LLRF Topical Workshop on Timing, Synchronization, Measurements and Calibrations

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High-precision clocks and triggers for longitudinal beam measurements in high energy synchrotrons

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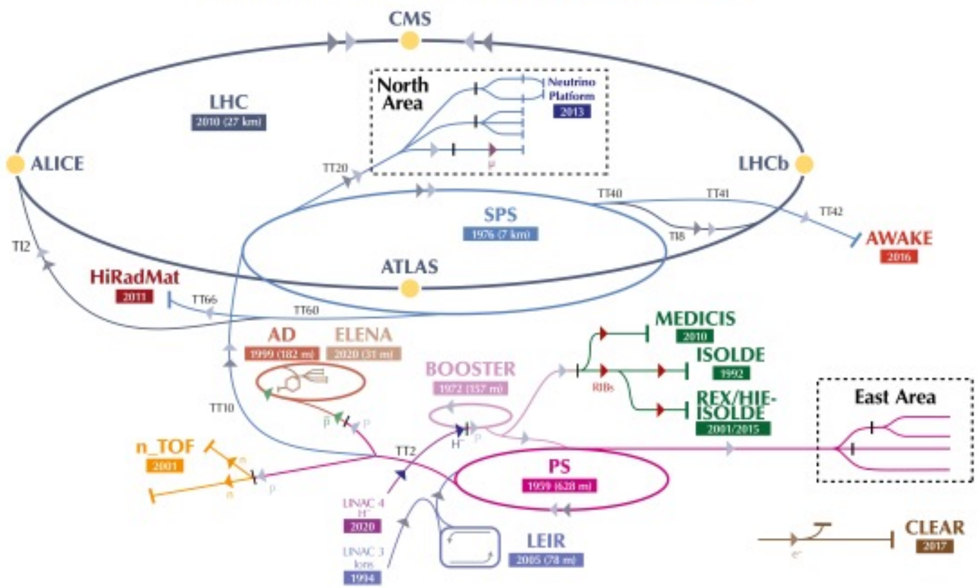
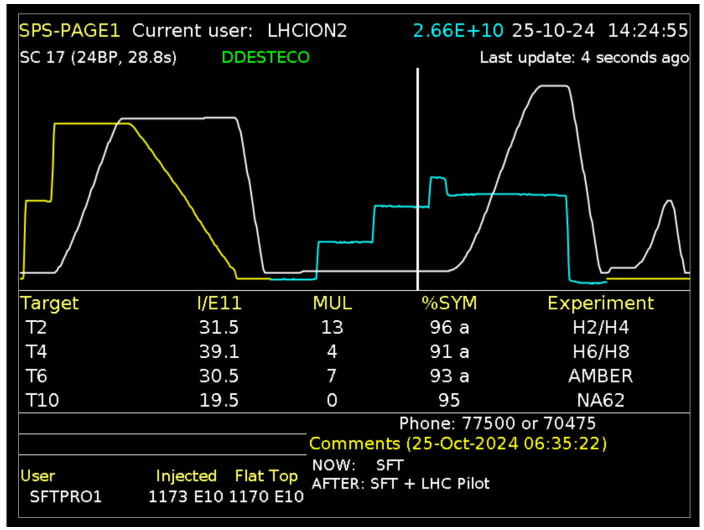
outline

- introduction on SPS, SPS RF
- SPS longitudinal beam observation systems
  - in particular Mountain Range and Beam Quality Monitor
- standard triggering scheme
  - including limitations, especially for ion operation
- triggering scheme with WR2RF

introduction: the SPS

- Super Proton Synchrotron (SPS): second largest CERN accelerator
  - LHC injector, fixed target program in North Area, AWAKE, HiRadMat
  - different "users" served in the same minute

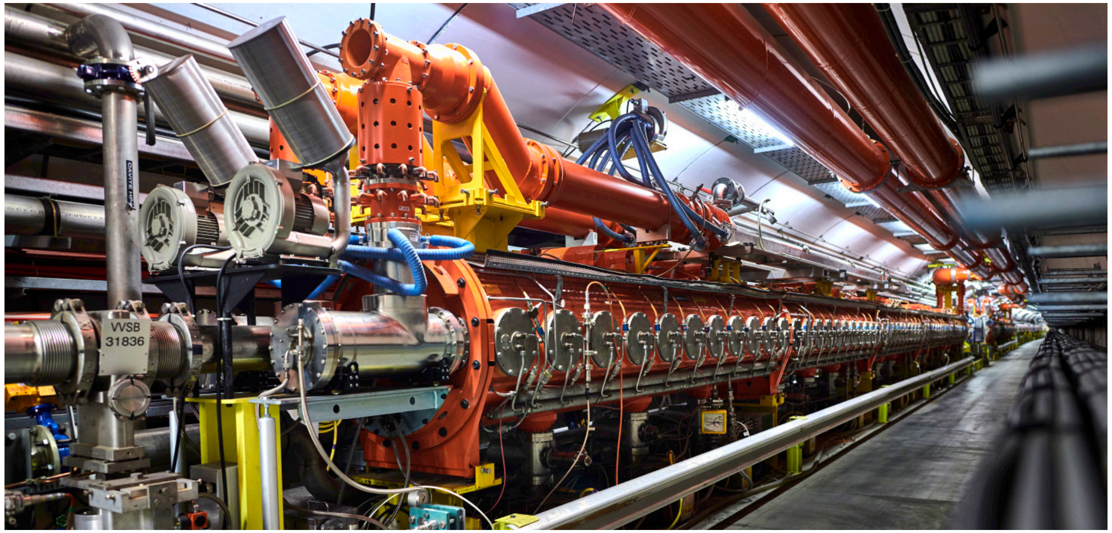




SPS status display (Page 1)

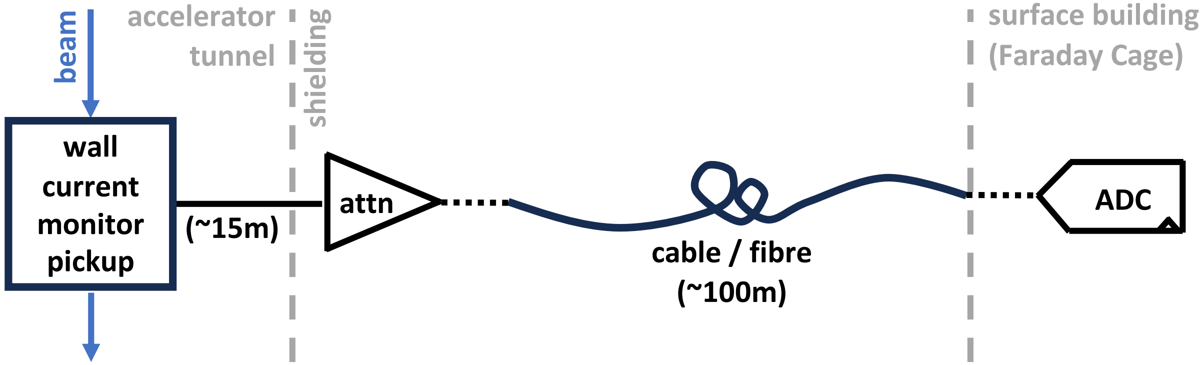
introduction: SPS RF

- 6x 200 MHz Travelling Wave structures
  - designed for 10 - 450 GeV/c protons
  - bandwidth: 199.5 - 200.4 MHz
  - for p+, $f_{RF} = h\ f_{rev}$, with h = 4620
    - Δf = 0.06-0.2%
  - note: operation for heavy ions is more complex



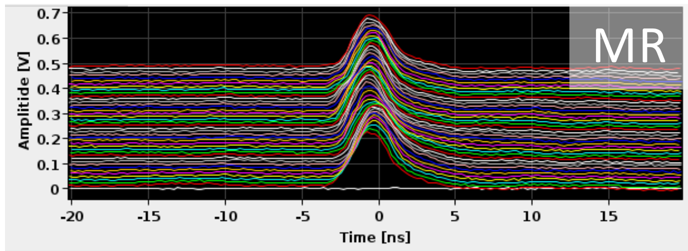
p [GeV/c]	f_{rev} [kHz]	f_{RF} [MHz]	bucket [ns]
10	43.186	199.5185	5.012
14	43.279	199.9468	5.001
26	43.347	200.2645	4.993
450	43.375	200.3944	4.990

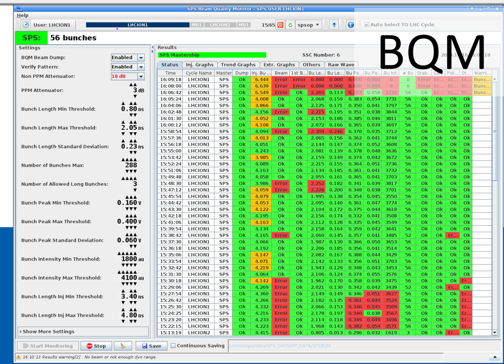
SPS longitudinal beam observation systems



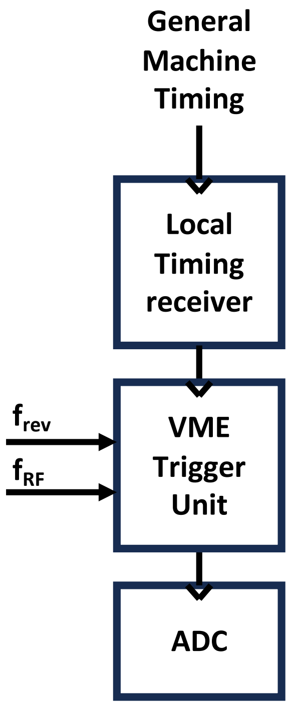
- several different systems
  - remotely controlled programmable attenuators
  - ~100 m on cable or fibre to ADC
  - ADC on the surface
  - (triggering scheme on next slide)

- two main systems used in operation
  - “Mountain Range” for visual checks
    - beam structure, injection phase, …
    - older pickup, transmission on cable
  - “Beam Quality Monitor” for automated evaluation of longitudinal beam quality and pattern
    - inhibits injection into the LHC if parameters out of spec
    - newer pickup, transmission on optical fibre for improved profile quality



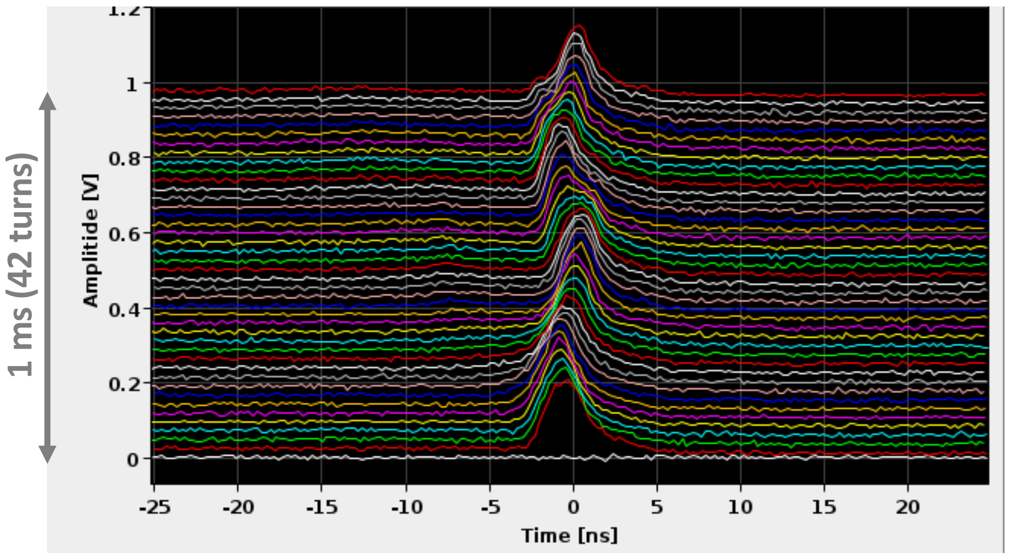


longitudinal observation triggering scheme



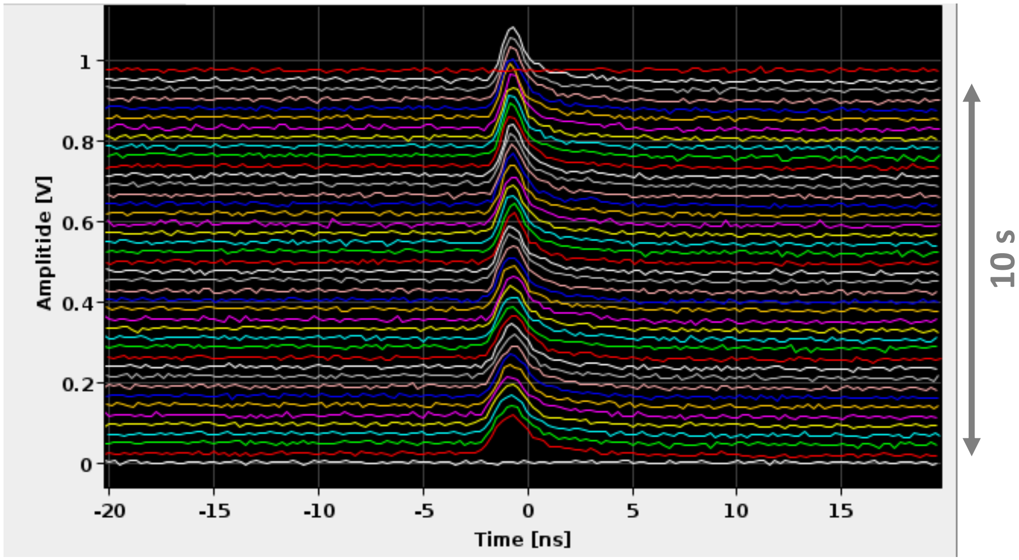
- General Machine Timing
  - telegram broadcast on cable to synchronize equipment to events like injection, start of ramp, start of flat top, start of fast or slow extraction…
- Local Timing receiver
  - outputs pulse triggered by timing event, with option of additional delay (generally ms precision)
- VME Trigger Unit
  - RF-synchronous counter, thanks to f_{rev} and f_{RF} inputs (despite the changing frequencies)
  - precise to the bucket + fine alignment down to 20 ps precision
  - started by local timing pulse and f_{rev}
    - alternatively to local timing, could also be started by e.g. injection or extraction pulse, for turn accuracy
  - can do single pulse, or pulse burst at chosen spacing
- VME Trigger Unit finally triggers the ADC
  - for desired user/cycle, at desired time in the cycle, at desired bucket, with fine alignment
- i.e. beam synchronous triggers at any azimuth with resolution of 20 ps
  - example: for standard MR, acquire bucket 1 for 42 consecutive turns (i.e. 1 ms) at every injection

examples of acquisitions with protons



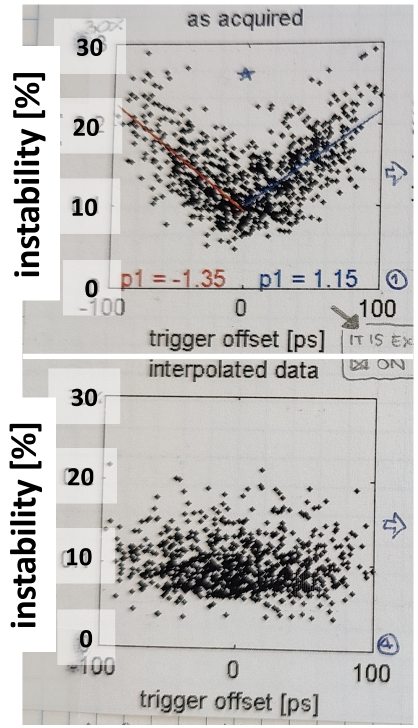
MR at injection

MR along the cycle



observation jitter

- BQM includes beam longitudinal stability analysis
  - comparison of 8 acquisitions at turn spacing of fraction of synchrotron period
  - must make sure it is not the trigger that moves!
- instability measurement includes component proportional to ADC trigger offset
  - trigger offset is due to free running clock of ADC, different for each acquisition, and <125 ps (ADC is 8 GS/s)
  - top plot: stable beam is measured as marginally unstable, proportionally to trigger offset excursion among acquisitions
  - bottom plot: if profiles are interpolated according to trigger offset, instability measurement is reduced
- for the purposes of longitudinal beam observation, the trigger jitter of the observation systems is negligible



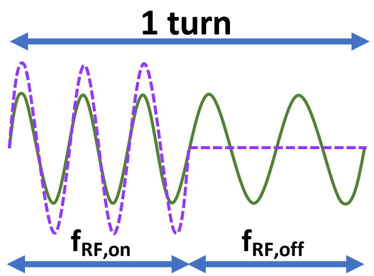
hand-written notes
from my 2009 logbook!

added complexity for ion operation

- f_{RF} = 4620 f_{rev} too low at injection for ions
  - e.g. for lead (Pb)
  - (cavity bandwidth: 199.5 – 200.4 MHz)
  - Δf = 0.9%

p [GeV] (Pb)	f_{rev} [kHz]	f_{RF} [MHz]
17.07	42.967	198.5094
451.15	43.375	200.3921

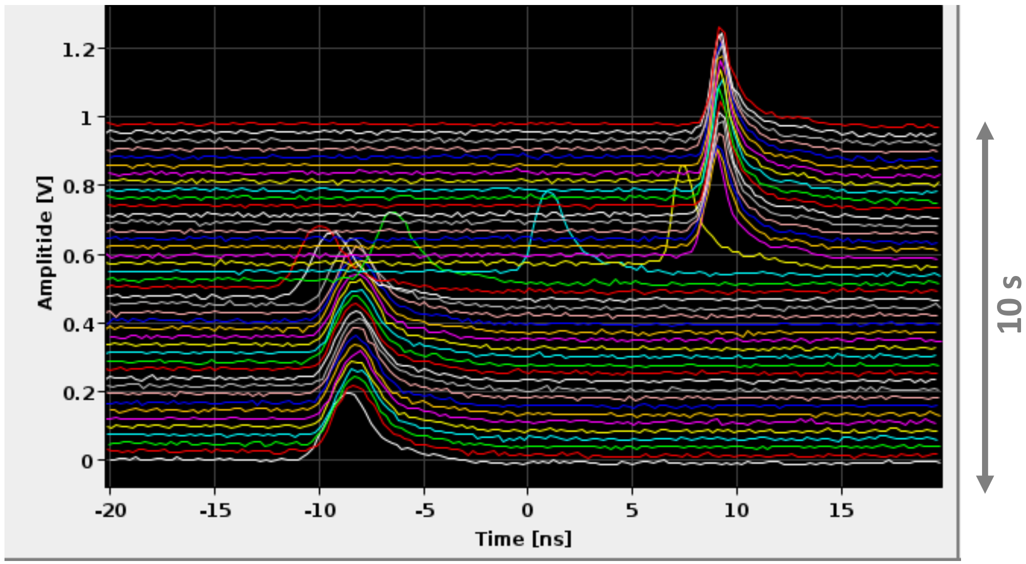
- use Frequency Shift Keying (FSK) and “Amplitude” Modulation (AM)
  - FSK: $f_{RF,on}$ and $f_{RF,off}$ in the same turn
  - AM: RF off for half of the time
  - choose $f_{RF,on}$ as needed for beam, within cavity bandwidth
    - at injection: bunch to bucket transfer from injector (CERN Proton Synchrotron), and capture at SPS (h = 4653, $f_{RF,on}$ = 199.9255 MHz)
  - $f_{RF,off}$ in the other half of the ring, such that beam is in bucket 1 and with correct phase after a turn
    - $f_{RF,avg} = 4620\, f_{rev} = (f_{RF,on} + f_{RF,off})/2$



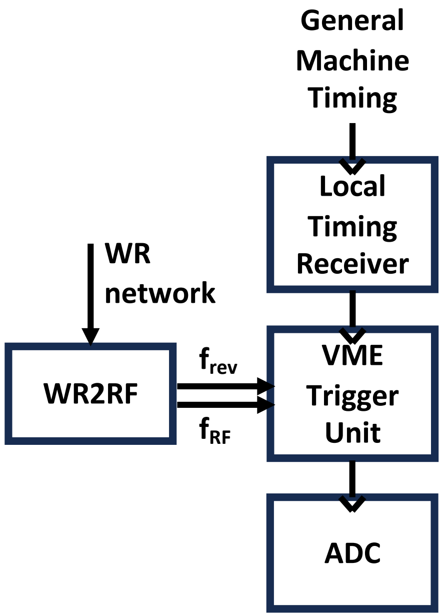
- in addition, Fixed Frequency Acceleration: accelerate with varying h ($f_{RF,cen}$ = 200.222 MHz)

examples of acquisitions with Pb ions

- complex RF operation complicates longitudinal observations
  - frequency swing from injection to high energy combined with cable delays results in moving acquisition
    - e.g. bucket 1 in MR acquisition moves by ~4 buckets
  - BQM needs to verify beam pattern: pattern matching depends on time in acquisition, and on phase of FSK modulation

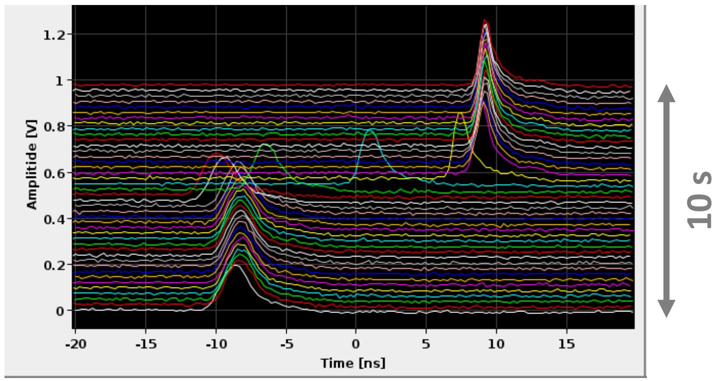


triggering scheme with White Rabbit

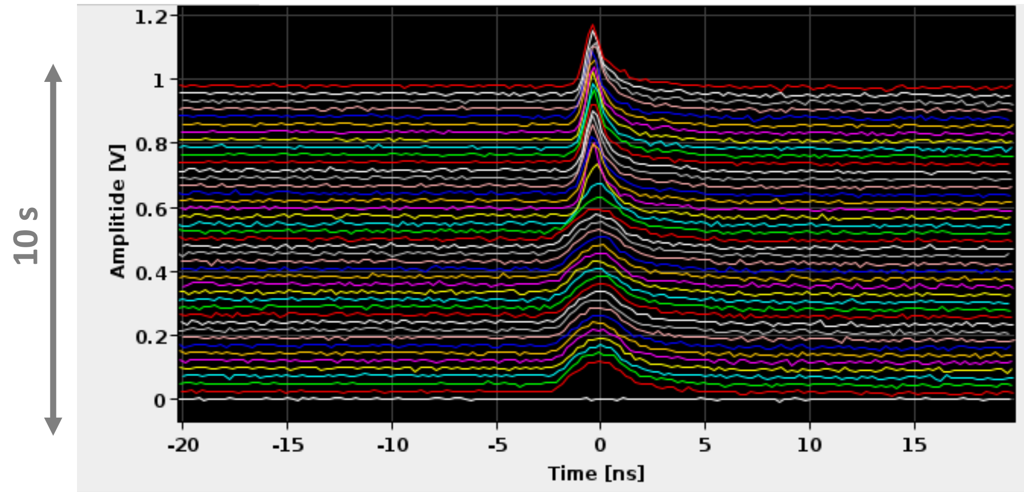


- in 2024, f_{rev} and f_{RF} synthesized locally by WR2RF (receives digitally the FTW for the f_{RF})
  - on WR2RF see **A. Spierer** and **G. Hagmann** at this workshop
  - delay compensation knob: calculate cable delay compensation, at every turn
  - FSK offset knob: adjust for counting $f_{RF,on}$ and $f_{RF,off}$
  - trigger unit offset: used for compatibility with previous setup
- advantages
  - observation does not slip with acceleration
  - same bucket 1 reference for different beams
    - results also in easier settings management for different users

examples of acquisitions with WR2RF - ions



with standard distribution



with WR2RF

present installation

Local Timing Receiver

WR2RF

VME Trigger Unit

General Machine Timing

conclusions

- several systems used at CERN SPS for longitudinal beam observations
  - e.g. Mountain Range for visual checks
  - e.g. Beam Quality Monitor for automated analysis of beam pattern, stability, … and inhibition of injection into LHC if parameters are out of spec
- improvement in longitudinal beam observations thanks to WR2RF
  - no observation slippage throughout acceleration ramp
  - single bucket 1 reference for different beam types
  - easier setting management
- WR2RF settings management to be improved
  - ideally, user to input delay and azimuth
  - results in cumbersome commissioning at present

references

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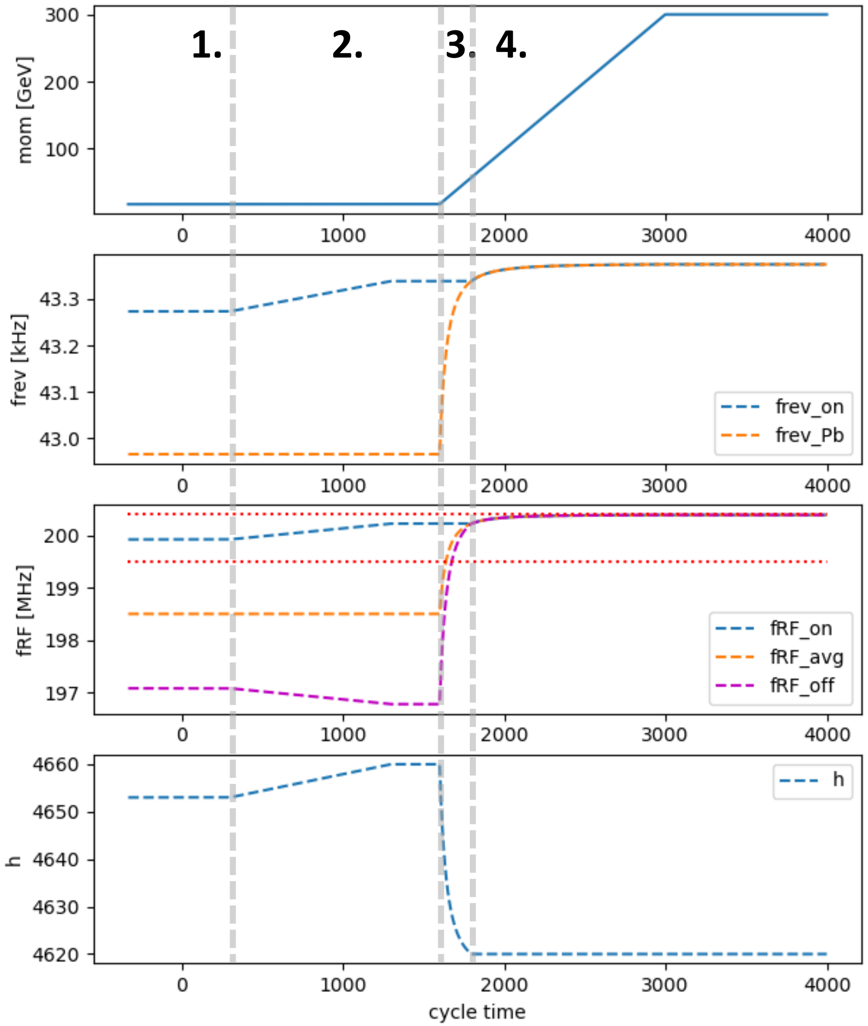
2. J. Coupard et al., "**LIU Technical Design Report- Volume I: Protons**", CERN, Geneva, Switzerland, Rep. CERN- ACC2014-0337, Dec. 2014.
3. E. Shaposhnikova, E. Ciapala, E. Montesinos, "**Upgrade of the 200 MHz RF system in the CERN SPS**", in Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11) IPAC11, San Sebastian, Spain, Sept. 2011, MOPC058.
4. D. Boussard, T. Bohl, T. Linnecar, U. Wehrle, "**Non integer harmonic number acceleration of lead ions in the CERN SPS**", 16th Biennial Particle Accelerator Conference and International Conference on High-Energy Accelerators, Dallas, TX, USA, 1 - 5 May 1995, pp.1506-1508.
5. information on **WR2RF**: https://www.white-rabbit.tech/rf-over-wr-cern/
6. Tomasz Włostowski et al.,"TRIGGER AND RF DISTRIBUTION USING WHITE RABBIT", ICALEPCS201.

spares

more on ion operation

1. injection: h = 4653 (AM and FSK)
2. after inj, before ramp: f_{RF} to $f_{RF,cen}$
   - f_{rev} constant, h varies, f_{RF} varies
3. during energy ramp: $f_{RF} = f_{RF,cen}$
   - f_{rev} varies, h varies, f_{RF} constant
4. stop FFA when $f_{rev,Pb}$ 4620 = $f_{RF,cen}$
   - continue with standard: f_{RF} = 4620 f_{rev}
   - stop FSK



abstract

- High energy synchrotrons, like the Super-Proton Synchrotron (SPS) and the Large Hadron Collider (LHC) at CERN, require high-precision beam synchronous triggers for longitudinal measurements, e.g. to acquire bunch profiles from a wall current monitor pickup.
- The observation triggering scheme is based on the General Machine Timing (GMT) followed by dedicated trigger units counting the revolution and RF frequency clocks to allow synchronisation to the exact RF bucket.
- Combined with a programmable fine delay, accurate triggers can be placed at any azimuthal position with a resolution of about 20 ps.
- The SPS installation is described in detail, including its additional flexibility for measurements at injection, extraction and bunch rotation.
- The performance and limitations of such an implementation are analysed in terms of jitter with respect to the beam, delay variation due to cable lengths between the clock generation and acquisition with a sweeping revolution frequency.
- Such varying delays can be compensated with the White Rabbit (WR) technology, and highlights from the recent upgrade in the SPS are presented.