SPS LLRF Upgrade project

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SPS RF Upgrade as HL-LHC injector

The demanding beam performance requirements of the High Luminosity LHC (HL-LHC) project and the available beam characteristics from the pre-injectors translate into a set of requirements for the SPS as HL-LHC injector.

- Protons [1]: Doubling beam intensity (25ns bunch spacing, 2.3×10^{11} p+/bunch at extraction, 2.5×10^{11} p+/bunch injected, up to 4 batches of 72 bunches/batch, 1.5A DC)
- Lead ions [2]: Bunch spacing of 50ns, long injection plateau of ~40s (3×10^{8} ions/bunch injected)

- Main limitations come from:
  - Beam-loading at very high beam intensity for protons (V_{RF}=1MV, ~2MV beam induced)
  - Longitudinal instabilities linked to longitudinal impedance

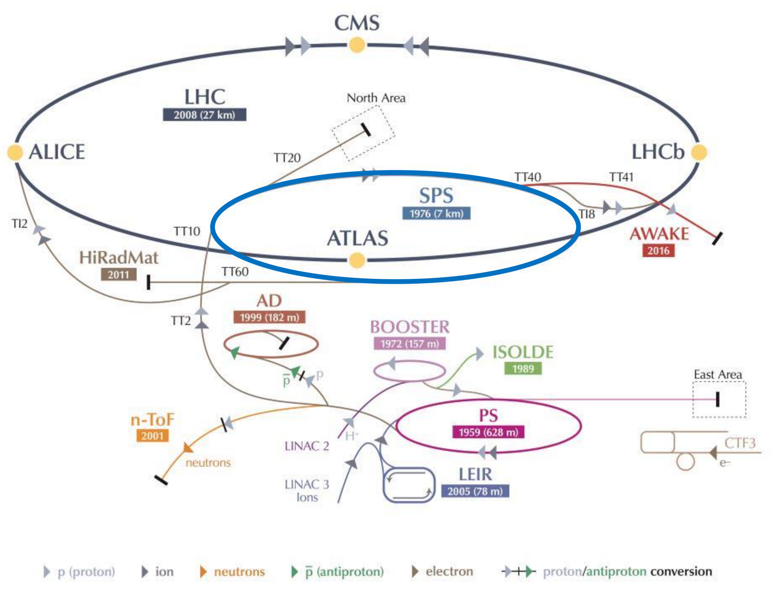

Figure 1 – CERN accelerators complex

SPS 800MHz RF systems upgraded in 2013-2014
- New power plants (IOT)
- New LLRF system (Cavity controllers, VME)

SPS 200MHz RF systems to be upgraded in 2019-2020
- 2 additional 200MHz travelling cavities of 32 cells
- Shortening another 2 cavities to 32 cells (RF voltage level increase, beam-loading reduction)
- 2 new power plants, upgrade of the current 4 power plants
- New LLRF cavity controllers (cavity impedance reduction to be improved by more than a factor 2, low noise)

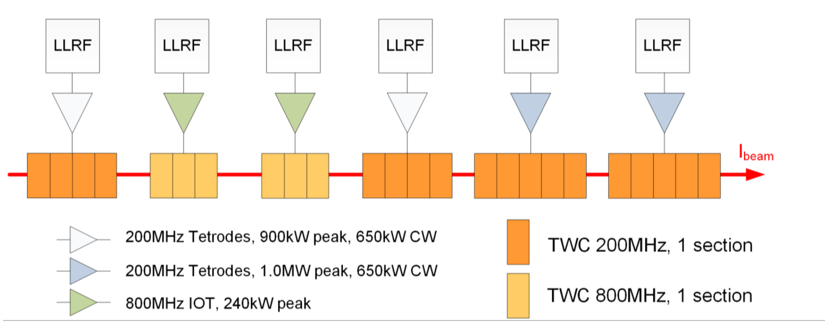

Figure 2 – SPS RF systems before LS2

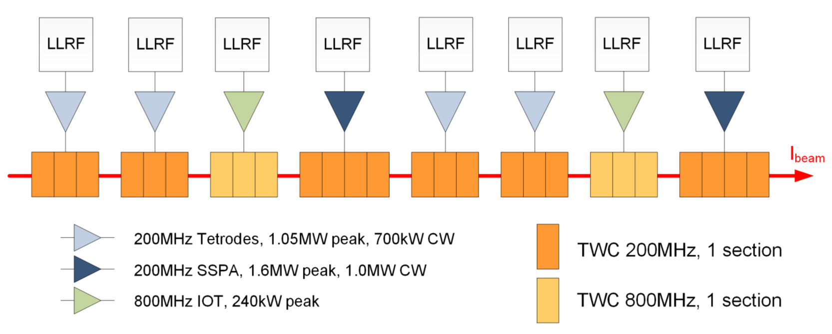

Figure 3 – SPS RF systems after LS2

SPS RF Beam-control upgrade in LS2 (2019-2020)
- New phase & radial position measurement (bunch per bunch)
- Fixed-frequency acceleration (FFA) for ion acceleration
- Fixed-frequency sampling
- Use of deterministic serial link (White-rabbit) for RF frequency and trigger distribution
- Momentum slip-stacking for 50ns ion bunch spacing, from 100ns spacing at injection

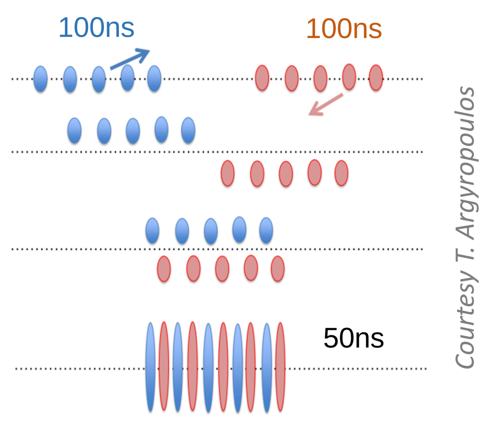

Figure 4 – Ions Slip-stacking [3]

SPS LLRF Architecture

The SPS LLRF is divided in 6 distinct systems:
- ***Beam phase measurement*** (bunch per bunch) from resonant pick-up or wall current monitor
- ***Beam radial position measurement*** (bunch per bunch) from strip-line pick-up
- ***Cavity controller*** to regulate the cavity voltage and to compensate for transient beam loading
- ***RF-Synchro*** to generate and distribute beam synchronous signals or triggers
- ***RF-Diagnostic*** system for beam measurement (beam quality monitor, mountain range of beam profile, beam observation)
- ***Beam control*** system which implements all beam-based loops (synchro, phase and radial loops).

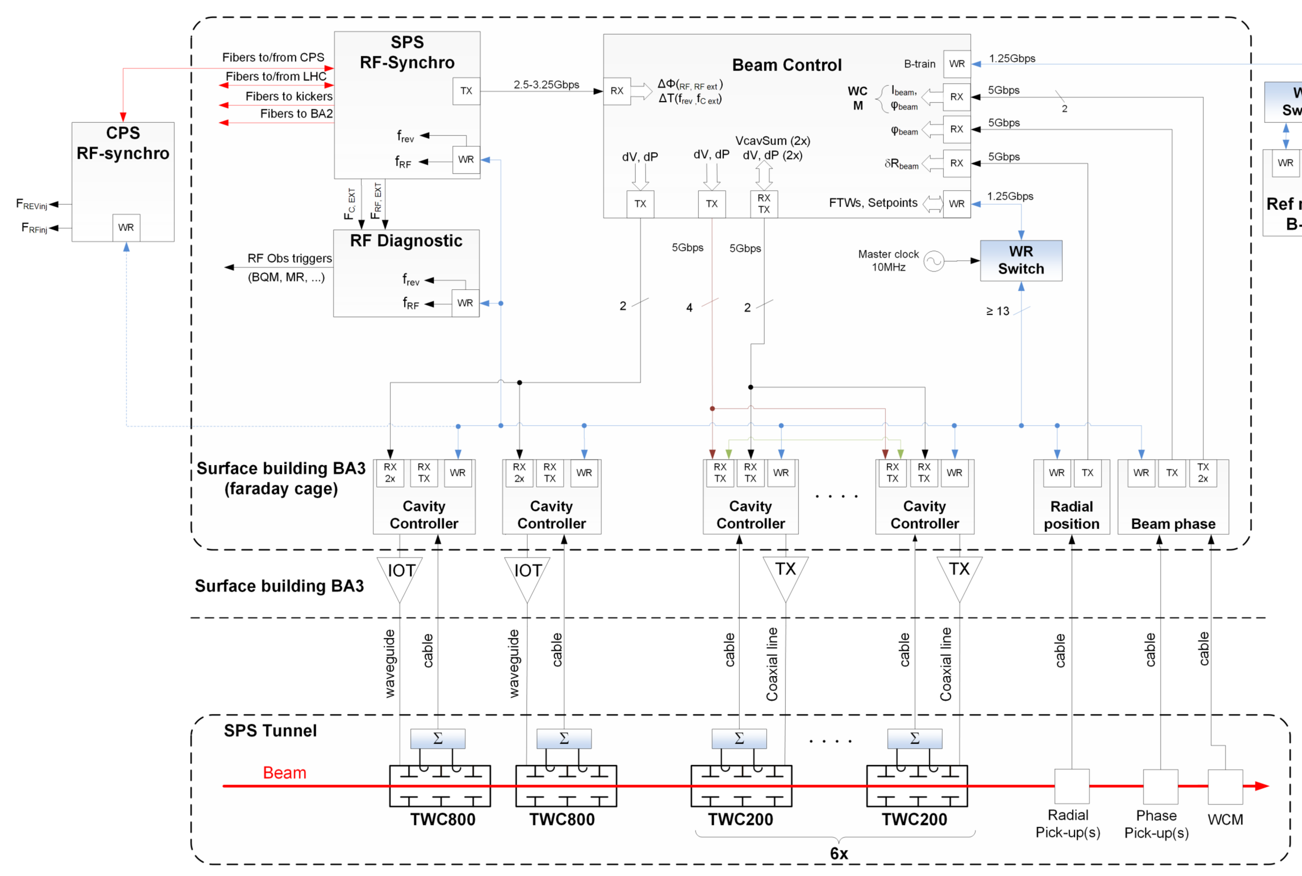

Figure 5 – SPS LLRF architecture

Beam parameters (phase, radial position) and cavity voltages are sampled at one location only and then transmitted over fast serial links of up to 5Gbits/s to the beam control and across the cavities. That will make a MIMO feedback around the cavities of different lengths possible.
The beam control based on a SoC architecture (FPGA+ARM processor) will also receive the B-field over a serial link as part of the CERN renovation campaign of B-train distribution over White-rabbit. The RF frequency will be transmitted by several FTWs to allow for operating two sets of cavities at different frequencies for ion slip-stacking.

Fixed-frequency sampling & White-rabbit

A big paradigm change was decided for the SPS LLRF upgrade by using fixed-frequency sampling. It simplifies the clocking scheme along with better noise performance but leads also to a much higher complexity in signal processing which can be handled by the larger FPGAs available today [4]. The generation of the bunch synchronous clock or triggers is done in the FPGA (NCO). It is compatible with the frequency modulation (≤1.7MHz) at $4\cdot f_{H1}$ used for the fixed-frequency acceleration of ions. The slip-stacking operation will be achieved by using different FTWs across the cavities. The NCO generates the LO for up/down modulation synchronously with the revolution frequency.

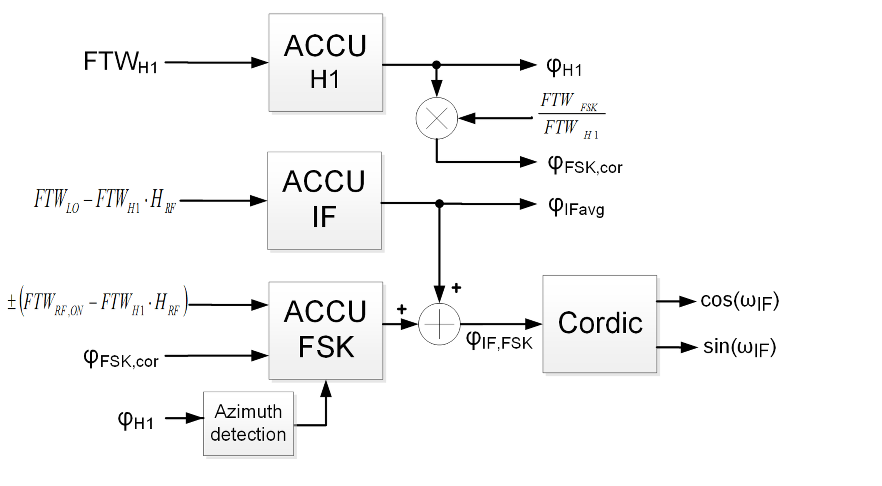

Figure 6 – NCO for up/down modulation in fixed frequency clock

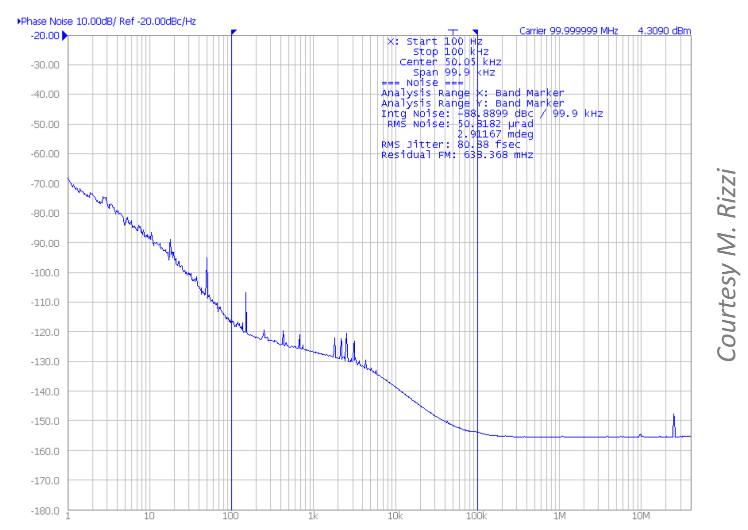

Figure 7 – recovered sampling clock from White-rabbit serial data stream

The fixed-frequency sampling is reconstructed from the white-rabbit data stream. Efforts are on-going to reduce the phase noise of the 125MHz clock below -130dBc/Hz for the offset range from 100Hz to 1kHz, that covers the synchrotron frequency range of protons and ions.
The phase stability of the 125MHz clock following power cycles is being studied.

SPS 200MHz Cavity controller

The design of the cavity controller with fixed-frequency sampling & processing clocks is on-going. It includes 3 regulation loops:
- ***One-turn delay RF feedback*** (IQ) for cavity voltage regulation and transient beam-loading reduction [4]
- ***Polar loop*** (gain & phase loop) for power amplifier noise reduction (amplitude & phase noise). It also maintains the open-loop phase for the RF feedback and linearizes the amplifier gain
- ***Feed-forward*** (IQ) further reduces the beam loading by increasing the regulation BW from the beam current measured in a wideband pickup

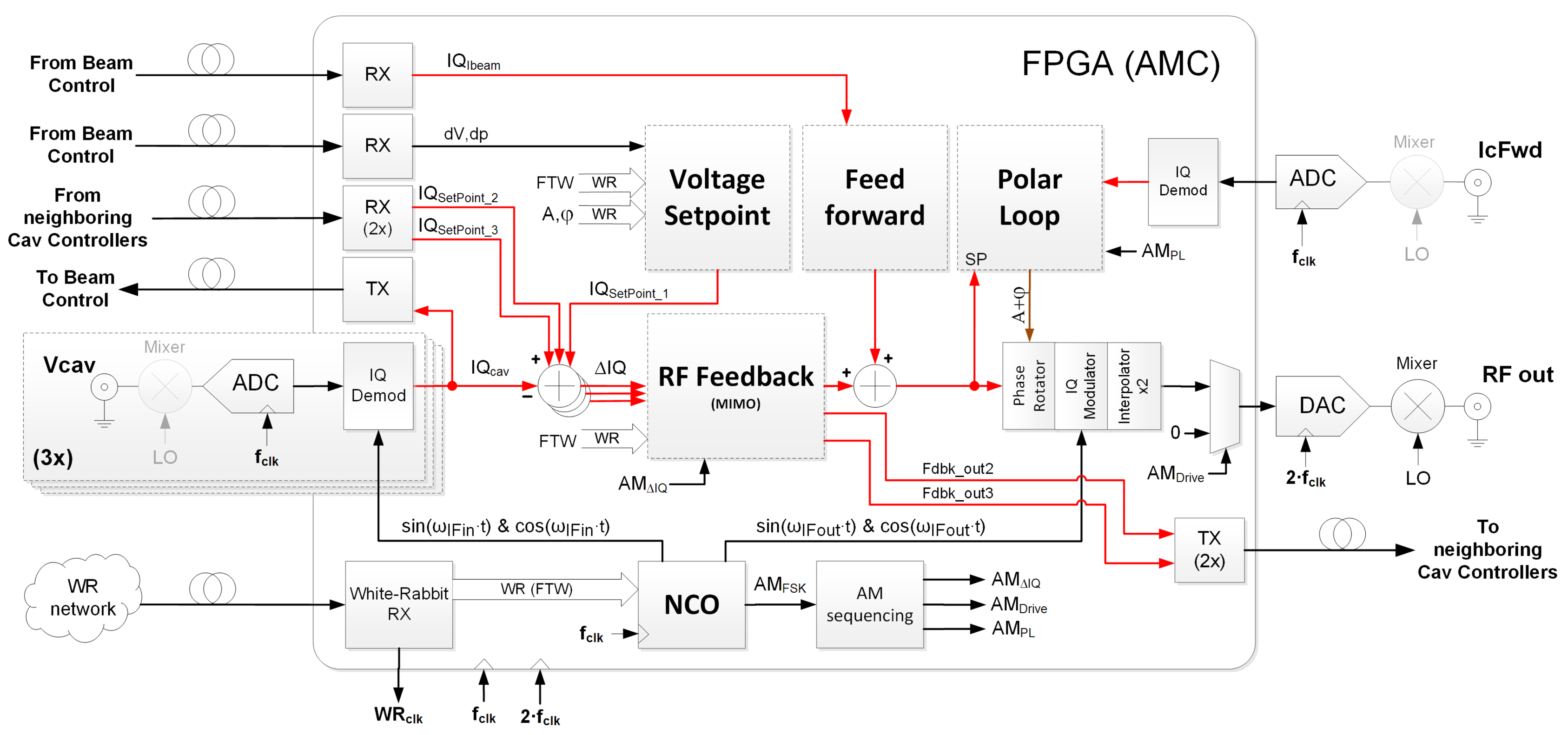

Figure 8 – SPS LLRF cavity controller diagram

μTCA platform

The μTCA platform fits all requirements for the SPS LLRF upgrade. Since the LHC design, the LLRF systems have been developed on VME/VXS platforms for all CERN accelerators. Within the CERN Beams department, the decision has been taken to move away from VME for new projects. We are now prototyping the μTCA alternative as joint effort with the CERN Controls group.

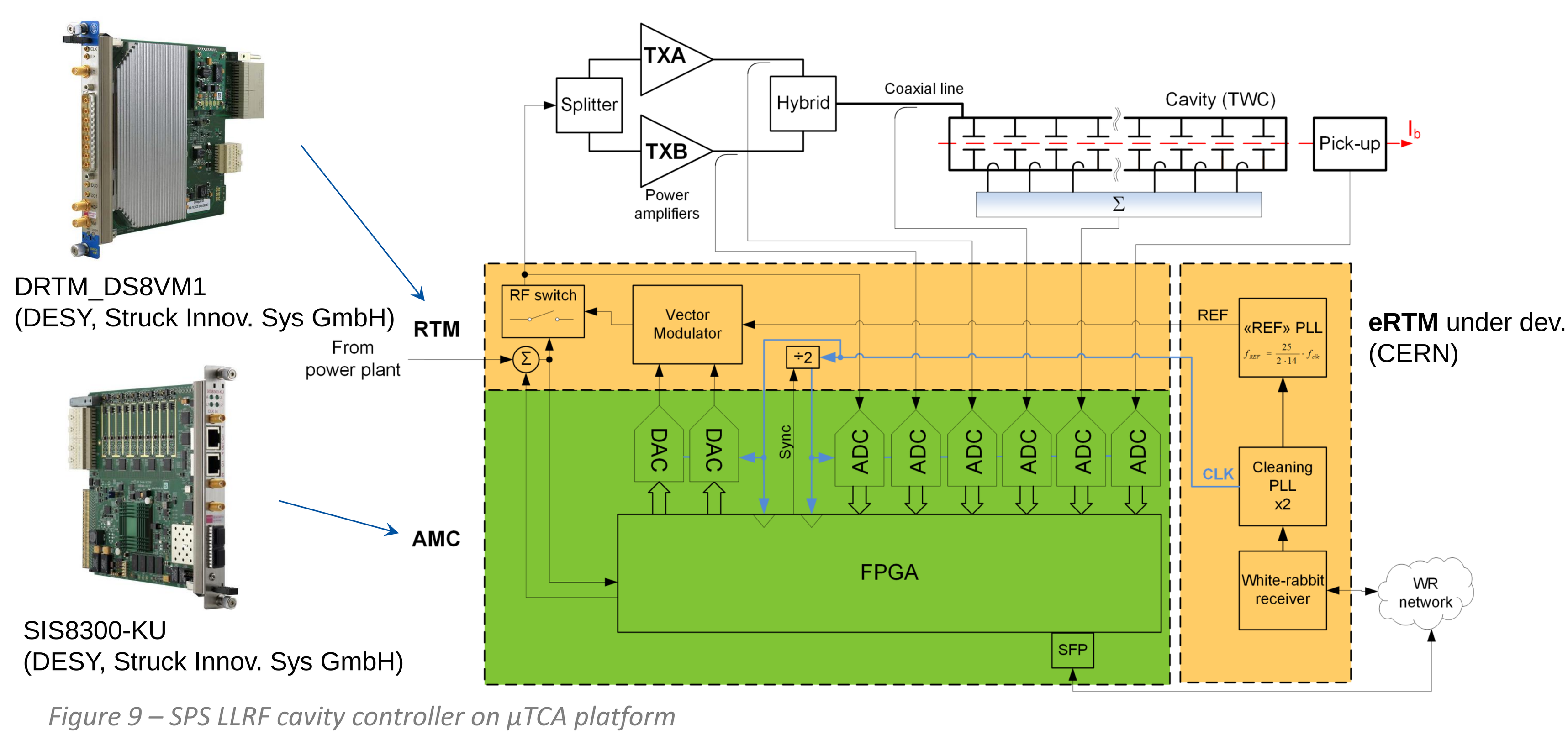

Figure 9 – SPS LLRF cavity controller on μTCA platform

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[2] J. Coupard & al. LHC INJECTOR UPGRADE – Technical Design Report – Volume II: Ions, CERN-ACC-2016-0041, 01.04.2016
[3] T. Argyropoulos, MOMENTUM SLIP-STACKING OF THE I-LHC BEAM IN THE SPS, talk at LIU-SPS BD WG, CERN, 27.02.2014
[4] L. Schmid & al., ONE-TURN DELAY FEEDBACK WITH FRACTIONAL DELAY FILTER, Poster P-77, LLRF workshop 2017, Barcelona