RF Commissioning with Beam

P. Baudrenghien AB/RF

Part 1: Numbering the bunches

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LEADE WG on May 7, 2007

Numerology (1)

- For each ring:
  - The 400 MHz RF defines 35640 buckets, spaced by one RF period, and numbered from 1 to 35640
  - Convention (proposed): Bucket 1 is the first bucket after the 3 μs long abort gap (defined from bucket 34442 to 35640)
  - Convention (proposed): For the instrumentation to work, the first (maybe only) bunch must be in bucket 1
  - For 25ns operation the bunches will occupy buckets 1, 11, 21 etc. with gaps occurring every PS or SPS kicker gap. For 43 bunch operation the bunches will occupy buckets 1, 811, 1621, etc. (see LHC-OP-ES-0003 rev 1.0 for the different schemes).

Numerology (2)

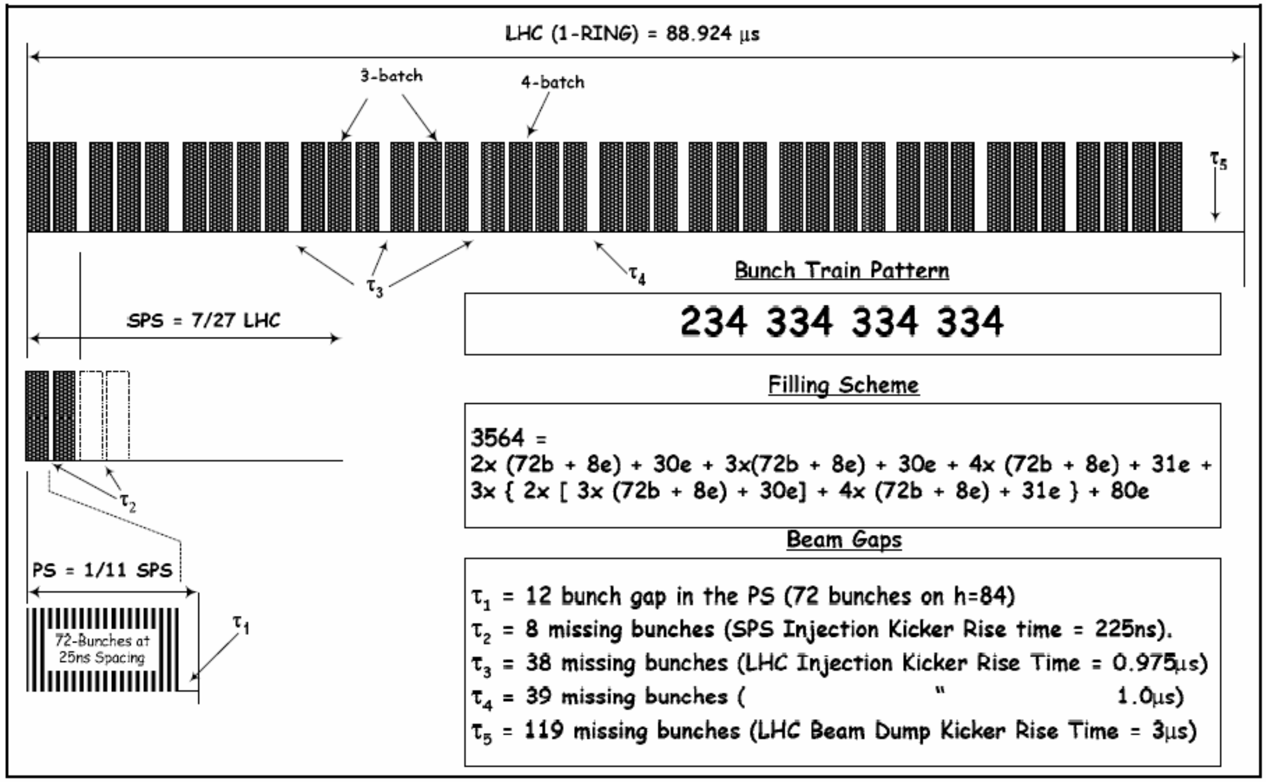


Figure 1: Schematic of the Bunch Disposition around an LHC Ring for the 25ns Filling Scheme (2808 Bunches/Ring).

- For 25ns operation the bunches will occupy buckets 1, 11, 21 etc. with gaps occurring every PS or SPS kicker gap. (see Figure 1 above reproduced from *LHC-OP-ES-0003 rev 1.0*).

Numerology (3)

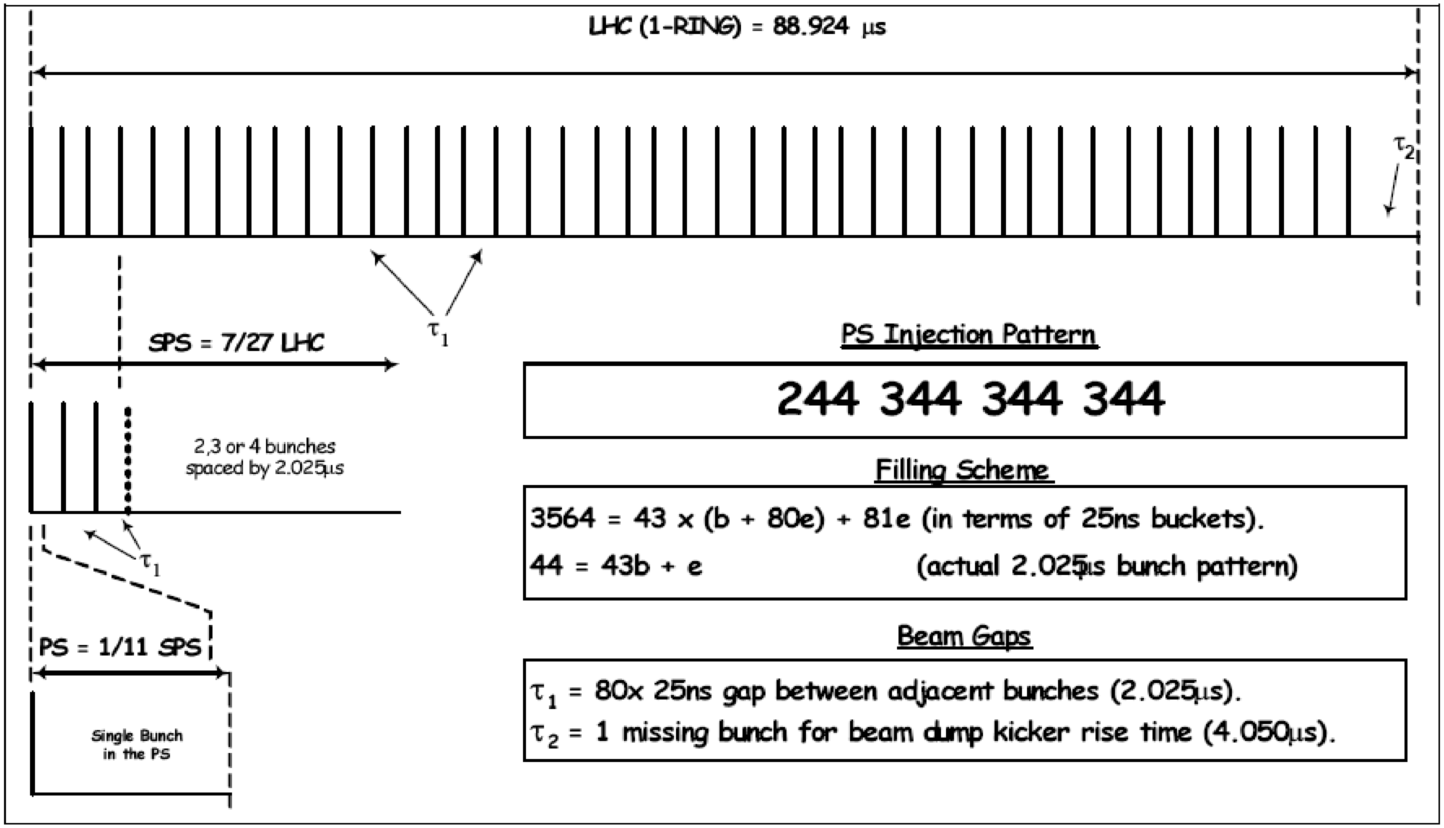


Figure 3: Schematic of the Bunch Disposition for the 43-Bunch Filling Scheme (43 Bunches/Ring).

- For 43 bunch operation the bunches will occupy buckets 1, 811, 1621, etc. (see Figure 3 above reproduced from *LHC-OP-ES-0003 rev 1.0*).

Revolution Frequency or Orbit

- For each ring:
  - The revolution frequency (Frev or orbit) is a train of pulses, with one 5 ns long pulse per turn. This pulse points to bucket 1. The revolution frequency is obtained by dividing the RF by 35640
  - At a **given place** in the machine, and at a **given beam energy** (that is fixed RF frequency) the **delay between the pulse and the passage of a bunch in bucket 1 will be fixed from run to run**
  - Drift during the ramp: Signals remain in phase with the corresponding beam in IP4 (RF cavities). During the acceleration, the revolution frequency increases by 2.2 ppm for protons (868 Hz @ 400 MHz) and 14 ppm for Pb (5.5 kHz @ 400 MHz). [*See LHC Radio-Frequency Swing, P. Baudrenghien, 14 th Leade meeting, Dec 15th, 2003*]. At a given place, but varying energy (frequency) the Frev-bunch delay will drift during the acceleration ramp due to the difference between signal transmission delay and the beam time of flight. For protons we have 6.5 ps/km, for ions 41.25 ps/km. Hopefully not a problem.

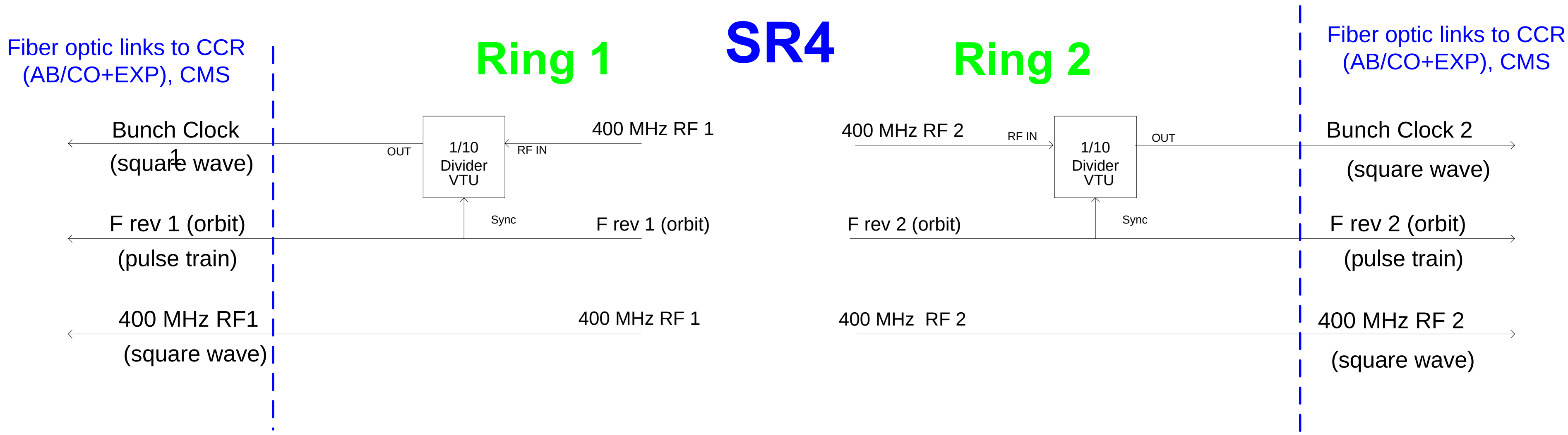
Bunch Clock

- For each ring:
  - The Bunch Clock is a square wave obtained by dividing the RF by 10. The divider is synchronized on the Revolution Frequency (see page 9)
  - At a given place in the machine, and at a **given beam energy** (RF frequency) the **delay between the edge of the Bunch Clock and the passage of a bunch will be fixed** from run to run
  - Drift during the ramp: During the proton ramp the Bunch Clock frequency increases by 86.8 Hz (protons) and 550 Hz (Pb). At a given place, but varying energy (frequency) the edge will drift with respect to the bunch. (Same figures as for the Revolution Frequency pulses.)

Collision Pattern

- Ring 1 w.r.t. ring 2:
  - While for each ring bucket 1 and its revolution frequency are locked together, the two bunch patterns can be "rotated" with respect to each other so as to move or set the collision points
  - This is usually done before the injection process with collision (and crossing) points defined before filling. This is the preferred method as it keeps crossing points fixed from injection to physics
  - It can also be done after injection by changing the phase of one RF system (and thereby the corresponding beam) with respect to the other (Machine Development)
  - Convention (proposed): bunches in bucket 1 of the two rings collide in IP1 (or any other IP. To be agreed before start commissioning)

Clock Generation

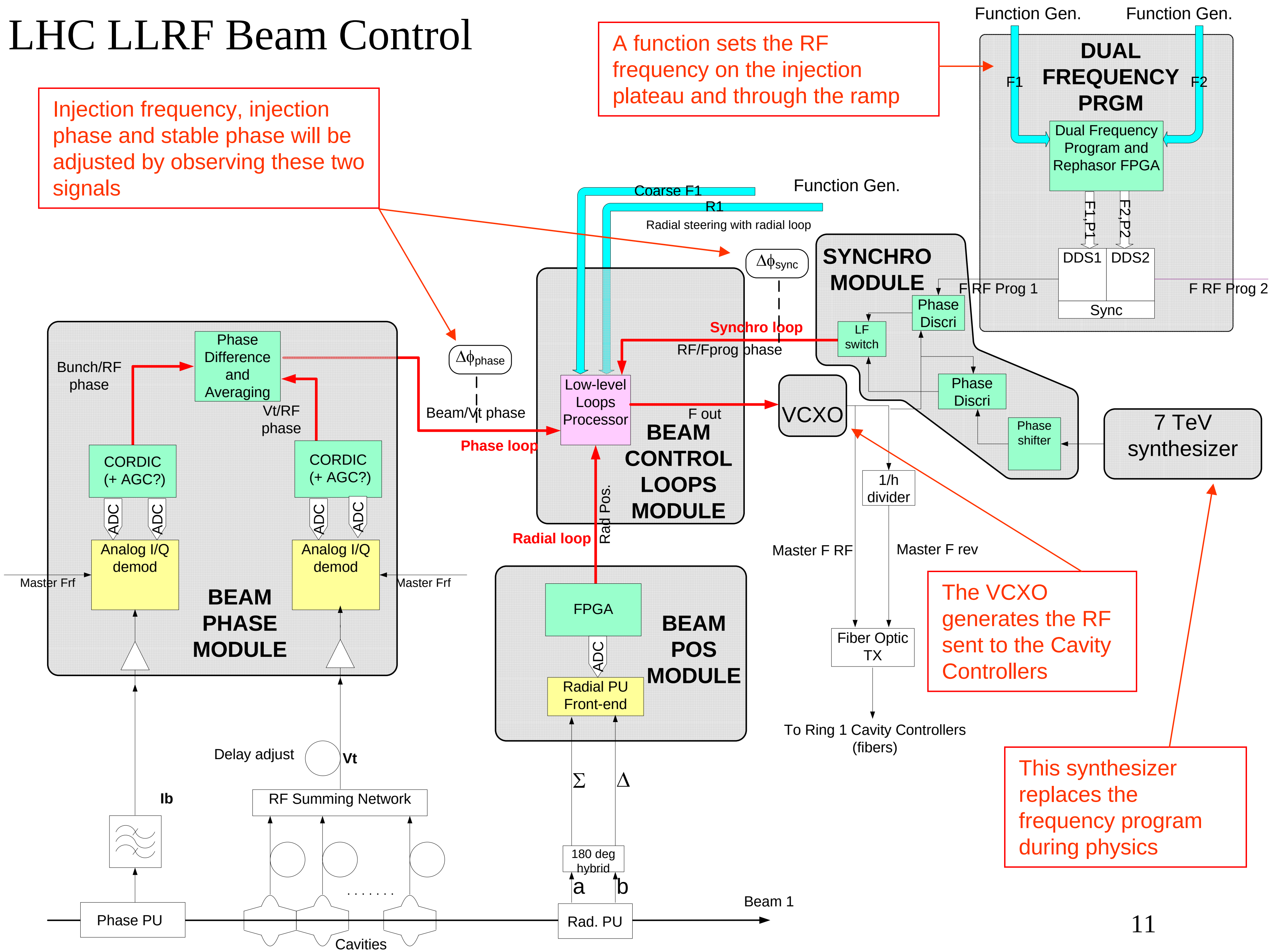


- All signals are generated in SR4
- They are transmitted to CMS (point 5) directly
- And they are transmitted to AB/CO and the other experiments via CCR
- Revolution Frequencies and Injection Pulses are sent to AB/BT on private links (not shown above)

Part 2: Commissioning with beam

blue = time requested by RF (dedicated)

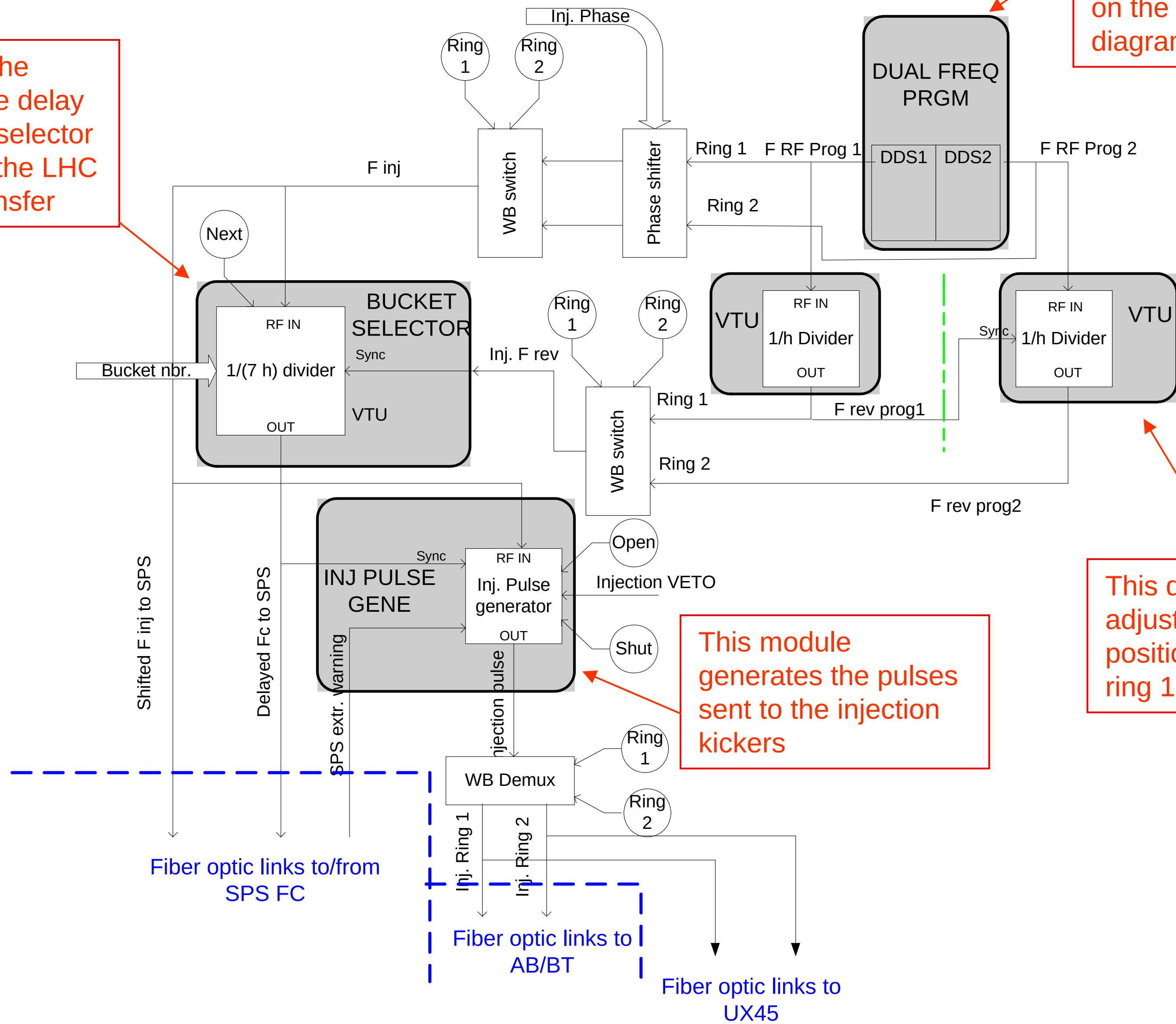
LHC LLRF Beam Control



LHC LLRF RF Synchronization

By changing the programmable delay in the bucket selector one chooses the LHC bucket for transfer

This is the Dual Freq Program represented on the previous block diagram



This module generates the pulses sent to the injection kickers

This divider will adjust the relative position of ring 2 vs ring 1

A1
First Turn Pilot

Pre-requisite

- Reliable timing (GMT)
- Beam at the end of transfer line
- AB/BT ready to observe Beam plus Kick and to adjust their delay
- Experiments are ready to observe Beam and adjust 40MHz and F_{rev} clock delay
- RF:
  - RF off
  - Set the plateau in the frequency program function at the desired injection frequency and lock the VCXO onto it via the Synchro Loop. (Diagram on slide 11)
  - Adjust phase shift in the Synchro Loop module so that the phase discri output $\Delta\phi_{sync}$ is zero
  - All VTUs ($F_{revprog}$, Master F_{rev}) set to B=0 (or default value). See diagrams on slides 11 and 12

Goal

- Inject pilot and centre first turn
- RF sub-goal:
  - Label buckets (numerology and cogging)
  - Adjust front end gains to see PU signals (APW and BPM)

Strategy (1)

- Generate the LHC injection kick (RF).
- Observe kick+beam. (BT). They adjust their delay (or ours?) to kick the beam.
- Get the beam to make a few turns (OP)
- Adjust the gain of the RF front end of the Beam Position and Beam Phase module + time alignment and F_{rev} marker (RF). *Dedicated RF 8 hours*. To do that:
  - Set the Observation memory to trigger on the "Beam In" timing.
  - Observe the PU signal (APW in Beam Phase module and BPM in Beam Position module).
  - Adjust gain/attenuation
  - Align the signals from the 2 inputs (OK for APW and Δ,Σ from BPM. More difficult for cavity sum as the beam induced voltage will be very small with pilot. Coarse adjustment must be done without beam)
  - Adjust the F_{rev} marker (offset in memory addressing) so that marker points to bucket 1

Strategy (2)

- Adjust delay in the F_{rev} sent to the beam dump. Observe our signal at the beam dump location. Compare to bunch position. Adjust. (BT). The abort gap ends just before the passage of bucket 1 (proposed convention)
- Adjust delay in the 40 MHz/F_{rev} clock received by the experiments (EXP)

A2
Capture and Circulating Pilot

Pre-requisite

- Cavities have been phased
- Paths from 8 cavities to the cavity sum have been phased (taking time of flight into account)
- APW and CAV SUM signals have been aligned in the Beam Phase module. (During hardware commissioning we must measure difference cable length APW->module and CavSum->module)
- All Cavity Controller loops commissioned: Tuner, RF feedback, Klystron Polar Loop
- Cavities conditioned to 10 MV/m for all coupler positions (Q= 20000 to 60000)
- Phase loop already tested to lock with beam replaced by a train of pulses

Goal

- Capture and centre the closed orbit.
- Get pilots to collide at the right point (cogging)
- RF sub-goal:
  - Commission phase loop and synchro loop.
  - Capture
  - Adjust relative positions of the 2 rings for collisions in IPs (cogging)

Adjust Inj Freq (coarse)

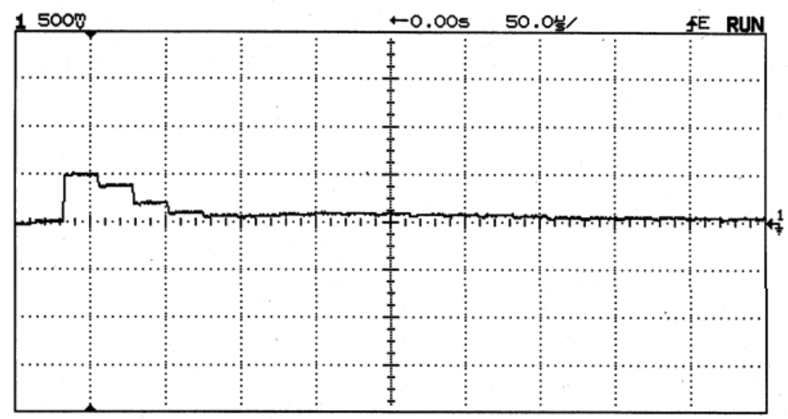
8 hours OP and RF

- Keep Synchro loop On, Phase loop OFF, Radial loop OFF, RF OFF
- RF OFF -> beam debunches in ~10 ms (100 turns)
- At injection (γ=460, γ_t=53.7) a Δp/p of 10^{-3} gives Δf = -120 Hz @ 400 MHz and ΔR= 1.5 mm
- Measure the Beam/RF phase slip turn after turn, using either
  - The Observation memory in the Beam Phase module. It measures the 400 MHz component of beam signal and will thus stop working as beam debunches (zero signal when σ_{rms} has increased from 0.4 ns to 0.9 ns, that is after <~ 100 turns. Can be improved by injecting shorter bunches?) With pilot assume a 30 degrees drift measured over 100 turns (9 ms) -> we can measure frequency errors within 10 Hz
  - Direct observation of PU signal. Not sensitive to bunch lengthening. Hardware ready (Acquiris/Oasis) on APW platform plus PU signal routed to SR4 on copper.
- Re-adjust Injection Freq and B field (OP) to get:
  - First turn centered
  - Beam freq=RF freq

Commission Phase Loop (1)

2 x 8 hours OP and RF

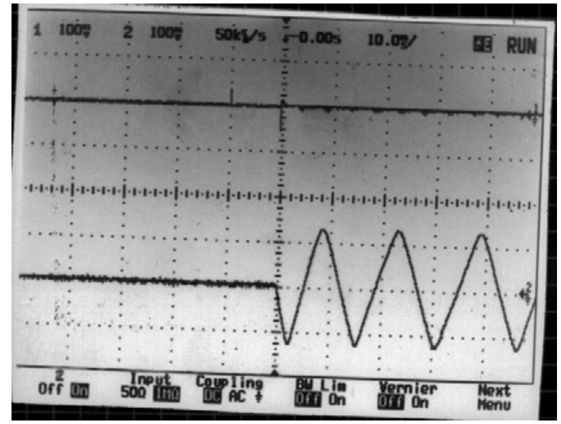
- RF ON, 1 MV/cav
- At injection, switch Phase Loop ON and Synchro Loop OFF
- Observe the Bunch/V_t phase on first few turns (Phase Loop phase discri $\Delta\phi_{phase}$). The phase loop will lock but, as the stable phase is wrong, the beam will be accelerated or decelerated.
- RF ON but wrong stable phase. In the worst case (90 degrees error) the beam will be driven out of chamber in 140 turns or 14 ms (max kick = 8 MeV/turn, take aperture ΔE/E=2.5 10-3).
- Adjust the phase loop gain to get a decent response. (If needed use the injection phase to increase the phase error at injection)



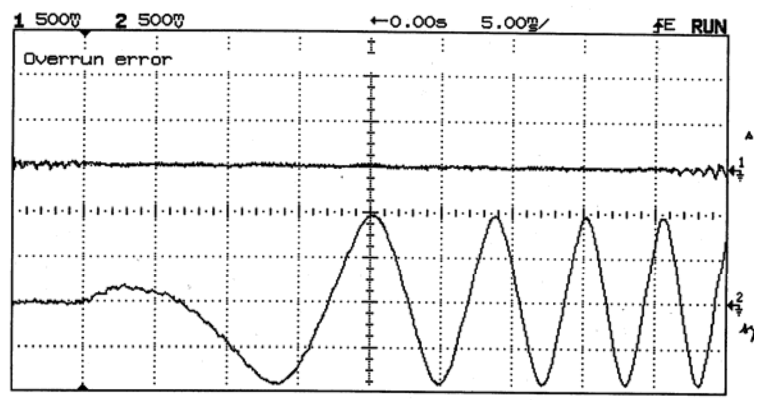
SPS phase loop phase discri at injection

Commission Phase Loop (2)

- Look at the Synchro Loop phase discri output $\Delta\phi_{sync}$. As we are on phase loop the beam imposes the RF frequency. The beating of the Synchro Loop phase discri is thus the injection frequency error. In addition the stable phase error can be deduced from an acceleration (increasing beat freq) or deceleration (decreasing beat freq).



SPS phase loop and synchro loop discri at injection. Synchro loop OFF. Wrong freq.



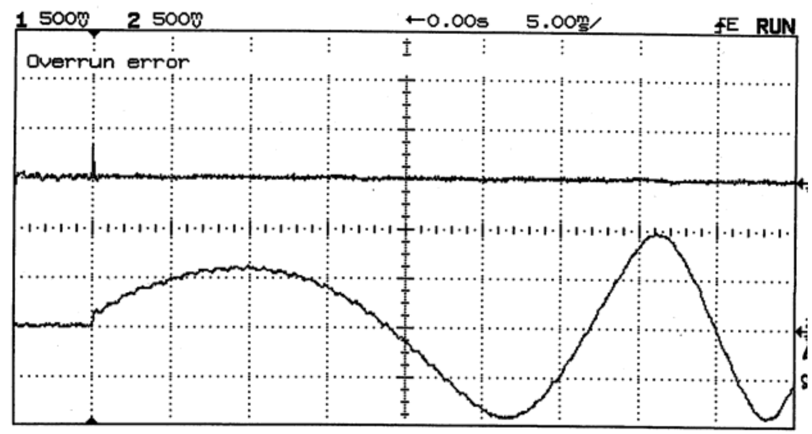
SPS phase loop and synchro loop discri at injection. Synchro loop OFF. Correct freq. but wrong ϕ_s

Commission Phase Loop (3)

- Coarse adjust the Stable Phase to get a constant beat frequency. The beam is neither accelerated nor decelerated
- Then adjust the injection phase to cancel the transient in the Phase Loop phase discri output $\Delta\phi_{phase}$

Commission Phase Loop (4)

- Measure the beat frequency that is the frequency error at injection
- Re-adjust the Injection Freq (function) and B field in LHC and SPS(RF+OP) to get:
  - First turn centered
  - Beam freq=Inj freq
- This adjustment is now fine as the RF keeps beam bunched

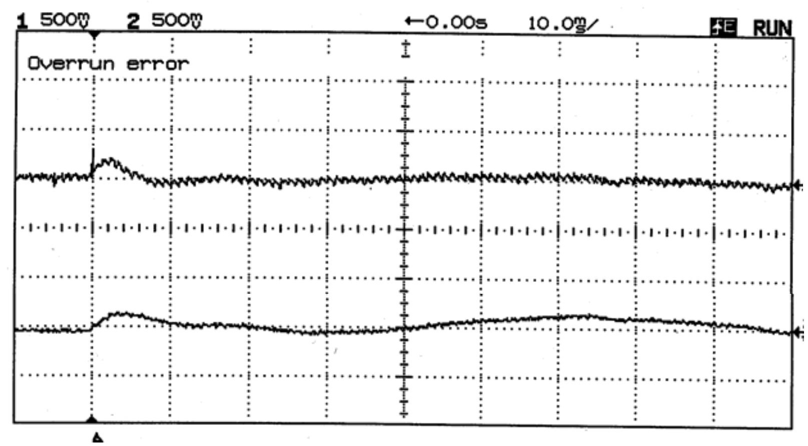


SPS synchro loop phase discri at injection. Synchro loop OFF. No beat

Commission Synchro Loop

8 hours RF

- Now leave the Synchro Loop ON at injection. As the stable phase error is small (few degrees) and the frequency error is small compared to the loop response (a bit slower than the synchrotron freq = 60 Hz), the loop should lock
- With both loops locked, fine tune the injection phase and the stable phase
- Small freq error at injection can be deduced from the slope of the synchro loop phase discri $\Delta\phi_{sync}$



SPS phase and synchro loop phase discri at injection. Both loops ON

Adjust Synchro Loop dynamics

- With both loops ON, measure the synchro loop step response
- Adjust synchro loop gain and phase advance to fine tune the response
- As this depends on the RF voltage via synchrotron freq we want to do it at different voltages. But it is not urgent.

Check phasing of cavity sum

8 hours RF

- Now try to capture the beam with one cavity at the time
- Observe synchro loop phase discri output $\Delta\phi_{sync}$ after transient
- If non-zero, fine-tune the delay in Cavity Sum for that cavity

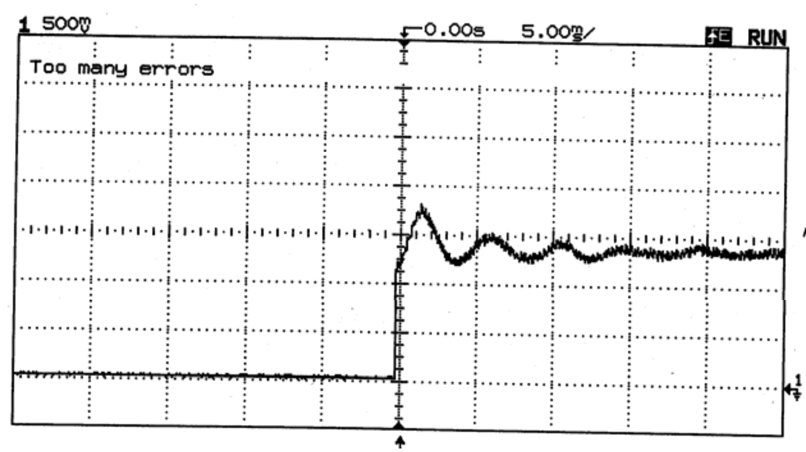
Closed orbit

- As soon as the beam is captured, BI can use the F_{rev} for synchronous acquisition. They must first adjust their delays to trigger on bucket 1 (BI+OP)
- Check that closed orbit = first turn = centered

Fine tune capture

2 x 4 hours RF

- Voltage matching SPS-LHC. Observe 400 MHz component of bunch intensity using Bunch Phase module (or APW peak). Minimize quadrupole oscillations
- Measure bunch profile at injection (scope in SR4 or Acquiris/Oasis)
- Measure lifetime (scope in SR4 or Acquiris/Oasis). Not urgent



SPS AEW peak at injection with mismatched voltage

Align the two rings

4 hours OP,BI and RF

- This stage has been advanced compared to the original OP scenario
- Get 1 circulating pilot in bucket 1 of each ring
- Measure the collision point. This requires an acquisition in a PU that sees both rings (first BI, then EXP).
- Adjust one ring with respect to the second to get collision in IP1 (?), using $F_{rev\ prog\ 2}$ B# of the second ring. See diagram on page 12

A3 to A11

As soon as things improve in the transverse plane, measure lifetime

- Observe 400 MHz component of bunch intensity over time using Bunch Phase module (or APW peak).
- Compare it to the bunch intensity over time (Fast BCT from BI)
- Deduce the longitudinal losses
- Measure longitudinal profile and bunch length over time (scope in SR4 and Acquiris/Oasis).

Commission the radial loop

8 hours OP and RF

- Switch Radial Loop On (and Synchro Loop OFF) after injection transient
- Displace the beam with radial steering (OP)
- Apply a step to measure the Radial Loop response
- Optimize the loop dynamics (gain)
- Important to have radial loop working before we start ramping

Multi-bunch injection

8 hours CO and RF

- Commission the *Filling Pattern* mask (Array[1,3564] of {0,1}) (CO and RF)
  - Transmitted in the timing
  - Used in the Beam Phase module and Beam Pos module
- Check behavior of Phase Loop and Radial Loop
- Measure bunch parameters for each bunch
  - At injection: phase error, total intensity, 400 MHz component, bunch length and profile
  - After a few seconds: total intensity, 400 MHz component, bunch length and profile
- Probable: optimize injector chain

Multi-batch injections

8 hours CO and RF

- Timing: Injection Bucket number and ring identifier must be supplied on-the-fly via the timing system to the Bucket Selector (diagram slide 12) (CO, OP and RF)
- At each injection the Phase Loop module receives a new *Filling Pattern* mask and the Phase loop includes the new incoming bunches in the average phase after a delay (damping of the injection phase/energy error or filamentation)
- Ideally we need to commission the longitudinal damper (likely to be postponed)

Increasing bunch and beam intensity

- Up to 156 bunches 9 10^{10}/bunch no need to commission 1-T feedback or Half Detuning (*parasitic*)

Ramping

3x 8 hours RF

- Ramping with
  - Synchro loop (if frequency program function is accurate enough)
  - Radial loop
- Changing the cavity loaded Q (reduces coupling) before ramping with simultaneous adjustment in RF feedback gain and tuner input phase shifter
- Optimizing voltage function through the ramp
- Bunch parameters measurements

Rephasing on the flat top

2x 8 hours RF (OP and EXP)

- Optimizing RF voltage on the flat top
- Rephasing each ring to the 7 TeV Synthesizer (see diagram slide 11)
- Fine adjustment of collision point (OP and EXP)

Relevant material

- Procedures for the Energy Matching of the two LHC rings to the SPS, G. Arduini, April 6, 2007
- LHC Timing Issues, P. Baudrenghien, 37 th LEADE meeting, May 7, 2007
- Circulating Beams and RF Capture, G. Arduini, A. Butterworth, 2 nd LHCCWG meeting, March 22, 2006