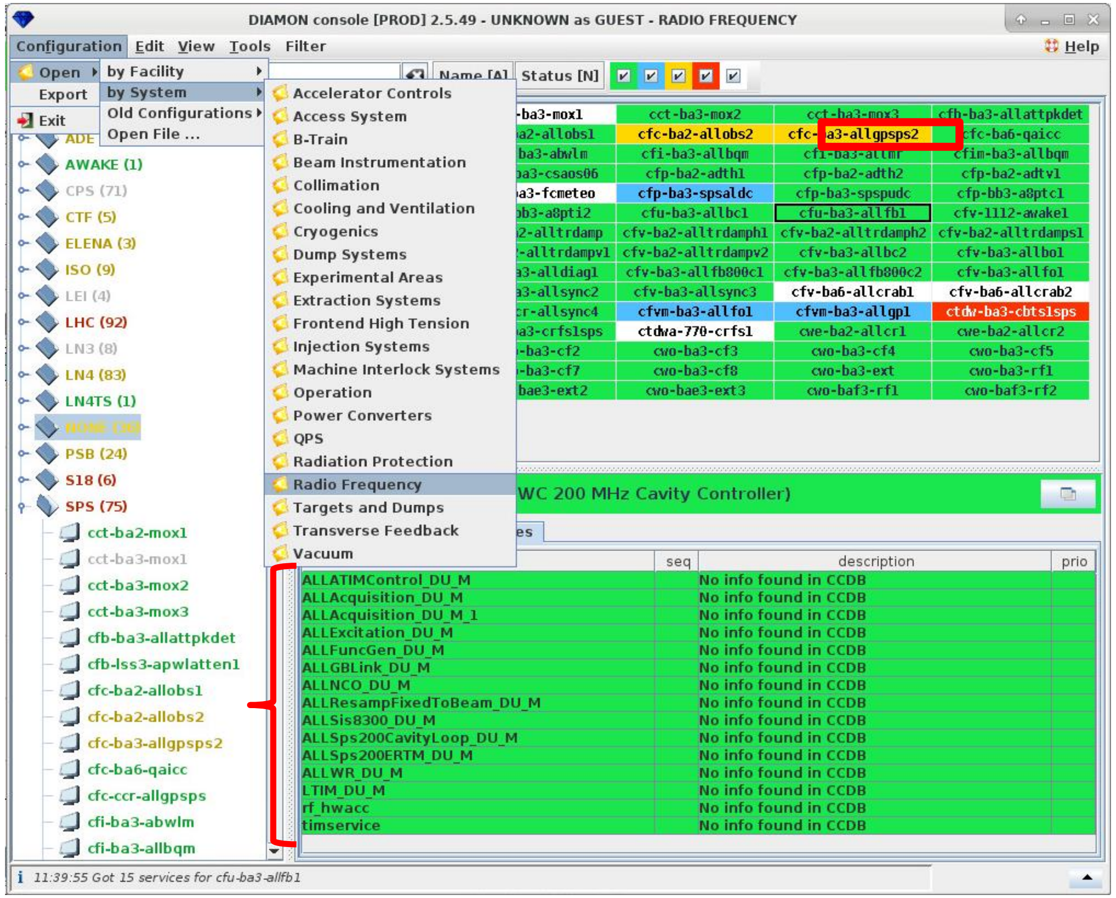
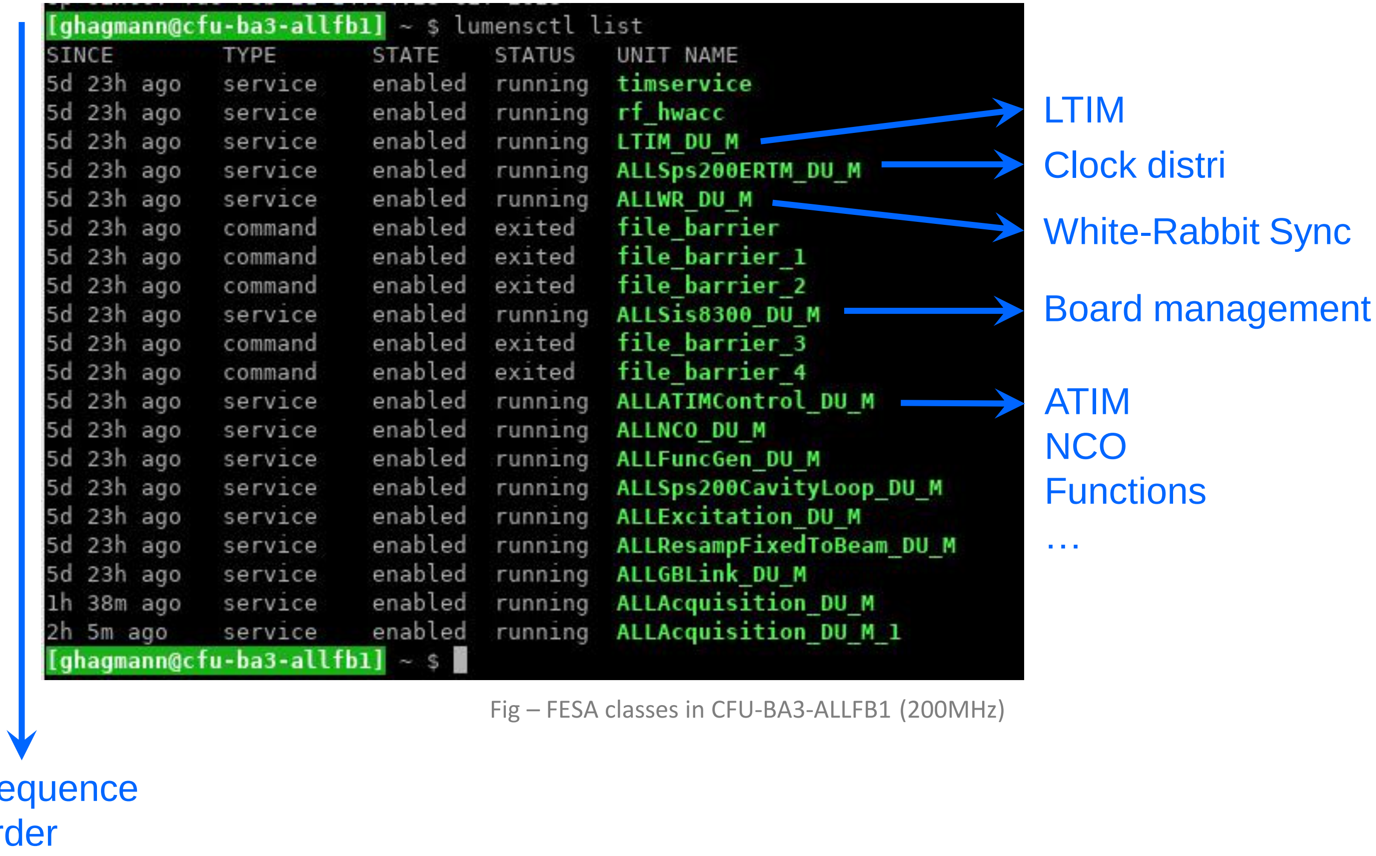



Fig – DIAMON for CFU-BA3-ALLFB1 (200MHz)

# Basic system checks – Remote

1. **FECs for the Cavity-Controllers**
   - cfu-ba3-allfb1
   - cfv-ba3-allfb800c1, cfv-ba3-allfb800c1
   - cfc-ba3-allgpsps2
2. **FEC connection**
   - DIAMON (from CCM)
   - try ping or ssh connection
3. **FESA classes running**
   - DIAMON services all green?
   - logged on the FEC (advanced boot state)
     - **~$ lumensctl list**
   - Power supplies status
     - CCM SPS Crates Monitoring
   - Grafana (FEC, network, history, …)
     - CCM Micro TCA LLRF Monitoring



```
[ghagmann@cfu-ba3-allfb1] ~ $ lumensctl list
SINCE       TYPE     STATE    STATUS   UNIT NAME
5d 23h ago  service  enabled  running  timservice
5d 23h ago  service  enabled  running  rf_hwacc
5d 23h ago  service  enabled  running  LTIM_DU_M
5d 23h ago  service  enabled  running  ALLSps200ERTM_DU_M
5d 23h ago  service  enabled  running  ALLWR_DU_M
5d 23h ago  command  enabled  exited   file_barrier
5d 23h ago  command  enabled  exited   file_barrier_1
5d 23h ago  command  enabled  exited   file_barrier_2
5d 23h ago  service  enabled  running  ALLSis8300_DU_M
5d 23h ago  command  enabled  exited   file_barrier_3
5d 23h ago  command  enabled  exited   file_barrier_4
5d 23h ago  service  enabled  running  ALLATIMControl_DU_M
5d 23h ago  service  enabled  running  ALLNCO_DU_M
5d 23h ago  service  enabled  running  ALLFuncGen_DU_M
5d 23h ago  service  enabled  running  ALLSps200CavityLoop_DU_M
5d 23h ago  service  enabled  running  ALLExcitation_DU_M
5d 23h ago  service  enabled  running  ALLResampFixedToBeam_DU_M
5d 23h ago  service  enabled  running  ALLGBLink_DU_M
1h 38m ago  service  enabled  running  ALLAcquisition_DU_M
2h 5m ago   service  enabled  running  ALLAcquisition_DU_M_1
[ghagmann@cfu-ba3-allfb1] ~ $
```



Fig – FESA classes in CFU-BA3-ALLFB1 (200MHz)

# Basic system checks – Remote

1. **FECs for the Cavity-Controllers**
   - cfu-ba3-allfb1
   - cfv-ba3-allfb800c1, cfv-ba3-allfb800c1
   - cfc-ba3-allgpsps2
2. **FEC connection**
   - DIAMON (from CCM)
   - try ping or ssh connection
3. **FESA classes running**
   - DIAMON services all green?
   - logged on the FEC (advanced boot state)
     - **~$ lumensctl list**
   - Power supplies status
     - CCM SPS Crates Monitoring
   - Grafana (FEC, network, history, …)
     - CCM Micro TCA LLRF Monitoring

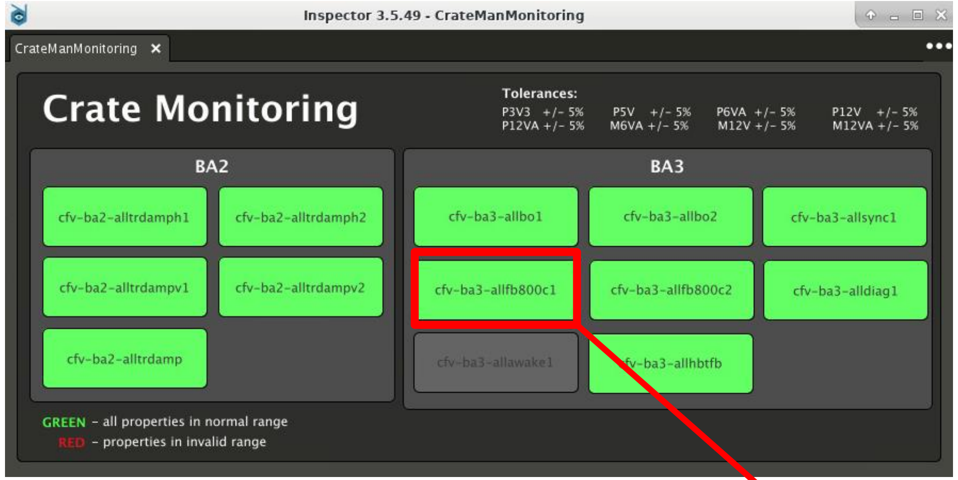
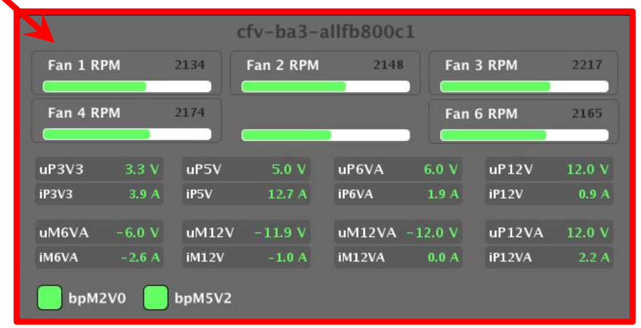



Fig – BA3 Crate monitoring (without MicroTCA)



# Basic system checks – Remote

1. **FECs for the Cavity-Controllers**
   - cfu-ba3-allfb1
   - cfv-ba3-allfb800c1, cfv-ba3-allfb800c1
   - cfc-ba3-allgpsps2
2. **FEC connection**
   - DIAMON (from CCM)
   - try ping or ssh connection
3. **FESA classes running**
   - DIAMON services all green?
   - logged on the FEC (advanced boot state)
     - **~$ lumensctl list**
   - Power supplies status
     - CCM SPS Crates Monitoring
   - Grafana (FEC, network, history, …)
     - CCM Micro TCA LLRF Monitoring

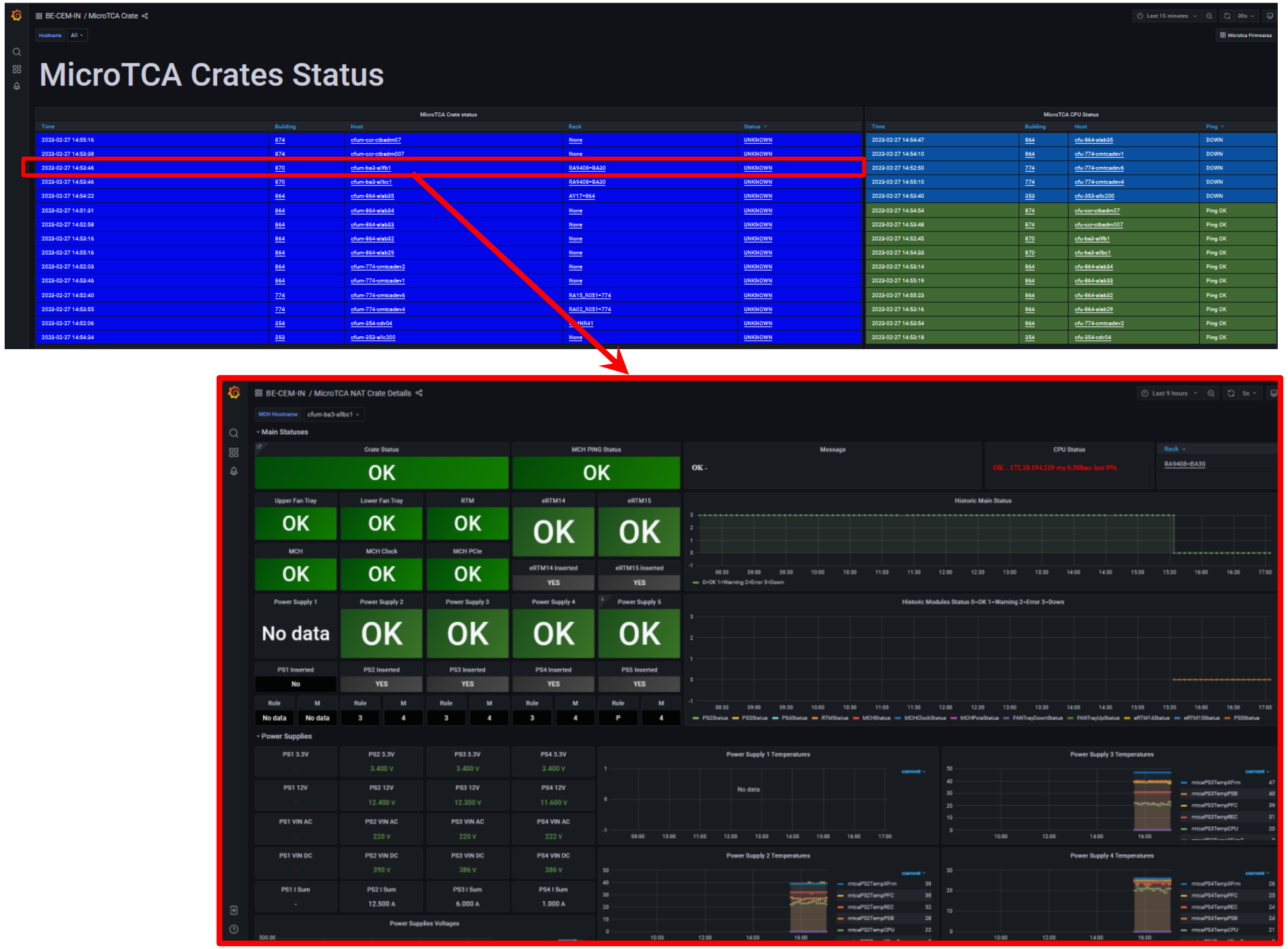



Fig – Grafana for CFUM-BA3-ALLFB1 (200MHz)

# Basic system checks – on-site

- **Power supplies**
  - VME: rear power supplies (green LEDs)
  - VME: Module *Power* LED
  - MicroTCA: Power supplies, eRTM
  - MicroTCA: Board failure (LEDs)
  - Local Veto (FTCI)
  - WR network switch

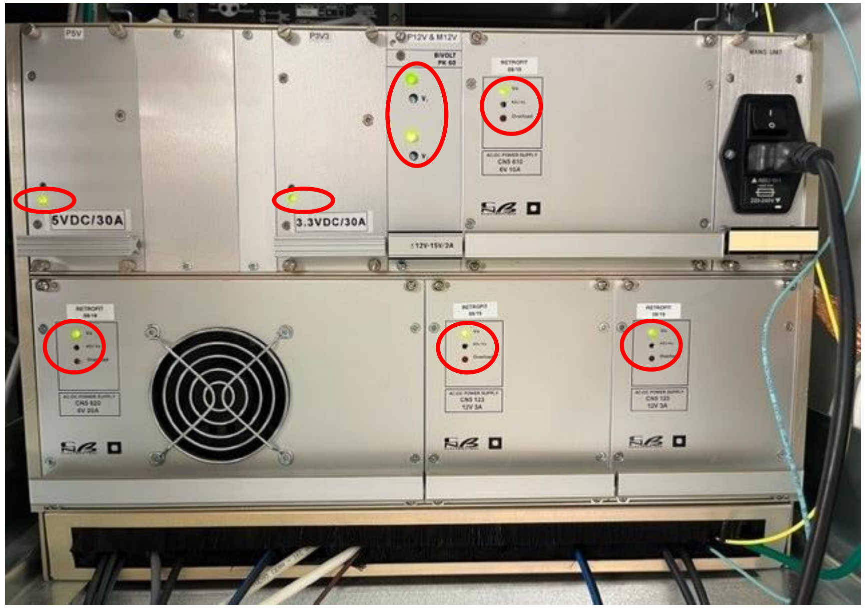



Fig – TWC800 crate (Rear)

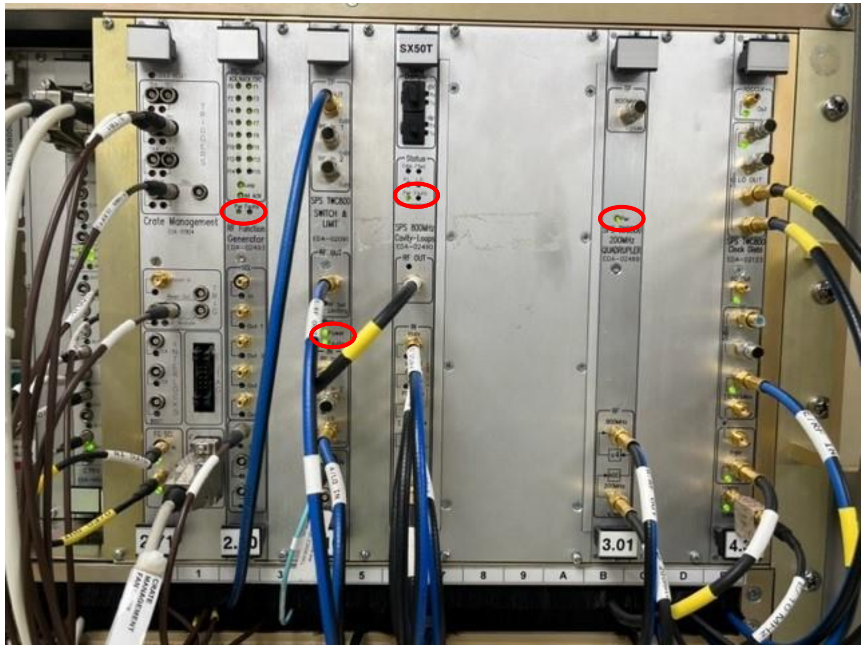



Fig – TWC800 crate (Front)

# Basic system checks – on-site

- **Power supplies**
  - VME: rear power supplies (green LEDs)
  - VME: Module *Power* LED
  - MicroTCA: Power supplies, eRTM
  - MicroTCA: Board failure (LEDs)
  - Local Veto (FTCI)
  - WR network switch

Status LED (green)

Fig – eRTM, clocks distribution


Fig – Power supply, MCH

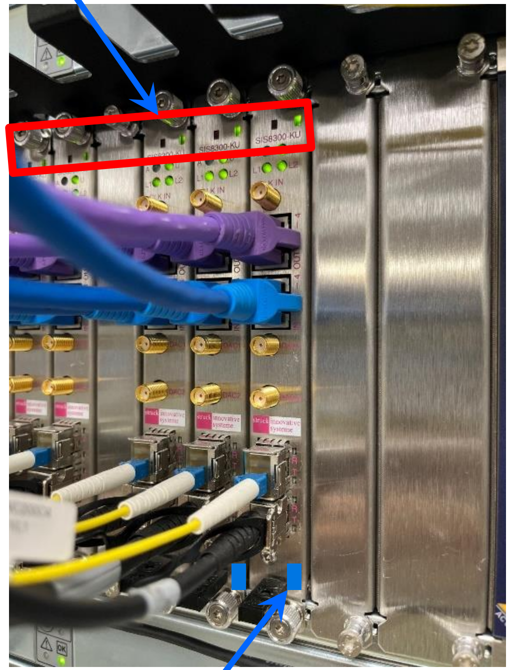


Fig – Cavity-Controller modules (SIS8300)

Board powering status LED:
- off : ok
- blue: power down

# Basic system checks – on-site

- **Power supplies**
  - VME: rear power supplies (green LEDs)
  - VME: Module *Power* LED
  - MicroTCA: Power supplies, eRTM
  - MicroTCA: Board failure (LEDs)
  - Local Veto (FTCI)
  - WR network switch

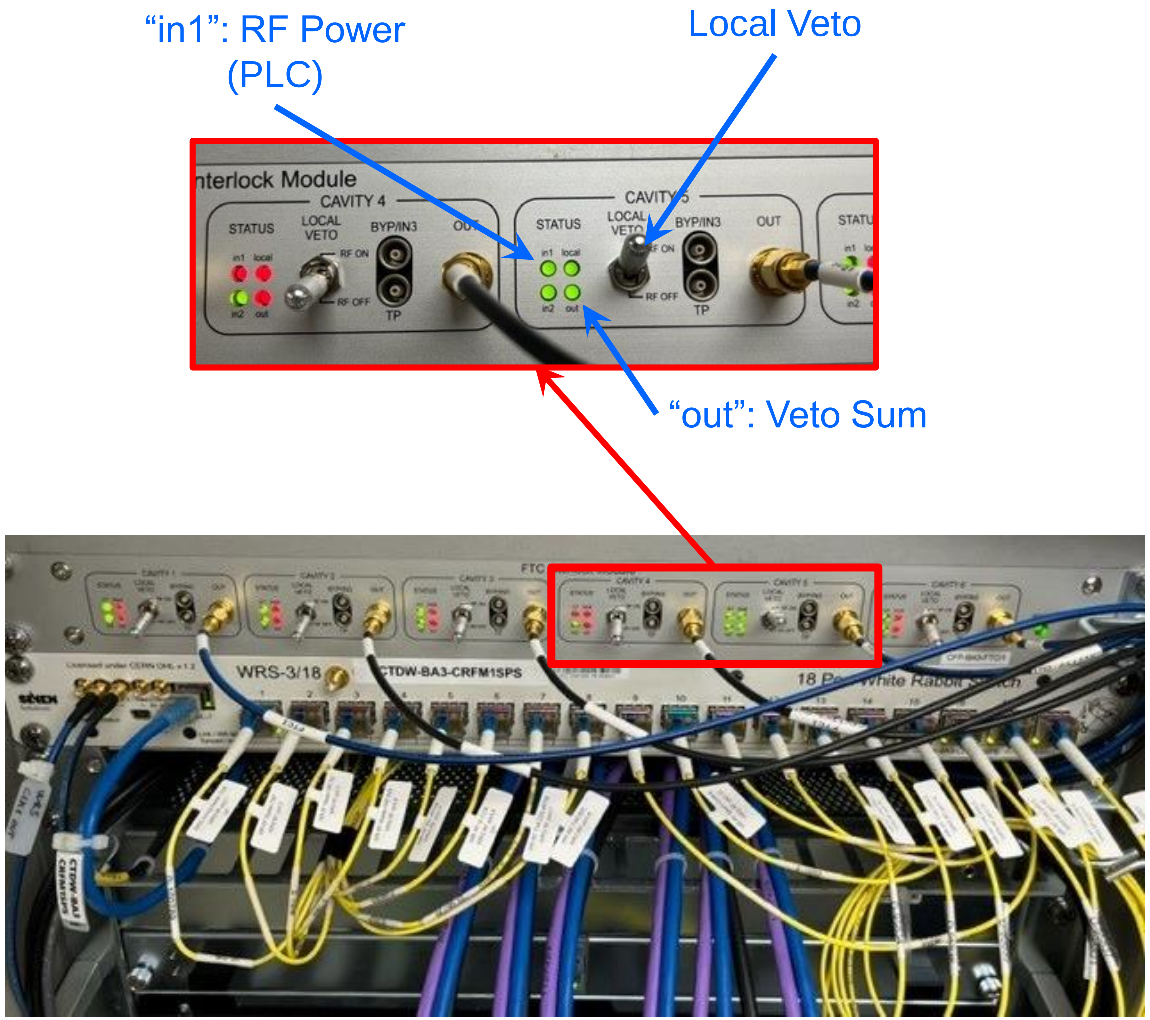



Fig – Interlock module FTCI

# Basic system checks – on-site

- **Power supplies**
  - VME: rear power supplies (green LEDs)
  - VME: Module *Power* LED
  - MicroTCA: Power supplies, eRTM
  - MicroTCA: Board failure (LEDs)
  - Local Veto (FTCI)
  - WR network switch

Power LED (green)

Status LED (green)

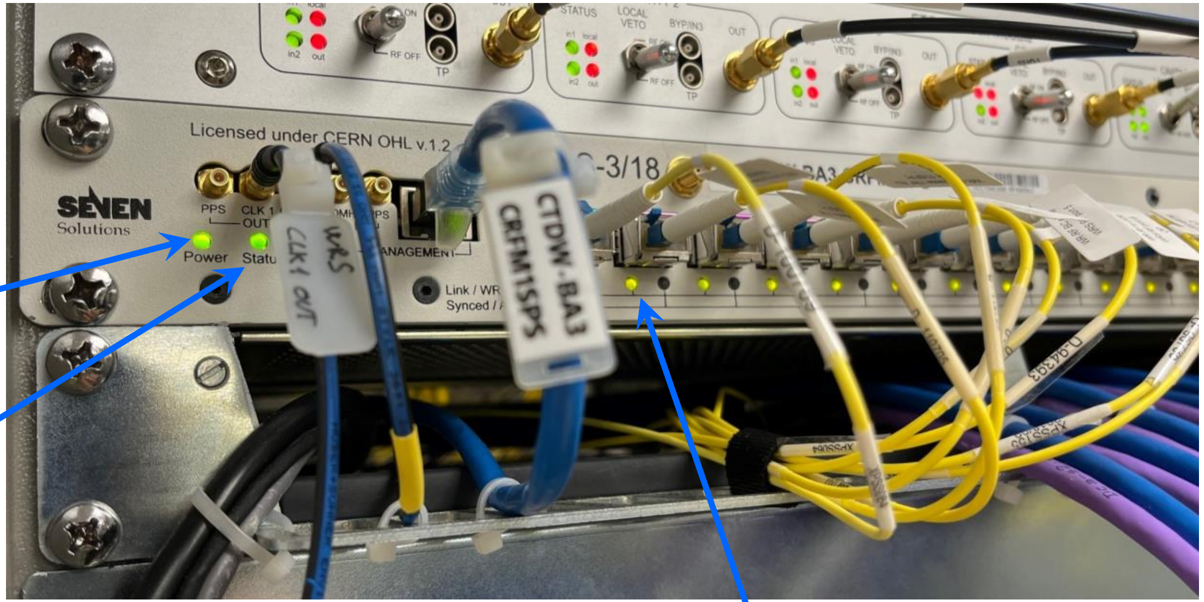



Fig – White-Rabbit switch status

SFPs LEDs
- left: green
- right: blinking orange (activity)

# Low Level RF loops

- **Remote checks**
  - Switching loops (on/off)
  - Expert acquisition (piquets or experts)

- **On-site checks (piquet or expert)**
  - Cavity phasing
    - Oscilloscope
    - Vector voltmeter
  - Cavity voltage spectrum
  - RF power measurement

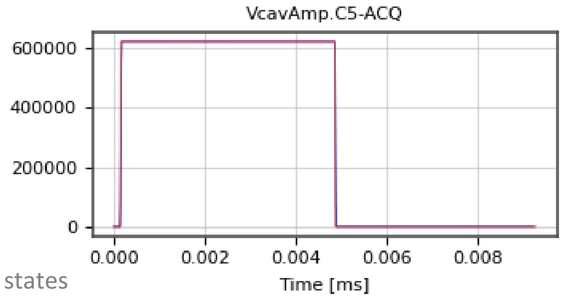
# Low Level RF loops – Remote checks

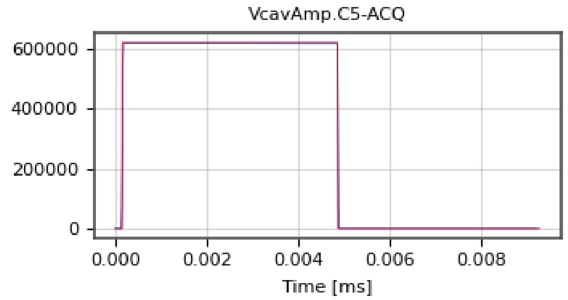
- **Disable the loops in a sequence**
  - Static Voltage setpoint
  - RF Feedback (OTFB) OFF
  - Static frequency (NCO)
  - PolarLoop OFF
  - LLRF Output OFF
- **Enable the loops in a sequence**
  - LLRF Output ON
  - PolarLoop ON
  - WR (RF-train) frequency (NCO)
  - RF Feedback (OTFB) ON
  - Voltage setpoint functions

**Constraints:** RF feedback (OTFB) requires the PolarLoop ON!


Fig – SNES, Vcav acquisition with all system (loops) on

# Low Level RF loops – Remote checks



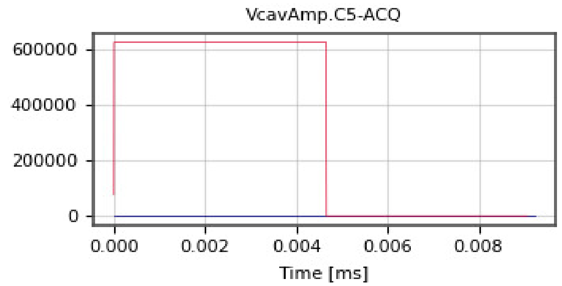
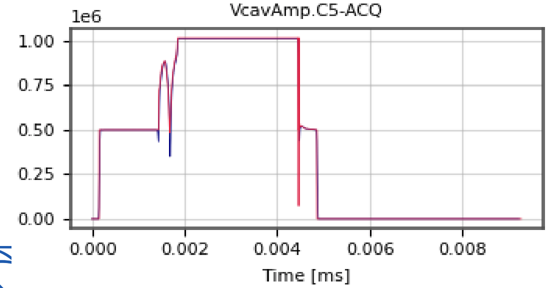
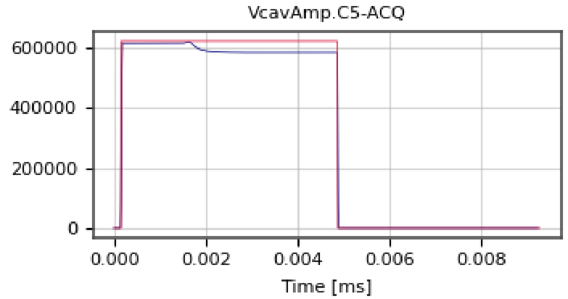
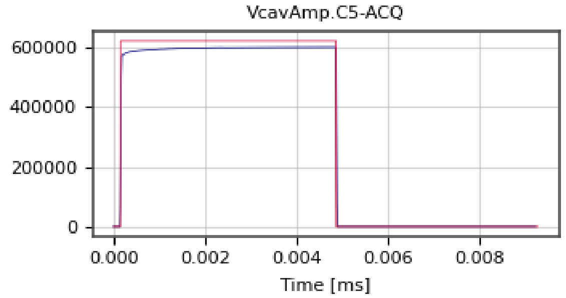




Fig – SNES, Vcav acquisition in various states

| | Cavity 5 | Cavity 5 | Cavity 5 | Cavity 5 | Cavity 5 | Cavity 5 |
|---|---|---|---|---|---|---|
| **Interlocks** | | | | | | |
| **NCO** | WR | WR | WR | STATIC | STATIC | STATIC |
| **Voltage Setpoint** | FUNCTION | STATIC | STATIC | STATIC | STATIC | STATIC |
| **Polar Loop** | CLOSED | CLOSED | CLOSED | CLOSED | OPEN | OPEN |
| **OTDFB** | ON | ON | OFF | OFF | OFF | OFF |
| **Feedforward** | OFF | OFF | OFF | OFF | OFF | OFF |
| **Long. damper** | OFF | OFF | OFF | OFF | OFF | OFF |
| **Output Enable** | ON | ON | ON | ON | ON | OFF |



# Summary

- **The RF system is based on the following *paradigms***
  - Use of the **White Rabbit** (WR) network
    - keep the various nodes (cavities, beam-based measurements, BI,…) in synchronism
    - Transmission of the **RF frequency** as **Numerical Word** over the WR.
    - Analog (fiber, copper) transmission of reference RF signals for legacy (Synchro with PS, BI, etc.)
  - All Beam-Control, TWC200 digital electronics clocked with a **fixed frequency** distributed by the WR
  - Controls of TWC800 similar to TWC200, only expert acquisition.
  - Beam-Control and TWC200 on a **μTCA** platform (COTS, in-house), TWC800 on VME (in-house)
- **Controls & Diagnostics**
  - Cavity voltage Fixed displays (SNES, RF lowlevel status, Grafana) for daily operation
  - Expert application for deeper analysis : Inspector, Pegasus
  - Setting generation almost fully automatic (Value Generators and make rules)
  - Basic sanity checks:
    - Fixed displays
    - FEC status, HW status
    - Separate Cavity-Controller from Beam-Control (static frequency, static setpoint)
    - Loops sequencings (on/off

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[2] I. Karpov, LIU intensity ramp-up: longitudinal beam dynamics and RF aspects, JAPW dec 2022, CERN, Geneva, Switzerland, Indico event 1194548, https://indico.cern.ch/event/1194548

[3] D. Boussard, Reduction of the apparent impedance of wide band accelerating cavities by rf feedback, IEEE Trans. Nucl. Sci. 30 (1983) pp.2239, $10^{th}$ Particle Accelerator Conference, Satna Fe, USA,, DOI: **10.1109/TNS.1983.4332774**

[4] G. Hagmann, LIU-SPS LLRF TWC200 Functions specification, V1.0, CERN 2023, EDMS SPS-A-ES-0028, **https://edms.cern.ch/document/2342832**

[5] G. Hagmann, LIU-SPS LLRF TWC800 Functions specification, V1.4, CERN 2020, EDMS SPS-A-ER-0003, **https://edms.cern.ch/document/1766989**

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