LHC Injectors Upgrade

Low Level RF Control Algorithms for the CERN LINAC4

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The LLRF design has started in 2009. Several persons have contributed. In order of appearance in the project: *A.K. Bhattacharrya, D. Stellfeld, J. Noirjean, G. Hagmann, D. Valuch, J. Galindo, M. Ojeda Sandonis, V. Costa, B. Kremel, J. Simonin, K. Adrianek, M. Andersen*

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Thanks to *K. Fung* from TRIUMF for discussions on the AFF during LLRF17 workshop.

Content

- Linac 4
- Field regulation. How precise must we be ?
- Field perturbations. What are the causes?
- Linac4 LLRF architecture
- Classic RF feedback (2013-2018)
- Linear Quadratic Gaussian (LQG) regulator (2019-)
- Adaptive Feed Forward (AFF) (2019-)
- Klystron Polar Loop (KPL) (2020-)
- Conclusions

Linac 4 [1]

- **H- ions**
- **Acceleration to 160 MeV**
- **352.2 MHz RF**
- **Injection of protons into the PSB synchrotron, after stripping foil**
- **1.2 s repetition time**
- **At each pulse it can accelerate up to 600 us of beam consisting of four batches (one per PSB ring) spaced by 2 us**
- **It includes a chopper at 3 MeV to**
  - remove the bunches that would fall outside the 1 MHz PSB bucket (h=1)
  - create empty 2 us long beam gaps to cope with the switching time of the distributing magnet that routes the Linac beam to the four superposed PSB rings
- **As a consequence, the cavities see *strong transient beam loading* as the beam intensity changes from zero to maximum beam current (presently 25 mA DC) in just 3 ns.**

Field stability margins

- Beam dynamics simulations have been carried out, early in the machine design, to define the maximum level of acceptable RF phase and amplitude jitter
- Table reproduced from [2]

	Amplitude Jitter (Uniform)	Phase jitter (Uniform)	Static field error – (Uniform)	Field unbalance for coupled cavities
RFQ	±1%	n/a		n/a
MEBT bunchers	±1%	±1 deg	n/a	n/a
DTL	±0.5%	±0.5deg	±2%(random gap field error)	n/a
CCDTL	±0.5%	±0.5deg	±2% (tilt over 3 modules)	±5%
PIMS	±0.5%	±0.5deg	±5% (tilt)	Not investigated
Transfer line debuncher	±1%	±1 deg	n/a	n/a

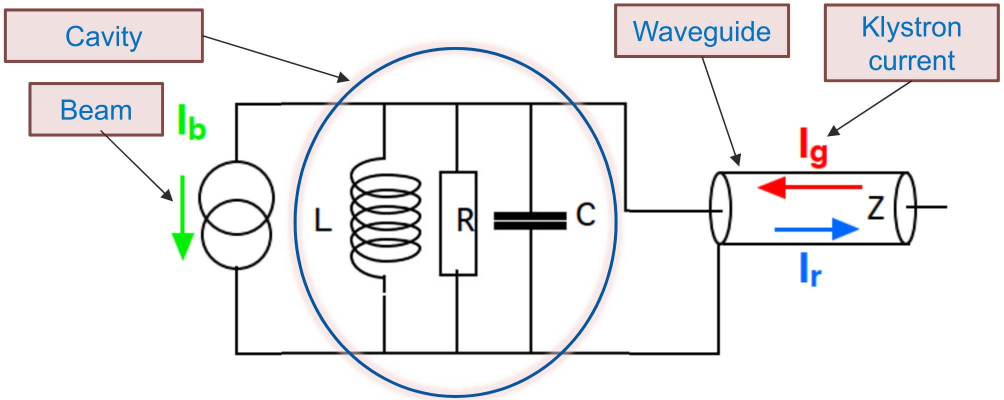
- So, the LLRF had to implement field regulation within **1 RF degree, 1% amplitude pk-pk** during beam pulse, for the nominal **40 mA DC** beam intensity.

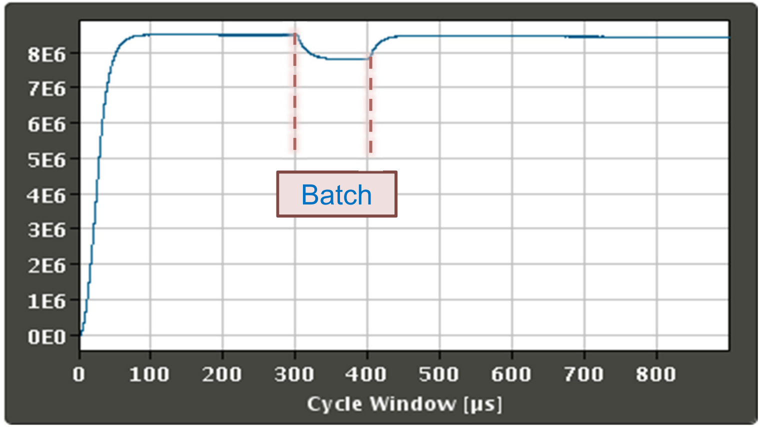
Field perturbations (1/2)

- Environmental causes
  - Temperature drifts will expand the tunnel floor and change cavity spacing
  - Temperature drift will affect **cable length** (and phase shift)
- Cavities
  - Will be subject to vibration and microphonics that may fall outside the range of the tuners
- Power amplifier
  - Solid state amplifiers show **gain/phase ripples** caused by the noise in their DC supply
  - Even worse with klystrons. LEP tubes show 0.1 dB and 8 RF deg/ % HV voltage drift. A **5% change in HV** results in **6 % amplitude** and **40 RF deg change** in cavity field (voltage)
    - The slow drift during the pulse is called *klystron droop*
    - The higher frequencies come from noise in the generation of HV (rectifiers).

Field perturbations (2/2)

- Beam loading
  - A cavity is a resonant circuit excited by **two currents** [3]: The RF amplifier I_g (for generator) and the beam I_b
  - This is **by far the largest perturbation** in the L4 cavities
  - The **25 mA DC** beam current induces almost **1 MV** in the CCDTL1 cavity. Shown is cavity voltage amplitude without regulation. For nominal **40 mA** the beam induced voltage will be 1.6 MV, that is **20 %** amplitude variation. To respect the specifications **the beam loading peak must be reduced by 20 linear minimum.**

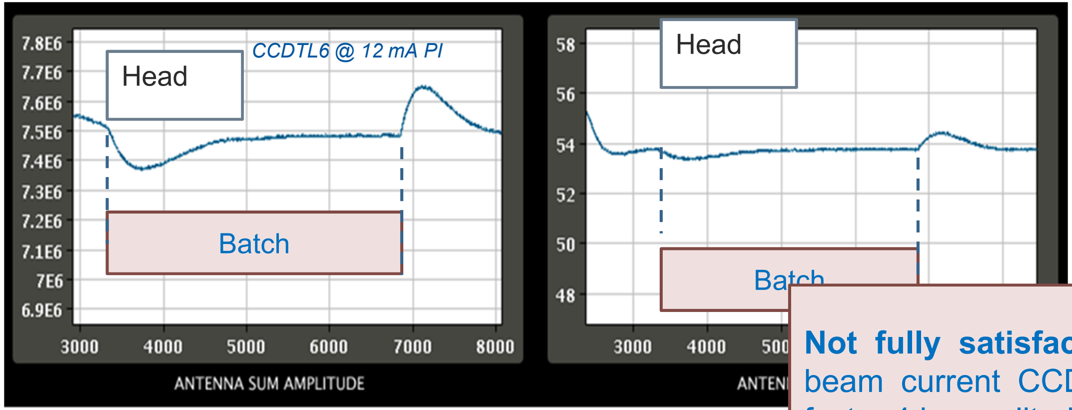




CCDTL1 voltage amplitude (in V) without regulation with a 25 mA DC beam current.

Classic RF feedback 2013-2018

- The LLRF was first commissioned with a classic RF feedback [5]
- The LLRF consisted of a *PI Controller*, including a proportional (P) and an integral (I) gains
- The limitation of this simple regulator comes from the loop delay including TX, circulator, waveguide, antenna cable and LLRF latency. **Total around 2.5 us.**
- The plots show the performances with PI controller and 12 mA beam current (2017).

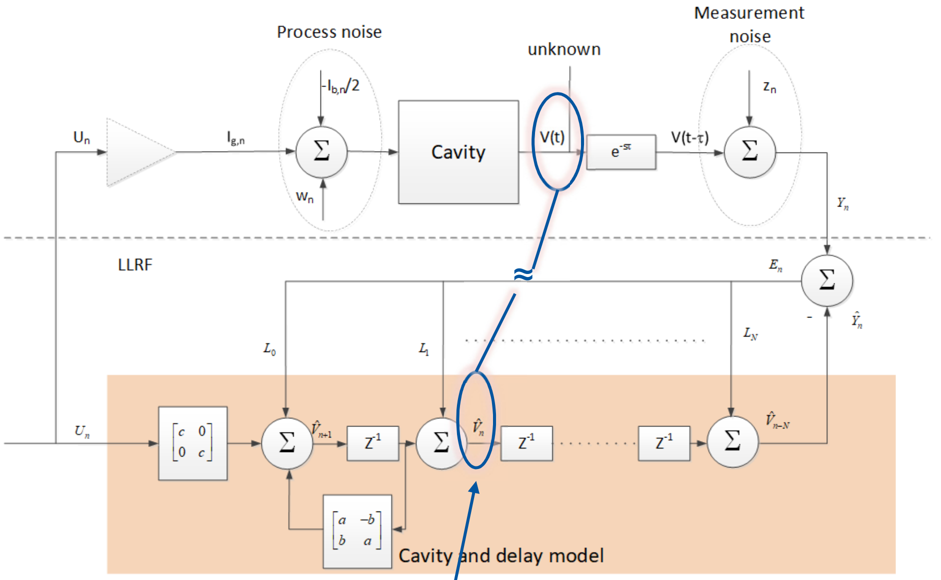


Antenna Sum amplitude and phase sampled at Frf/16 (45.45 ns/sample).
The regulation is slow: the transient affects the first 40 μs of beam.
For CCDTL6 we have 0.1 MV pkpk (1.3%) fluctuation in voltage and 0.5 deg in phase .

Not fully satisfactory: Scaling to nominal 40 mA beam current CCDTL6 would exceed tolerance by factor 4 in amplitude and almost 2 in phase.

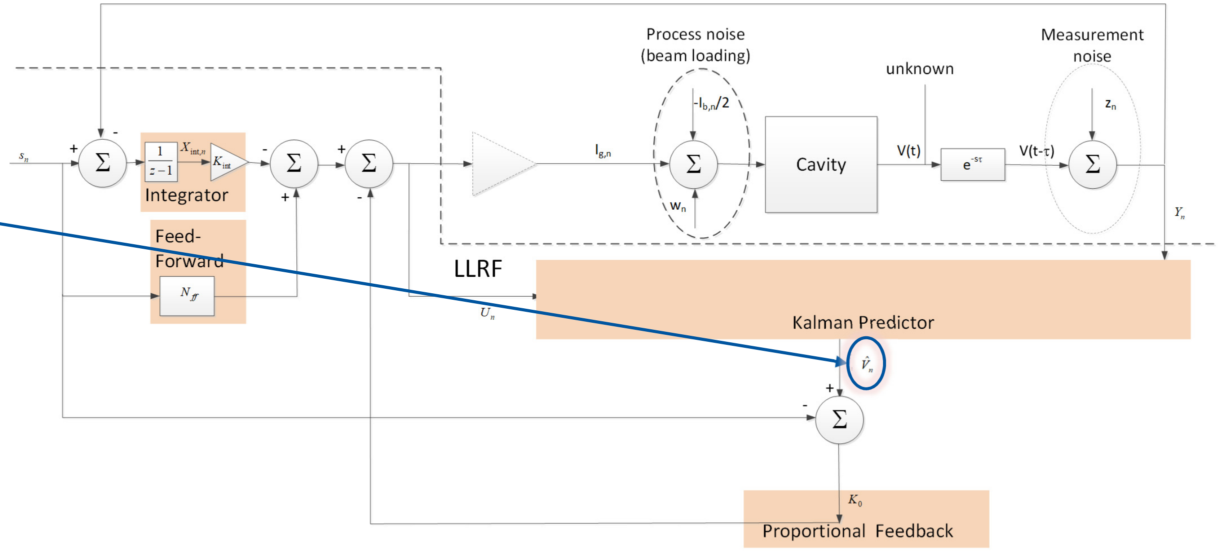
Model based. LQG regulator [6]. 2019

- **Step 1. The Kalman predictor**
  - Implement in the LLRF a **model of the cavity plus delay**
  - Feed it with the **same *drive*** as the cavity amplifier
  - Of course the model output will not be exactly the cavity output. The difference comes from inexact model plus the **noise injected into the cavity and absent in the model**. This is called ***Process noise***. In our case that is mainly the **beam loading**
  - **Update** the model states by **comparing** the model and cavity output
  - There will be noise at the cavity output, the so-called ***Measurement noise*** (small in our case)
  - The optimum matrix *L* depends on the relative importance of process noise and measurement noise. If process noise is high compared to measurement noise (our case), the **correction will be applied strongly as we have much confidence in the measurements.**



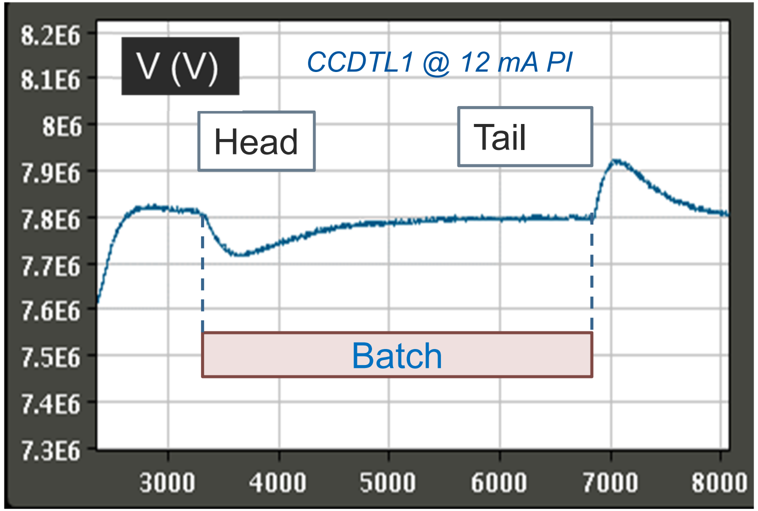
What have we gained?
We have reconstructed a signal in the LLRF that is a good *estimate* of the cavity voltage and …**available without delay**

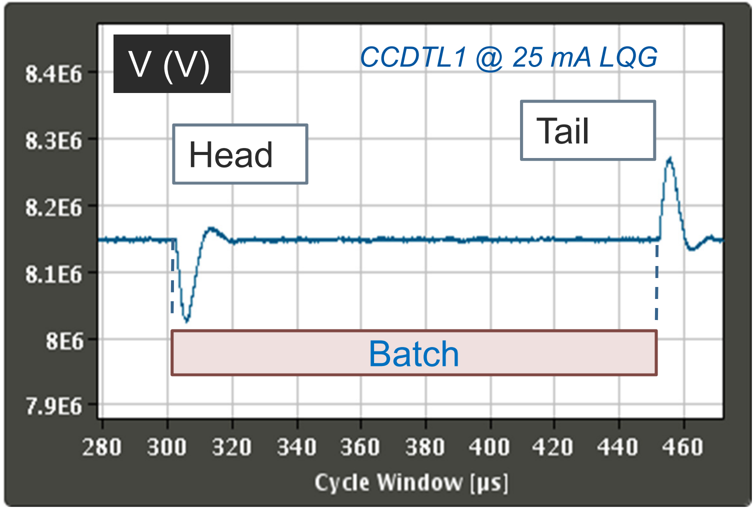
- ## Step 2. The Feedback
  - We now implement a proportional-integral (PI) feedback using the cavity voltage **estimate**
  - We optimize the feedback using the Linear Quadratic Regulator method (LQR).



What have we gained?
As long as our *estimate* is very close to the cavity voltage, we have a feedback **without delay.**
The Kalman Predictor must react significantly faster than the LQR.
In our optimization we have
- Kalman Predictor responding in 200 ns
- LQR responding in 900 ns.

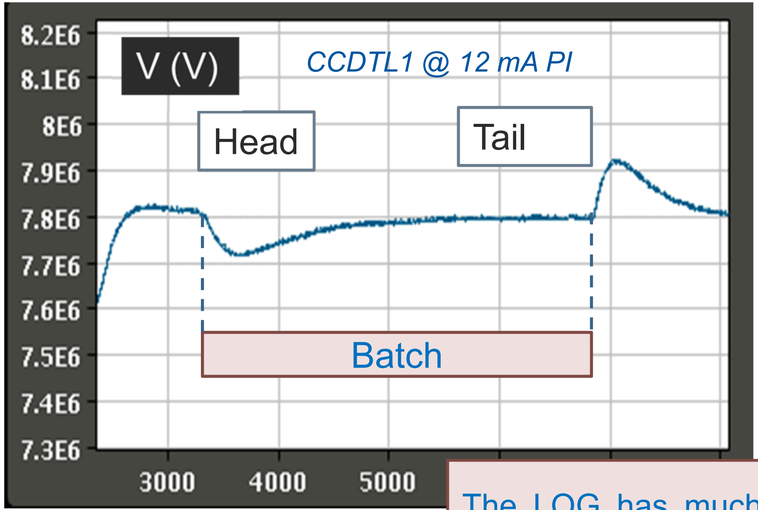
LQG feedback installed begin 2019

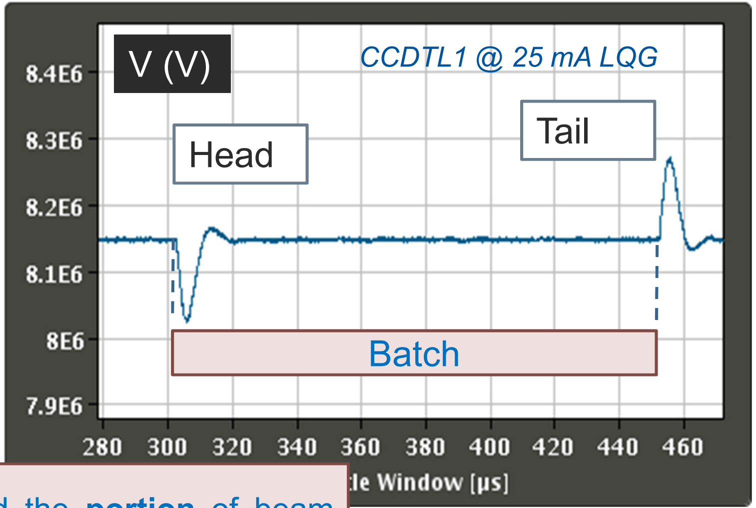




Voltage (Antenna Sum)
Left: performance measured with PI controller (2017), 12 mA DC (45.42 ns/sample)
Right: idem measured with LQG regulation (2019), 25 mA DC
The pk-pk amplitude is reduced by almost two (accounting for the different beam intensity) and **the regulation is much faster**: Only the first 5 µs of beam are now affected.

LQG feedback installed begin 2019





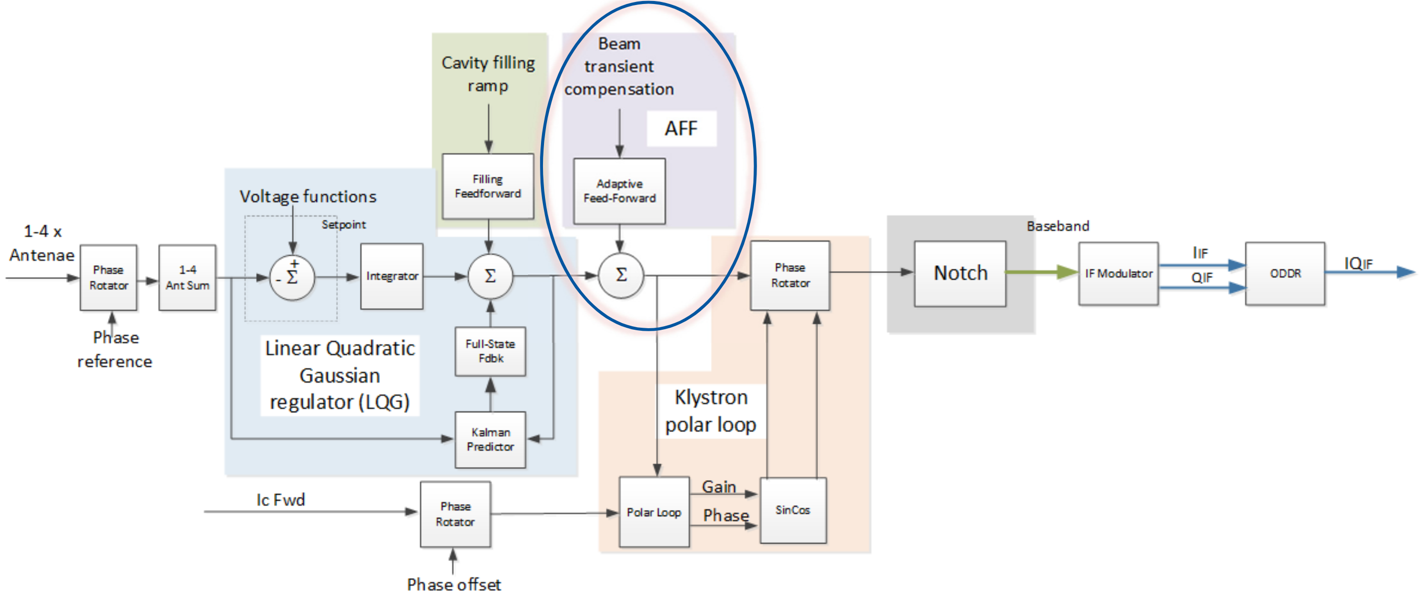
The LQG has much reduced the **portion** of beam affected…but we still observe a **significant but short transient at the beginning of the batch**.

Voltage (Antenna Sum)
Left: performance measured with
Right: idem measured with LQG
The pk-pk amplitude is reduced by almost two (accounting for the different beam intensity) and **the regulation is much faster**: Only the first 5 µs of beam are now affected.

Adaptive Feed Forward (AFF). 2019

- As long as we react pulse per pulse, we cannot completely cancel the transient at the head of the batch due to causality. We cannot ***anticipate*** the required increase of klystron power
- Assuming that this transient is similar from pulse to pulse, we could base our correction on the observation of previous pulses and…***anticipate*** for the present pulse
- That is the idea behind **Adaptive FeedForward** (AFF). It works great for **repetitive** perturbations
- What perturbations are pseudo-periodic (similar from pulse to pulse)?
  - **Beam loading**? **Yes,** because source current does not change much from pulse to pulse
  - **RF noise caused by klystron HV ripples**? **Not** in the L4 as the modulators as not synchronized to the pulsing
  - **Vibrations** (microphonics)? **No**
- In L4 AFF is **very effective** for the compensation of the beam loading transient **at the batch head**.

AFF. How?

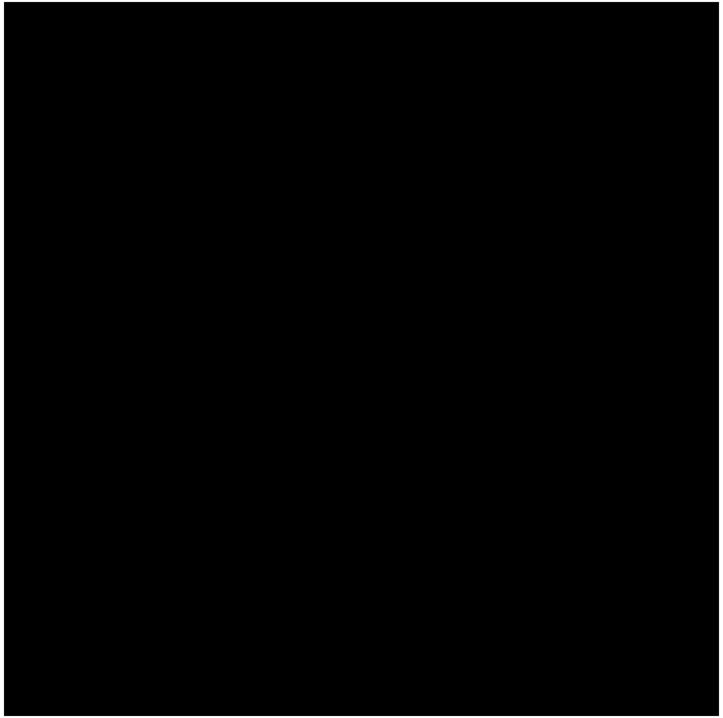


- The AFF is a correction based on the observation of the voltage error over the few previous pulses
- It is added to the klystron drive
- It is computed **off-line** (FEC). We use an algorithm similar to the one developed at TRIUMF [8]: We filter the voltage error with an impulse response **advanced correctly in the pulse**. Critical!
- It is loaded in the firmware at each pulse.

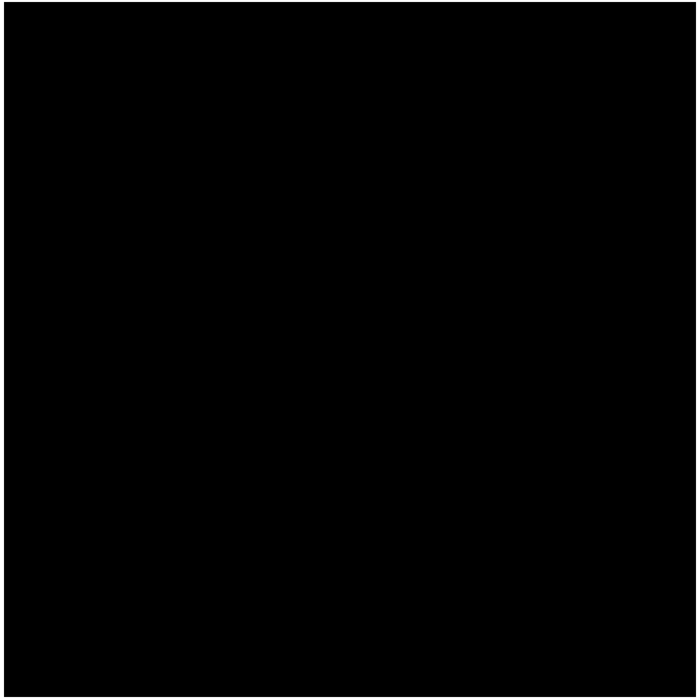
AFF Learning

Error Vcav-Vset (I,Q)

AFF correction drive (I,Q)



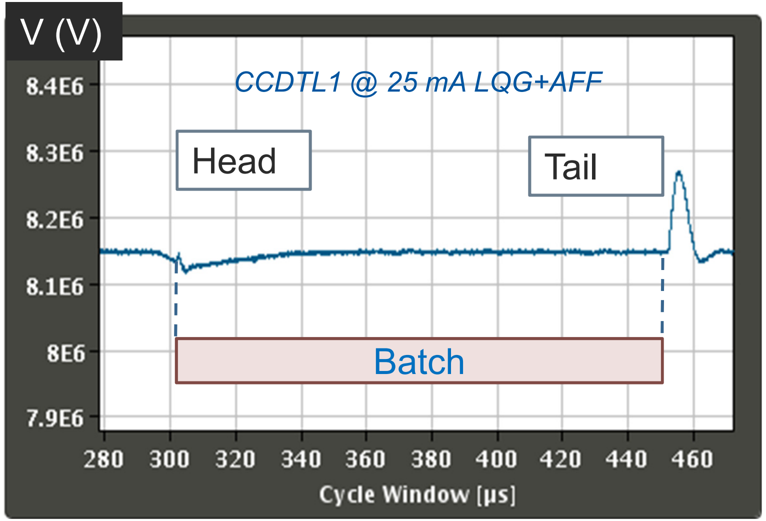
Cavity voltage (V)

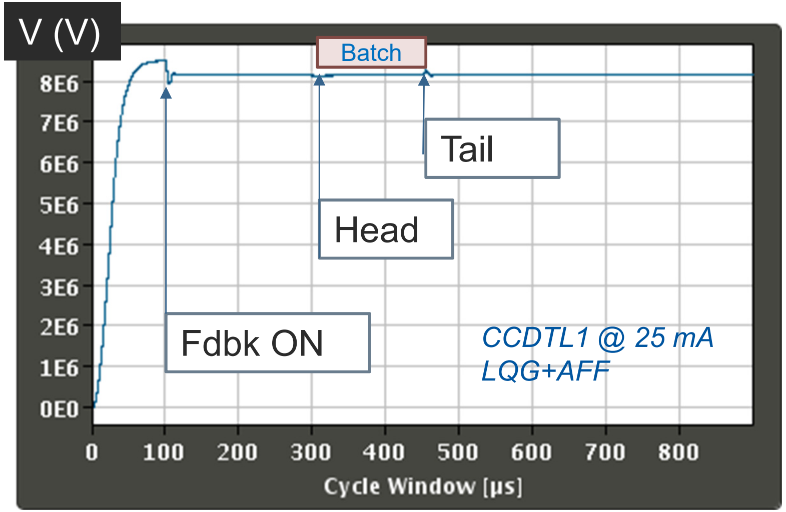


Cavity phase (deg)

- **I/Q error and correction (left) and cavity voltage amplitude/phase (right) during AFF learning**
- **Four batches, 100 us long, with 2 us gaps**
- **The correction is reset at beginning and in the middle of the record.**

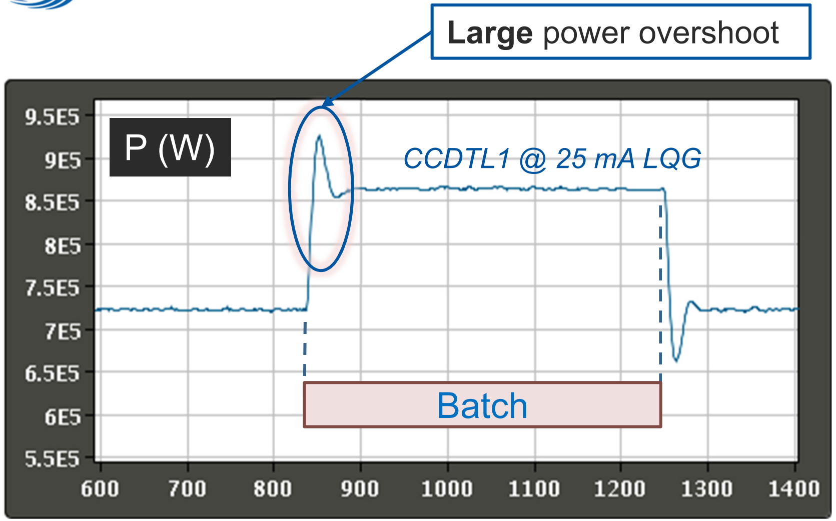
Overall performances

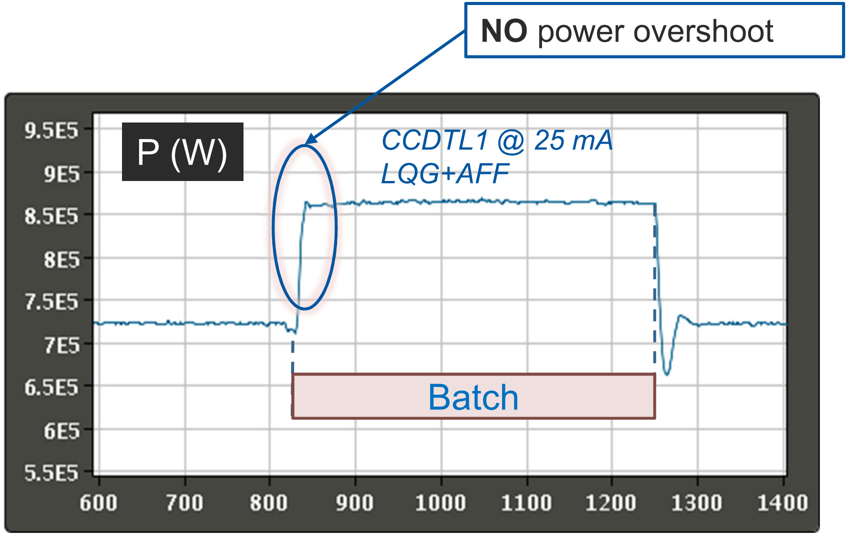




- Uncompensated beam loading 30 kV pk-pk, that is 0.375 % for 25 mA DC -> **0.6 % for nominal 40 mA DC** current. **Factor 2 better than specs**....
- The beam becomes barely visible in the overall pulse
- The AFF is switched off at the end of the batch, therefore the transient.

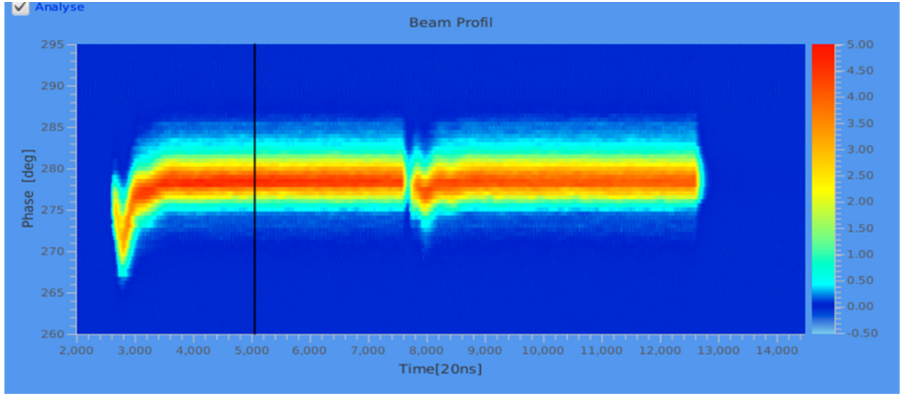
Power required

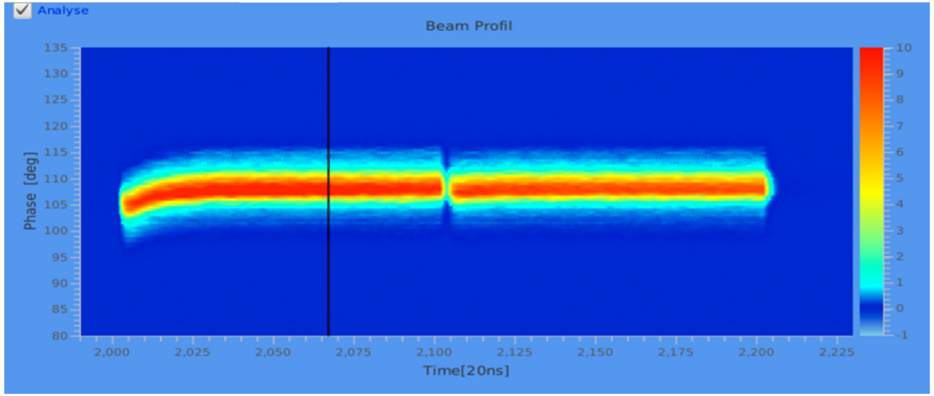




- The LQG regulation cannot anticipate the arrival of the head of the batch. It is caught by surprised and reacts violently causing a **peak of demanded power**
- With the AFF active the system **anticipates** and there is **no power surge** at the batch head
- The undershoot in power is present in both figures as the AFF is switched OFF at the end of the batch.

Bunch phase along batch(es)



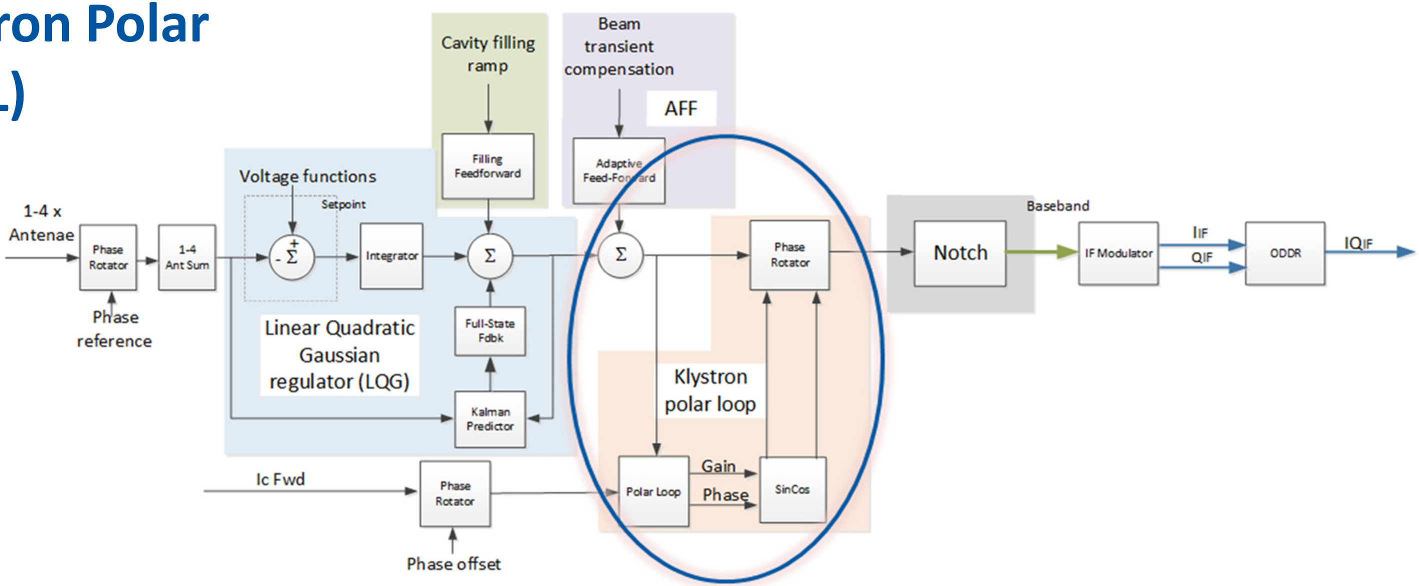


Beam Phase Monitor measurement: Density plots showing the longitudinal position, within the reference 352.2 MHz buckets

- Two batches
- Left: LQG only
- Right: LQG + AFF

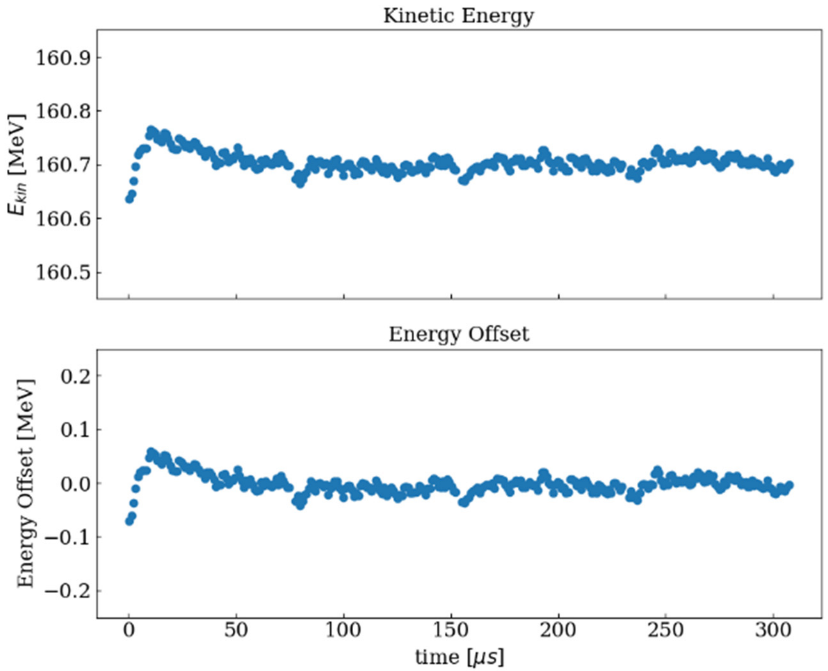
Courtesy of Piotr Skowronski, CERN BE-OP

The Klystron Polar Loop (KPL)



- **Another noise is the modulation of amplifier gain and phase, consequence of the ripples on the High Volt-age supply**
- **Multiplicative noise, therefore best compensated by acting on the LLRF gain and phase shift (polar)**
  - We compare the forward current at cavity input Ic,fwd (measured with a coupler in the waveguide before the cavity main coupler) to the sum of LQG and AFF outputs
  - We apply gain and rotation to keep the overall gain and phase shift constant, including klystron and circulator.
  - The reaction time is chosen to be much slower than the LQG, but sufficient to cover slow HV drifts and the rectifiers ripples measured around 10 kHz.

Conclusions



- The field regulation relies on the **LQG**, the **AFF** and the **KPL**
- The plots show **beam energy measurements along the batch** with four 75 us long batches spaced by 2 us, 21 mA DC
- The energy measured at Linac4 output deviates by **±50 keV pk-pk** around the 160.7 MeV design value
- That is within specs, given the **design rms energy spread** of the individual 352.2 MHz bunch, that is **250 keV**
- It will still be acceptable extrapolating to the future 40 mA DC current.

Thank you for your attention
Questions? Comments?

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