A digital system for longitudinal emittance blow-up in the LHC

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Abstract

In order to preserve beam stability with nominal bunch intensity in the LHC, longitudinal emittance blow-up is performed during the energy ramp by injecting phase noise in the main accelerating cavities. The noise spectrum spans a small frequency band around the synchrotron frequency. It is generated continuously in software and streamed digitally into the Digital Signal Processor (DSP) of the Beam Control system where it is added to the pick-up signal of the beam phase loop, resulting in a phase modulation of the accelerating RF. In order to achieve reproducible results, a feedback system, using as input the measured bunch lengths averaged over each ring, controls the strength of the excitation, allowing the operator to simply set a target bunch length. The spectrum of the noise is adjusted to excite the core of the bunch only, extending to the desired bunch length. As it must follow the evolution of the synchrotron frequency through the ramp, it is automatically calculated by the LHC settings management software from the momentum ramp and RF voltage. The system is routinely used in LHC operation since June 2010. We present here the details of the implementation in software, FPGA firmware and DSP code, as well as some results with beam.

Motivation

- First attempt to ramp nominal intensity single bunch (Fig. 1).

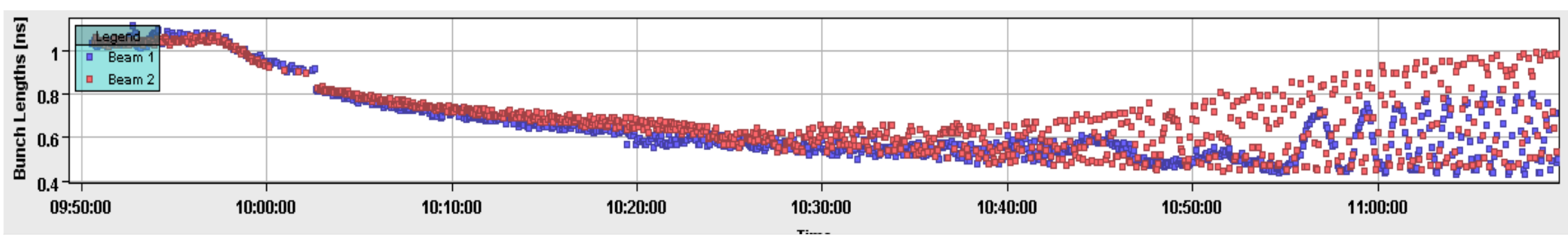

Fig. 1. Bunch length during ramp. The longitudinal emittance is too low (¡0.4 eVs). The bunch becomes unstable (quadrupole oscillations).

- As bunch length decrease during the acceleration ramp, the beam become unstable after a certain threshold [1].
  - A temporary solution in the beginning, was to increase the bunch length from the SPS[2], but there were increased capture losses due to the mismatch between the LHC and SPS buckets.
- The LHC blow-up was deployed during the summer of 2010. The blow-up is active through the ramp and adjusted to keep the bunch length at 1.2 ns, thus achieving longitudinal stability[4].

System overview

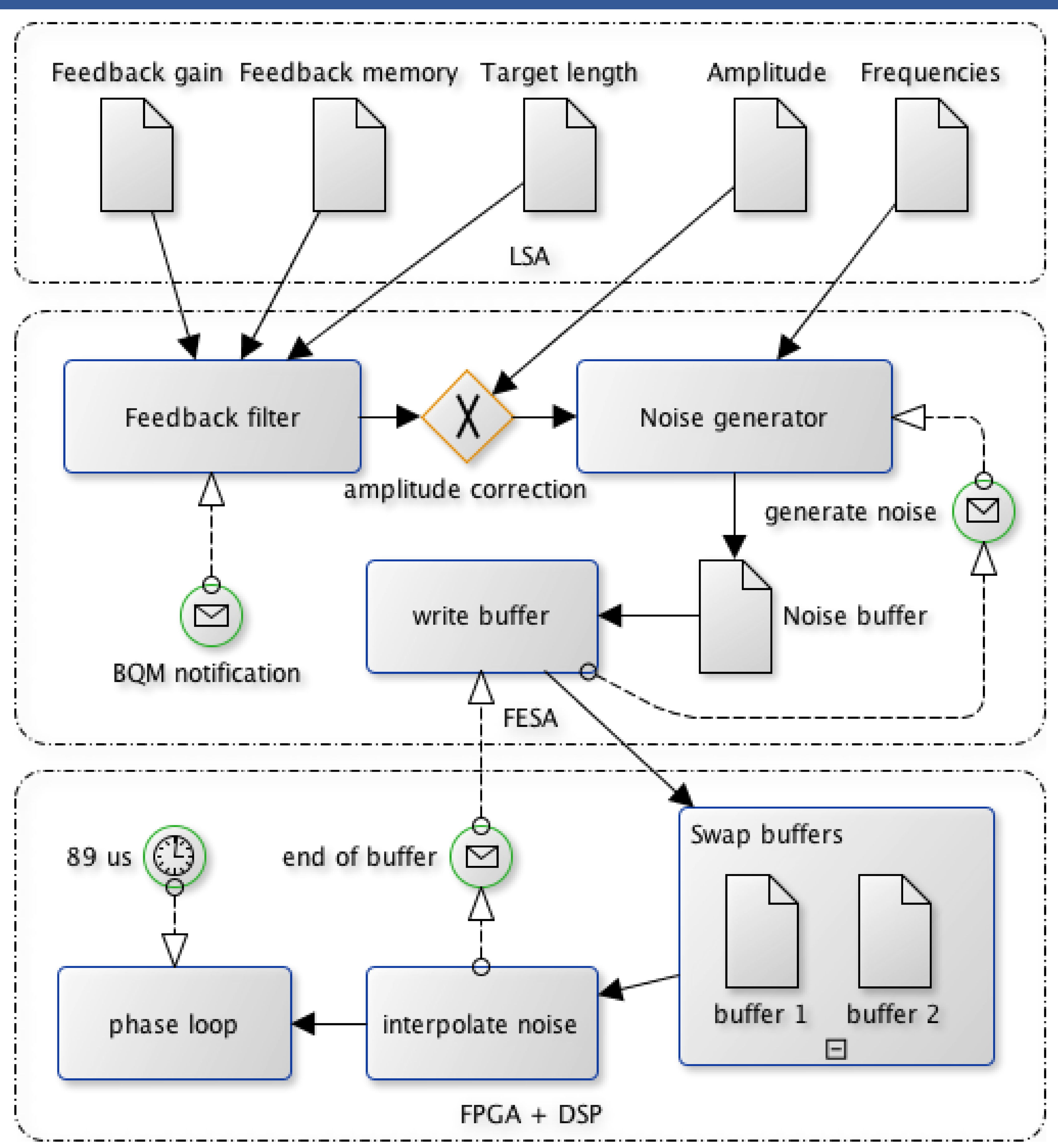

Fig. 2. The 3 layers of this system.

- The system contains 3 layers:
  - The LSA layer [6] keeps track of the settings and regenerates them if anything relevant changes.
  - The FESA layer [5] uses the settings sent by LSA to calculate on the fly the noise. It also talks with the FPGA to refill the noise buffer each time the DSP empties a buffer.
  - The hardware layer (FPGA + DSP) injects the noise into the phase error correction, acting on the fundamental RF system (400.8 MHz). The DSP interpolates one noise value each turn of the beam (89 μs) from the noise buffer.

Noise algorithm

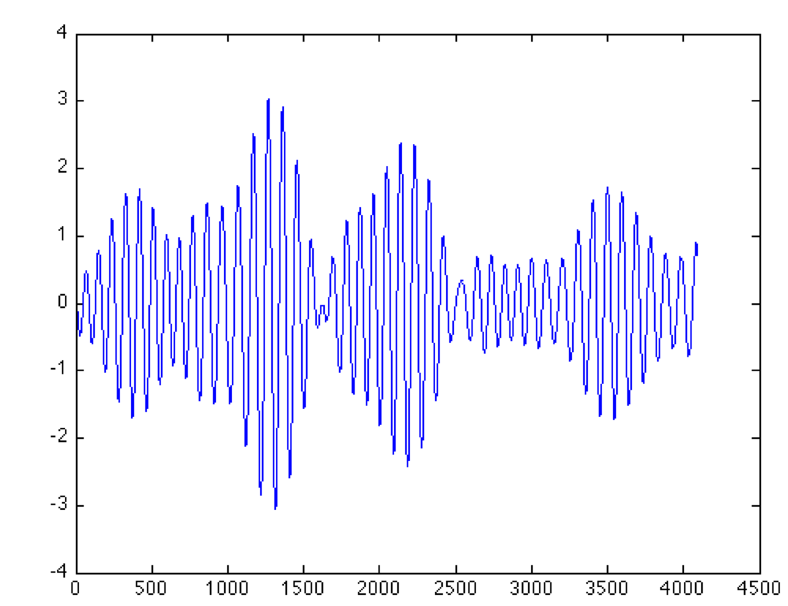

Fig. 3. Example of one buffer of noise.

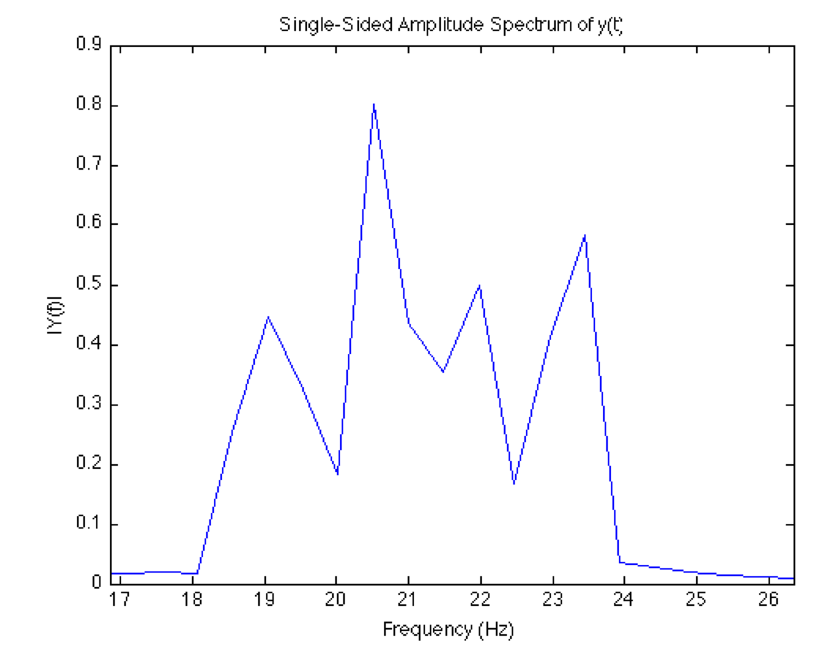

Fig. 4. FTT of noise buffer in Fig. 3.

- Allows the generation of precisely band-limited noise[7].
- Allows custom spectral shape.
- Uses sine and cosine generators, initialized to a random phase and scaled with a random amplitude
- Generates noise in a normalized frequency range, with the generator frequencies equally spaced between 0 and 1
- The noise is then translated numerically to the correct frequency range

Feedback

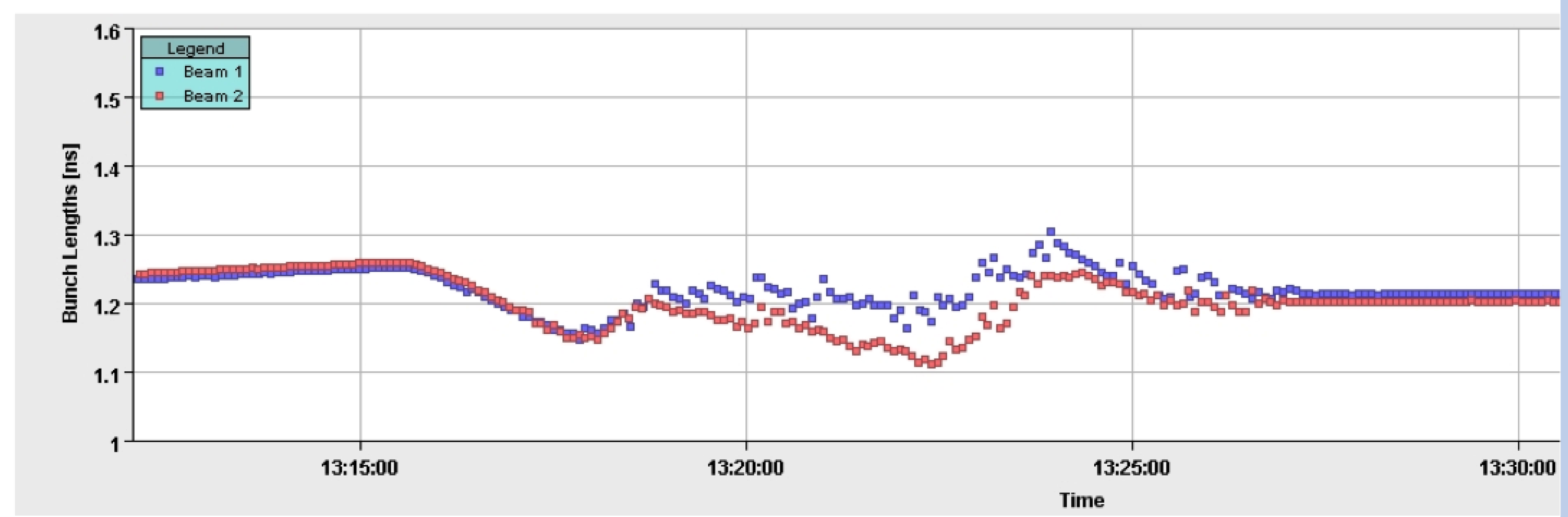

Fig. 5. Four-sigma bunch length evolution during a ramp with the blow-up system set for a 1.2 ns target. Start of ramp at ∼13:16, end at ∼13:27.

- Feedback is implemented as a low-pass filter using as input the difference between the measured mean bunch length[8] and the target one.
- As seen in Fig. 5, the mean bunch length evolution is not predictable
- Feedback is a must to achieve reproducibility in the results, thus guaranteeing a constant mean bunch length from fill to fill of the LHC.

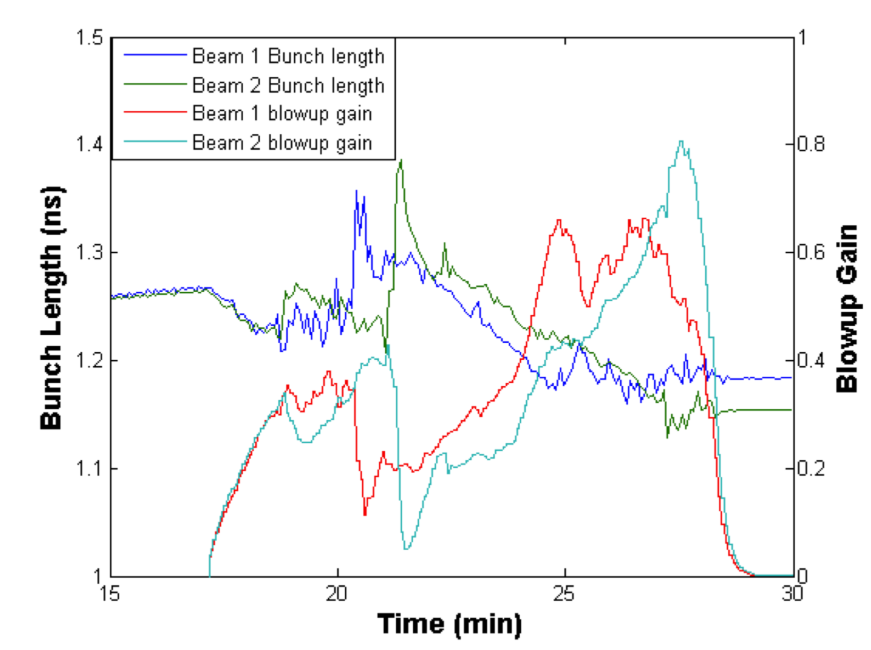

Fig. 6. Bunch length (mean over 1380 bunches/beam) and excitation (blowup gain) during the ramp.

Results

- Without the longitudinal blow-up system, the LHC would not be able to ramp nominal bunches.
- Achieves reproducibility with a $\pm$ 50 ps error[3].
- Reduces the spread of bunch lengths, see Fig. 7.
  - Spread is about 60 ps after injection and is reduced to around 15 ps at flat top.
- Improvements are in the pipeline to increase the measurement rate of the mean bunch length done by the BQM (currently 5 s)
  - Lower time constant means higher gain without instabilities.

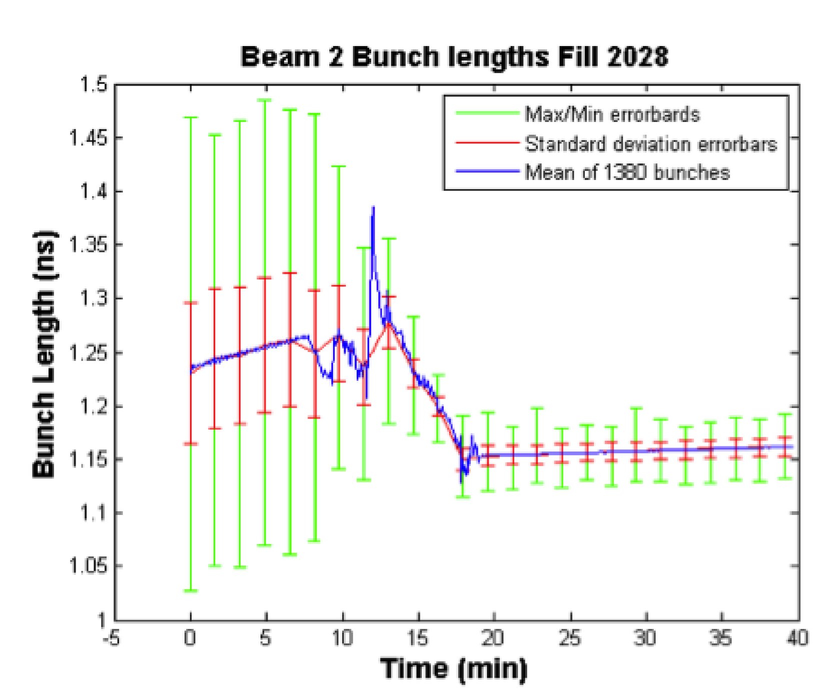

Fig. 7. Statistics on bunch length (mean, min, max and standard deviation error bars) measured by the BQM during the ramp.

References

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