



Overview

Machine parameters:

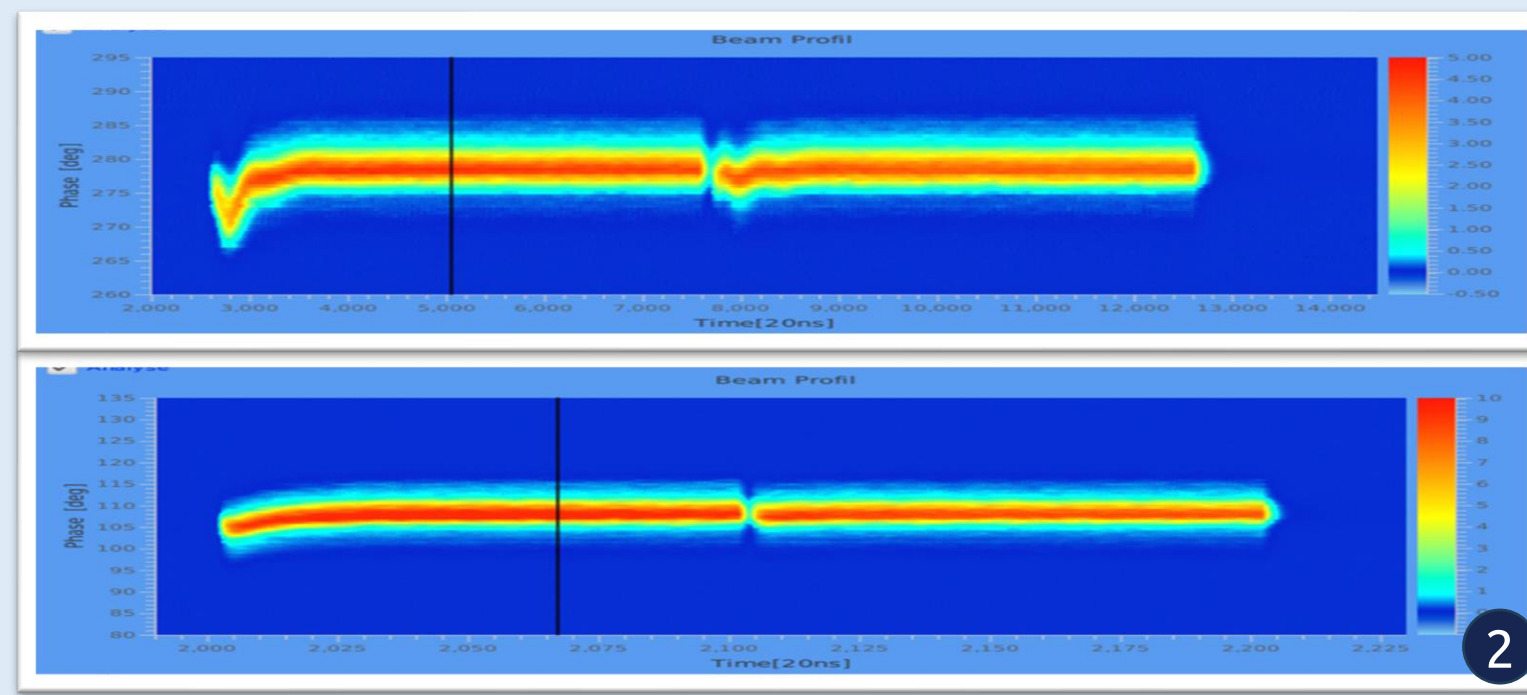
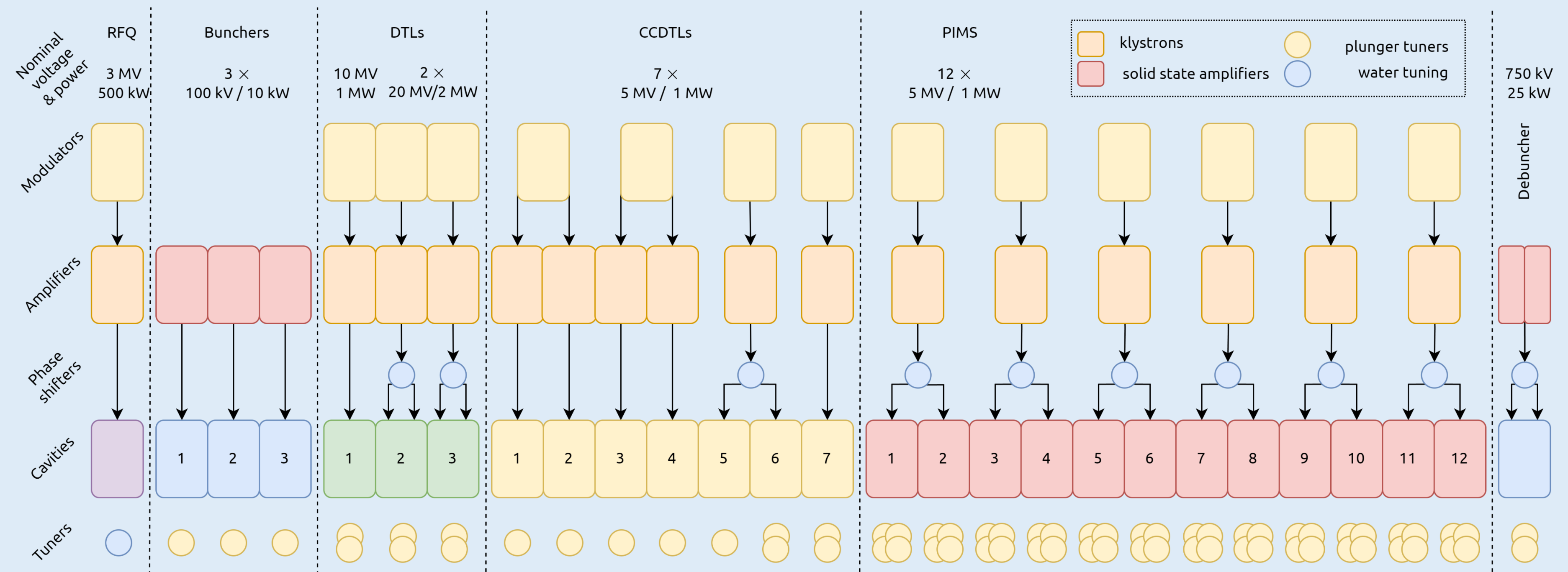
- length: 80 m,
- accelerated ion: H⁺,
- RF Frequency: 352.2 MHz,
- output energy: 160 MeV,
- avg. beam current: 25 mA (nominal 40 mA),
- pulse length: 600 μ s,
- basic period: 1.2 s
- field regulation: <1% amplitude, <1° phase

Heterogeneous system:

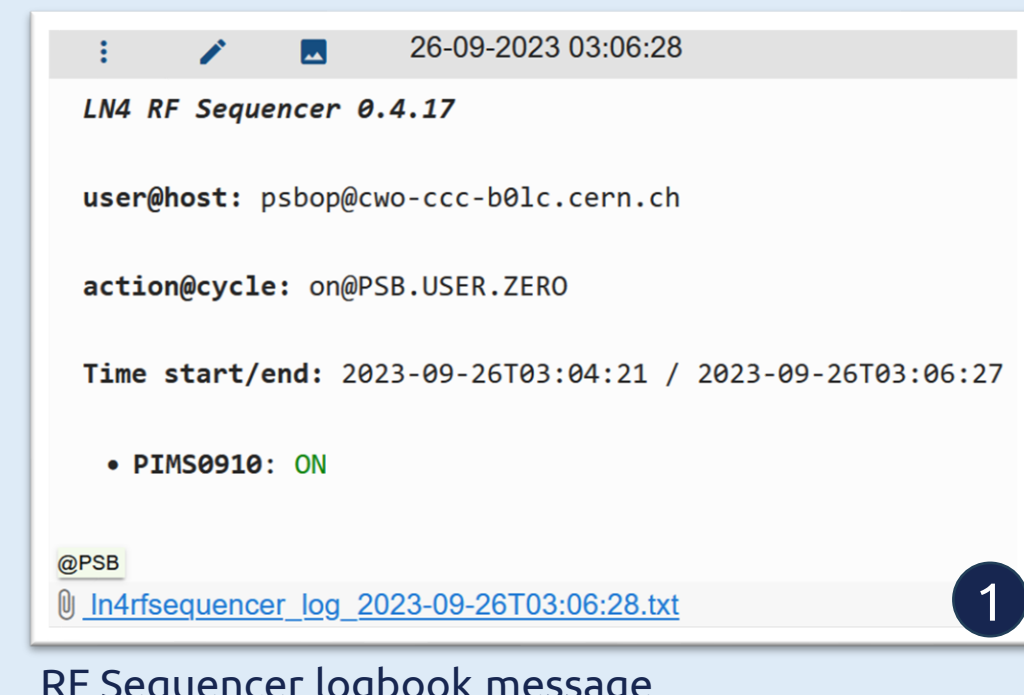
- Multiple line/cavity types and configurations,

LLRF:

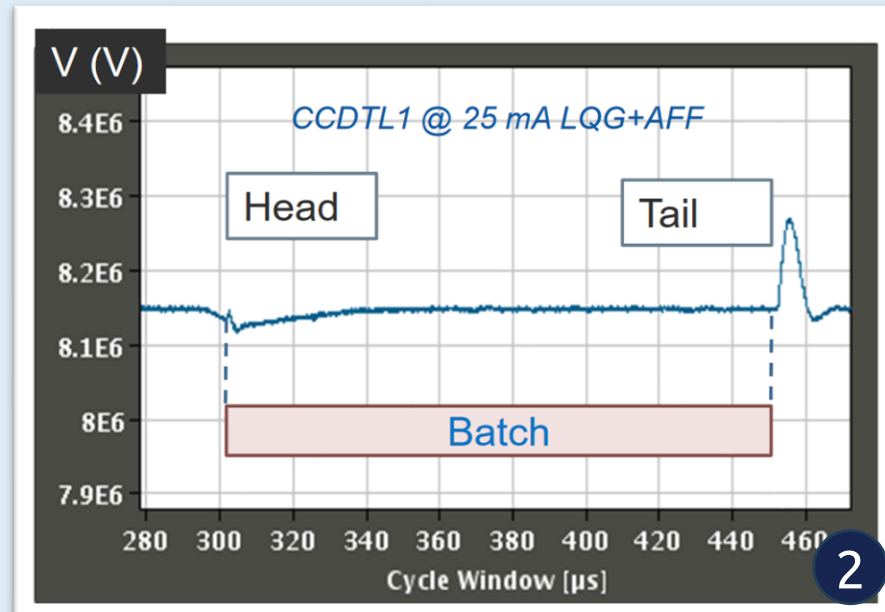
- VME single board computer,
- Payload cards: FPGAs, ADCs and DACs
- Low level SW: C++ and FESA,
- Automation: Python + Java + Inspector
- High level: Java GUIs + Inspector



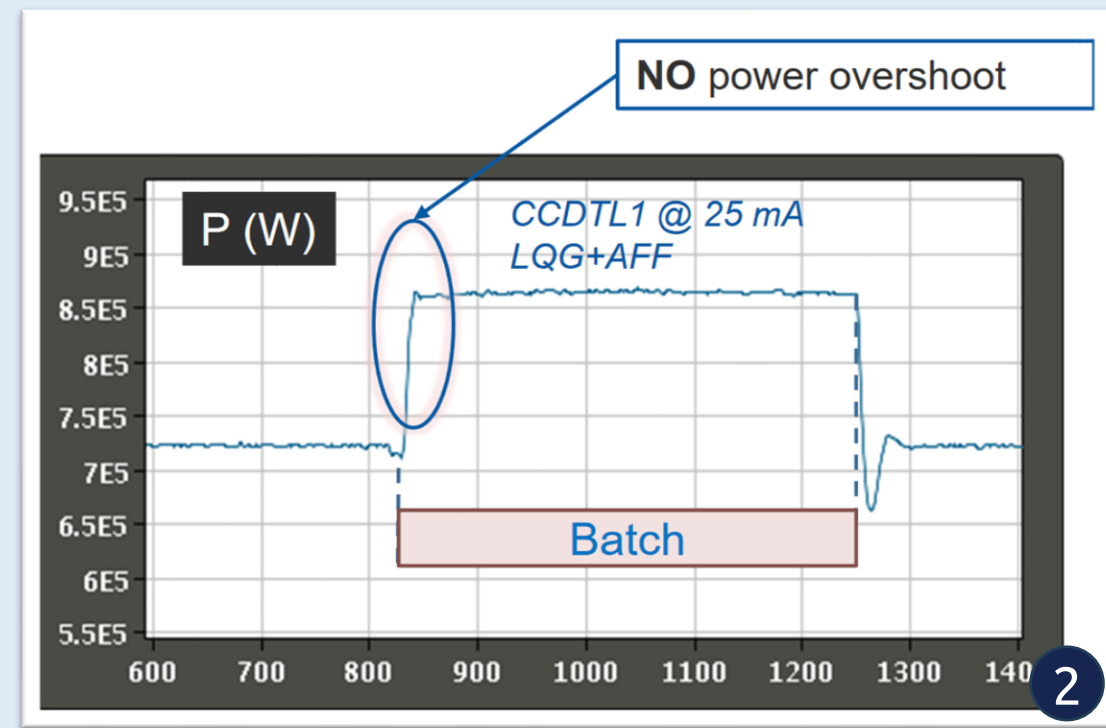
Beam phase before and after LQG & AFF



RF Sequencer logbook message



Field flatness with AFF



Power consumption with AFF

Completed (2017) Reliability Run (2018)

RF Sequencer (2017-2023)
A development of Python tool simplifying and automating starting and stopping RF system starts.

LQG & AFF (2019-10)
A new Linear-Quadratic-Gaussian controller and Adaptive Feed Forward were added to the firmware and software greatly improving pulse flatness and response time.

Feedback simplification (2020-06)
M. Andersen has performed analysis of the feedback system and proposed simplification of the LQG controller.

Tuner FW problems (2018-10)
Spurious tuner measurements were causing rapid cavity detuning. Fixed with software median filter.

RF ON from PSB (2019-11)
On trigger sourced from the Proton Synchrotron Booster timing to synchronize with the Chopper.

AFF Simplification (2020-07)
Single AFF correction buffer more efficient than per-ring configuration. Introduced automatic state resetting.

Phase Monitoring (2019-02)
Environmental factors can make cavity phases drift. Phase monitoring rises an alarm when phase drifts too far.

Beam Performance Tracking (2020-04)
After problems with some LLRF attenuators a tool for plotting long term RF stability was introduced.

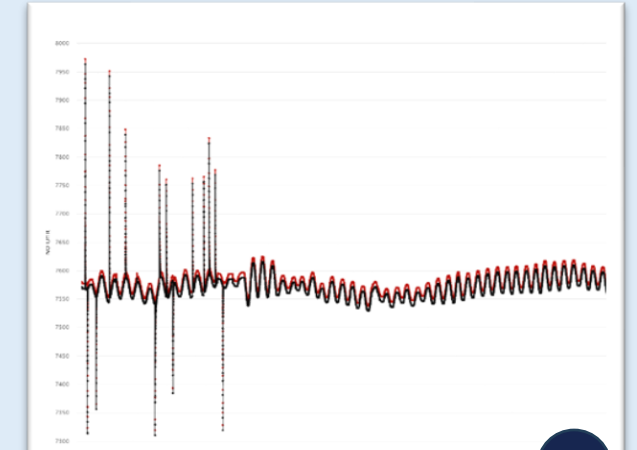
RFQ Breakdowns (2020-06)
During an RFQ inspection lots of breakdown marks were discovered on the vanes. Software Breakdown Protection was designed to automate detection and provide protection for the cavity.

PSB Connection (2020-12) First beam (2021-01)

CTU trips (2021-02)
The Chopper Trigger Unit software had a bug that was impeding operation. The problem was traced to wrongly set software execution priorities.

Sag correction (2021-03)
Accumulated field sagging along the linac is corrected using an external measurement and Longitudinal Painting prototype.

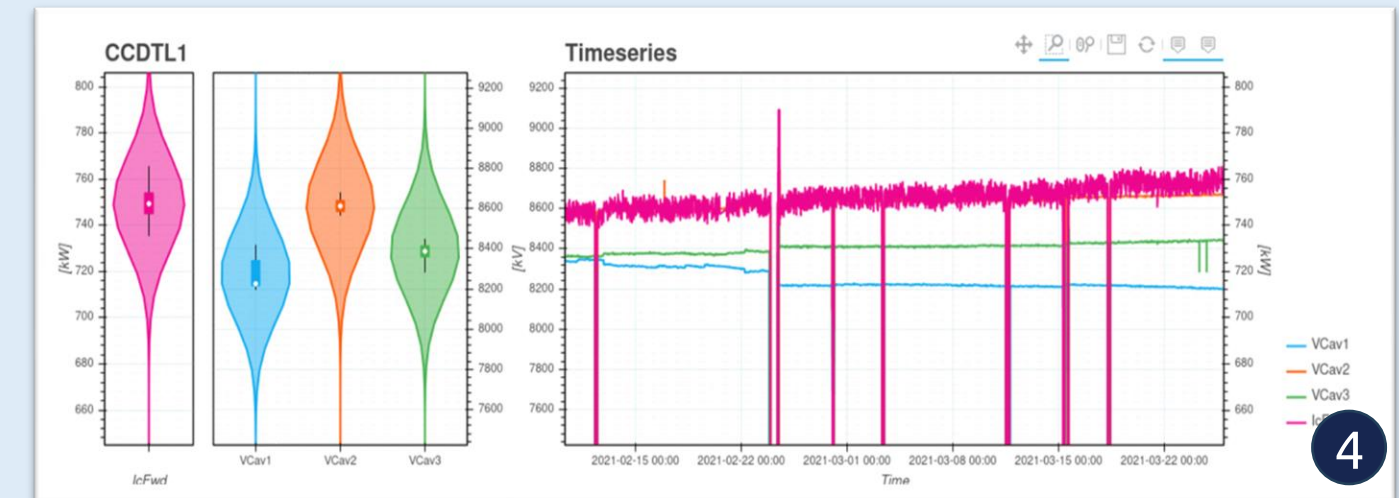
CDU trips (2021-09)
An oscilloscope connected to monitor chopper plates' voltages causes an interlock in Chopper Drive Unit. During autocalibration input impedance changes.



Tuner error signal

AFF Bad Pulse Detection (2021-03)
AFF was observed learning from bad (tripped) pulses. A detection was added so only good pulses were taken into account.

AFF on Debuncher (2021-03)
Some beams were not passing by the debuncher cavity making AFF unable to reach a stable state. AFF was made aware of beam destination.



Measurement drift due to a failing attenuator



Breakdown Protection & Recovery GUI

Improved tuning (2022-01)
Improved (software) tuning algorithm implemented to take into account lines with varying set-points.

BD on DTL1 (2022-04)
Frequent breakdowns in the DTL1 cavity. HW & SW initially developed for the RFQ is added to this line as well.

Longitudinal Painting (2023-01)
The LP is being prepared to be used for operational beams. The software is updated to provide true operational interface.

Improved signal statistics (2023-01)
With the introduction of operational LP interface new set of pulse-by-pulse statistics were made available in the software.

Phase Monitoring Update 2023-09
To limit false phase alarms due to temperature and humidity changes a new system that uses relative phase drifts is put in place.

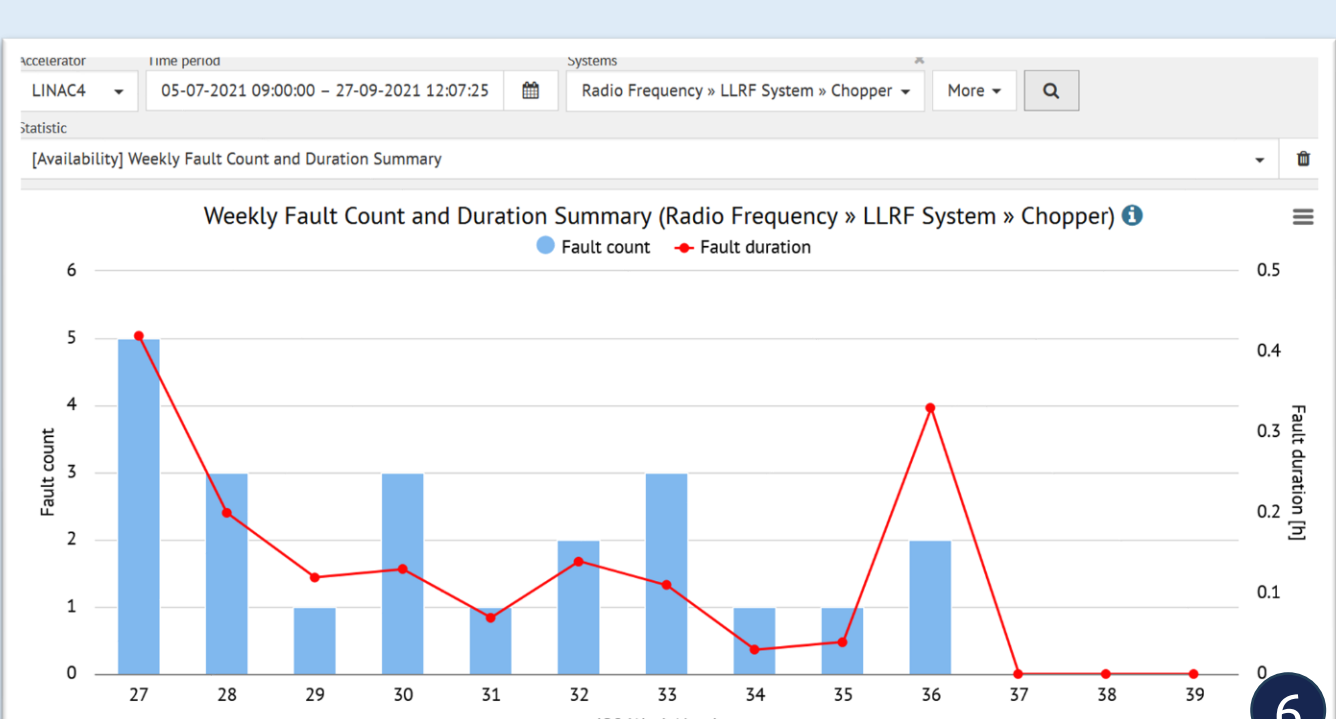
Feedback on both PIMS cavities (2022-02)
The feedback on double-cavity lines was set to use voltage measurement from both cavities. This change made sag correction obsolete.

BP Polar Loop reset (2022-09)
After a breakdown the polar loop would learn wrong gain. Before putting the line back in operation the state is now reset.

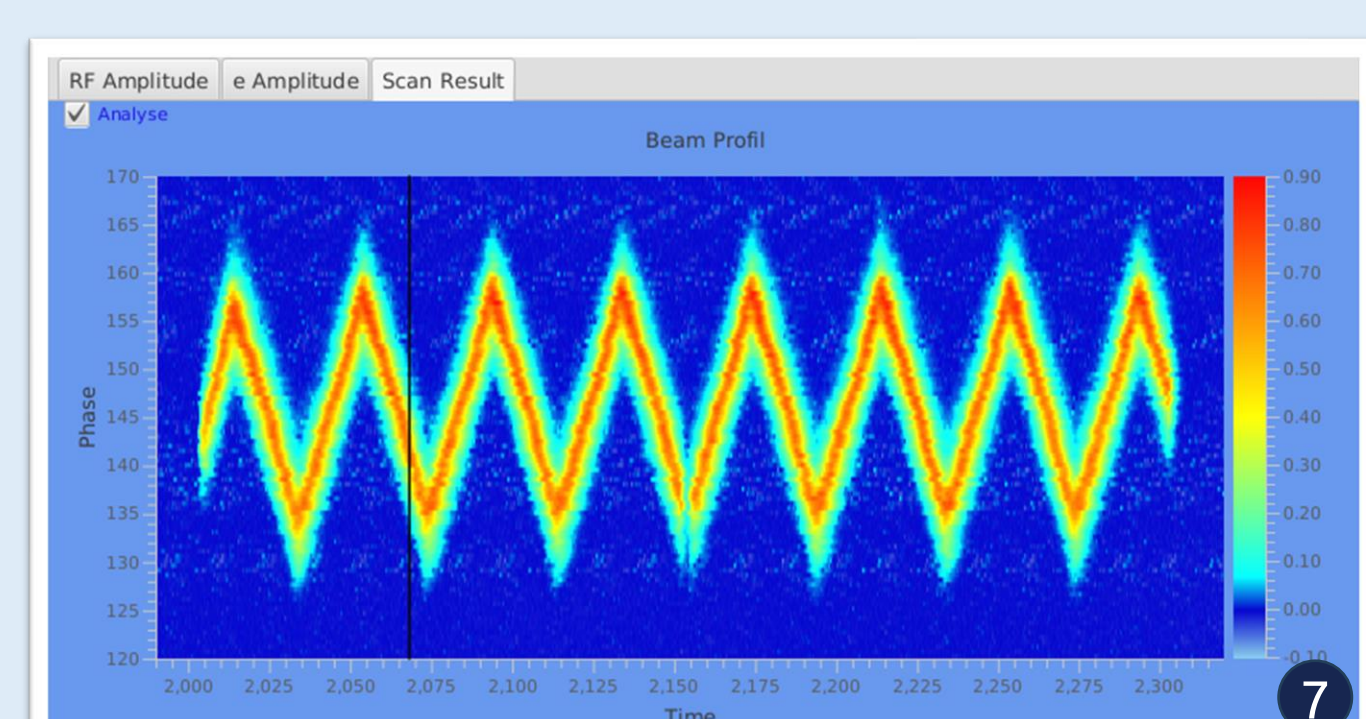
AFF Learning Inhibit (2023-01)
Beam monitoring systems can now notify AFF to disregard the last pulse and not learn from it.

Improved bad pulse detection (2023-01)
With the introduction of operational LP some valid painted pulses could be considered invalid. The software had to be made aware of the painting waveform.

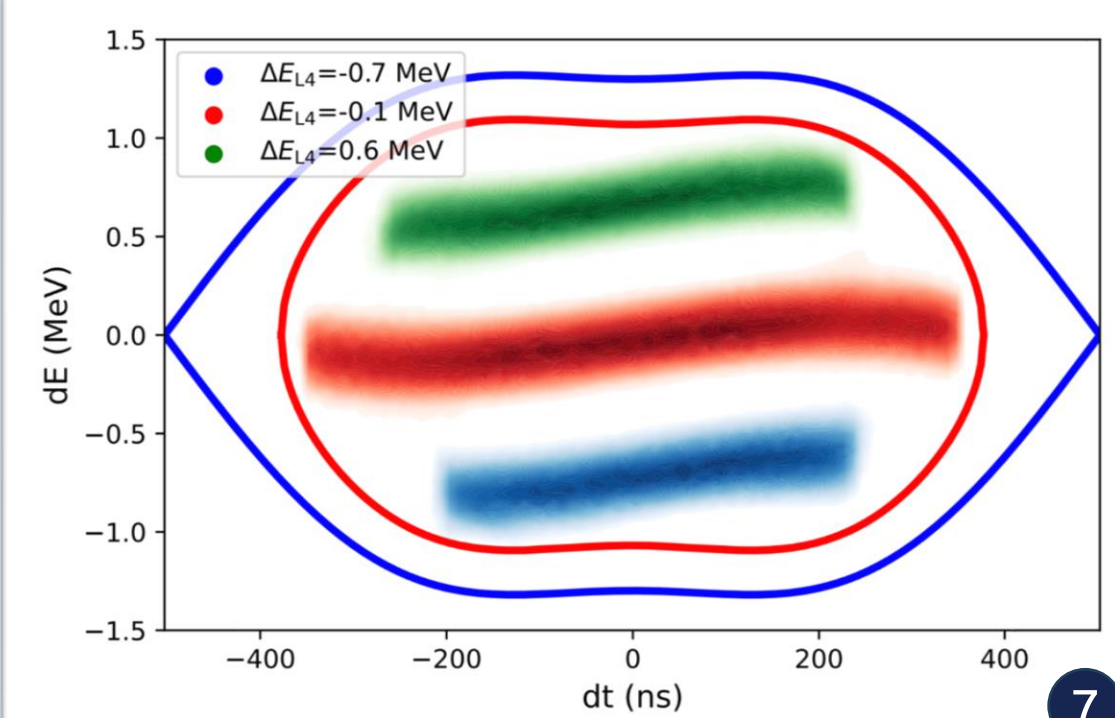
BP on all lines (2023-01)
All RF lines were equipped with HW and SW for breakdown detection and recovery.



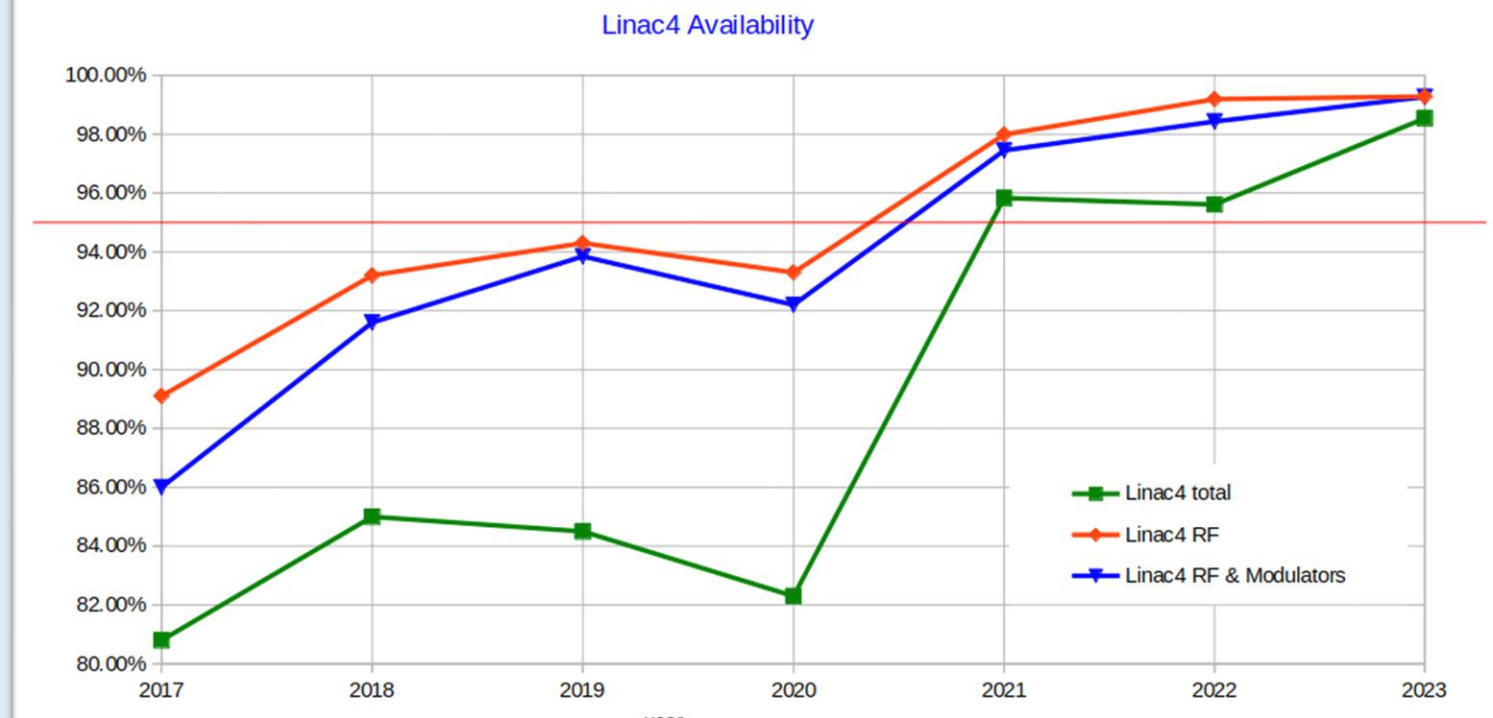
Number of CDU trips in corresponding weeks



Beam phase during Longitudinal Painting tests



Designed Longitudinal Painting schema



Linac4 availability

Insights & Conclusions

After the physical completion of CERN Linac4, a three-year testing phase ensued, during which multiple enhancements were implemented. These improvements included the integration of LQG and AFF (with improved timing), along with additional state monitoring features such as phase, voltage, and power. Moreover, measures for breakdown protection were introduced to ensure the safety and automated conditioning of the RFQ.

Upon connecting to the PSB in 2021-2022, further challenges linked to intensive machine operation were identified and successfully resolved. These challenges encompassed control adjustments for the chopper lines, both in software and monitoring hardware, as well as the utilization of AFF under real-world beam conditions. The pulse flatness was significantly enhanced by leveraging voltage signals from all double-cavity lines, rendering ad-hoc solutions like sag correction obsolete.

Over the past year, our focus has centered on augmenting the machine's reliability and automation. Longitudinal painting, previously in a testing stage, now boasts an operational interface, and preparations for its operational deployment are underway. Throughout the past six years of operation, we have systematically addressed and resolved issues, leaving only a limited number of expected improvements at this time.