Beam and RF operation in the PS

OP Shutdown Lectures
24/02/2023

A. Lasheen

Acknowledgements:
H. Damerau, B. Woolley, the RF-LIS/FB/BR/CS sections, the PS-MPC, the beam docs, the logbook and the tomoscope ref. files, and all of you operating that incredible machine!

Outline

- PS RF systems
  - *Overview of RF systems and their usage*
  - *Typical issues, tips and tricks*

- Construction of a cycle, RF processes
  - *Typical RF sequences in a cycle*
  - *Cavity matrix and timing trees*
  - *Overview across beams*

- Diversity of operational adjustments
  - *Based on longitudinal beam observation*
  - *A small subset to illustrate general approach*

- What's next?
  - *Future hardware changes*
  - *Future needs*

Agreements

- The focus is put on the general aspects of beam and RF operation in the PS, overview of systems, beam signals and guidelines for adjustments.

- Some aspects are not covered in details (e.g. controlled emittance blow-up, cavity feedbacks, beam control, implementation of coupled bunch feedback and principles of Landau damping…)

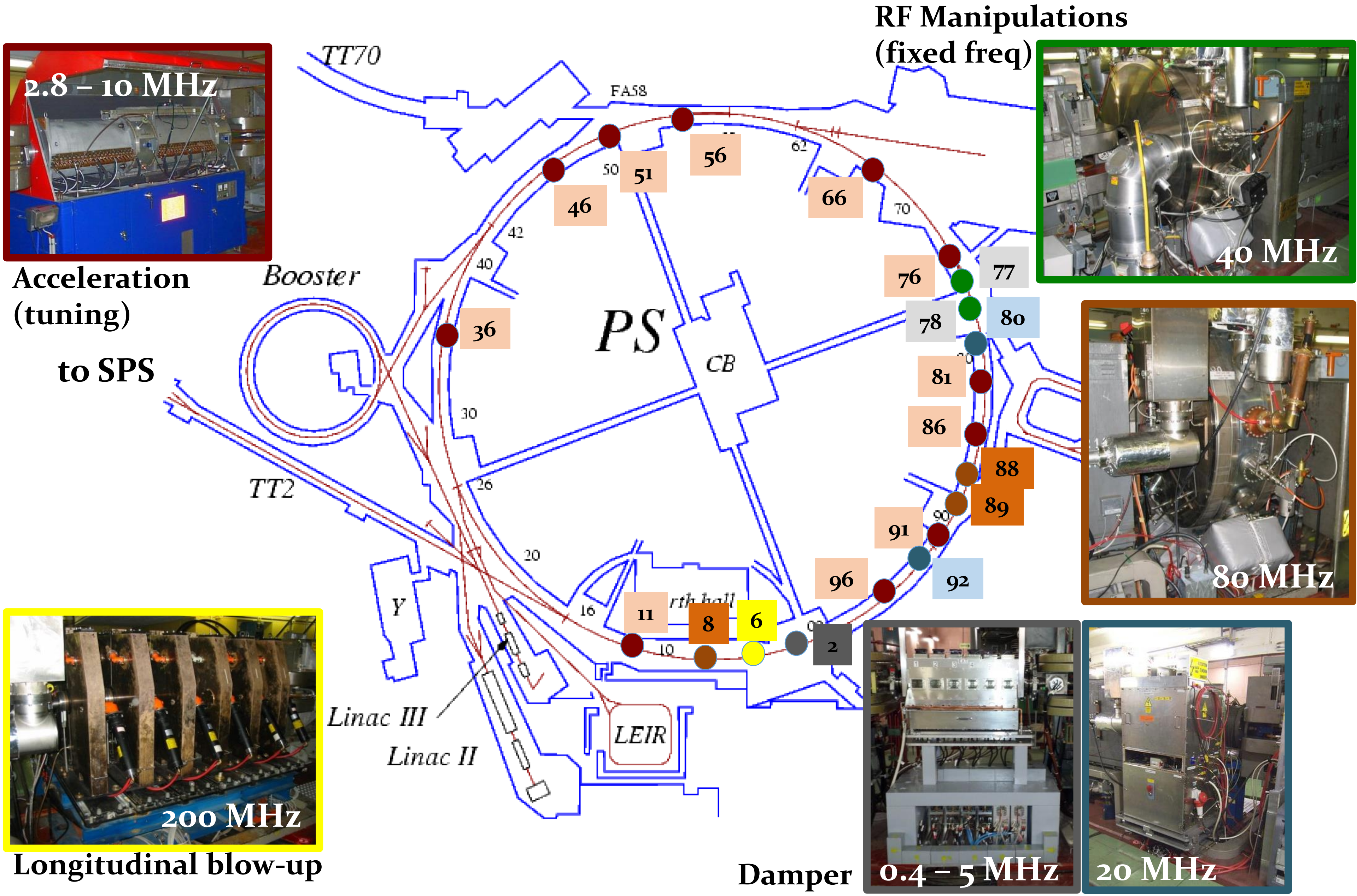
- The objective is to provide information relevant for PS operators, as well as PSB operators on shift in PS and curious SPS operators (willing to know why the beam is not coming).

PS RF systems

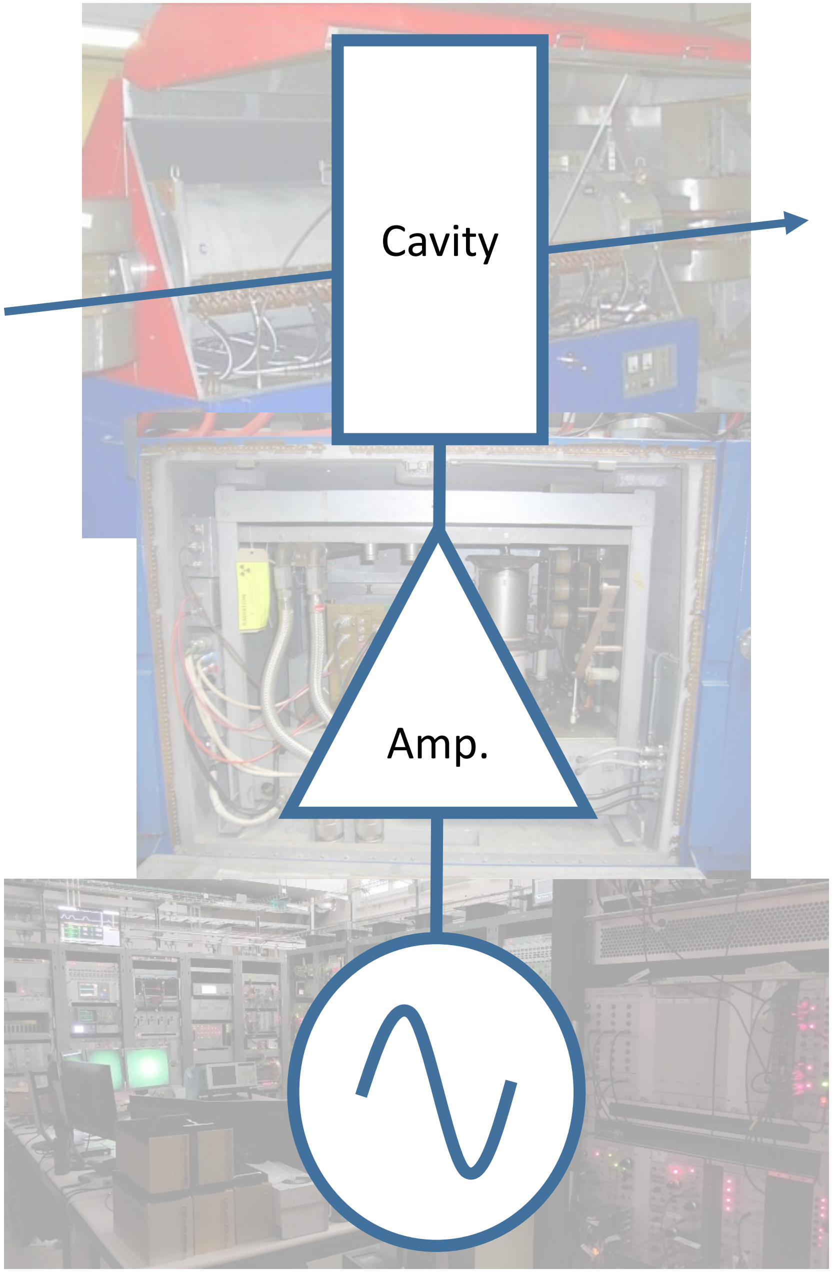
–

All instruments in the orchestra…

RF systems in the PS



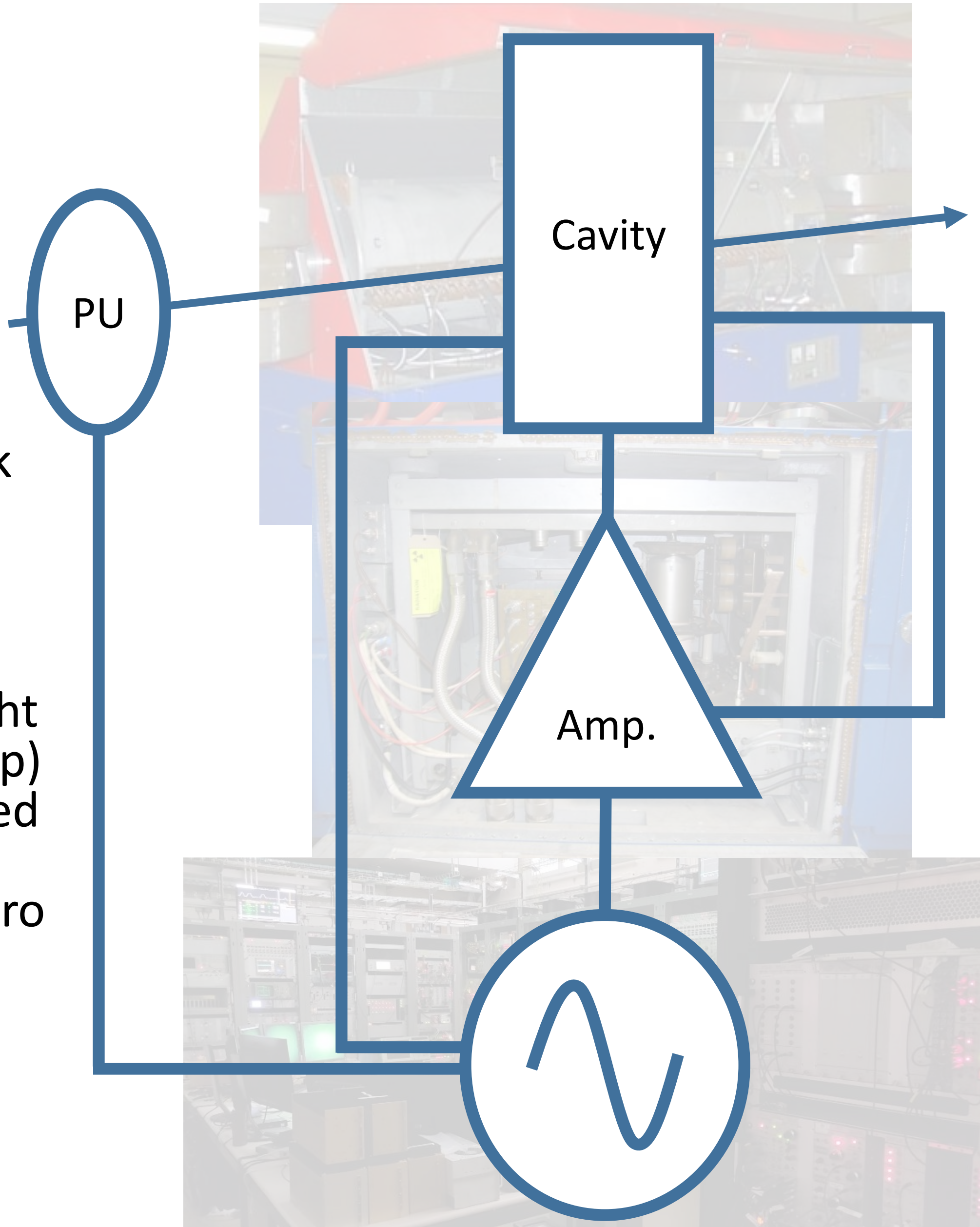
From low-level to high-level RF to the beam



- The power is transmitted in the RF gap where the beam passes and gets accelerated, manipulated, modulated…
- The signal is amplified to high-levels. Interlocks ensure that the amplifiers are not driven too high in power (cavity trip…).
- The low-level signals are generated from a source defining the expected waveform (RF voltage, frequency, phase).

Local and global feedback systems

Global feedback systems ensure that the beam stays in the RF bucket (phase loop), in the right orbit (radial loop) and synchronized to the next machine (synchro loop)



Local feedback systems around the cavity are used to reduce effects of beam induced voltage (e.g. one turn delay feedback 1TFB, multi harmonic feedback MHFB)

Usage of RF systems across beams

Beam	C10	C20	C40	C80	C200	Finemet
TOF						
EAST						
AD						
SFTPRO						
LHC#multib						
LHC#1b						
ION#multib						
ION#1b						

- RF systems have different purpose
  - C10 are used for acceleration and RF manipulations for all beams
  - C20, C40, C80 are used to shape the longitudinal beam distribution for all LHC beams (splittings, bunch shortening…)
  - The C200 are used for controlled longitudinal emittance blow-up and also 200 MHz modulation of the SPS fixed target beam
  - The Finemet cavity was originally designed for damping of coupled bunch instabilities and now for barrier bucket for transfer of the SPS fixed target beam

Beam controls

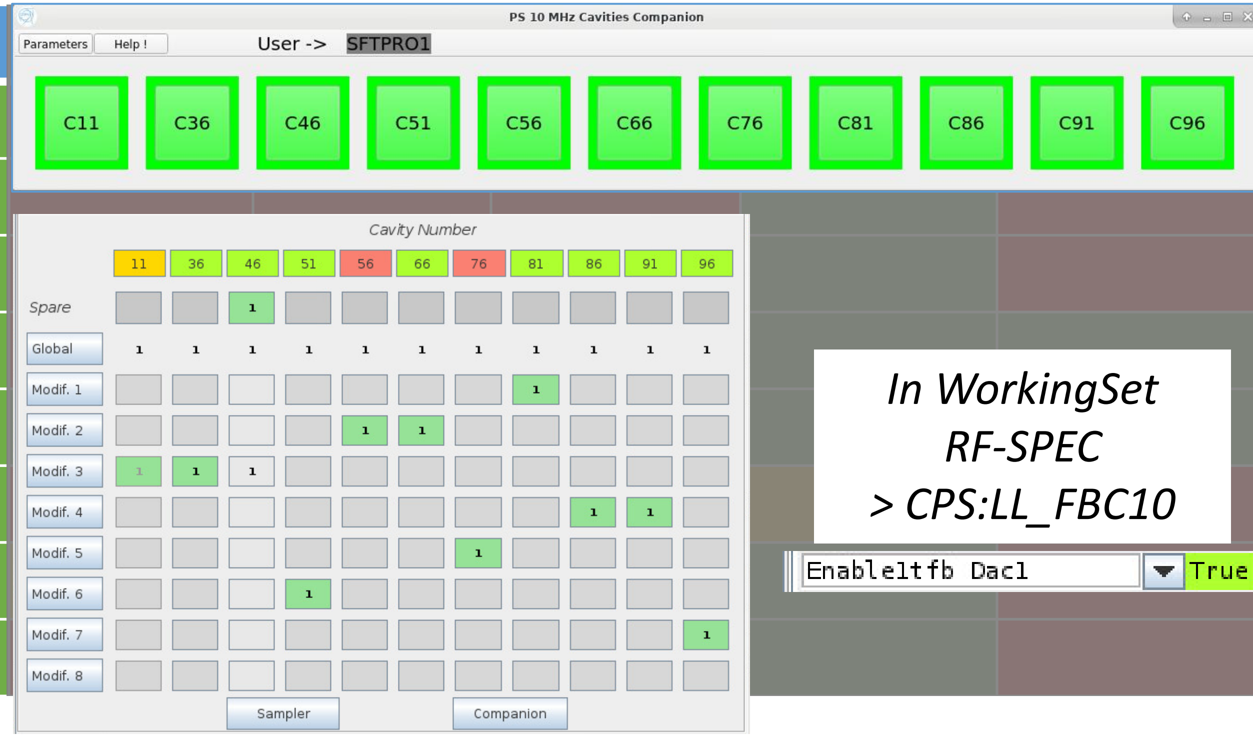
Beam	Beam control
TOF	H8H16
EAST	H8H16
SFTPRO	H8H16
AD	HSWP
LHC#multib	H21, H84
LHC#1b	H16LI, H84LI
ION#multib	H24ILHC, H169
ION#1b	H16ILHC, H169

- The HLRF systems are controlled by different LLRF systems depending on the beam, with their own setup for phase, radial, synchronization loops (i.e. some beams share the same non-PPM loop parameters).
- LHC type beams have different beam control during the cycle (with C10 cavities), then with high frequency cavities.
- Beam controls are linked to timing trees and (most often) have corresponding WorkingSets.

Usage of RF systems, typical issues C10

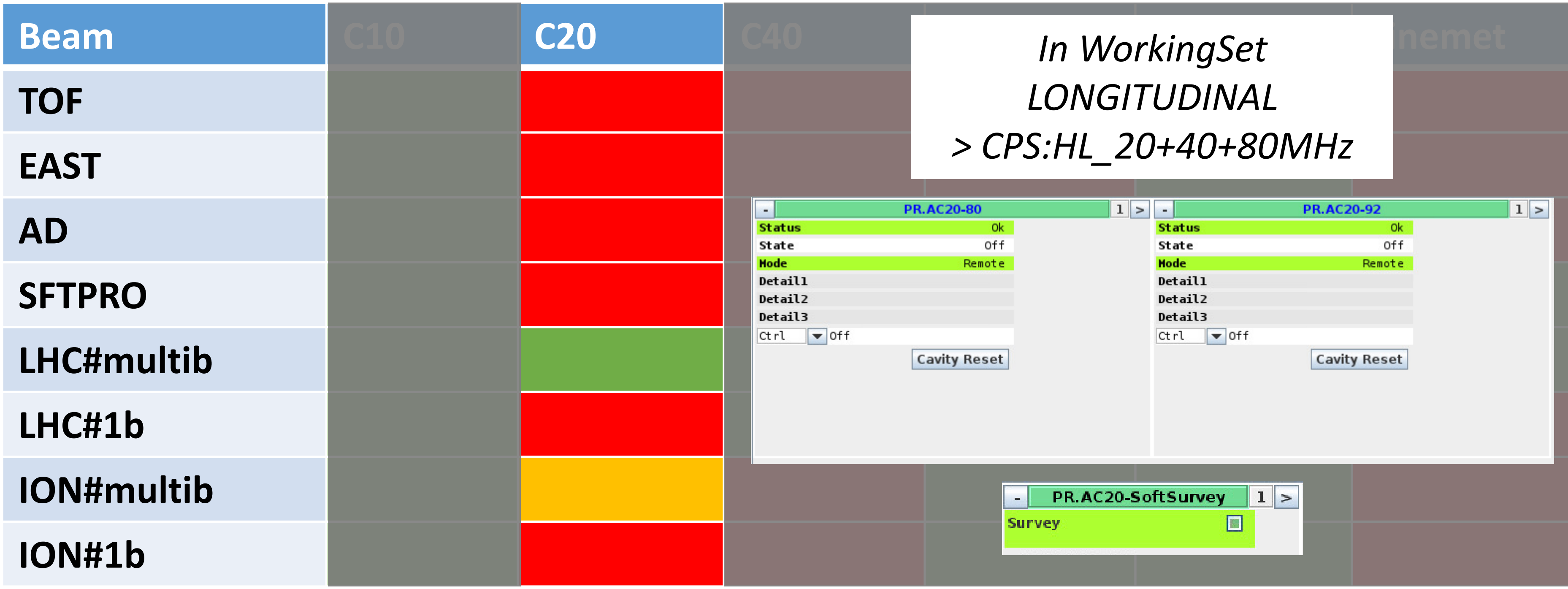
3 App counter!

Beam	C10
TOF	
EAST	
AD	
SFTPRO	
LHC#multib	
LHC#1b	
ION#multib	
ION#1b	



- C10 (10 + 1 spare)
  - A typical issue is that one (or several…) cavity trips or doesn't follow the voltage program. This should be visible in the "PS 10 MHz Cavities Companion" app.
  - A single faulty cavity can be replaced by the C11 using the "RF 10 MHz Matrix" app.
  - For very high intensity beams, cavity loops can be asking for large power. Disabling the 1TFB can be attempted (+ contact the RF experts).

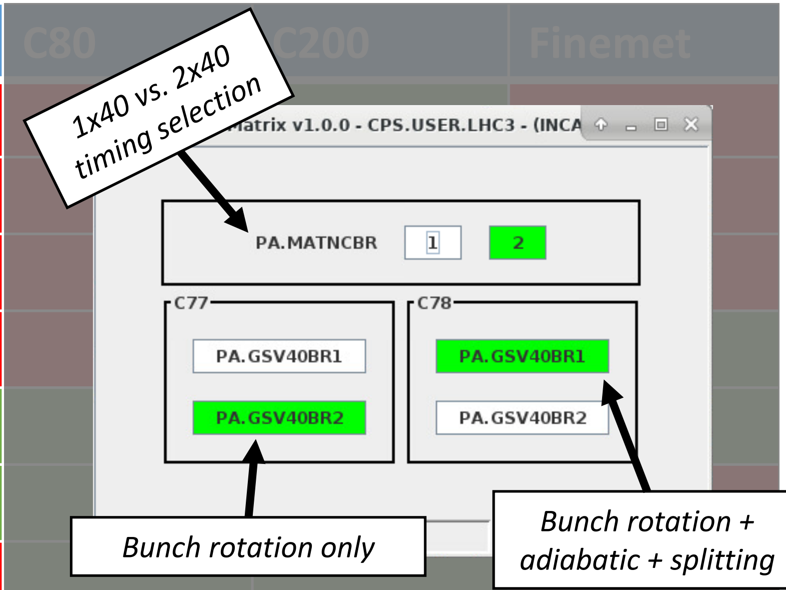
Usage of RF systems, typical issues C20



- C20 (1 + 1 spare)
  - A typical issue is that the cavity is not ON when SPS/LHC request beam. The amplifier is switched OFF after some time when not in use to increase the equipment lifetime. Switching the cavity ON takes some time (couple of minutes).
  - If C20 is off, C40 and C80 will not be pulsing on LHC multibunch beams (i.e. no splitting, beam lost entirely at SPS injection). Control is made via the WorkingSets.

Usage of RF systems, typical issues C40

Beam	C10	C20	C40	C80	C200	Finemet
TOF						
EAST						
AD						
SFTPRO						
LHC#multib						
LHC#1b						
ION#multib						
ION#1b						

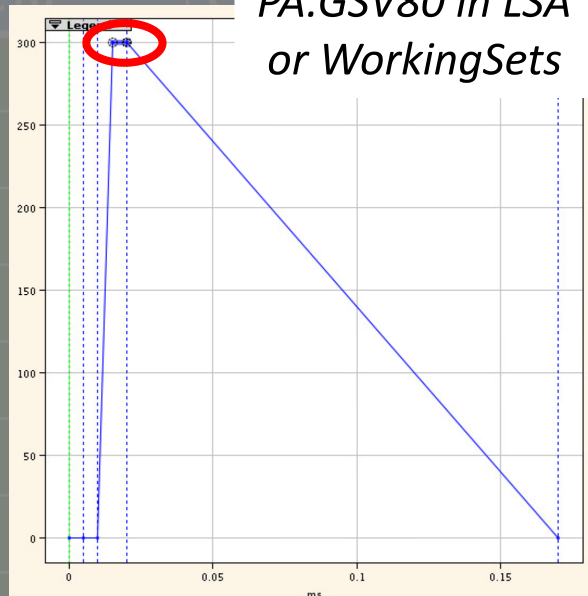


- C40 (2, or 1 in degraded mode)
  - A typical issue is that one cavity trips. It will manifest at PS-SPS transfer (no splitting structure, increased losses in SPS due to bunch rotation timings that should be changed).
  - The cavities can be switched using the “RF 40MHz Matrix” app, and the bunch rotation settings adapted from 2x to 1x cavity (“degraded” mode).

Usage of RF systems, typical issues C80

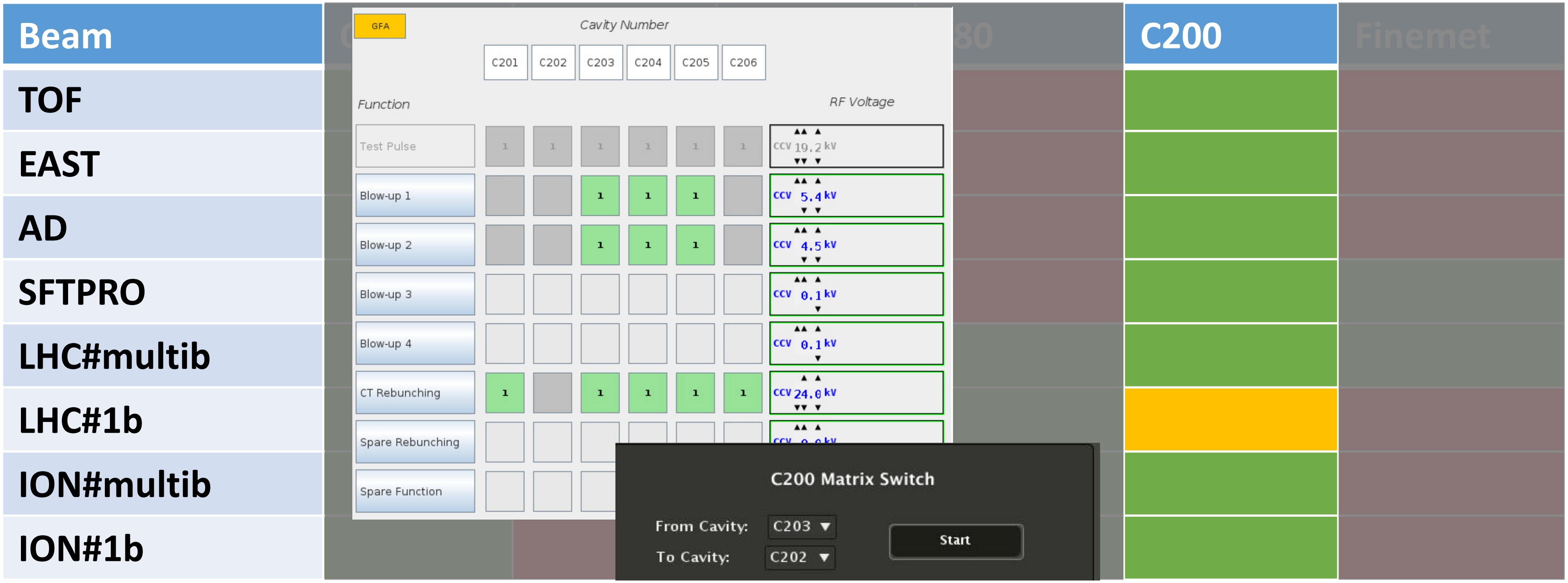
Beam	C10	C		C80	C200	Finemet
TOF						
EAST						
AD						
SFTPRO						
LHC#multib						
LHC#1b						
ION#multib						
ION#1b						

PA.GSV80 in LSA or WorkingSets



- C80 (2 for p+, 1 for ions)
  - Used for bunch rotation in LHC p+ beams. Used for adiabatic bunch shortening for LHC ion beams.
  - A typical issue is that one cavity trips. It will manifest at PS-SPS transfer (increased losses due to bunch rotation).
  - During the run with protons only, one C80 can be used as a spare (only if tuned on the proton frequency!).
  - A last resort is to reduce slightly the RF voltage via the PA.GSV80 parameter (+ contact the RF experts).

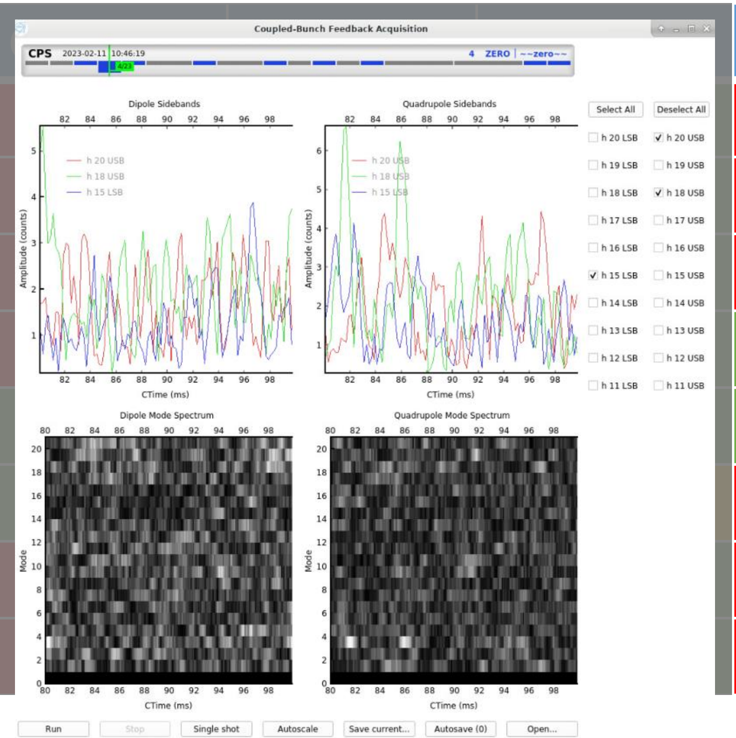
Usage of RF systems, typical issues C200



- C200 (5 + 1 spare)
  - A typical issue is that one cavity trips. It can be difficult to identify as the impact can be subtle (beam slightly more unstable, increased losses, reduced 200 MHz modulation…)
  - The first step is to very whether the cavities are pulsing (PA.VD200 sampler or per cavity PA.C20xVDET on OASIS)
  - Slight operational adjustments of the C200 voltage can be made but only together with systematic verification of longitudinal beam parameters (and not only based on BLMs…).
  - The faulty cavity can also be switched with the spare via the “RF 200MHz Matrix” applications (for a single cycle via the matrix or all users via the Inspector app).

Usage of RF systems, Finemet

Beam	Finemet
TOF	
EAST	
AD	
SFTPRO	
LHC#multib	
LHC#1b	
ION#multib	
ION#1b	



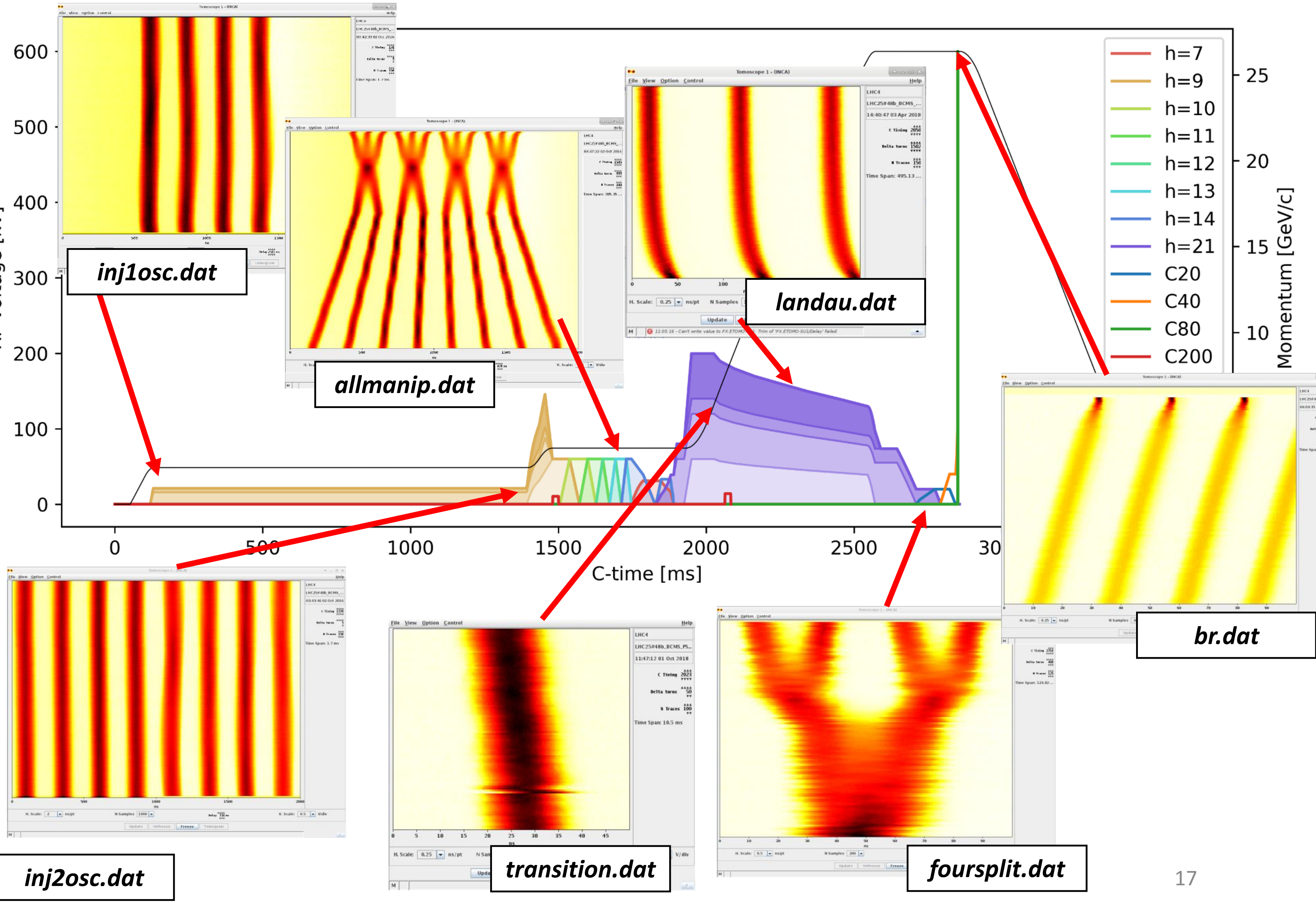
- Finemet (1 cavity, 6 gaps)
  - The main aspect to check is whether the cavities are on via the “HL_ADL” inspector panel.
  - The typical impact on LHC multibunch beams is that RF phases for the triple splitting will have large changes (10s degrees).
  - The cavities are not 100% integrated in nominal operation yet. Expert apps are under development and will require time for operational integration.

Construction of a cycle, RF processes

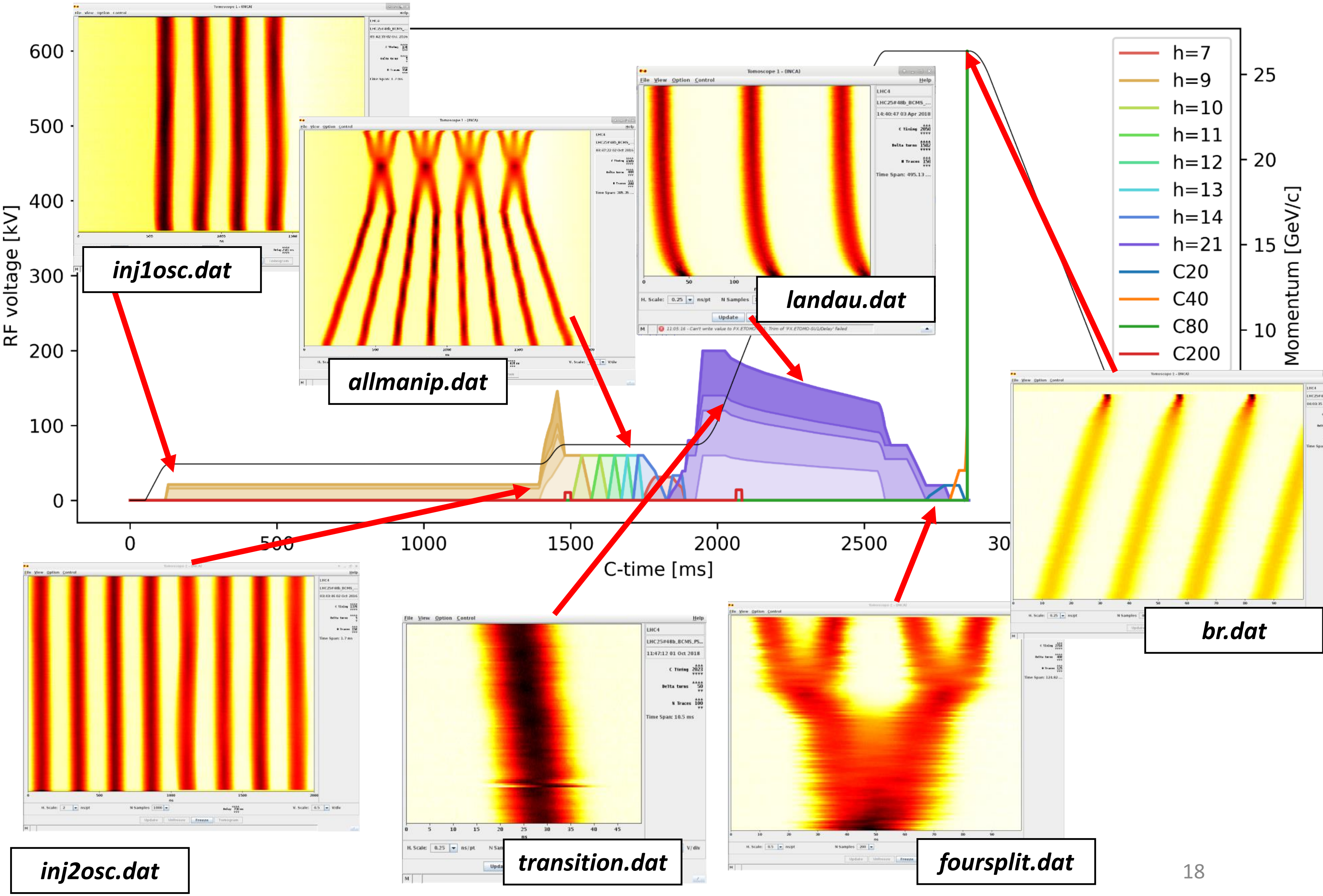
–

Deciphering the music sheet…

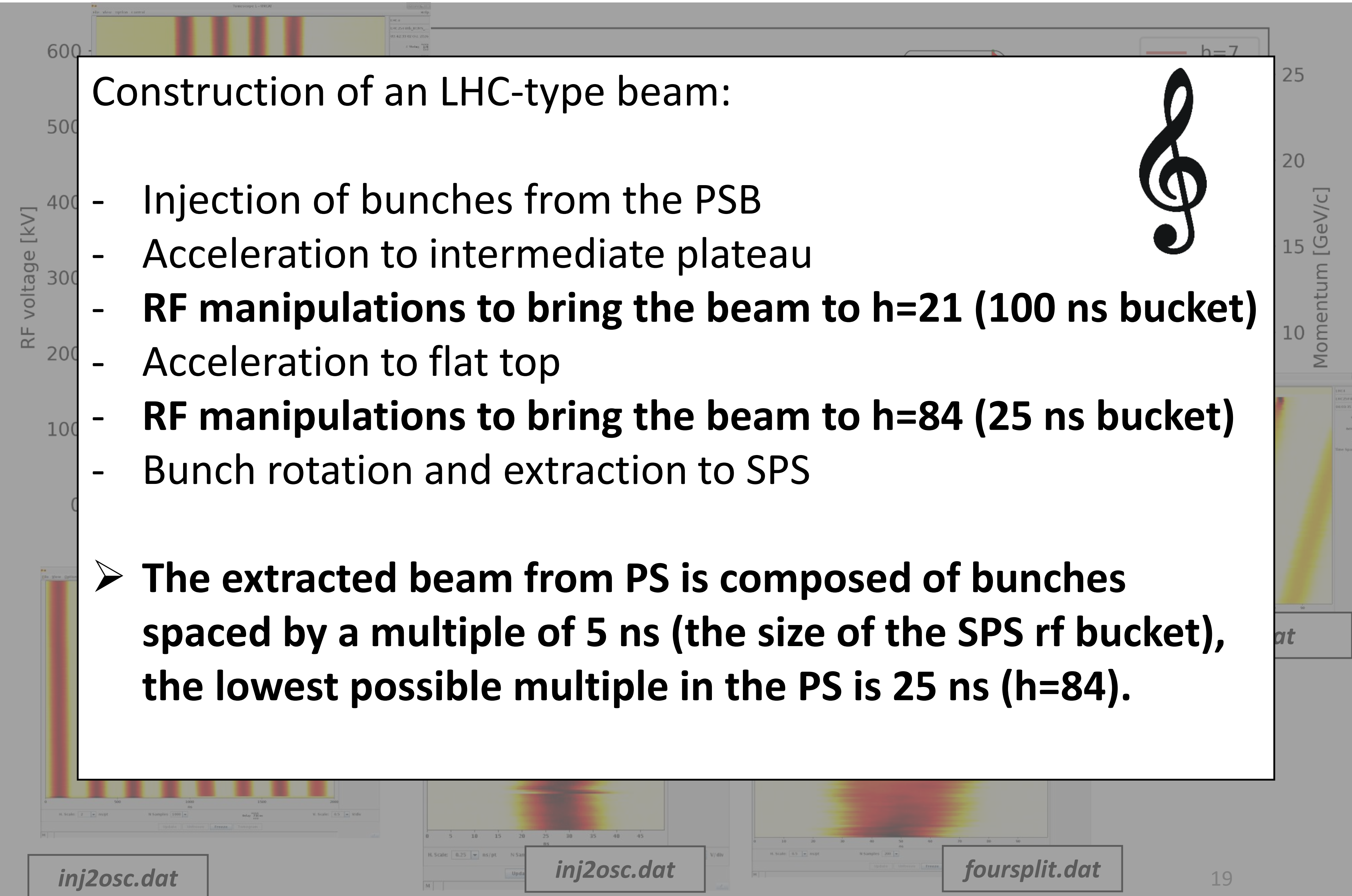
Overview of the BCMS cycle (Tomoscope ref)



Overview of the BCMS cycle (Tomoscope ref)



Overview of all LHC-type cycles

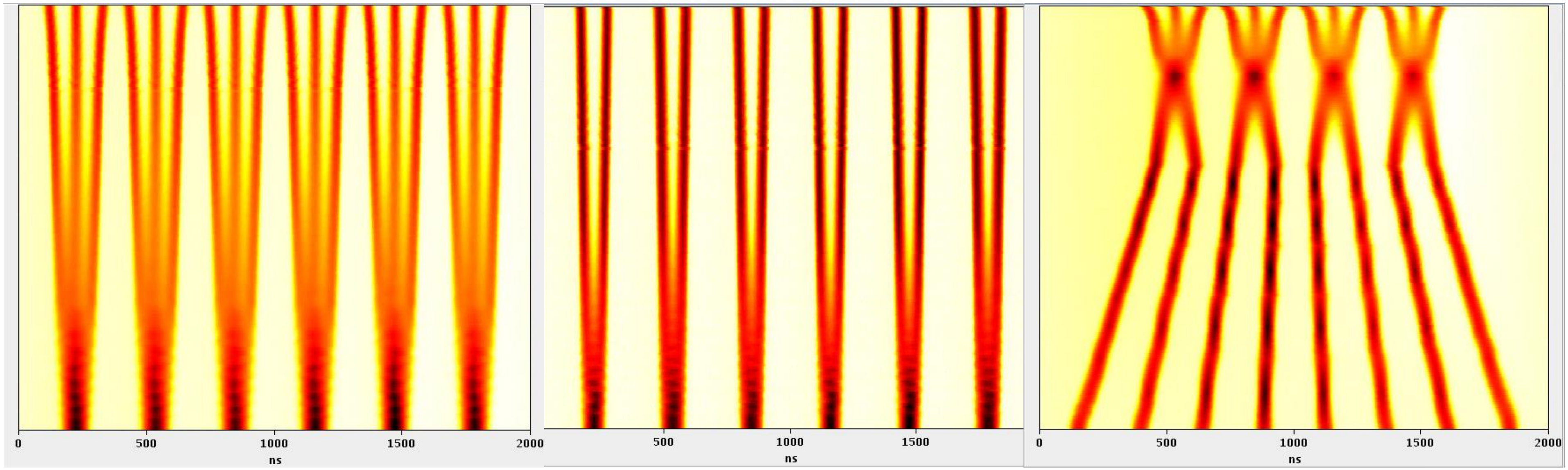


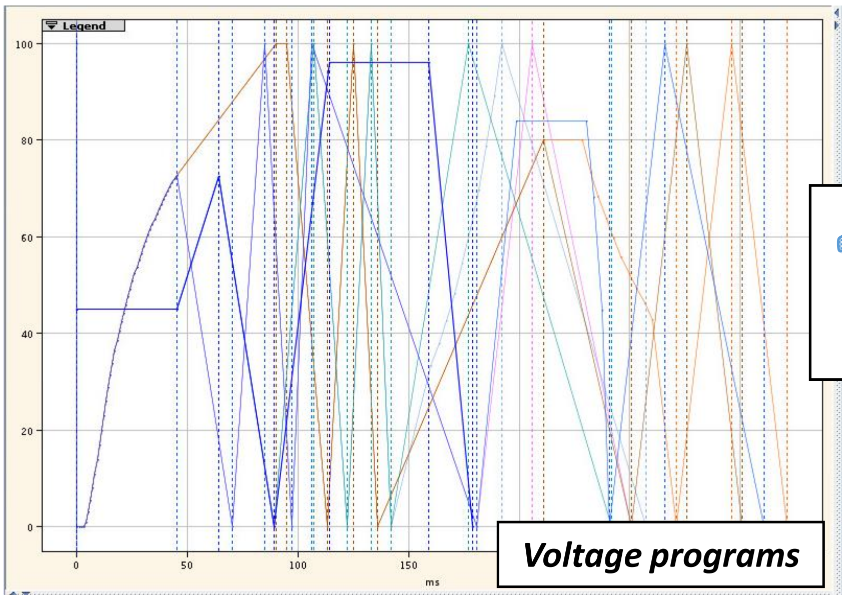
Construction of an LHC-type beam:

- Injection of bunches from the PSB
- Acceleration to intermediate plateau
- **RF manipulations to bring the beam to h=21 (100 ns bucket)**
- Acceleration to flat top
- **RF manipulations to bring the beam to h=84 (25 ns bucket)**
- Bunch rotation and extraction to SPS

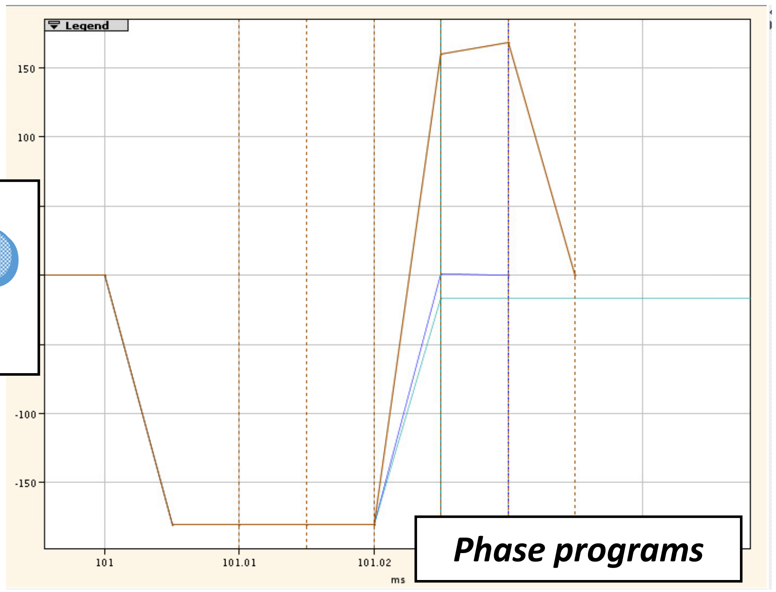
➢ **The extracted beam from PS is composed of bunches spaced by a multiple of 5 ns (the size of the SPS rf bucket), the lowest possible multiple in the PS is 25 ns (h=84).**

Variety of RF manipulations, variety of settings!

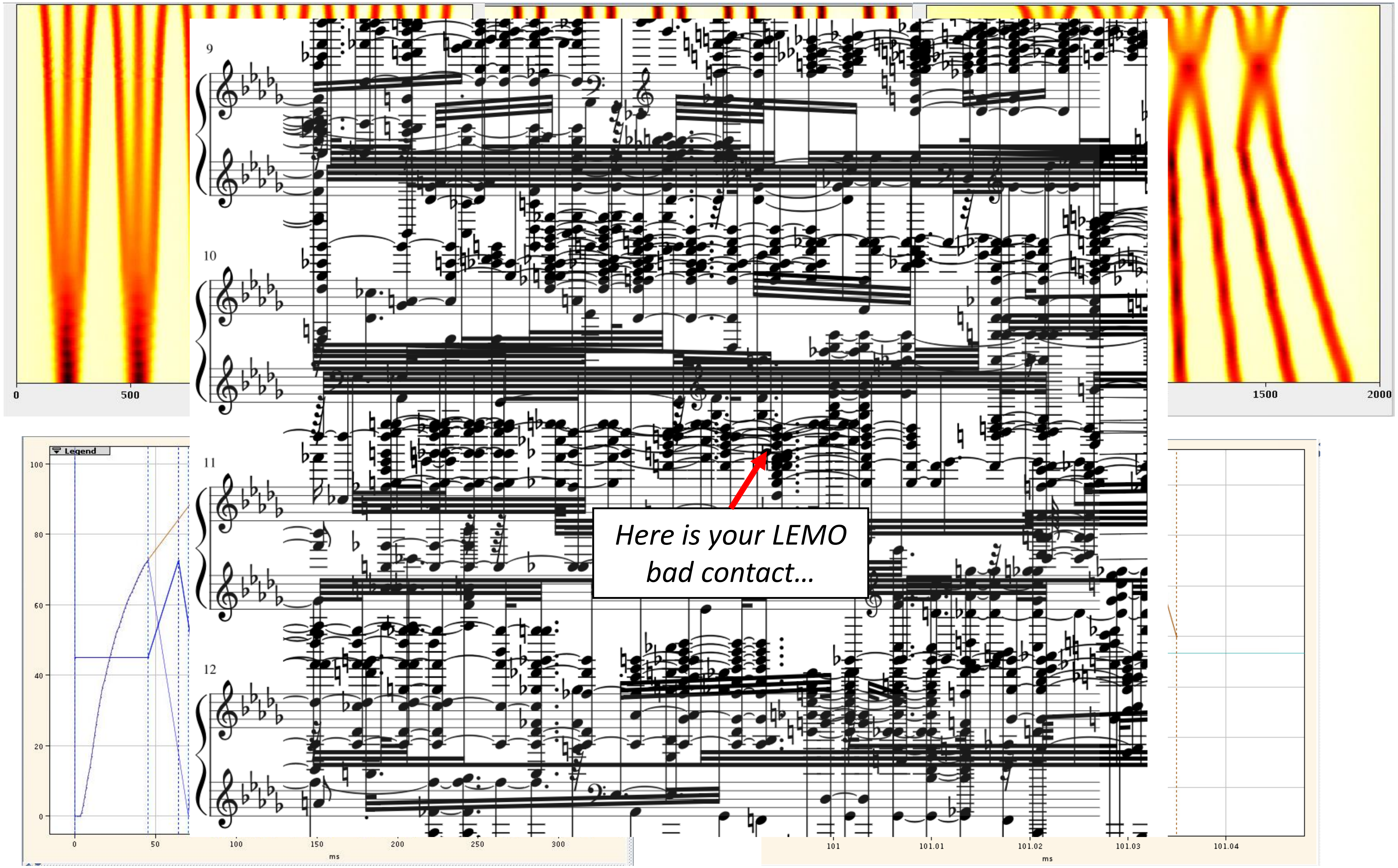




???



Variety of RF manipulations, variety of settings!



Grouping of “10 MHz” RF systems

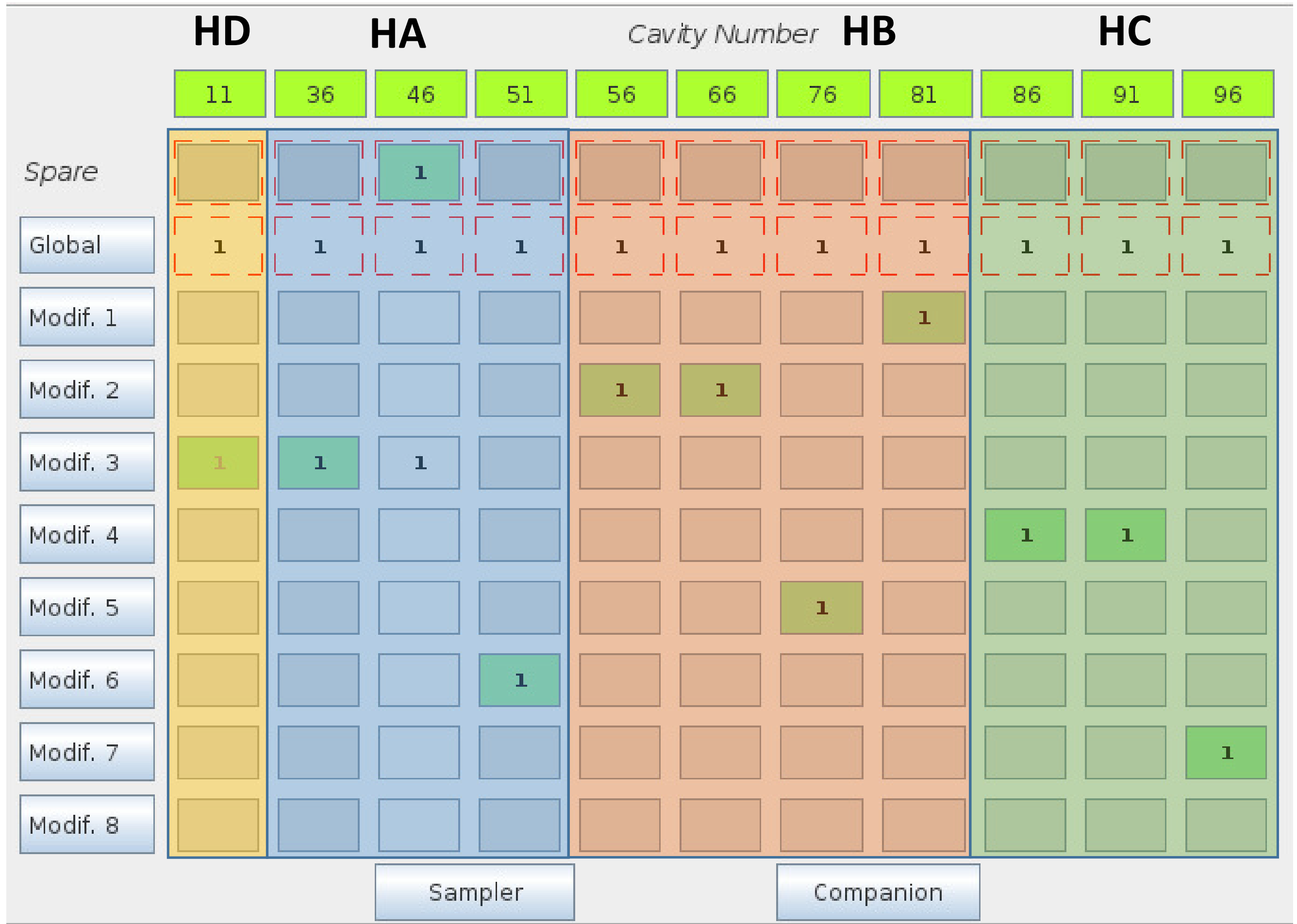
3+1x harmonic groups (tuning circuit hard wired, up to 3x3kA tuning current!)

Cavity tuning from 2.8 MHz to 10 MHz

Up to 20 kV per cavity

8x voltage programs, independent of the harmonic group

C11 as spare cavity to replace any other in case of issue



➢ The voltage program for a cavity is the product of settings:

$$V_{\text{cavity}} = V_{\text{global}} \times V_{\text{reduction}} \times V_{\text{modif}}$$

Timing trees (1)

Timing sequence for triple splitting nominal LHC beam

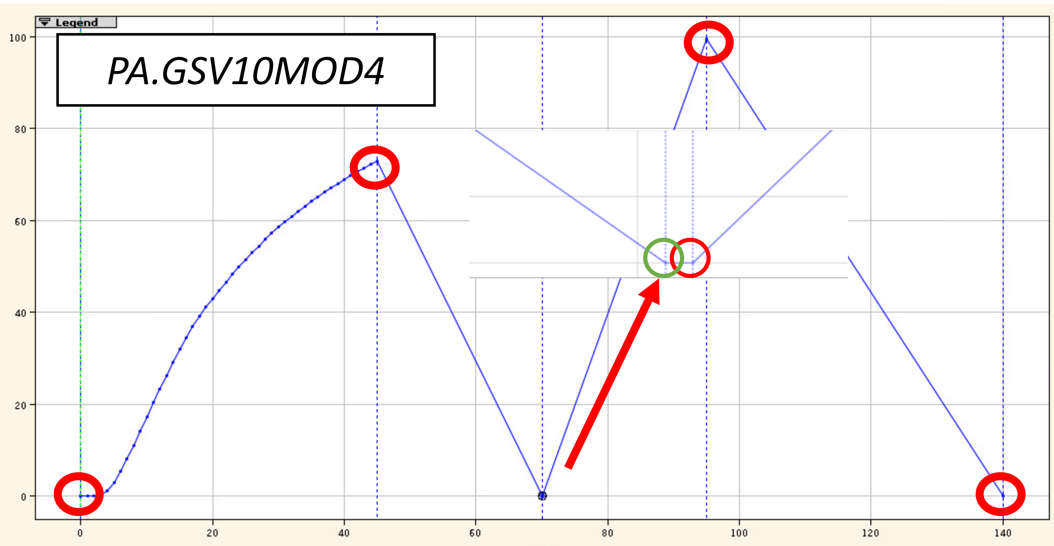
PAX.R2VMOD3	PAX.SH21	1	1,635.0...	1,785.000	-1.000	1,785.000	Permitted	Enabled	Root of triple splitting. Set initial h=7 voltage.
PAX.R2VMOD6	PAX.R2VMOD3	2	0.000	1,785.000	-1.000	1,785.000	Permitted	Enabled	Set initial h=7 voltage.
PAX.R2V10GLOBAL	PAX.R2VMOD3	2	-35.000	1,750.000	Virtual	1,750.000	Permitted	Enabled	Start global voltage reduction.
PAX.R3VMOD3	PAX.R2VMOD3	2	45.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=7 voltage reduction.
PAX.R3VMOD6	PAX.R3VMOD3	3	0.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=7 voltage reduction.
PAX.R3VMOD4	PAX.R3VMOD3	3	0.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=14 voltage.
PAX.R3VMOD7	PAX.R3VMOD4	4	0.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=14 voltage.
PAX.R3VMOD2	PAX.R3VMOD3	3	50.000	1,880.000	-1.000	1,880.000	Permitted	Enabled	Start h=21 voltage increase.
PAX.R3VMOD5	PAX.R3VMOD2	4	-50.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=21 voltage increase.
PAX.R1HPL	PAX.R3VMOD2	4	1.500	1,881.500	-1.000	1,881.500	Permitted	Enabled	Set phase loop offset and switch LOs to h=21.
PAX.R1H1RWHI	PAX.R1HPL	5	0.000	1,881.500	Virtual	1,881.500	Permitted	Enabled	Start h=7 radial position weight decrease.
PAX.R1H2RWHI	PAX.R1H1RWHI	6	0.000	1,881.500	Virtual	1,881.500	Permitted	Enabled	Start h=21 radial position weight increase.
PAX.SPLH21	PAX.R1HPL	5	0.045	1,881.545	-1.000	1,881.545	Permitted	Enabled	Switch to real cavity return.
PX.MP1HCH-TMS	PAX.SPLH21	6	0.000	1,881.545	-1.000	1,881.545	Permitted	Enabled	
PAX.R2HB	PAX.R3VMOD2	4	10.000	1,890.000	-1.000	1,890.000	Permitted	Enabled	Reset h=21 phase prior to acceleration.
PAX.R3HC	PAX.R2HB	5	0.000	1,890.000	-1.000	1,890.000	Permitted	Enabled	Retune group 4 on h=21.
PAX.R2HA	PAX.R2HB	5	0.000	1,890.000	-1.000	1,890.000	Permitted	Enabled	Retune group 3 on h=21.
PAX.R3V10GLOBAL	PAX.R2HB	5	5.000	1,895.000	Virtual	1,895.000	Permitted	Enabled	Start global voltage increase.
PAX.S2PPROG	PAX.R3VMOD2	4	65.000	1,945.000	-1.000	1,945.000	Permitted	Enabled	Restart phase programme.
PAX.R3VMOD1	PAX.R3VMOD2	4	10.000	1,890.000	-1.000	1,890.000	Permitted	Enabled	Start group 1 voltage.
PAX.R4VMOD3	PAX.R3VMOD1	5	35.000	1,925.000	-1.000	1,925.000	Permitted	Enabled	Restart group 3 voltage.
PAX.R4VMOD6	PAX.R4VMOD3	6	0.000	1,925.000	-1.000	1,925.000	Permitted	Enabled	Restart group 6 voltage.
PAX.R4VMOD4	PAX.R3VMOD1	5	35.000	1,925.000	-1.000	1,925.000	Permitted	Enabled	Restart group 4 voltage.
PAX.R4VMOD7	PAX.R4VMOD4	6	0.000	1,925.000	-1.000	1,925.000	Permitted	Enabled	Restart group 7 voltage.

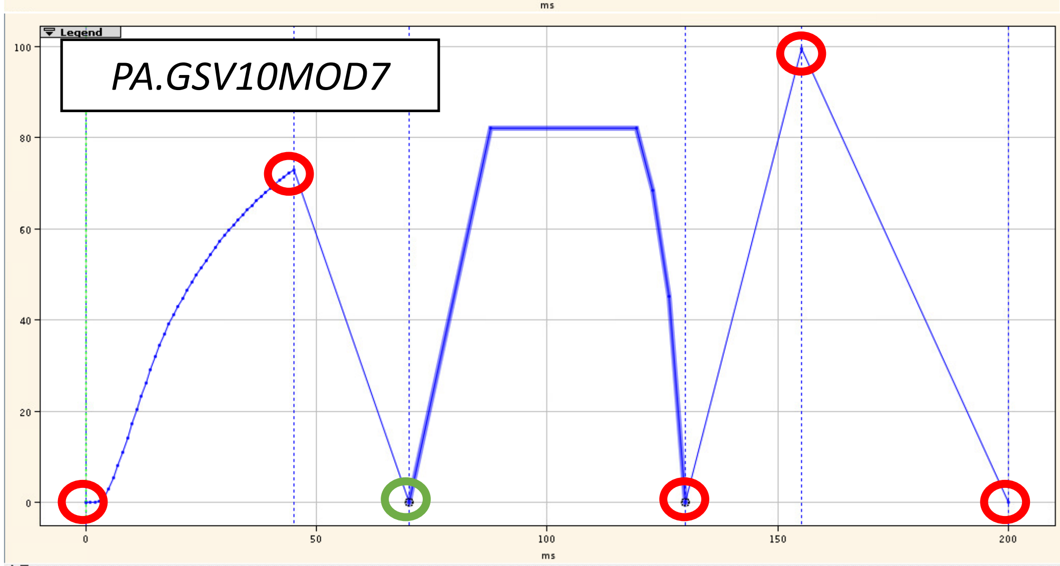
- First identify the timing trees that are “in use” (corresponding to the beam control effectively in use)
- Timings are organized hierarchically and define at which moment voltage programs are started (e.g. start RF manipulation)

Timing trees (2)

Timing sequence for triple splitting nominal LHC beam

PAX.R3VMOD4	PAX.R3VMOD3	3	0.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=14 voltage.
PAX.R3VMOD7	PAX.R3VMOD4	4	0.000	1,830.000	-1.000	1,830.000	Permitted	Enabled	Start h=14 voltage.





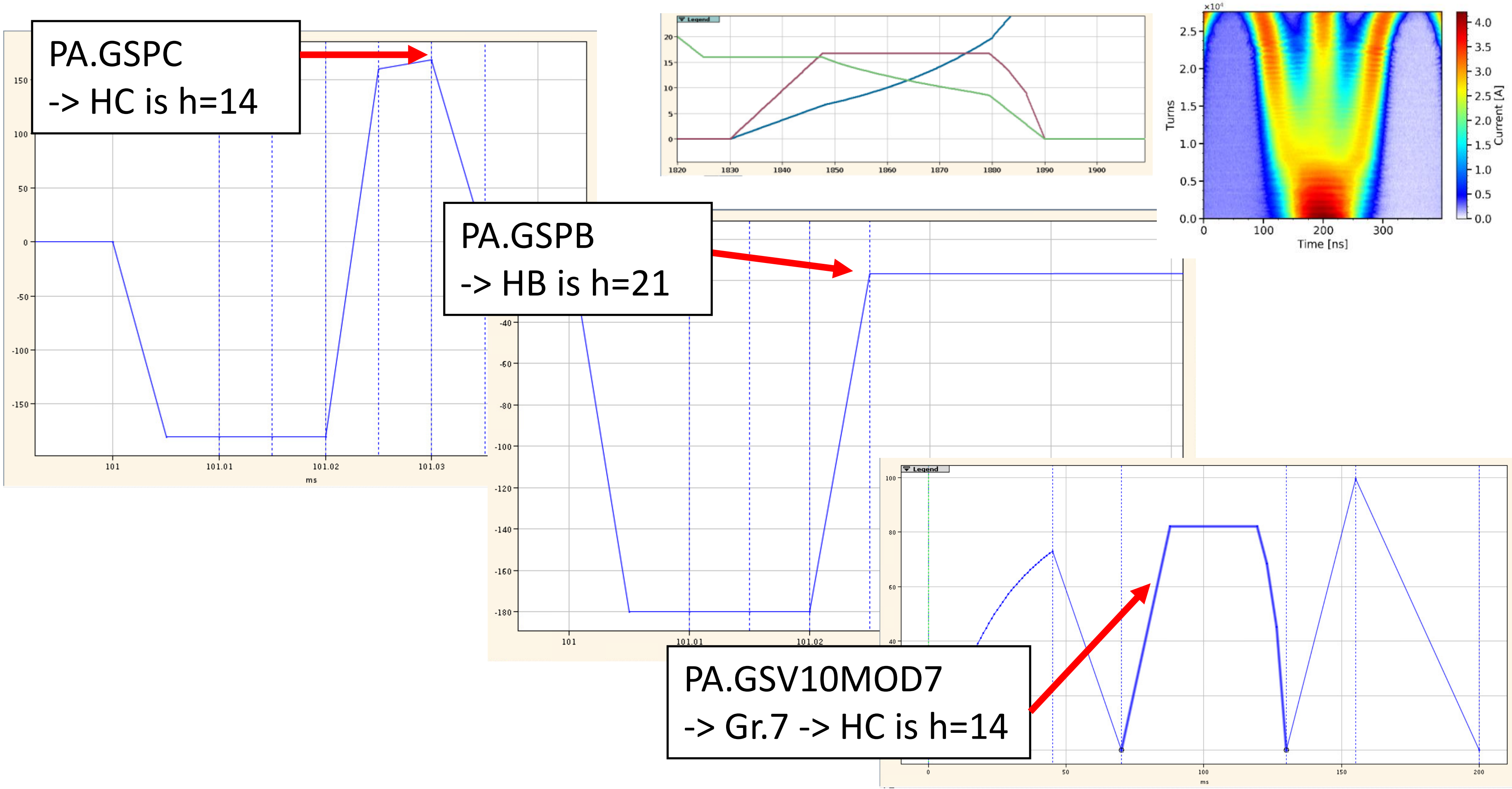
- Let's find which voltage should be adjusted for the triple splitting at h=14.

➢ Cavities of the voltage group 4 are going to play 0 V (these timings are kept should we need more voltage!)

➢ Cavities of the voltage group 7 are going to play the triple splitting voltage program (effectively a single cavity)

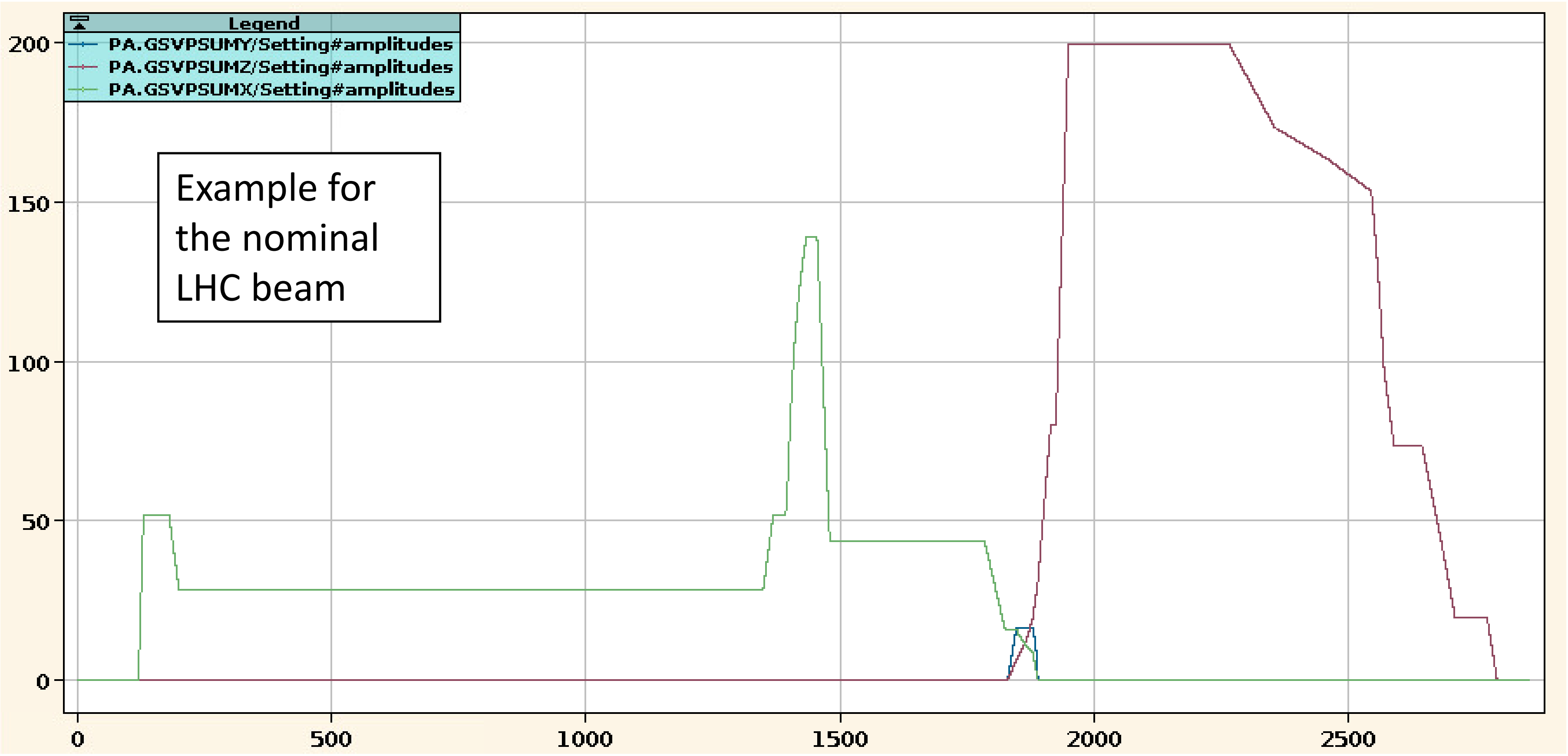
(NB: this function is available in the LL_MD workingset)

Adjusting the settings for the triple split.



- Two questions to practice until next time:
  - Where is the phase setting to adjust the merging?
  - Can you verify how we go from 36b to 48b BCMS by switching the RF phases?

Real time and per cavity functions



- Real time functions are available noted with the “RT” suffix, as well as function per cavities (PA.GSVPCxx, PA.GSRPCxx, PA.GSHCxx…).
- Processed samplers per harmonic show the effective total voltage (in CPS:RF-TREATED-BY-H workingset).
- The final voltage program per RF harmonic is available in the PA.GSVPSUMX-Y-Z functions.

RF processes and setting up across beams

Process	TOF	EAST	AD	SFTPRO	LHC#multib	LHC#1b	ION#multib	ION#1b
Injection1 (inj. phase, voltage, energy matching)	*-VJBR* BUP	BUP	BUP	(BUP)				
Injection2 (idem)					BUP, FSteer			
Intermediate plateau	BUP	BUP		Split, BUP	BC, Merge, Split, BUP	(BUP)	BE, Split, BUP	RB, BUP
Transition crossing	Phase jump amplitude + timing							
Ramp	HD	HD	HD, BUP	HD, BUP	HD, BUP, CBFB	HD		
Synchronization			Fine	H1H16	Coarse Fine	Coarse	Coarse Fine	Coarse Fine
Top energy			BC	(MTE)	Split	RB	RB, (BC)	RB
Extraction 1	PJBR -PJBR	PJBR -PJBR	PJBR	200MOD BB	VJBR	VJBR	AS	AS
Extraction 2	PJBR	PJBR2						

VJBR: (-Anti) Voltage jump bunch rotation
BUP: Long. blow-up
HD: Hereward damping
RB: Rebucketting ***BB: Barrier Bucket***

PJBR: (-Anti) Phase jump bunch rotation (2 osc. periods)
BC(E): Batch Compression (Expansion)
CBFB: Coupled bunch feedback
AS: Adiabatic shortening ***GREEN: at least 1 ref acq.***

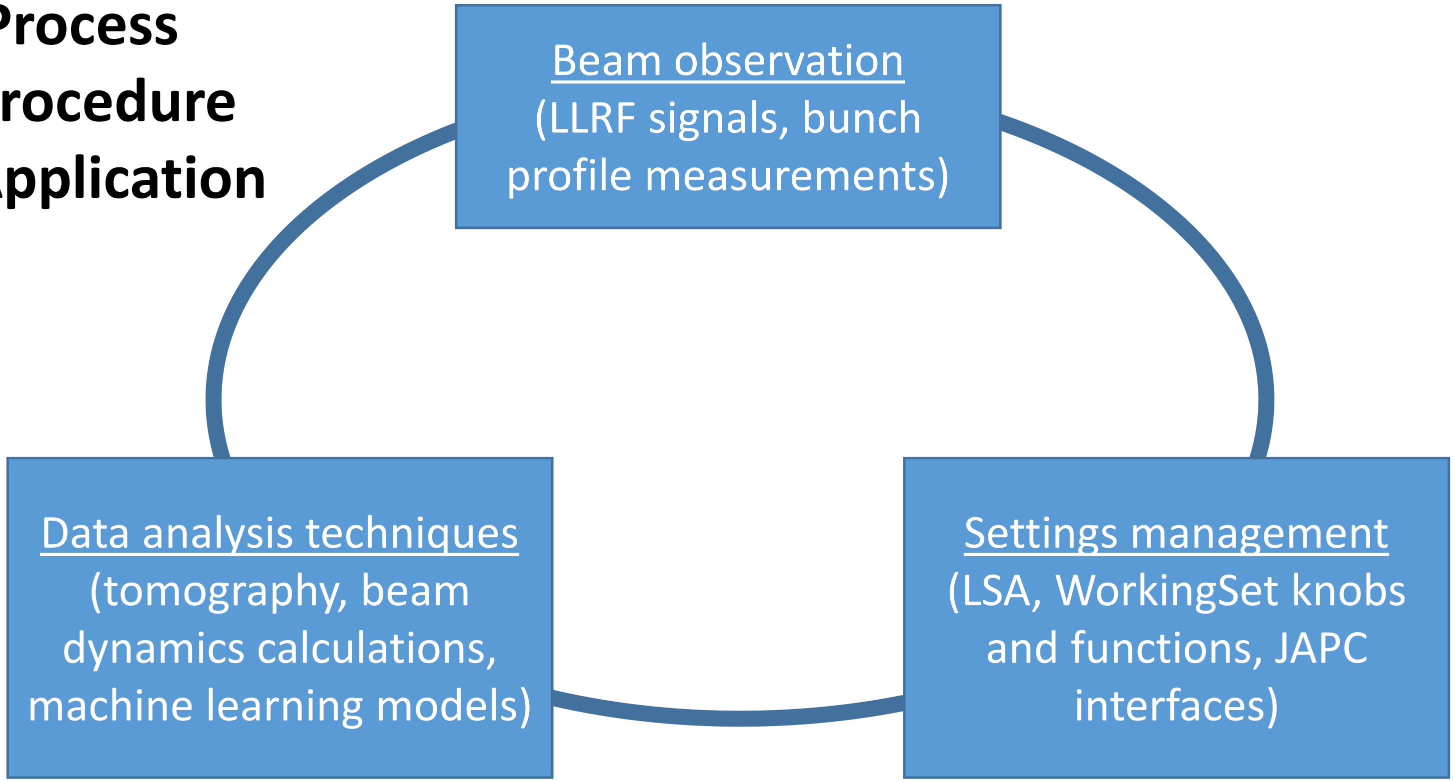
Operational adjustments

–

Tuning violins with various tools…

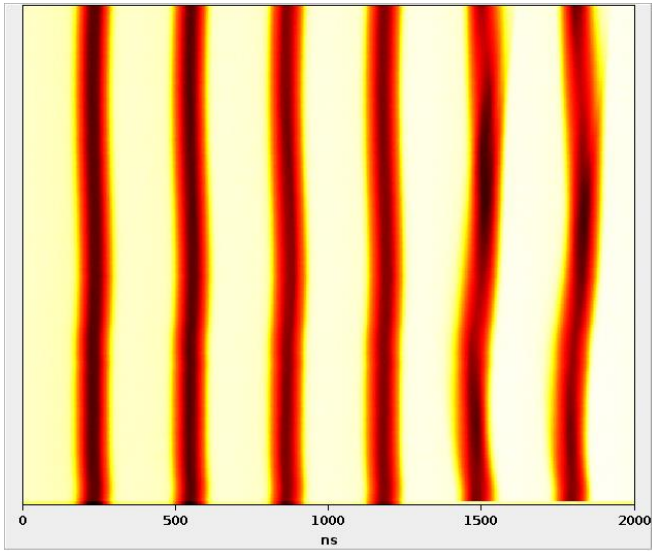
General model for settings adjustments

RF Process
-> Procedure
-> Application

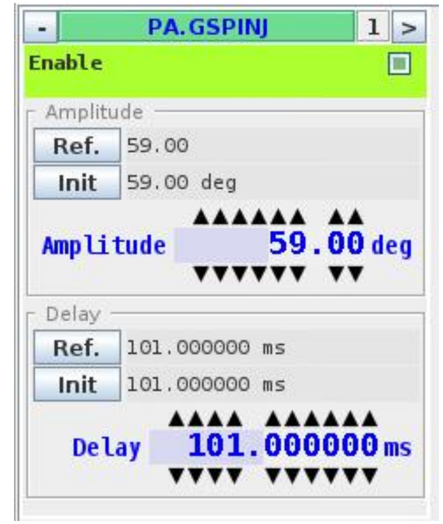


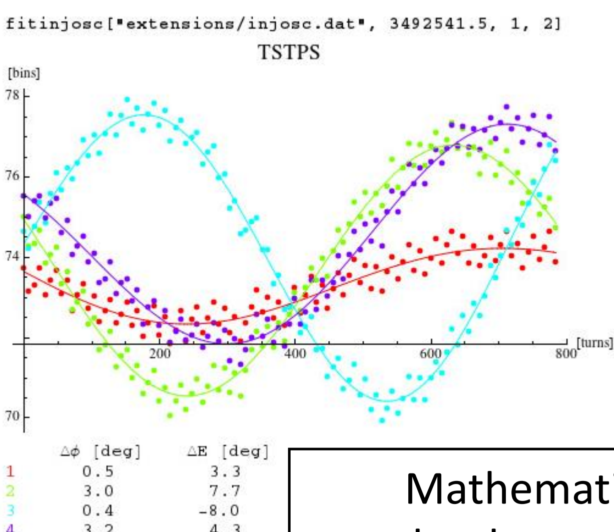
- Let’s check for some cases how you would optimize
  - Injection oscillations
  - Energy matching
  - Splittings
  - Synchronization

Injection oscillations, phase oscillations

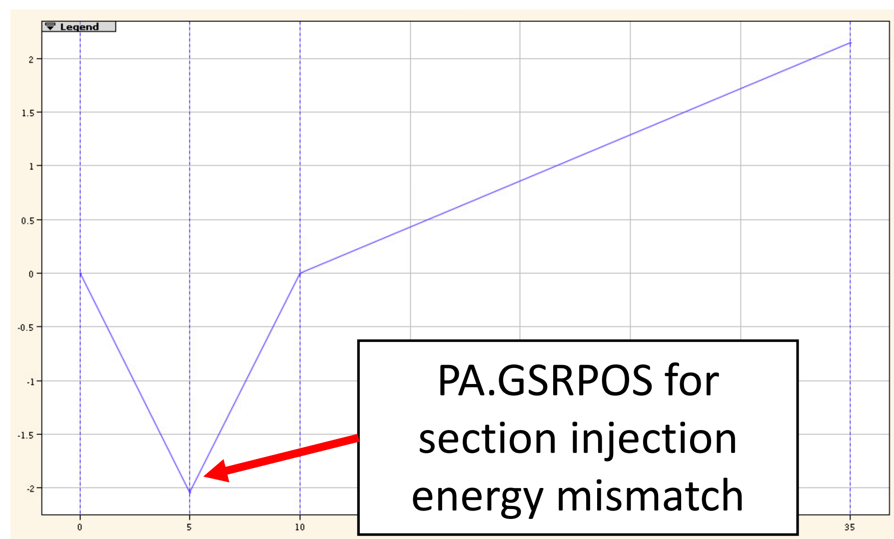


PA.GSPINJ for all bunches phase offset



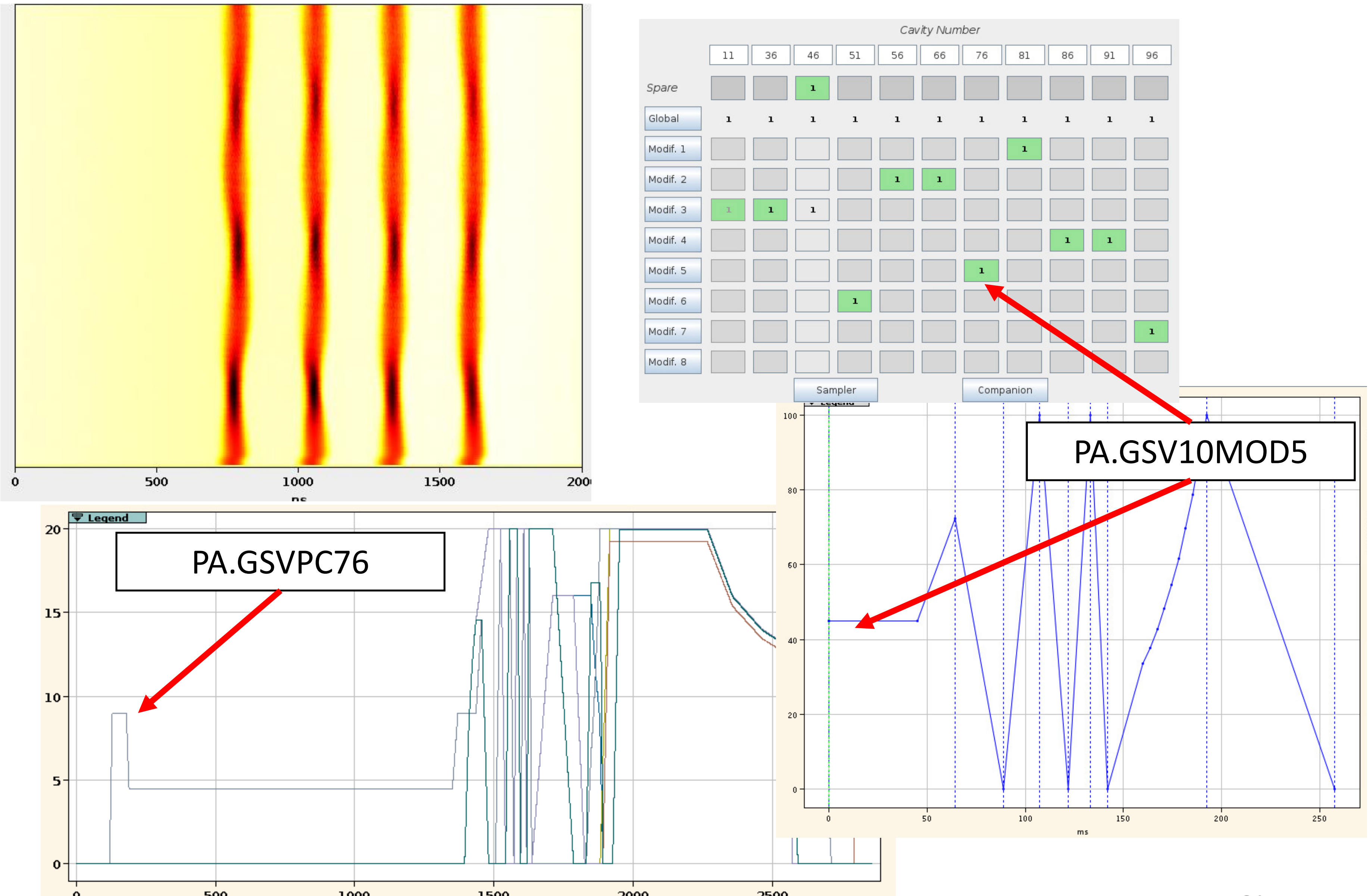


Mathematica notebook to compute expected phase

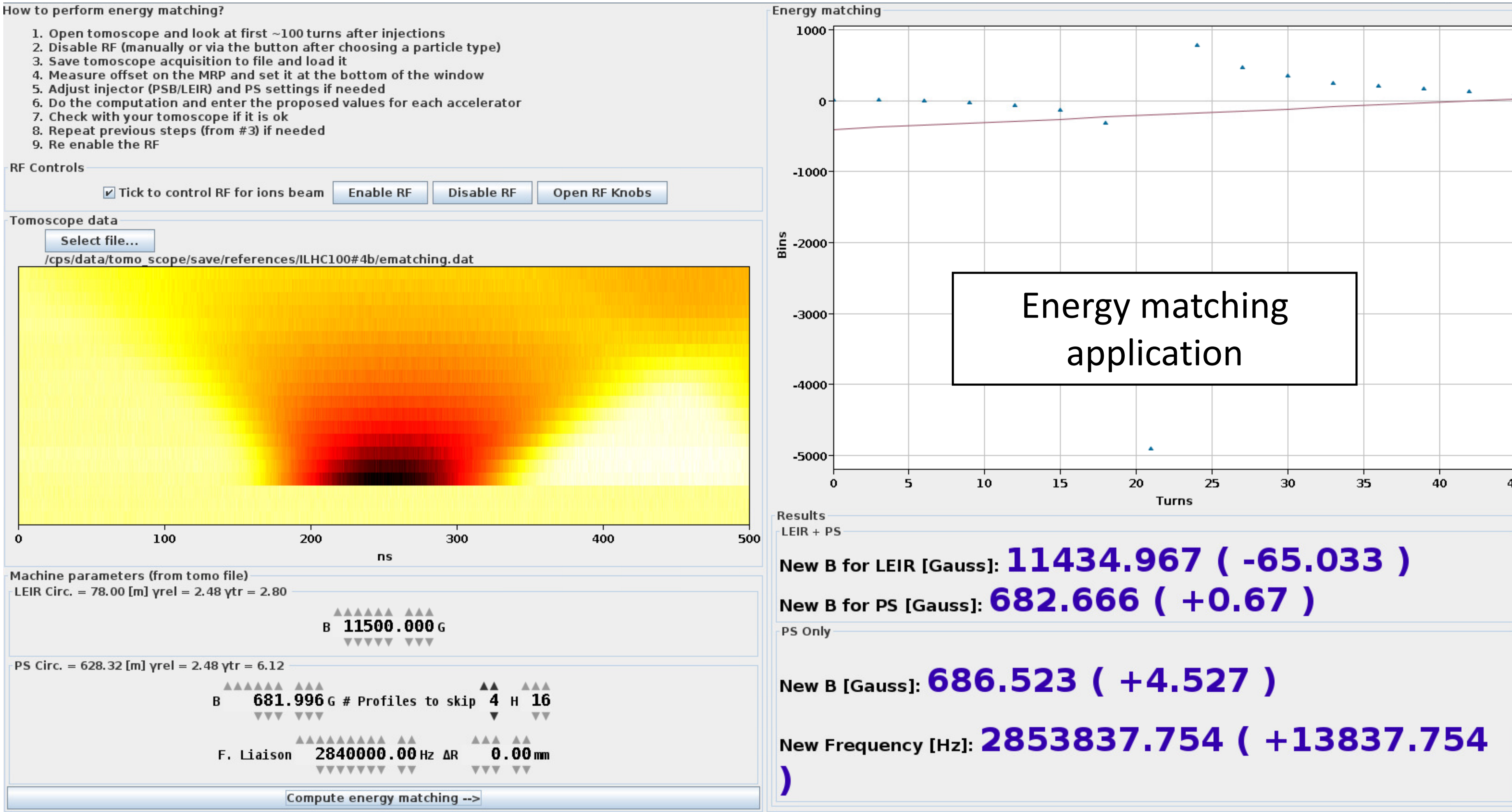


PA.GSRPOS for section injection energy mismatch

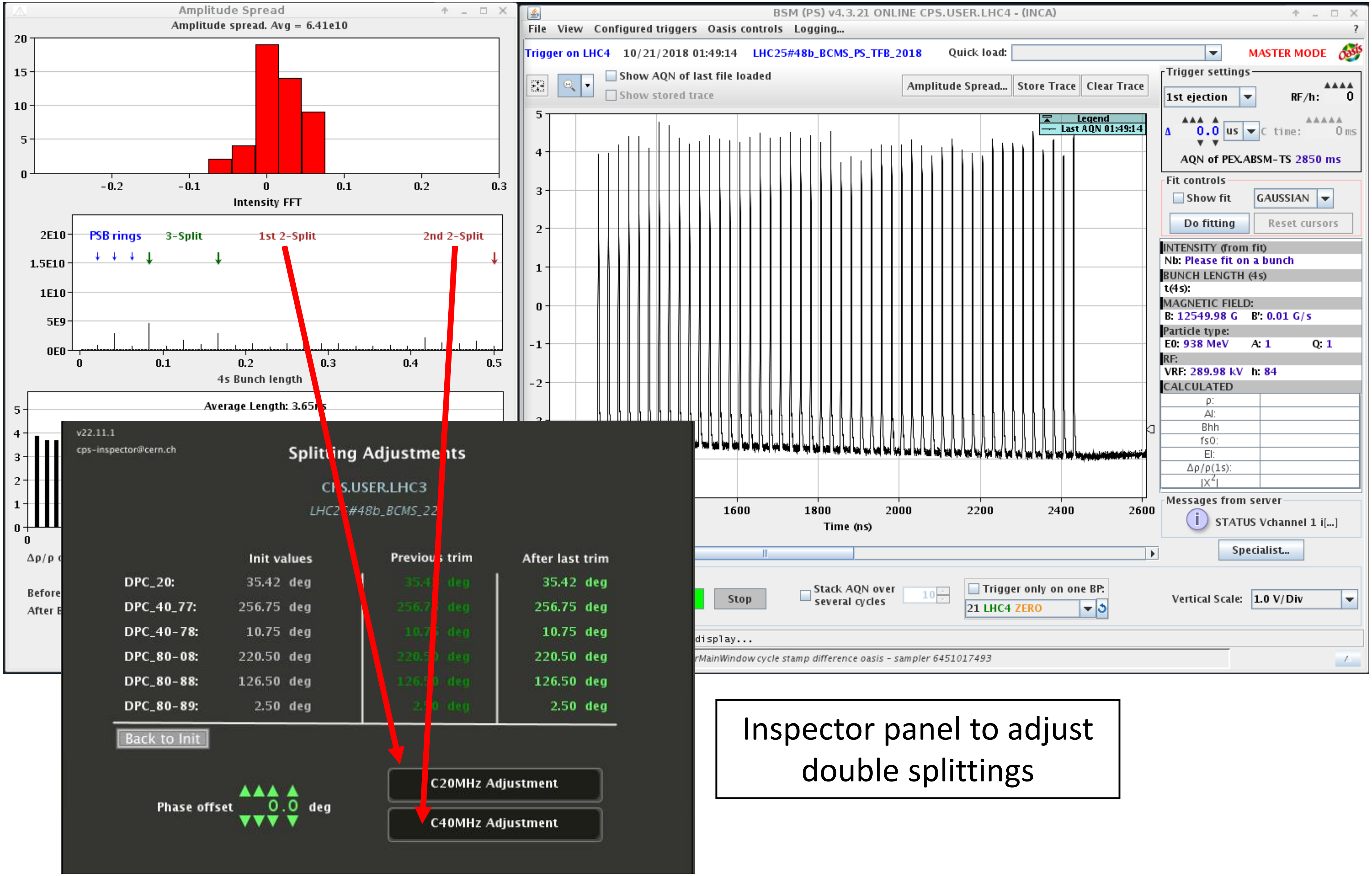
Injection oscillations, amplitude oscillations



Energy matching

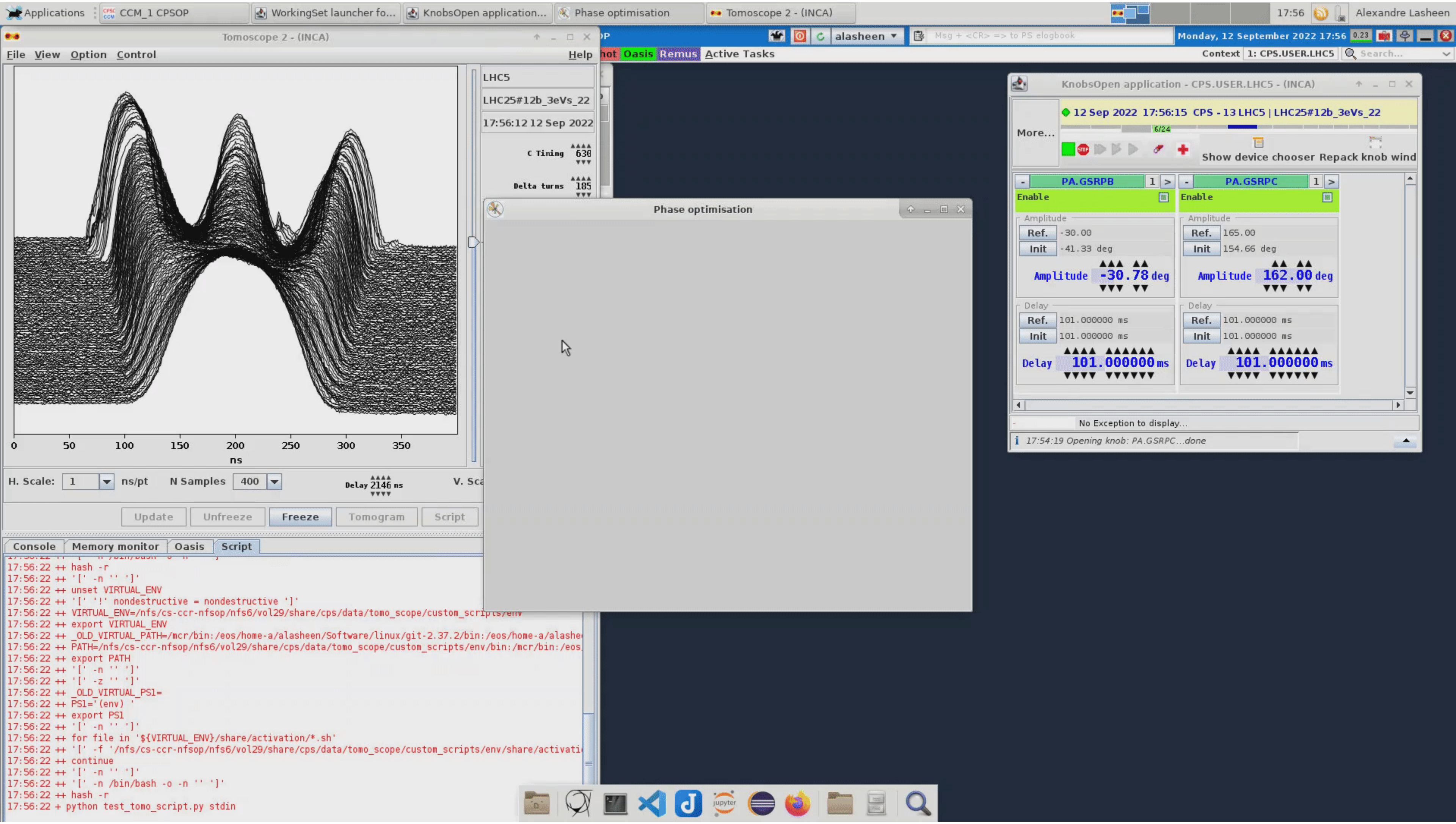


Double splittings adjustments



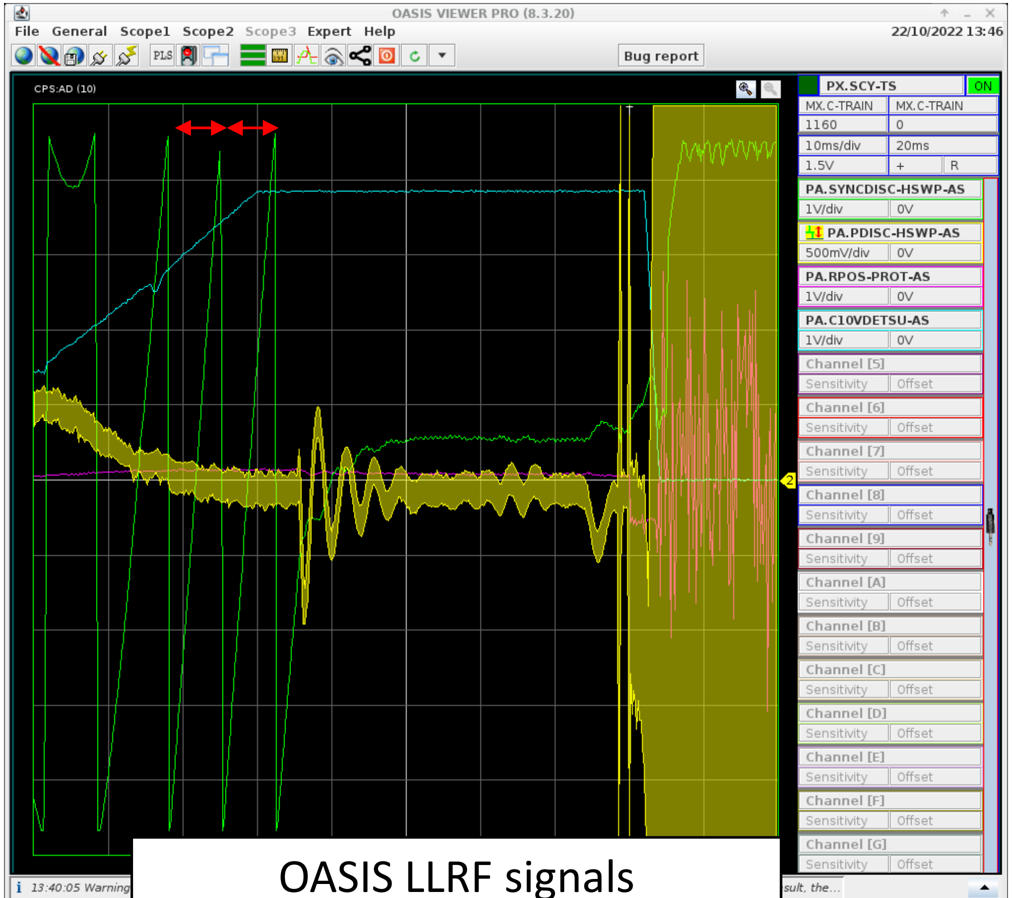
Inspector panel to adjust double splittings

RL applied to triple splitting

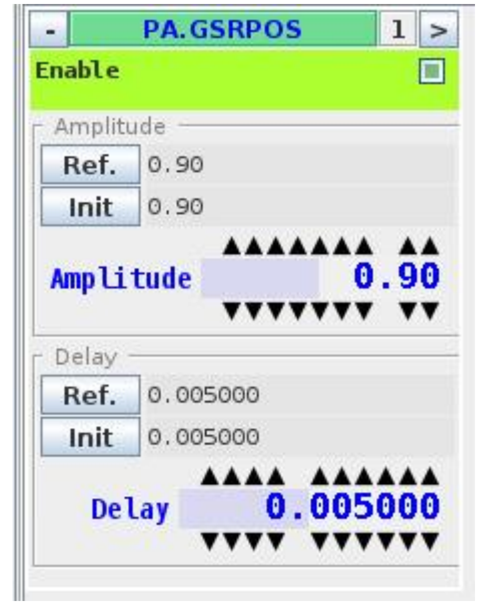


[J. Wulff, User instructions for running Automatic Splitting Optimization scripts - CodiMD (cern.ch)]

Synchronization



OASIS LLRF signals (PA.SYNCDISC or via global)



Changing radial placing to adjust synchro phase sweep

Present limitations for adjustments

RF Process
-> Procedure
-> Application

<u>Beam observation</u>
(LLRF signals, bunch profile measurements)

- Not permanently available
- Limited availability
- Difficult to set-up

<u>Settings management</u>
(LSA, WorkingSet knobs and functions, JAPC interfaces)

- Difficult to visualize
- Difficult to identify relevant parameters
- Different entry points for adjustments
- Reference settings difficult to determine

<u>Data analysis techniques</u>
(tomography, beam dynamics calculations, machine learning models)

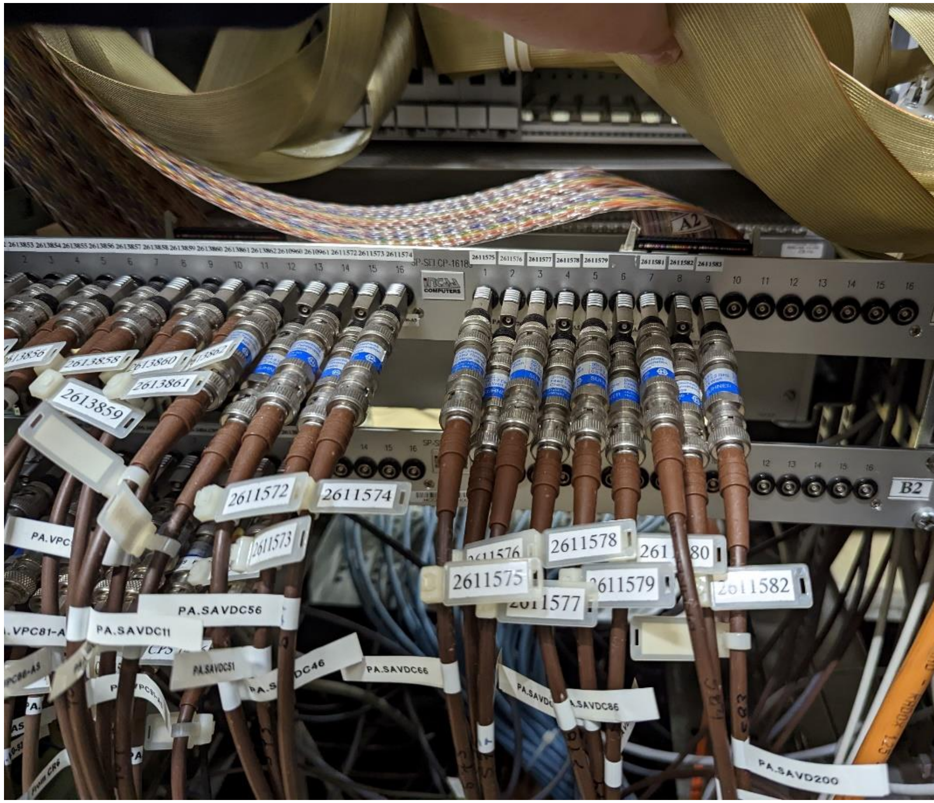
- Expert scripts (black boxes)
- Various scripting languages (fortran, mathematica, python)

What’s next?

–

From the analog to digital Stradivarius…

Installation of new LLRF Samplers



OASIS signal name	Duration	Signal source	Priority
PA.PDISC-H8H16-AS	Whole cycle	CR30-4/11 - CMR Buffer 5	1
PA.PDISC-H16LI-AS	Whole cycle	CR30-4/10 - CMR Buffer 2	1
PA.PDISC-HSWP-AS	Whole cycle	CR30-4/10 - CMR Buffer 7	1
PA.PDISC-LHC-AS	Whole cycle	CR6-1/11 - CMR Buffer 2	1
PA.PDISC-ION-AS	Whole cycle	CR30-4/12 - CMR Buffer 5	1
PA.PDISC-H42-AS	Flat top	CR6-1/11 - CMR Buffer 3	2
PA.PDISC-H84-AS	Flat top	CR6-1/11 - CMR Buffer 4	2
PA.PDISC-H169-AS	Flat top	CR30-4/12 - CMR Buffer 6	2

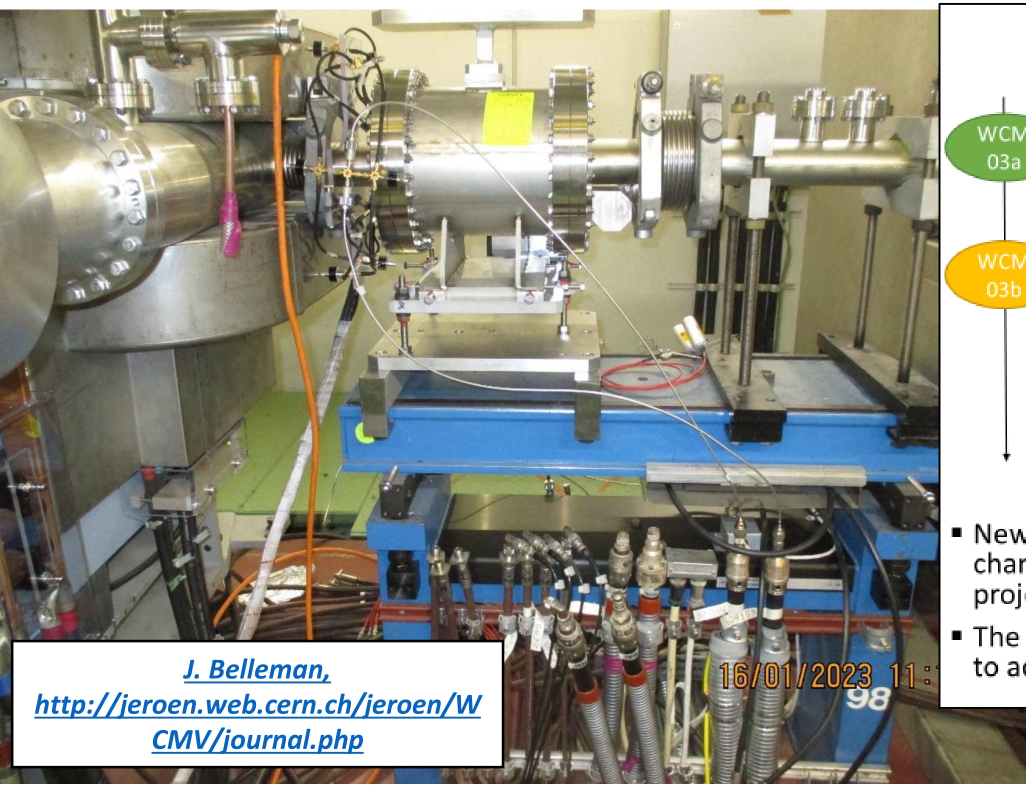
OASIS signal name	Duration	Signal source	Priority
PA.RPOS-PROT-AS	Whole cycle	CR30-4/12 - CMR Buffer 1	1
PA.RPOS-H16LI-AS	Whole cycle	CR30-4/11 - CMR Buffer 1	1

OASIS signal name	Duration	Signal source	Priority
PA.C10VDETSU	Whole cycle	CR28-1/5	1

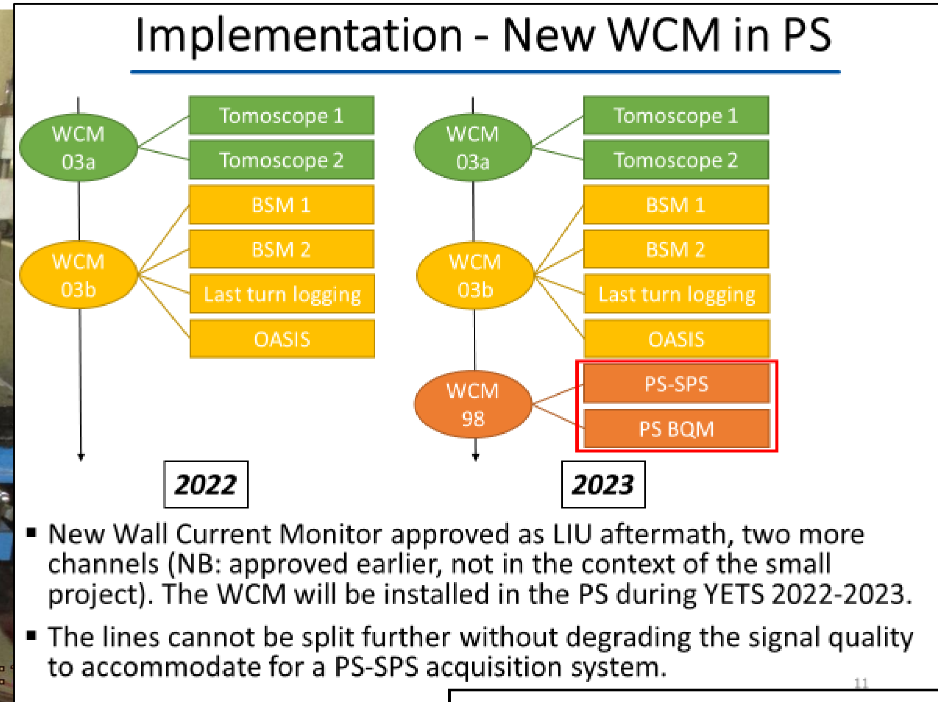
- Cavity voltage programs presently well covered by samplers.
- Low level RF signals are presently only available through OASIS which is not suited for online monitoring of signals.
- Aim at simplifying the maintenance and instructions for operational adjustments and optimization.

New Wall Current Monitor

???



[J. Belleman, http://jeroen.web.cern.ch/jeroen/WCMV/journal.php](http://jeroen.web.cern.ch/jeroen/WCMV/journal.php)



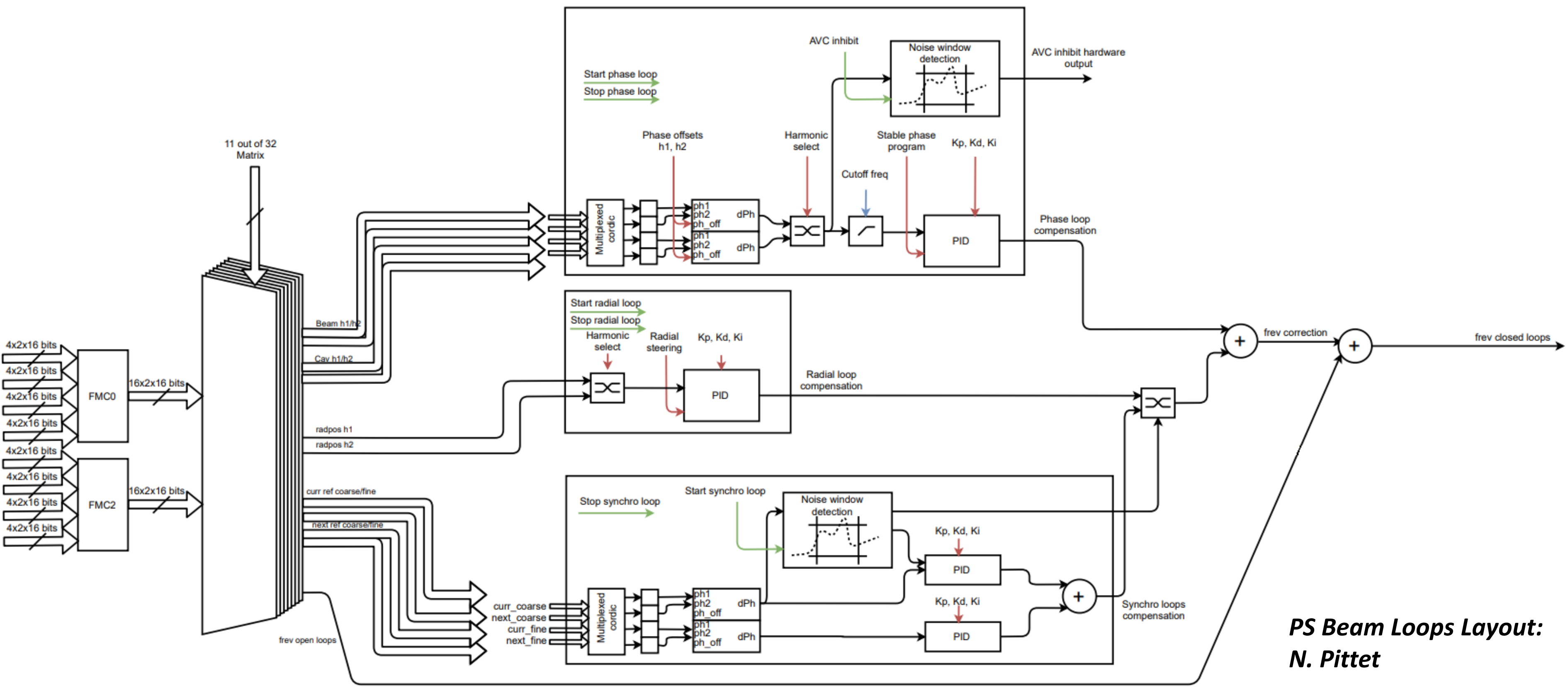
Injectors Performance Panel: Mini workshop on KPIs (29 April 2022) · Indico (cern.ch)

- New WCM install in SS98 in view of development for a PS Beam Quality Monitor.

- Together with a upgrade of all digitizer cards by BE-CEM (Tomoscope, BSM, last turn logging…), will require further developments to allow for more systematic data acquisition and analysis.

Digital beam control

???

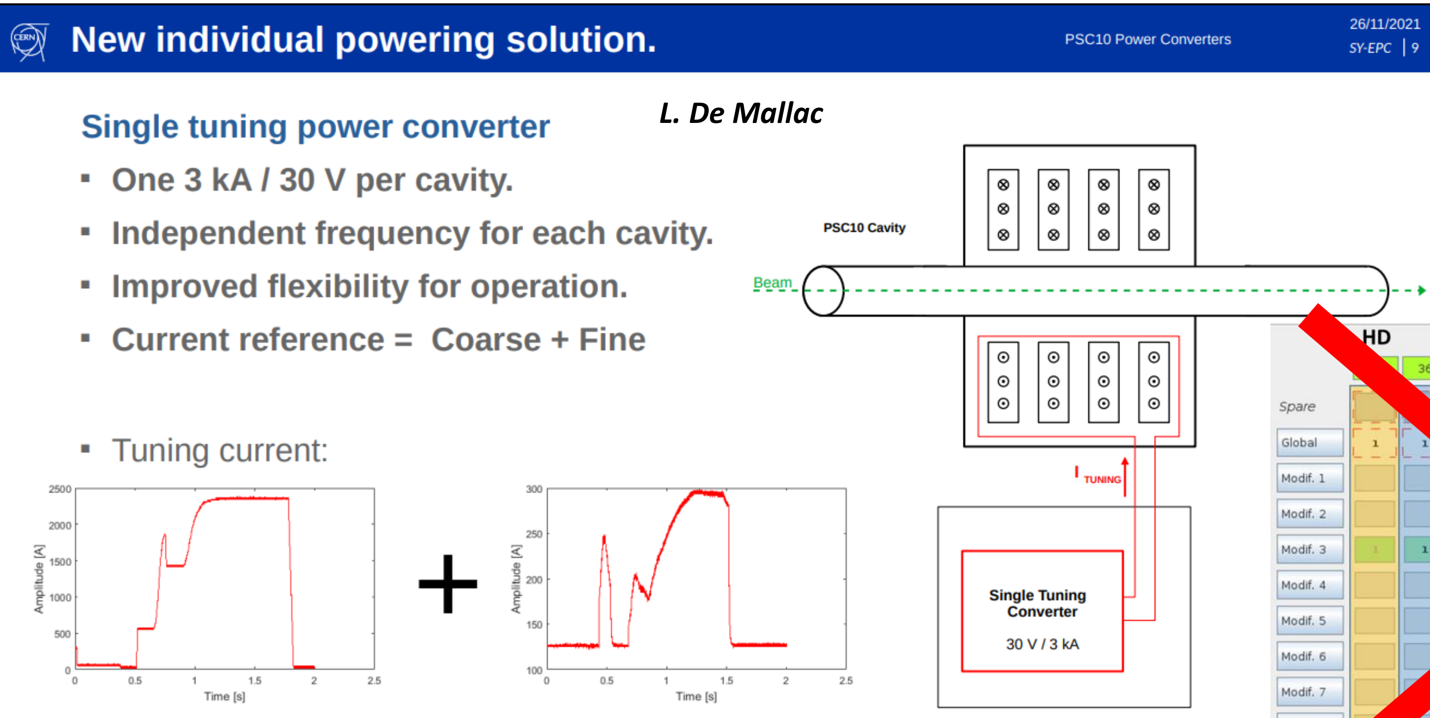


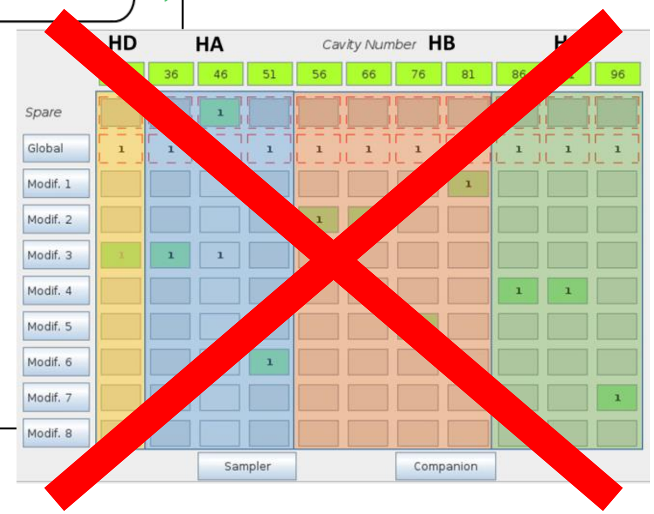
PS Beam Loops Layout: N. Pittet

- Digital beam control under development to be tested during the Run.
- Full operational implementation will require a whole new set of settings (controllable loop gains), procedure for operational adjustments…

New power converters for C10 tuning

???





- Present power converters reaching end of life, requires consolidation and installation during LS3.
- Present proposal to have single tuning power converter will give ultimate flexibility for operation, ease of implementation of high level parameters

[SY Technical Meeting - PS RF consolidation (30 September 2021) · Indico (cern.ch)]
[SY Technical Meeting - PS 10MHz (26 November 2021) · Indico (cern.ch)]

Final words

- The adjustment of RF parameters in the PS is a daily challenge. A full setting up and qualification or a beam requires experience, time and usage of heterogeneous environment.
- Future hardware changes will change in depth the mode of operation of RF systems in the PS. A review of the settings, observables, applications is needed in preparation for these changes.
- A review would also be necessary to address present issues and bottlenecks (update WorkingSets, missing Makerules, needs for permanent signals and online data analysis, interfacing with other machines…).
- This would also be an approach to consolidate knowledge and provide feedback on means to improve PS RF operation
An RF process a day, keeps the RF expert away…