Bunch-by-Bunch position measurement for the CERN-PS: coping with RF-gymnastics

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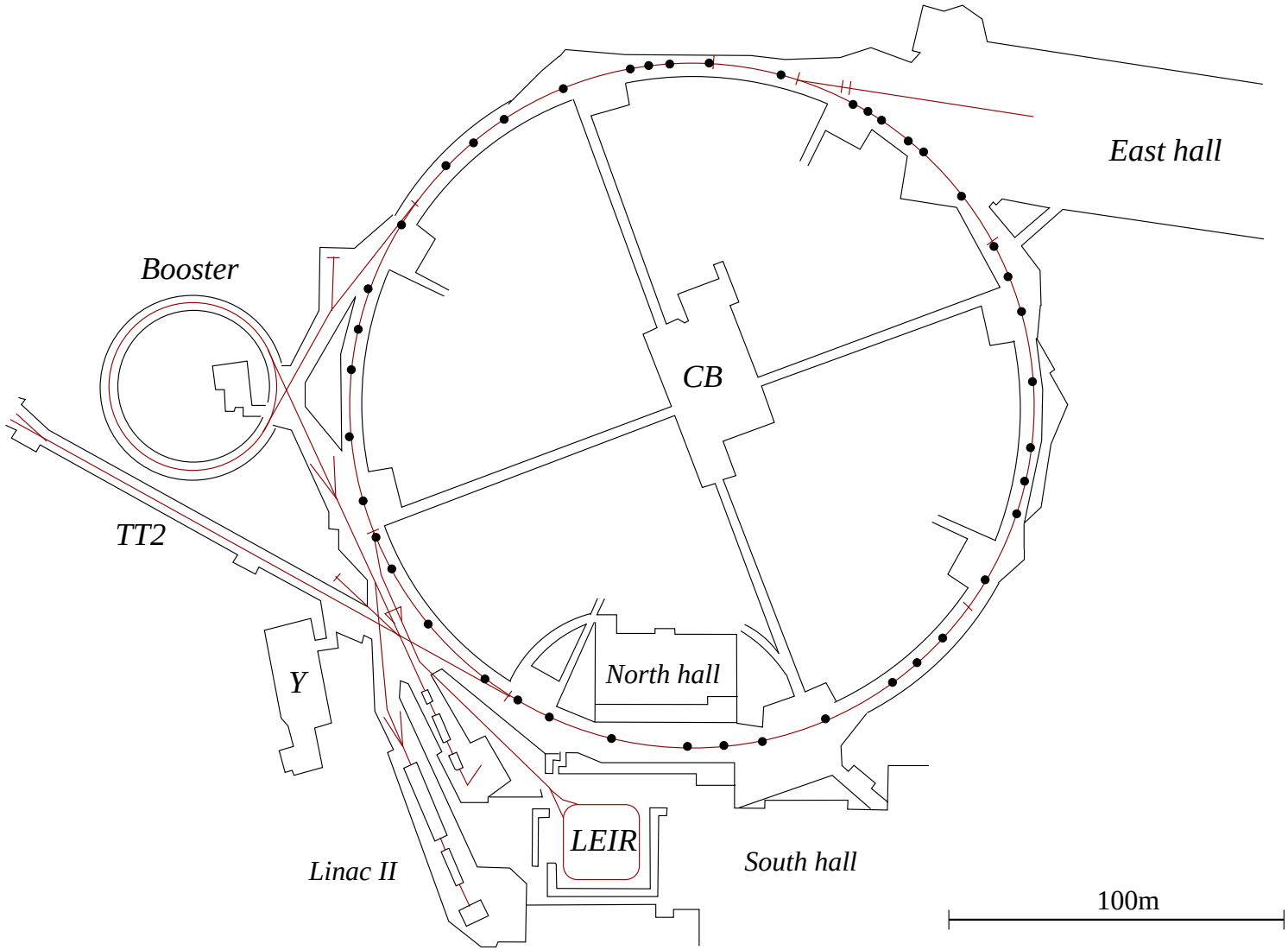
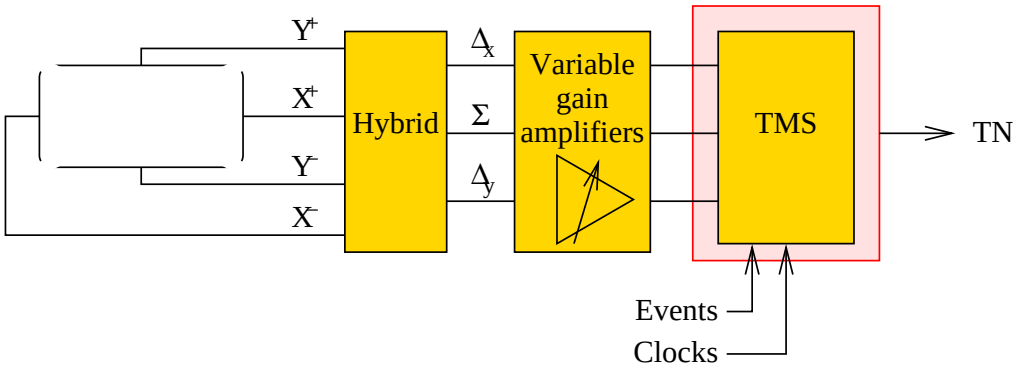
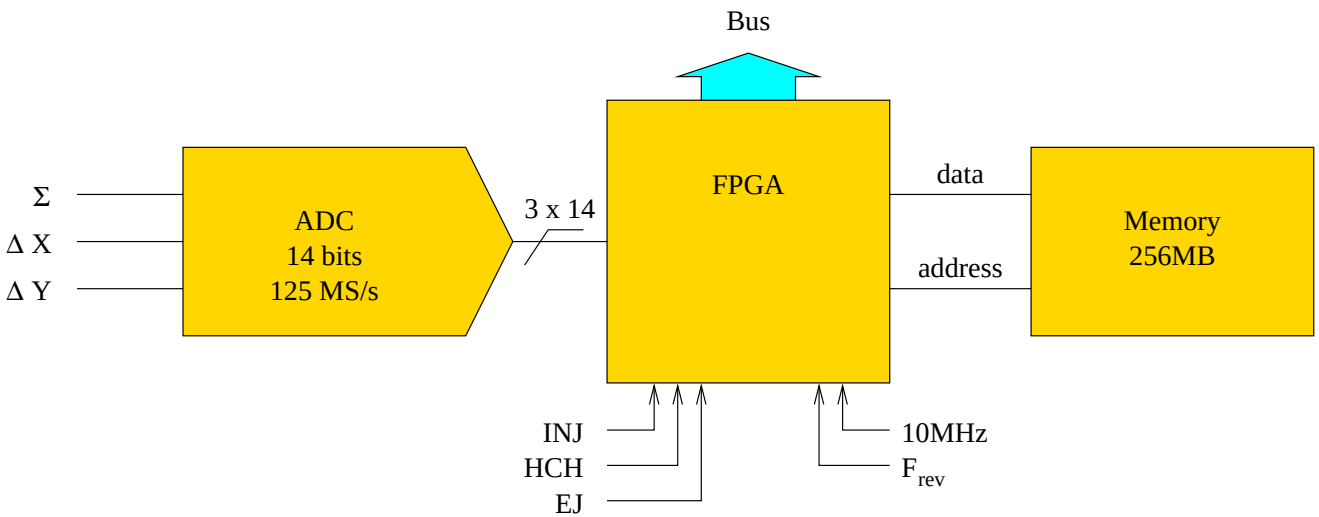
The PS Trajectory Measurement System uses 43 BPMs

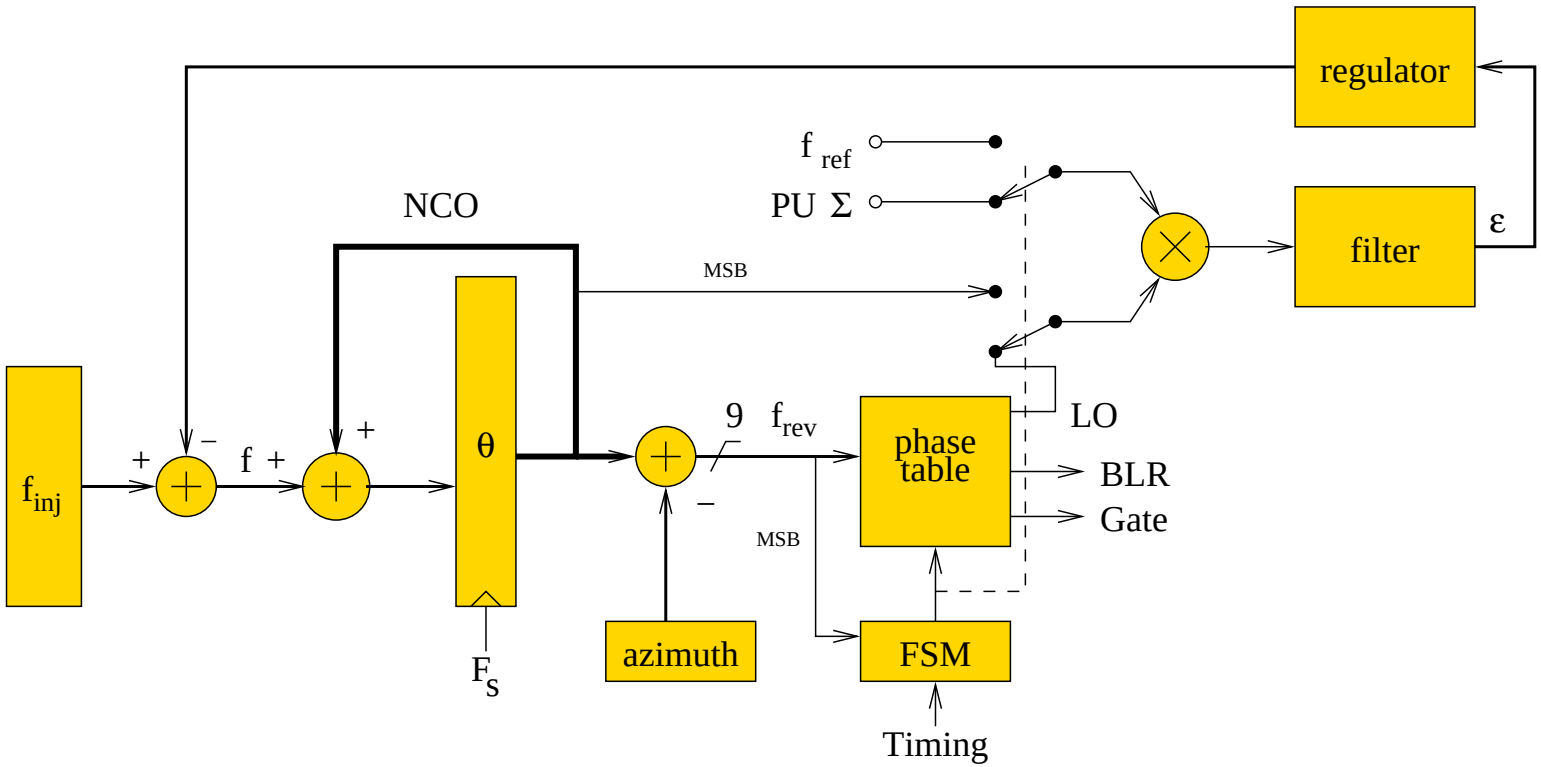


TMS architecture for one BPM station





Beam-synchronous signal generation



Beam-synchronous signal generation

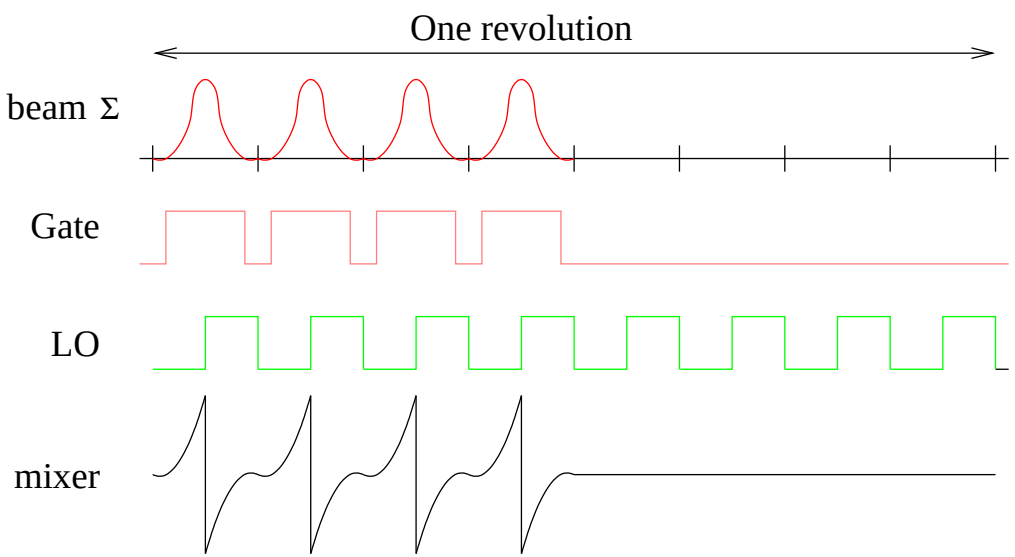
Direct Digital Synthesizer (DDS)

- NCO always runs at F_{rev}
- Update rate 125 MHz
- Phase table generates LO and Gate
- Timing-driven programmable FSM selects one of several possible LO and Gate signals
- FSM also controls BPM and F_{ref} signal routing
- Azimuth defines BPM position in ring
- F_{inj} provides F_{rev} at beam injection
- Regulator provides frequency and phase tracking

Beam-synchronous signals

Goal: Measure position of the centre of charge of each bunch

- For each of the signals ΔX, ΔY and Σ, integrate over bunch length
- Bunch position $= S\frac{\int \Delta}{\int \Sigma}$

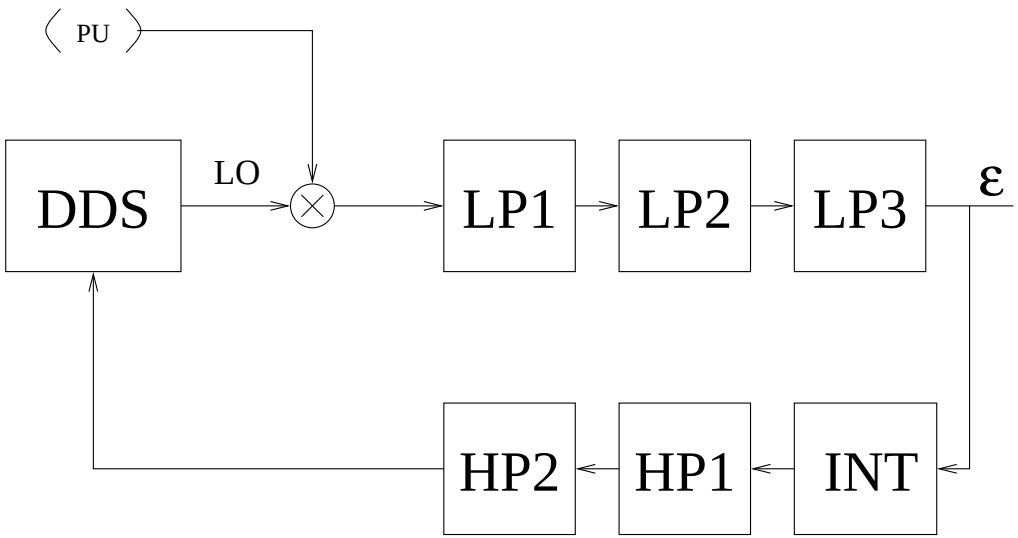


- Gate selects samples belonging to a bunch
- LO serves to derive a phase correction
- A mixer creates a phase error signal
- Can lock on (sub)harmonics

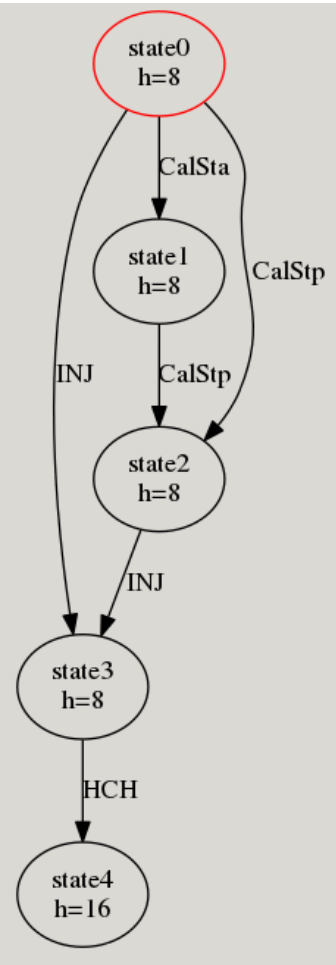
Phase loop dynamics

Discrete-time feedback loop

- In the locked steady state, LO and BPM signals are in quadrature
- The regulator design enforces a zero static phase error
- Beam intensity and number of bunches affect the loop gain



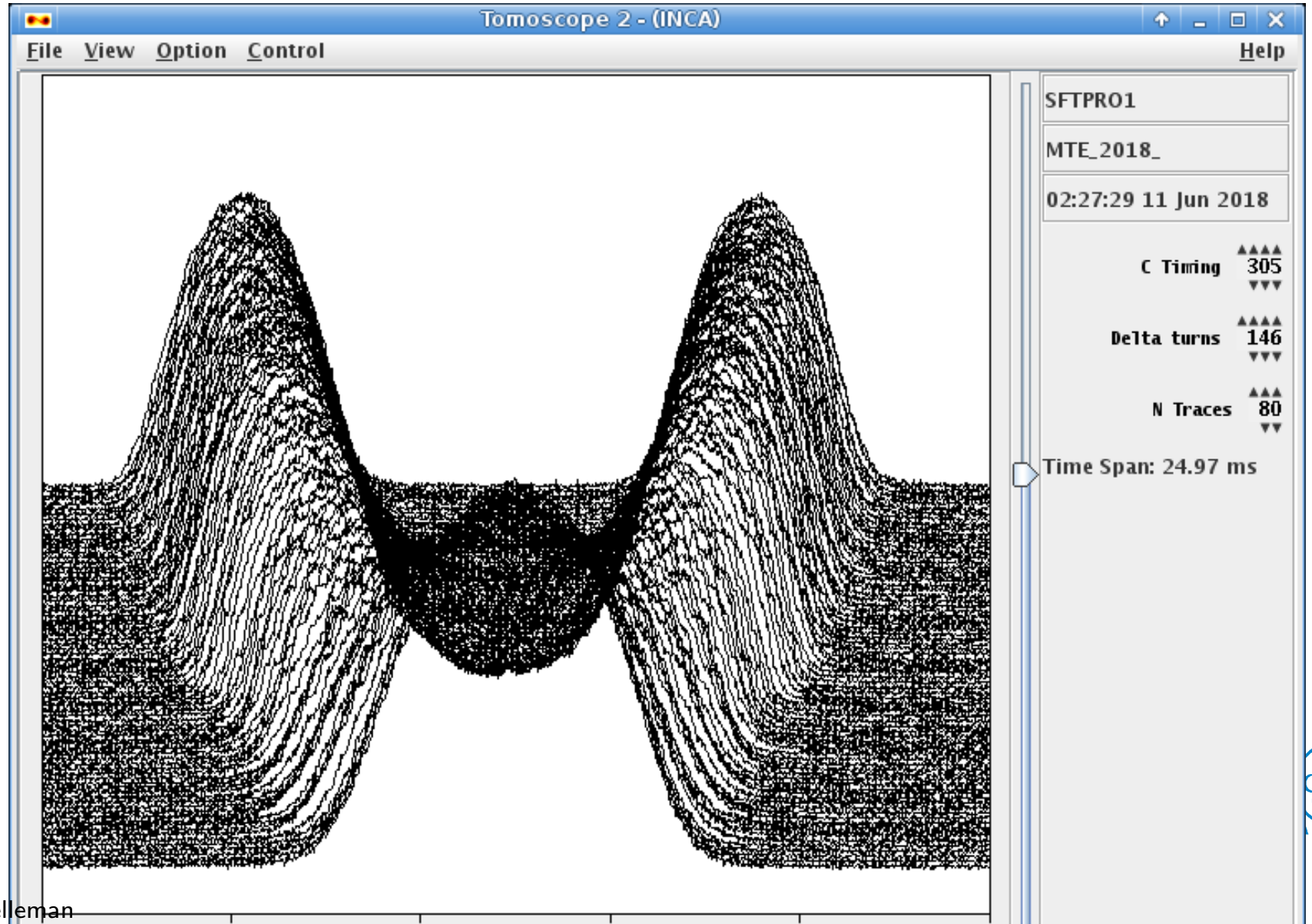
Sequencing



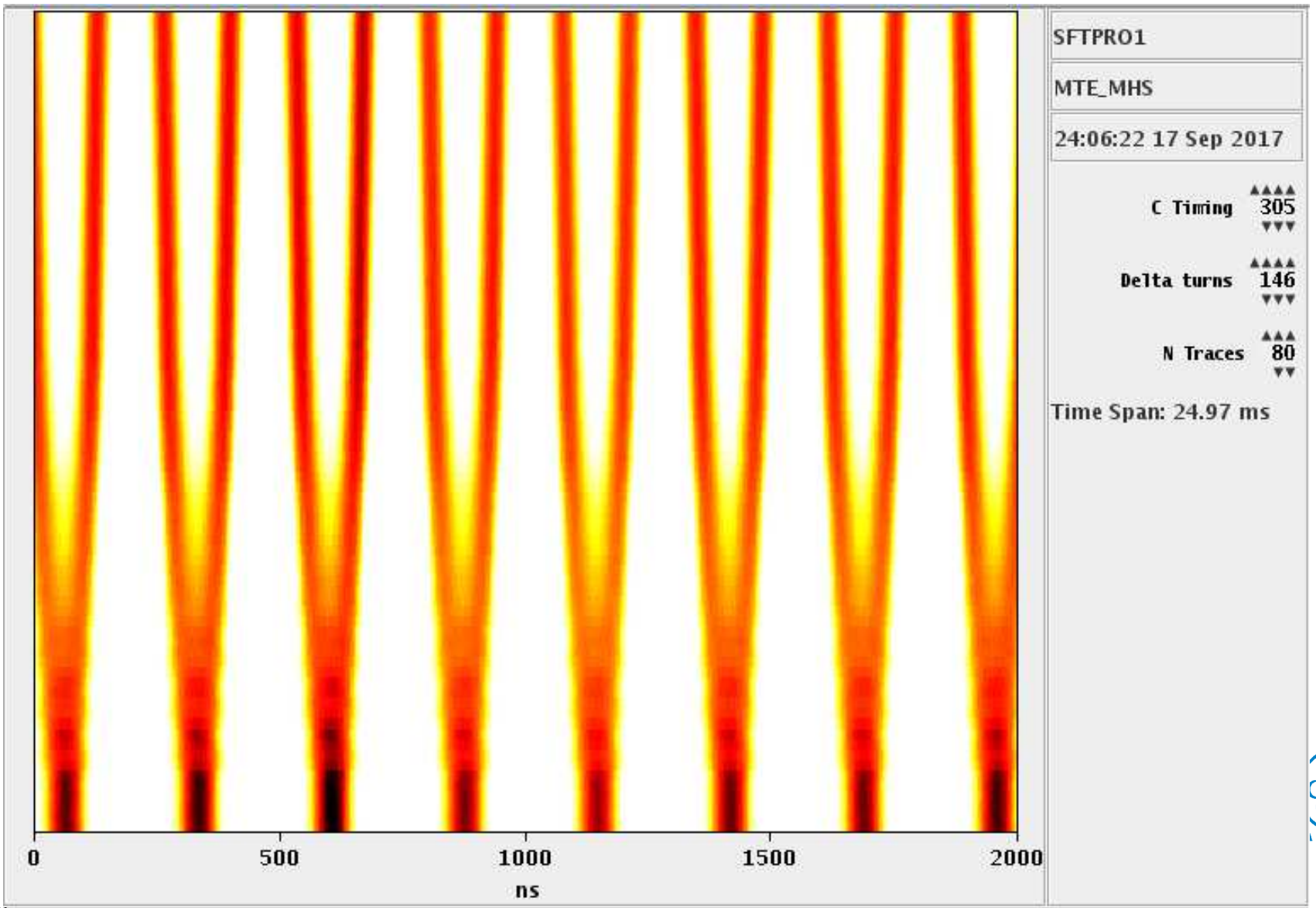
Programmable Finite State Machine

- Each state has associated Gate and LO signals and switch settings for the mixer inputs
- Sequence defined by a programmable transition table
- For each state and timing impulse, it specifies the next state
- Each state specifies a block of trajectory memory
- An event table records information about the location, size and structure of these blocks
- There is room for four of these tables, so we have time enough to read the interesting bits

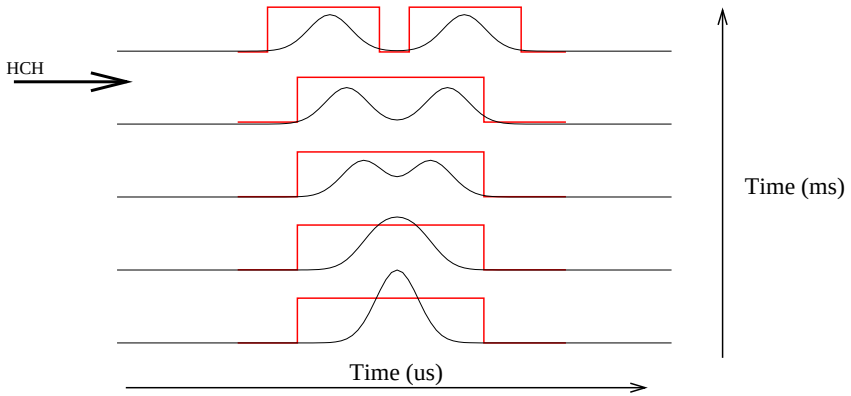
Splitting a bunch into 2



Splitting bunches into 2



Splitting a bunch into 2

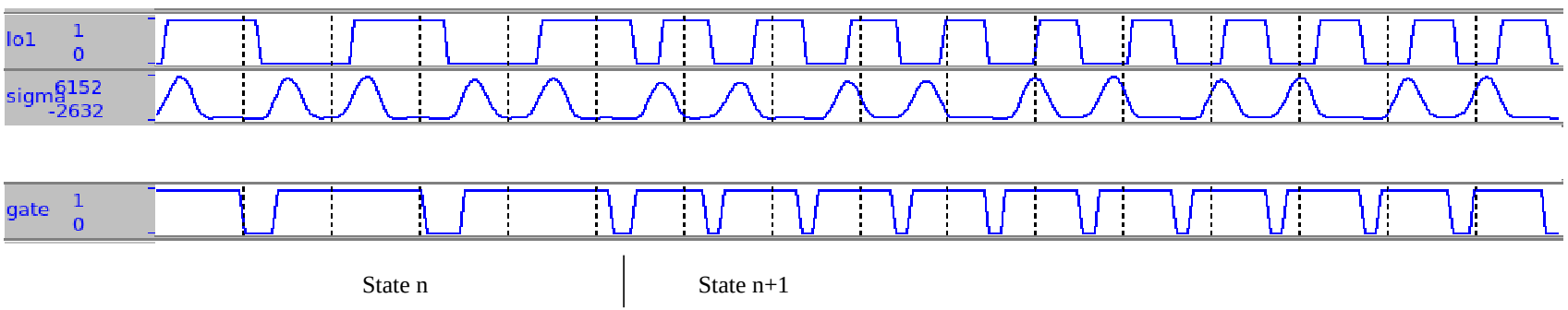


- A single Gate covers both bunchlets until splitting is nearly complete
- Even though splitting is gradual, the TMS switches instantly
- The switch is done on a turn boundary, starting from the injection BPM and propagating around the ring in synchronism with the beam
- A timing pulse derived from LLRF decides the appropriate instant

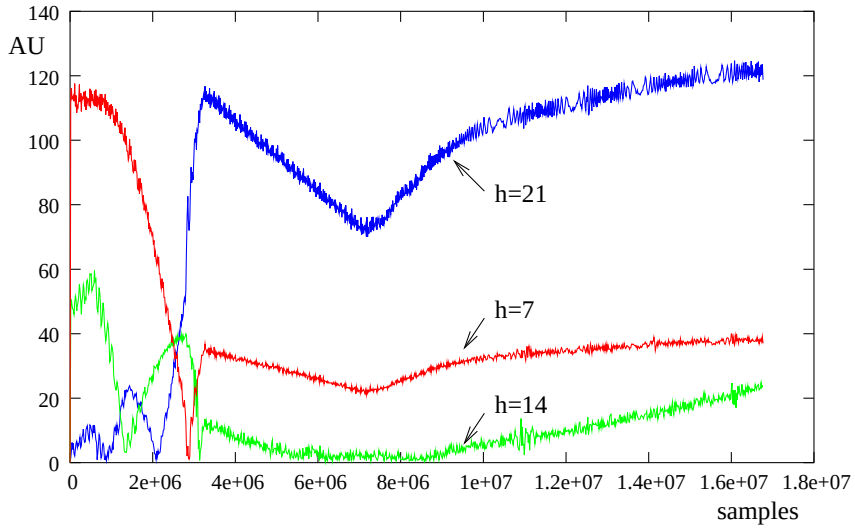
Splitting bunches into 2

Measured on the live system

A timing signal advances the FSM to select the new harmonic when splitting is almost complete. LO and Gate signals assume their new waveforms.



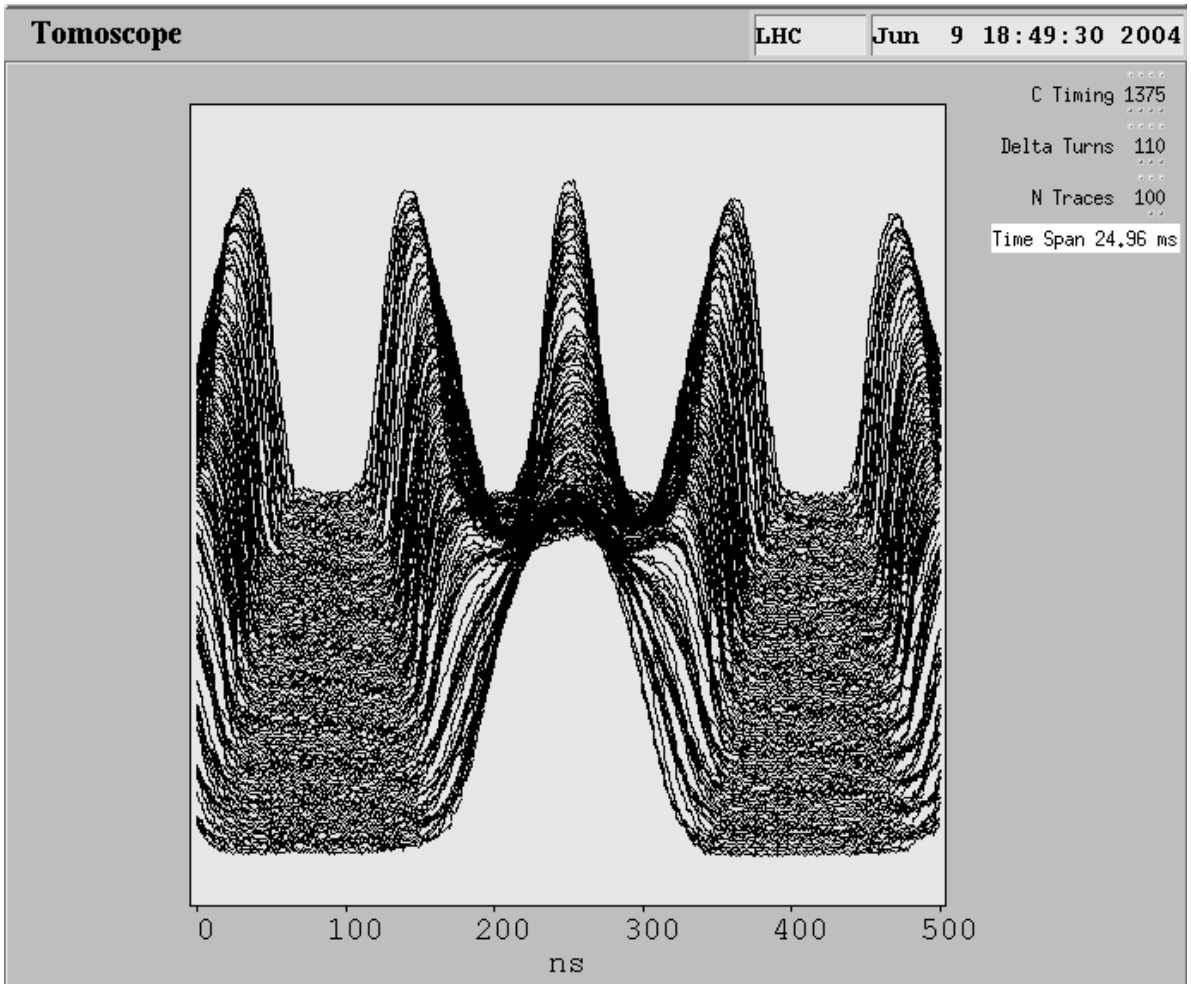
Splitting bunches: Frequency domain view



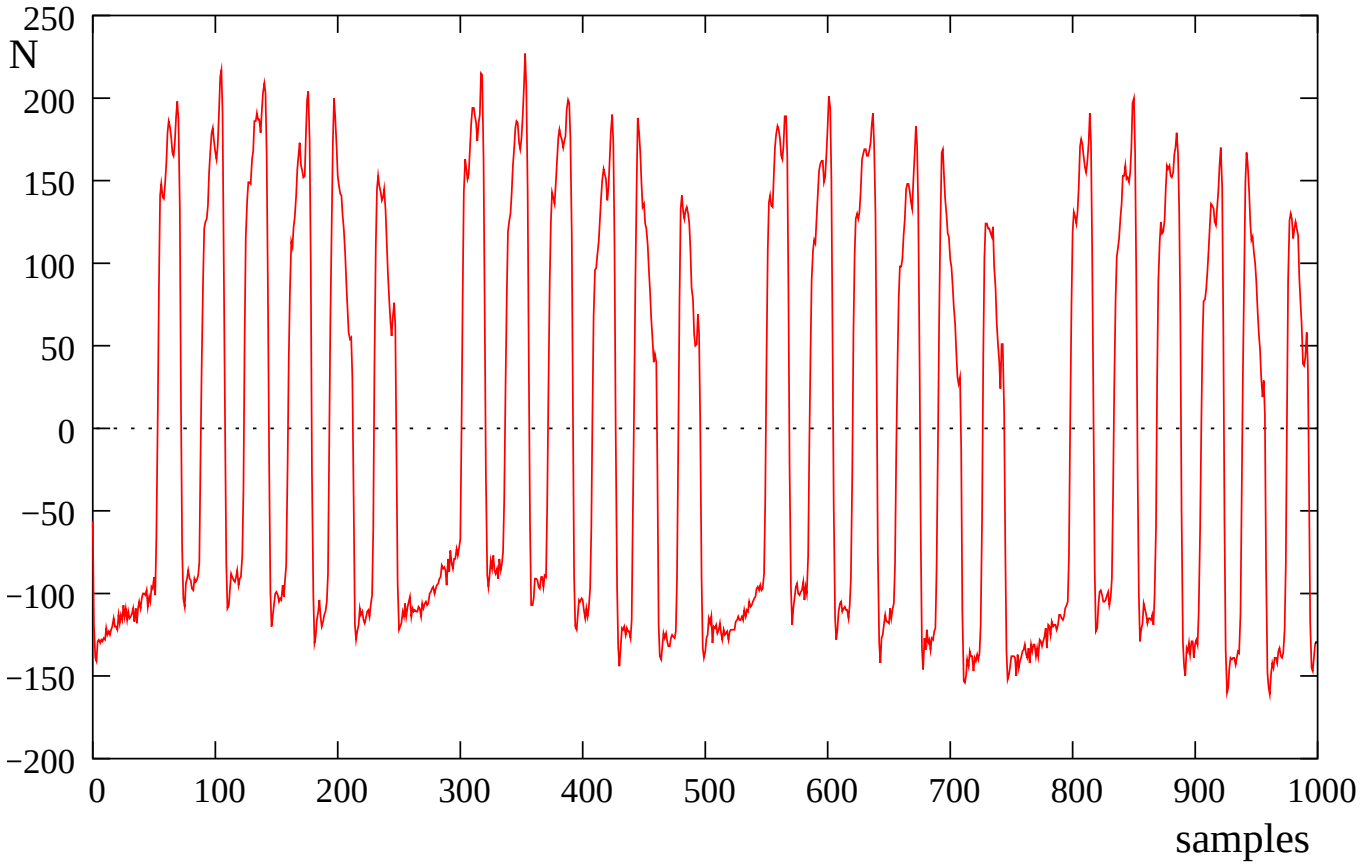
Amplitude of spectral lines over time during bunch splitting

- During the split, the magnitude at the original harmonic drops while the new one grows (This is a split into *three*!)
- Residual levels at the 'wrong' harmonic persist, but are unreliable
- Switching occurs at the cross-over of h=7 and h=21

Splitting a bunch into 3

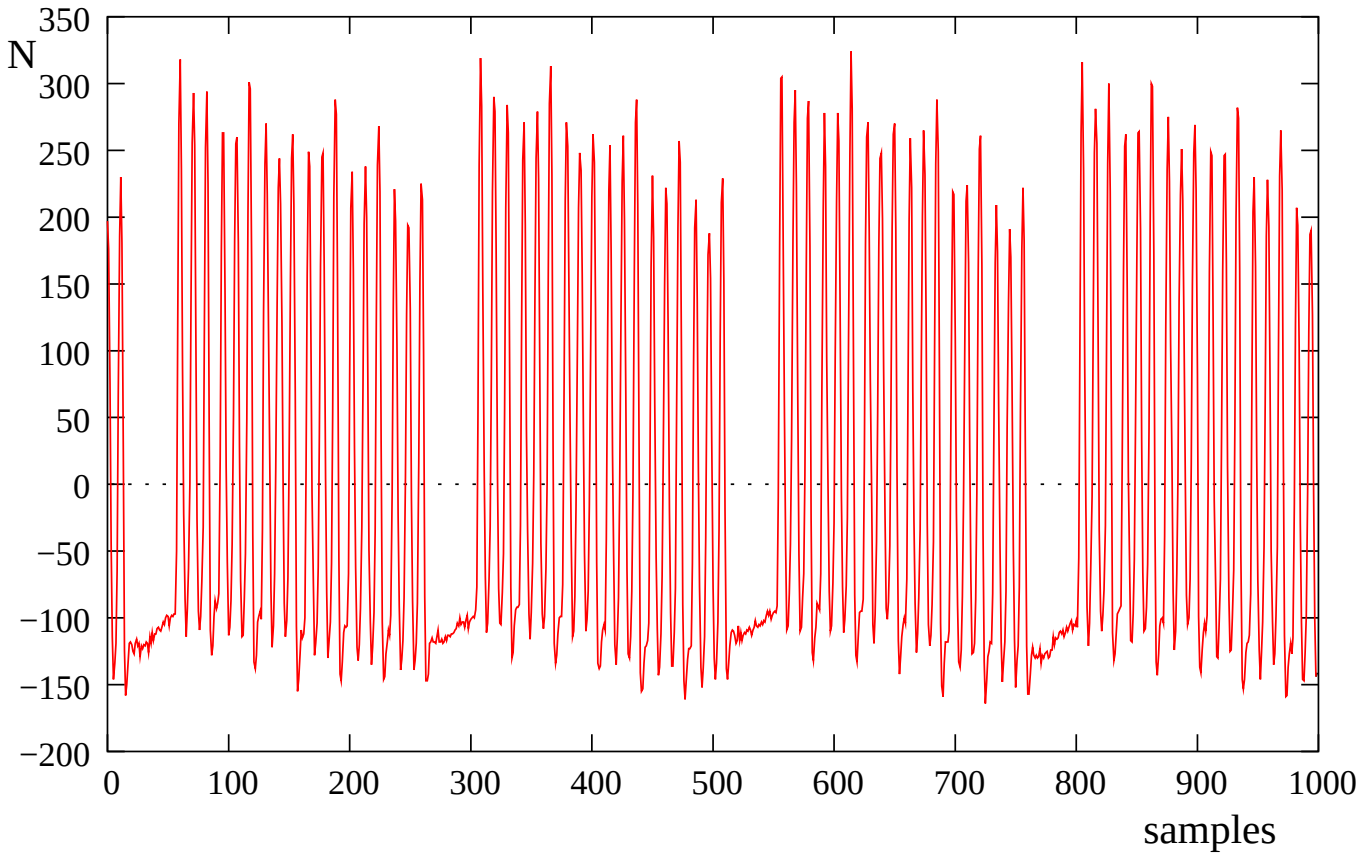


Beam on h=7



- Six bunches injected on h=7

Beam on h=21

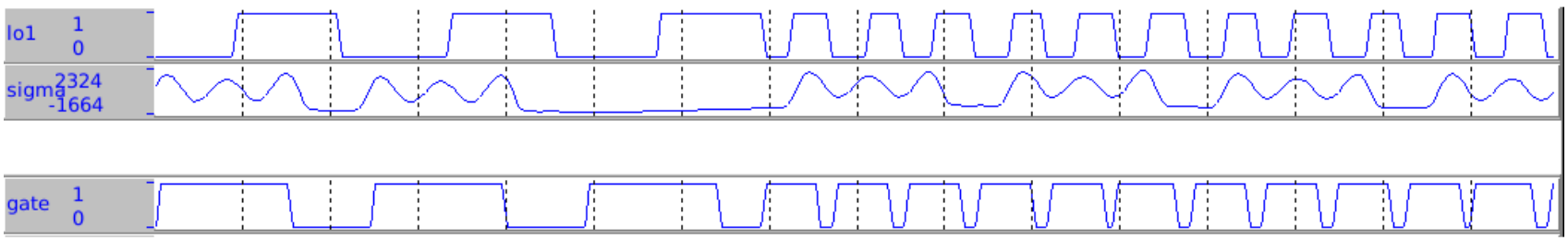


- Bunches are split into 3
- Eighteen bunches on h=21

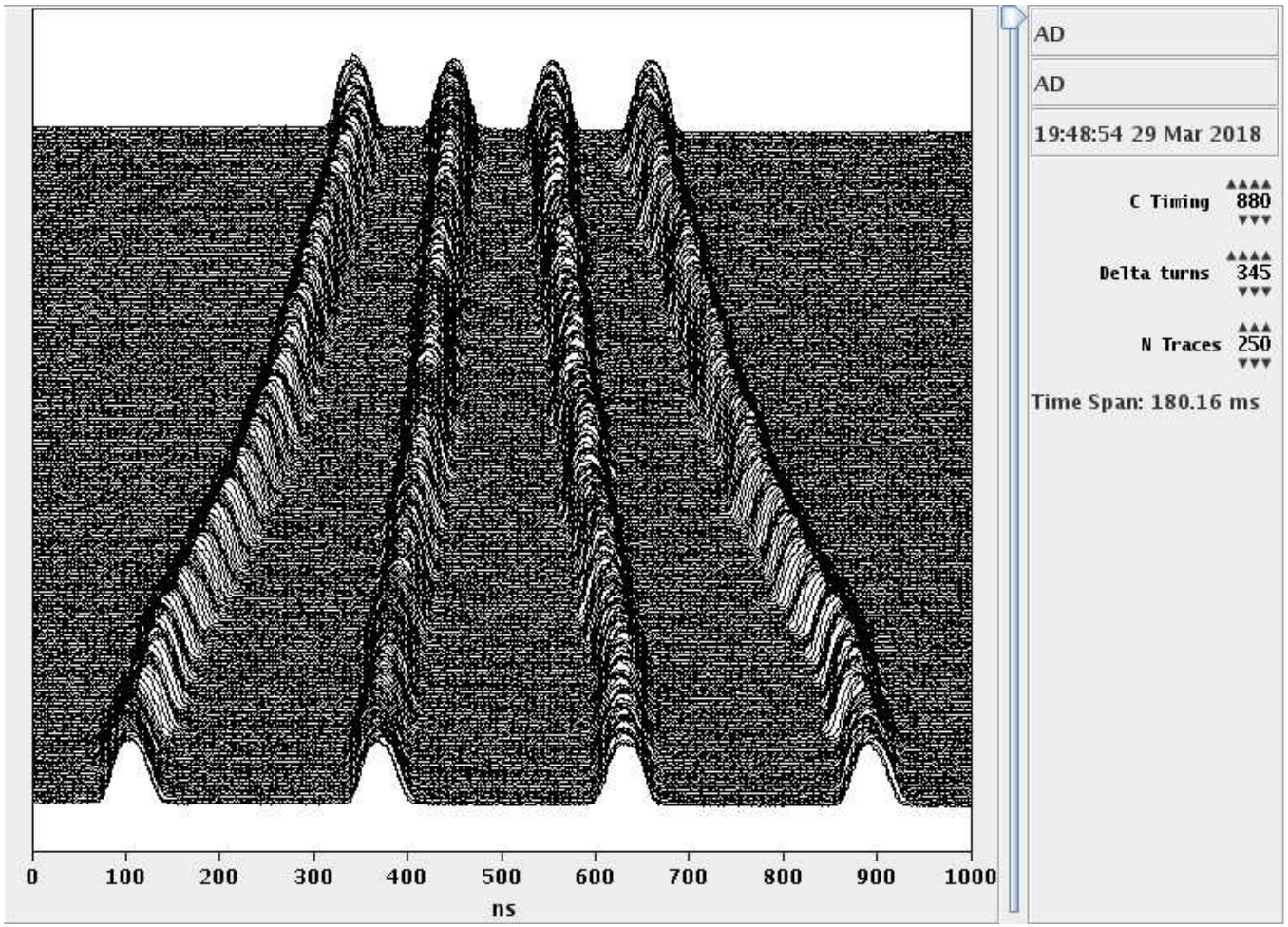
Splitting a bunch into 3

Acquired on the live system

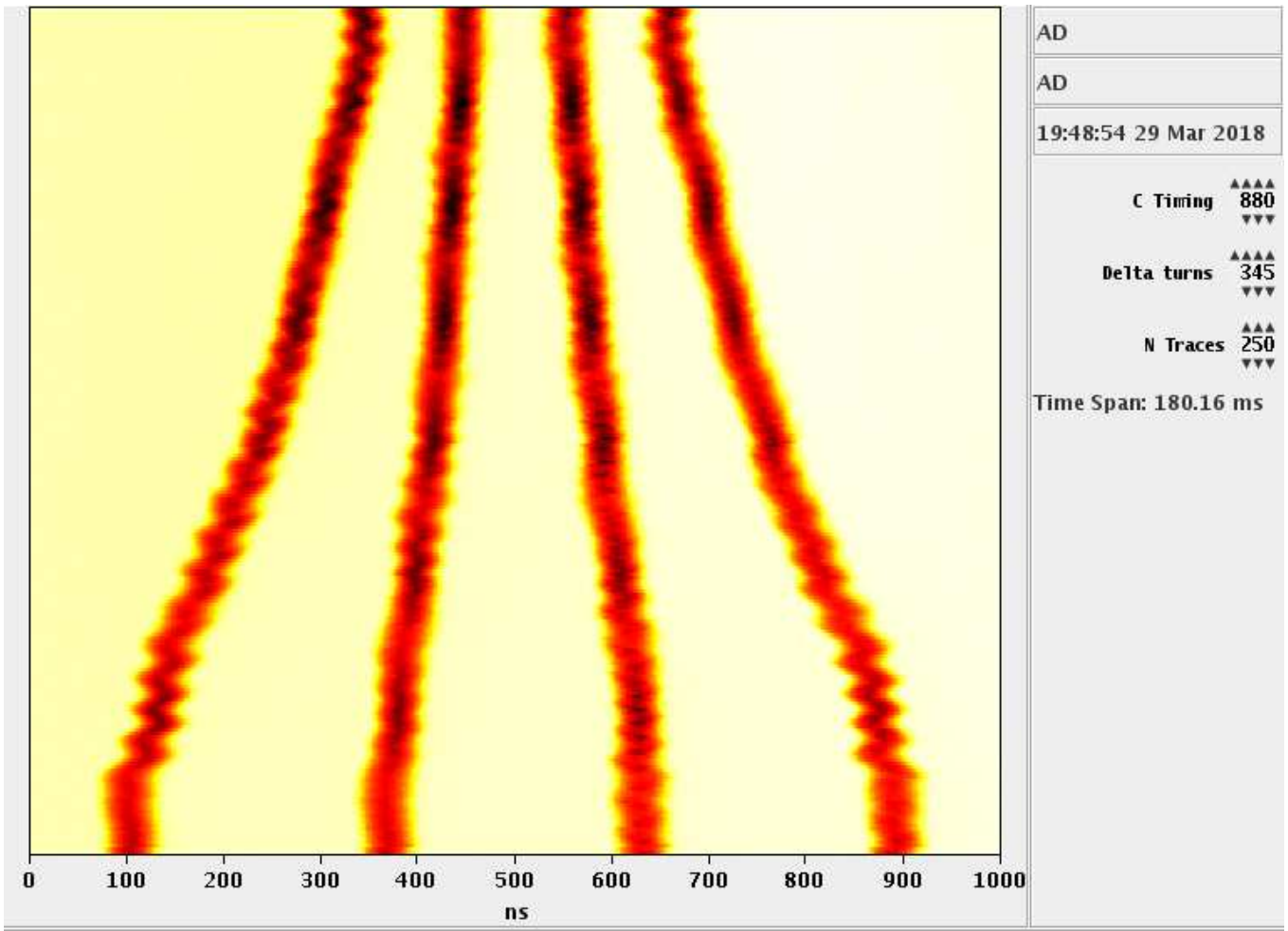
Alignment gets better as splitting progresses.



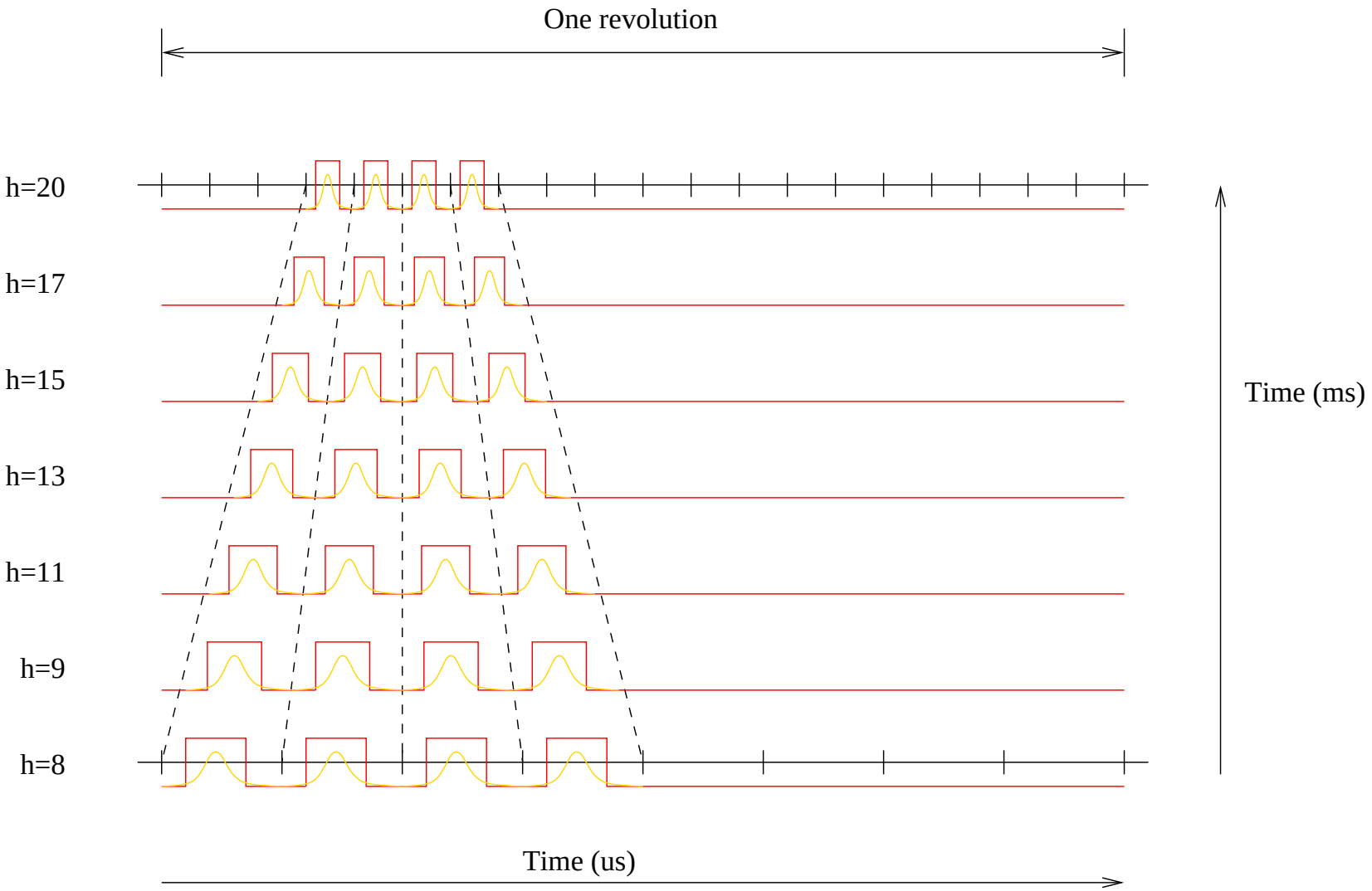
Batch compression on AD



Batch compression on AD



Batch compression



Summary

- The TMS is very flexible
- Records both orbits and trajectories of all bunches over complete acceleration cycles
- Delivers multiple subsets of data to multiple independent users
- No settings under user control
- BPMs, pre-amplifiers, timing hardware made in-house
- TMS was built by British industry
- Only the ADC/FPGA modules are custom-made hardware
- Custom software and firmware
- Crates and computers are COTS

Thank you

Small signal transfer function

The open loop transfer function:

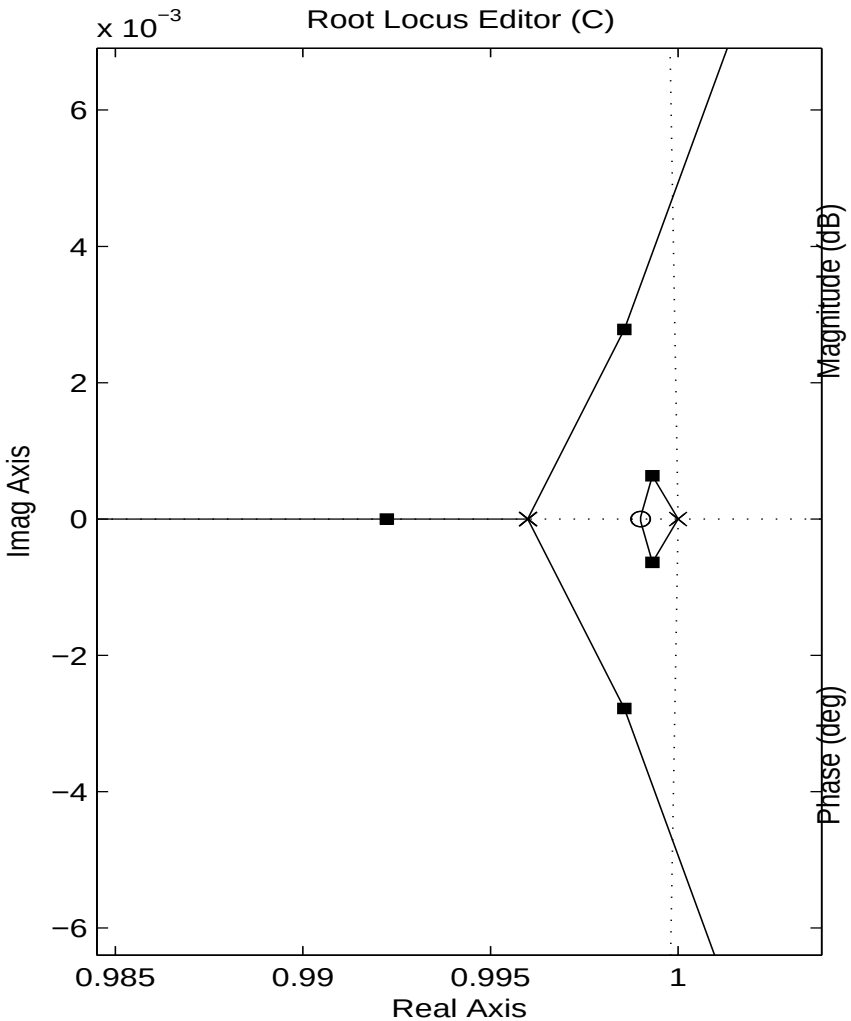
$$H_o = \frac{hz^{-1}}{A(1-z^{-1})} \cdot H_m \cdot \left(\frac{z^{-1}}{1-0.996z^{-1}}\right)^3 \cdot \frac{(1-0.999z^{-1})^2}{1-z^{-1}} \cdot z^{-n}. \quad (1)$$

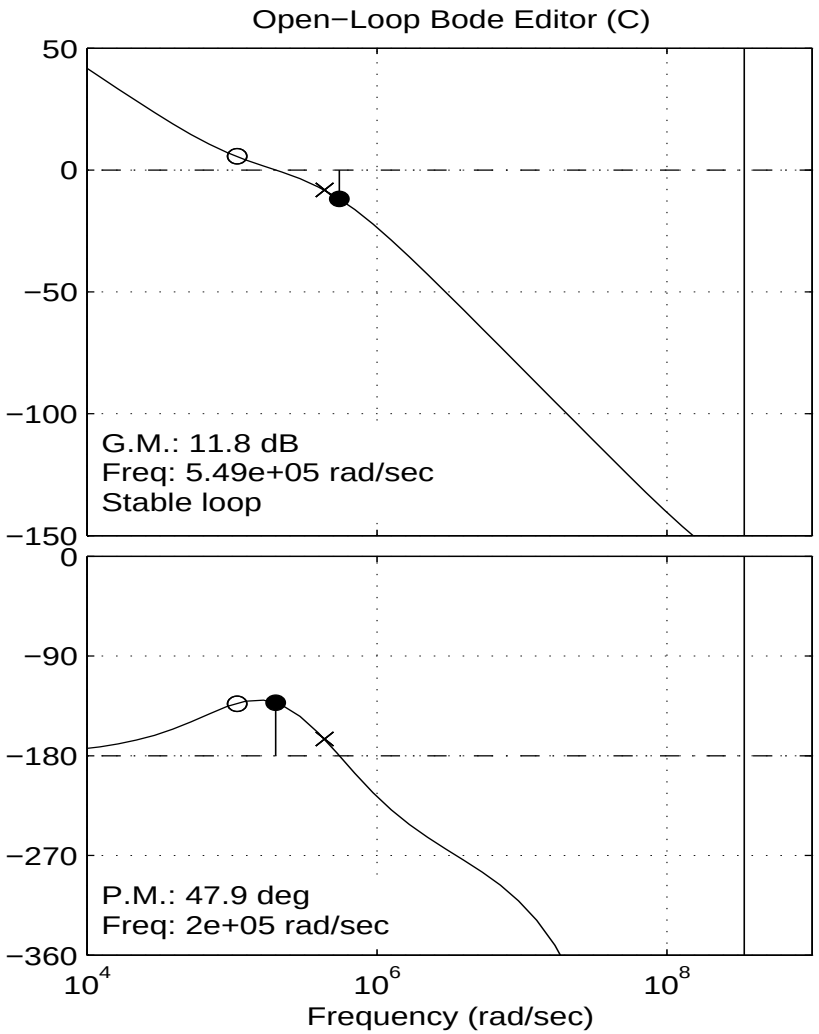
The closed loop transfer function:

$$H_c = \frac{H_o}{1+K_R H_o}. \quad (2)$$

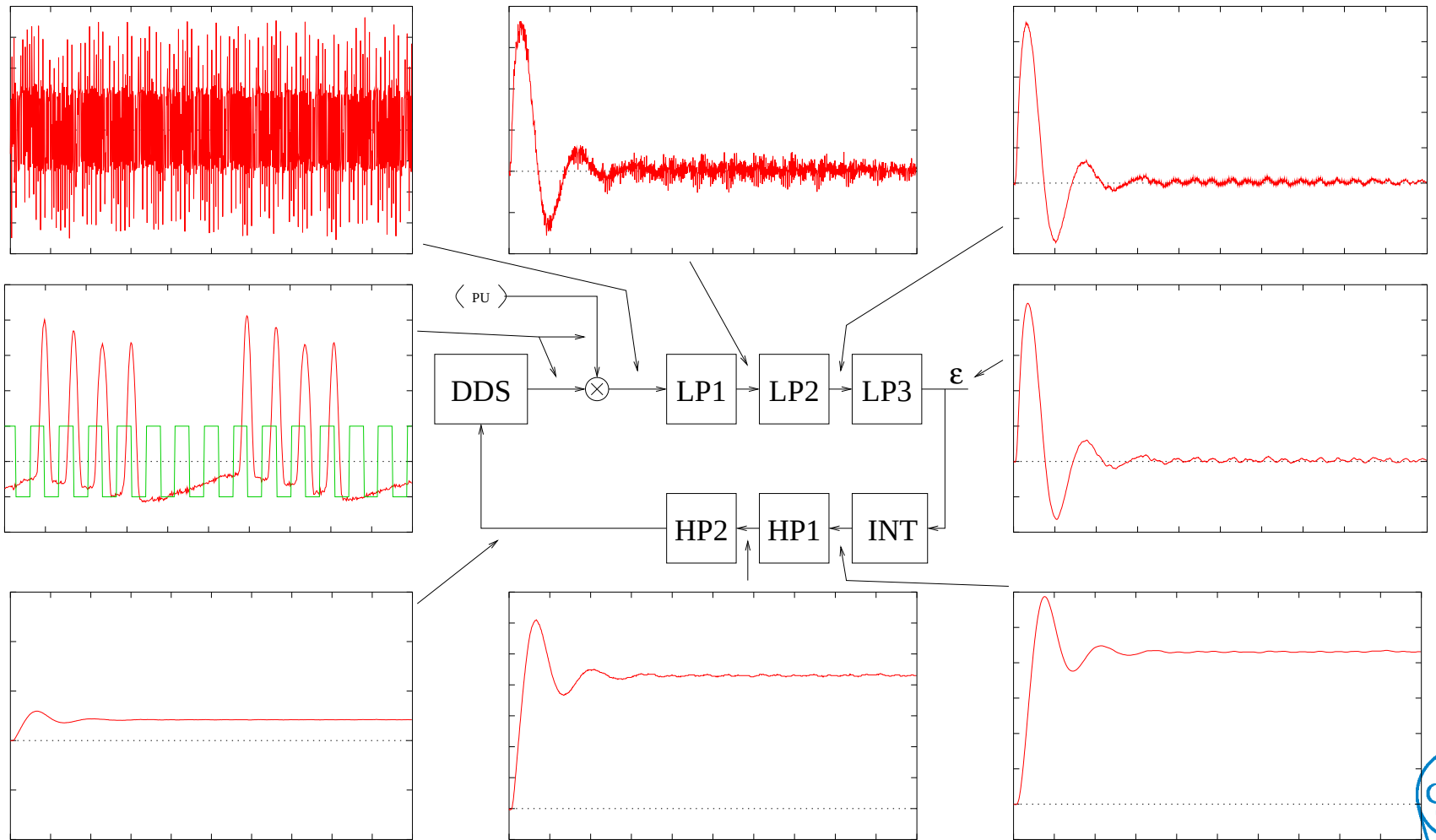
System dynamics determined by the poles of H_c

Root locus of PLL





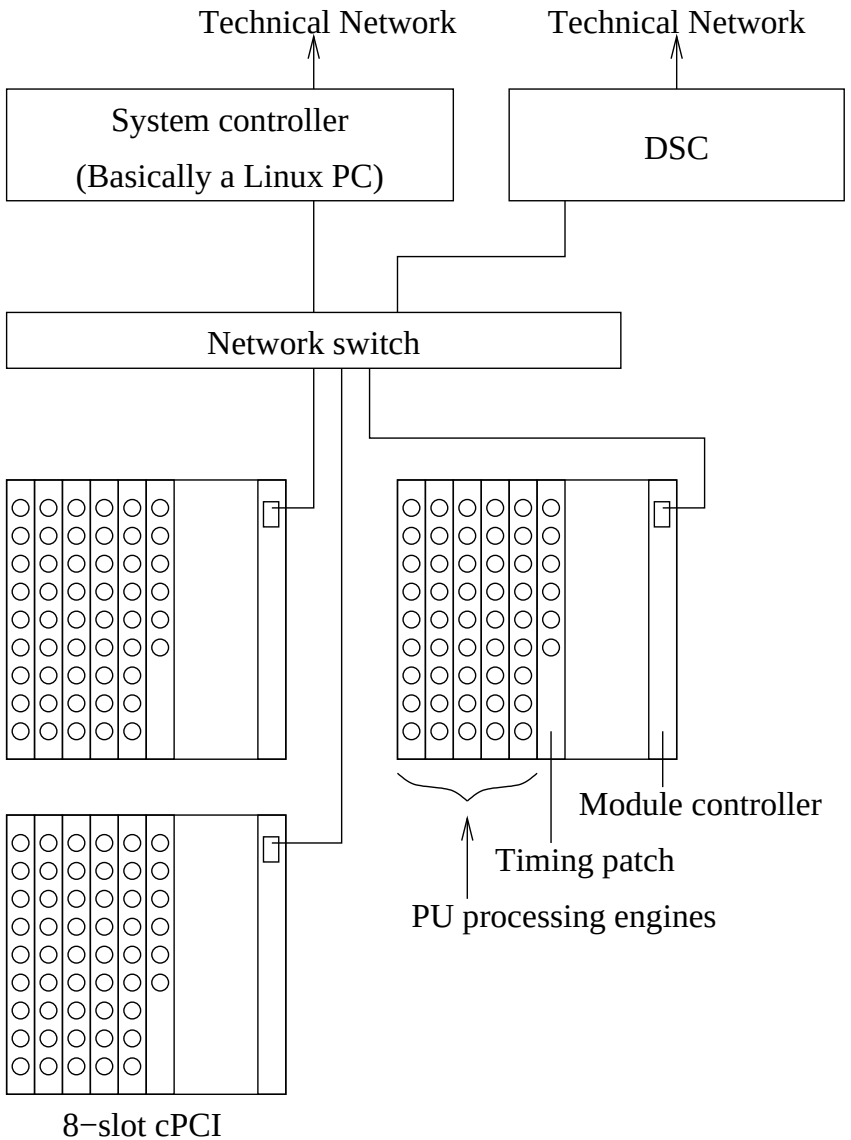
PLL loop frequency step response



Data block summaries

```
  2302:        SH8
period start end  h bunches mask      n
   0     0   986  0   0     0x00000  3090574
   1     5    95  8   1     0x00080    20968
   2   171   986  8   8     0x000ff  3069606
[...]
  2305: SH16-21LI
period start end  h bunches mask      n
   0     0  1351  0   0     0x00000  1774291
   1     5    95  8   1     0x00002    21671
   2   236   376 16   2     0x00003    76780
   4   376   396 14   2     0x00003    13444
   5   396   441 12   2     0x00003    30248
   6   441   466 24   4     0x0000f    33608
   7   466  1351 21   4     0x0000f  1598540
```

Hardware setup



Hardware and software organization