

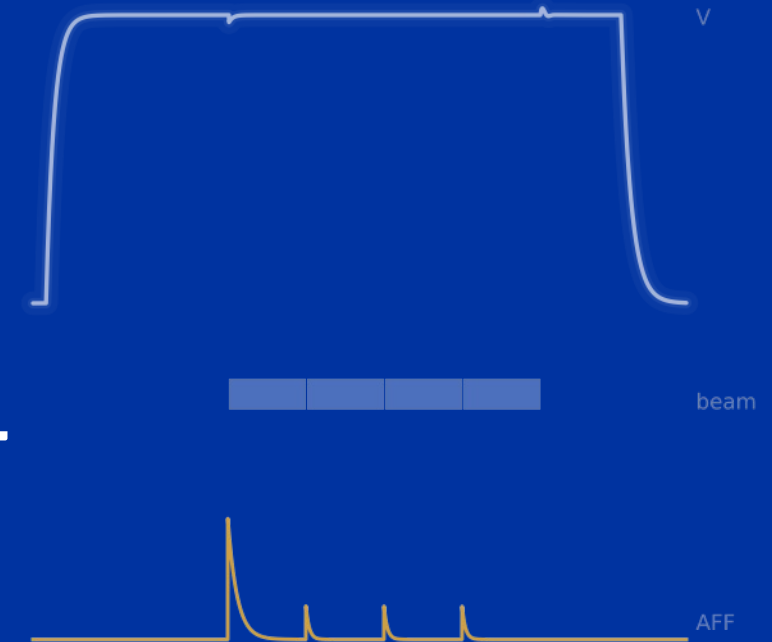


Operational Experience with the Adaptive Feed-Forward at CERN Linac4

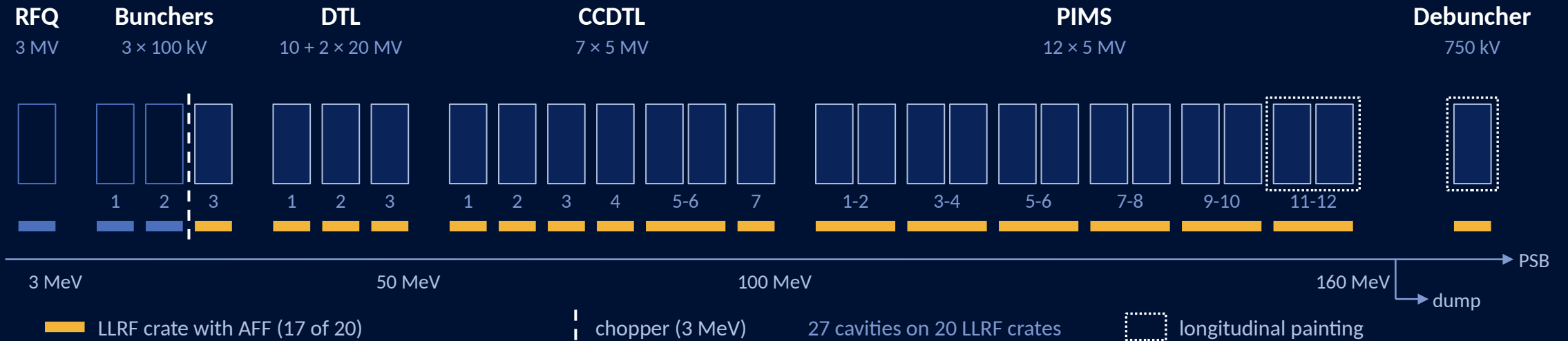
LLRF Topical Workshop on Advanced Feedback Control

Nova Gorica · 13 October 2026

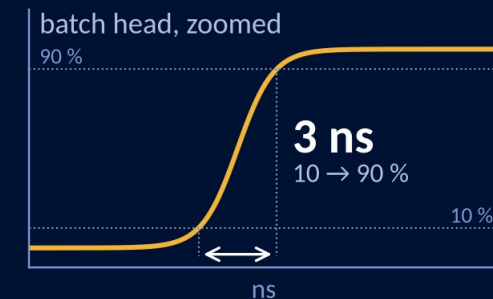
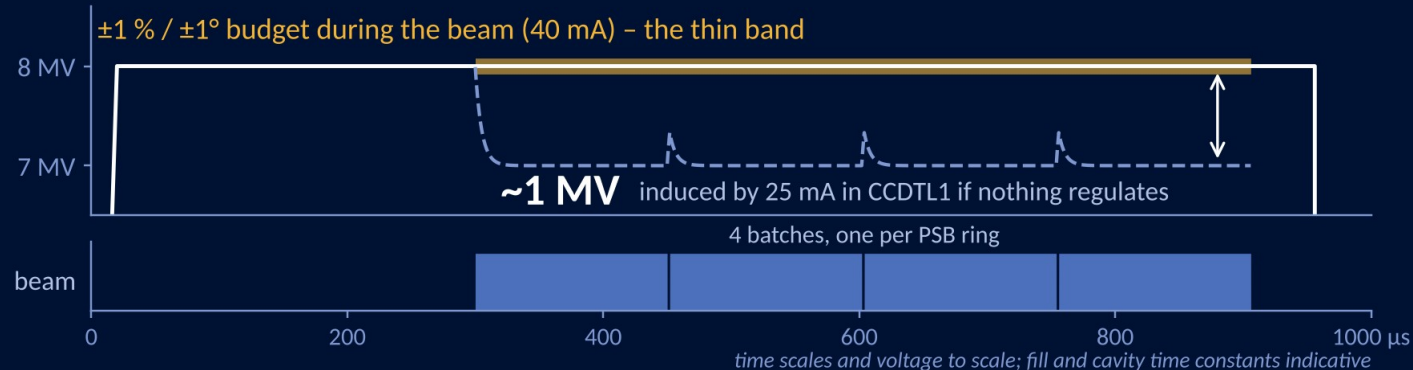
Bartosz Bielawski · CERN SY-RF



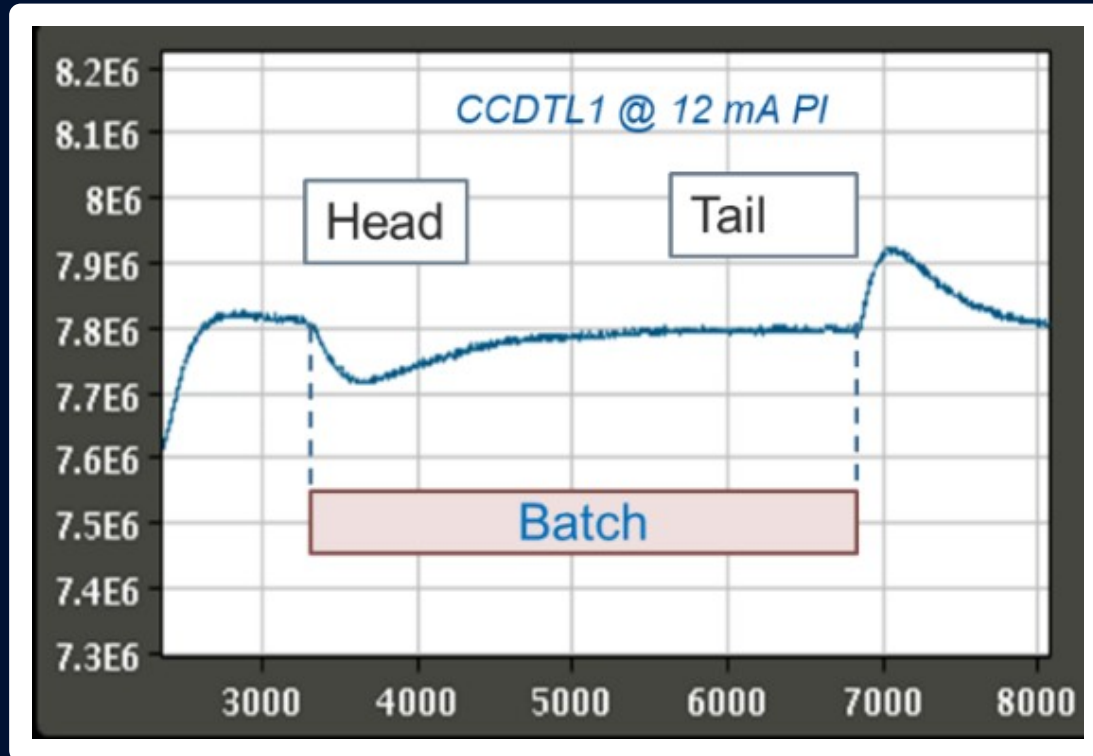
Beam loading is the largest perturbation in the Linac4 cavities



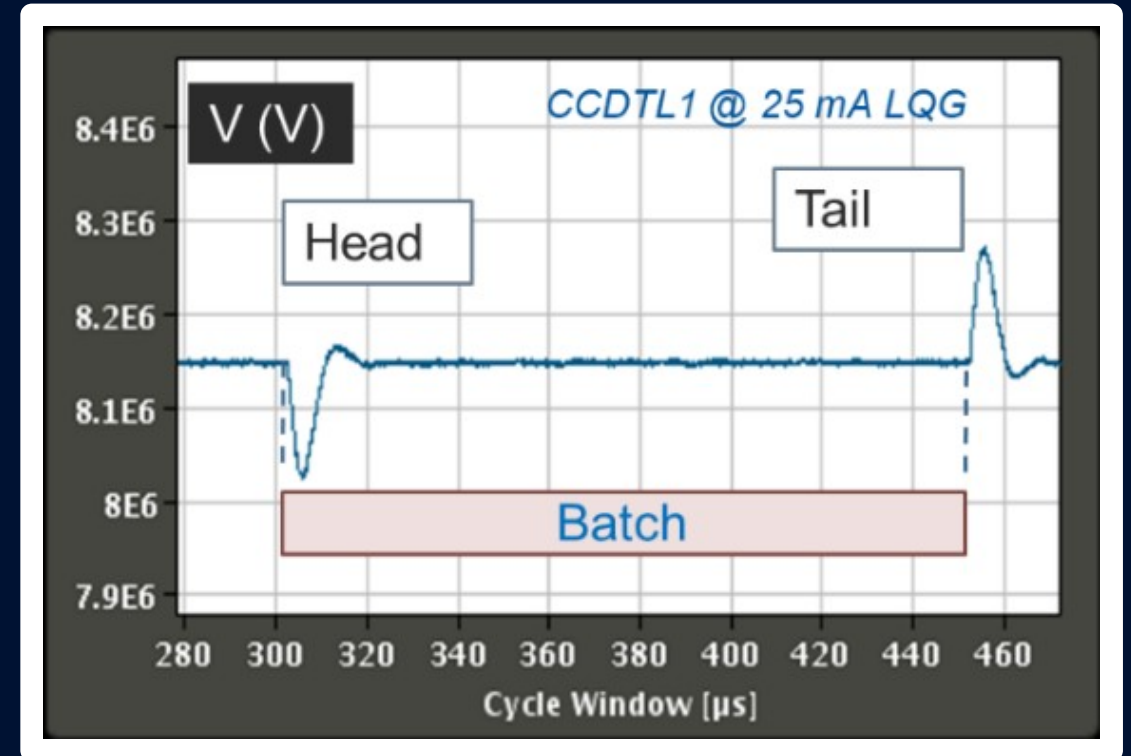
“...an RF feedback, a feed-forward and a one-repetition period feedback that keeps the accelerating voltage at the desired value in the presence of transient beam loading.” Linac4 TDR, 2006



Feedback reacts too late for the batch head



PI · 2017 · 12 mA – transient over $\sim 40 \mu\text{s}$



LQG · 2019 · 25 mA – only the first $\sim 5 \mu\text{s}$

Loop delay $\approx 2.5 \mu\text{s}$: the regulation sees the beam only after it has arrived.

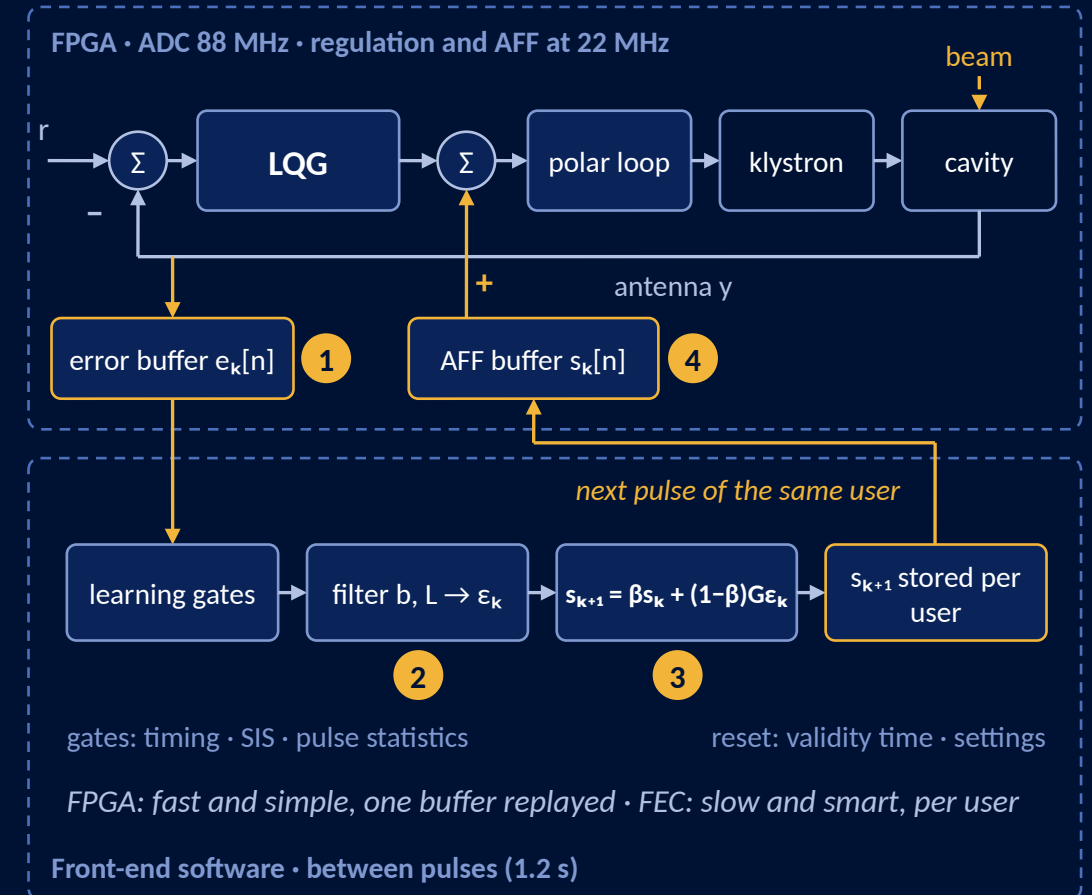
The AFF learns the correction from previous pulses

$$2 \quad \varepsilon_k[n] = \sum_{i=0}^{M-1} b_i e_k[n + i + L]$$

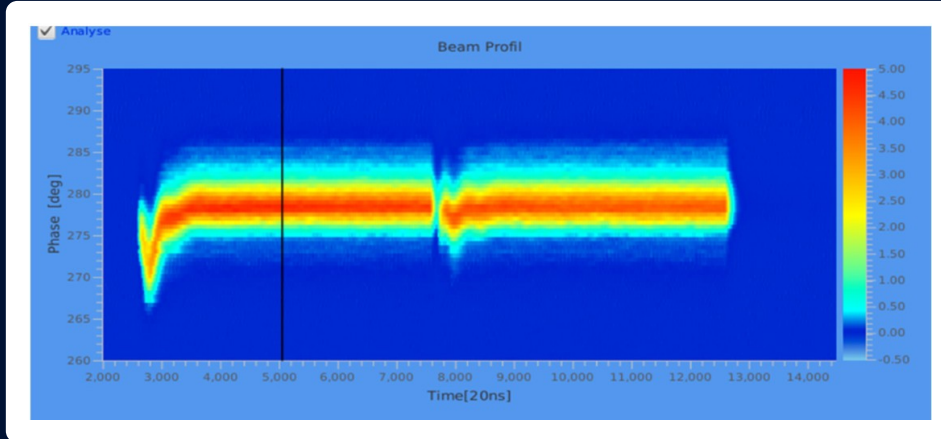
$$3 \quad s_{k+1}[n] = \beta s_k[n] + (1 - \beta) G \varepsilon_k[n]$$

k	pulse number – of the same timing user
n	sample (45 ns); window opens 50 μs early: the LPF smears the step
e_k[n]	field error recorded in pulse k, I and Q ①
b_i, M	low-pass FIR (software), by a script: window or step resp.; M ≤ 1024
L	look-ahead = loop delay, same script: 1.45–2.0 μs
ε_k[n]	filtered error ②
s_k[n]	correction added to the drive in pulse k ④
β	memory: 0.97 on all lines; near steady state within ~10 pulses ③
G	gain: 20–100 per line → residual ε ∝ 1/G ③

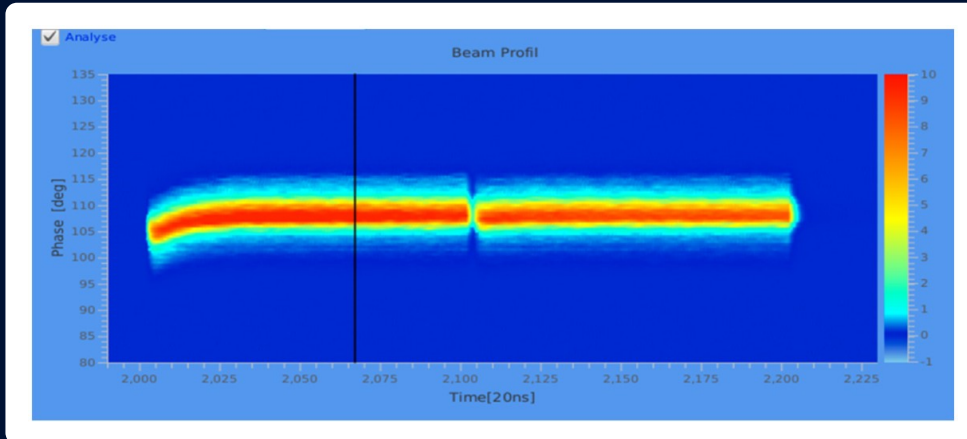
Inspired by K. Fong, TRIUMF (LINAC'16 TUPLR009)



The batch-head error now uses half of the budget



Beam phase along the batch – before LQG & AFF



... and after LQG & AFF

Field deviation at the batch head · CCDTL1

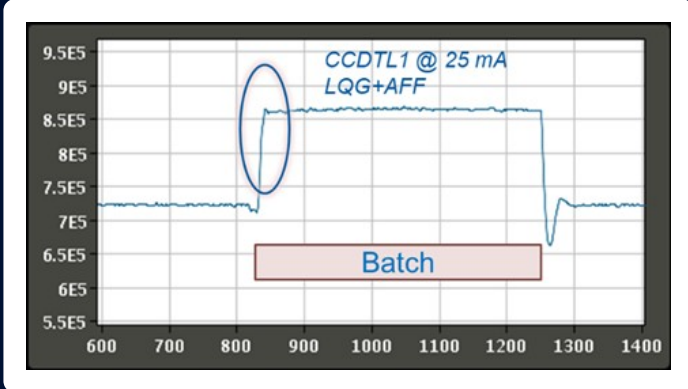
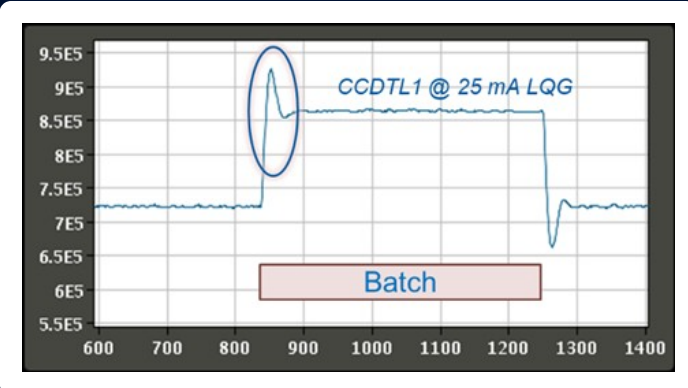
1 % specification

0.375 %

30 kV pk-pk at 25 mA – about half of the budget, even scaled to 40 mA

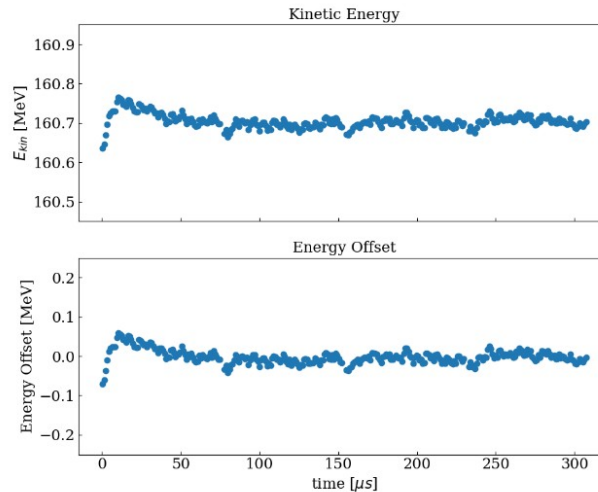
- No power surge at the batch head
- < 10 keV energy deviation at PSB injection
- High Current Mode (2024, 2026): no AFF issues
- Harder on the Thales-klystron lines

Flat power, flat energy – and the RF stays on



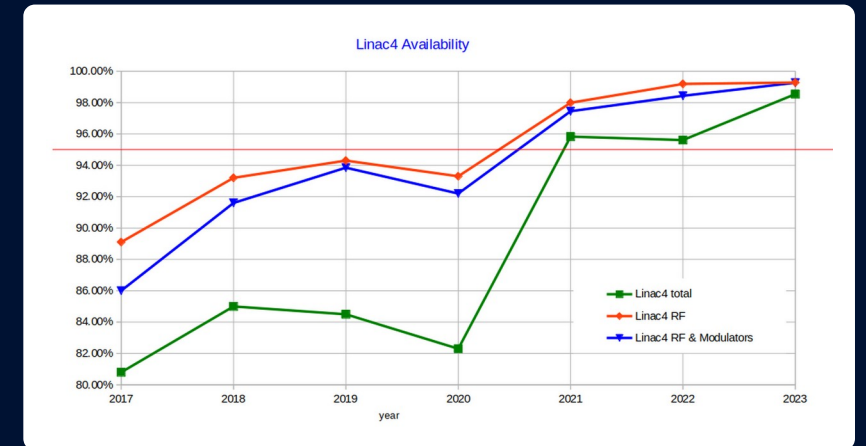
no surge

klystron power, CCDTL1 · 25 mA: LQG (top), LQG + AFF (bottom)



±50 keV

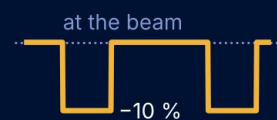
at the batch head, < 20 keV elsewhere · Linac4 output, 4 × 75 μs, 21 mA



99 %

RF availability 2022–23, from ~93 % in 2020 · whole RF system, the AFF is one part

The AFF buffers double as a set-up and diagnostic tool



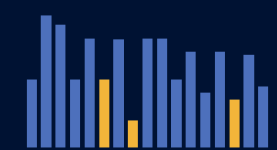
TEST Two fake beam-loading dips, -10 % of nominal, in the first and last quarter of the beam window – the AFF learns on them. Gain, filter and memory set up closed-loop, without beam.



EXCITATION The same dips from the start of the buffer, no learning. Delay of the line → look-ahead; step response → low-pass filter (some lines). Automatic: 16 pulses → fit → differentiate → half-Hanning → DC removed or kept → normalise.



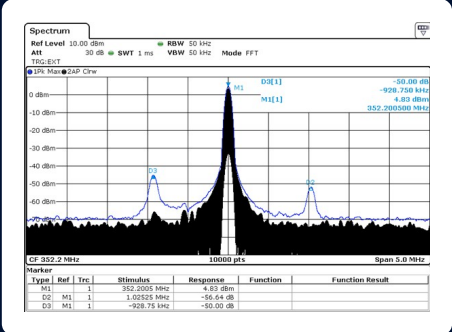
NOTCH SET-UP Rectangular drive pulses from the same buffer reveal parasitic modes of multi-cell cavities → notch frequencies.



TUNING PER LINE $\beta = 0.97$ everywhere; $G = 20\text{--}100$ and filter shape per line. Gains lowered for robustness: CCDTL4 20, PIMS0910 35, CCDTL2 50.



AFF panel: rings, gain, balance, look-ahead, modes

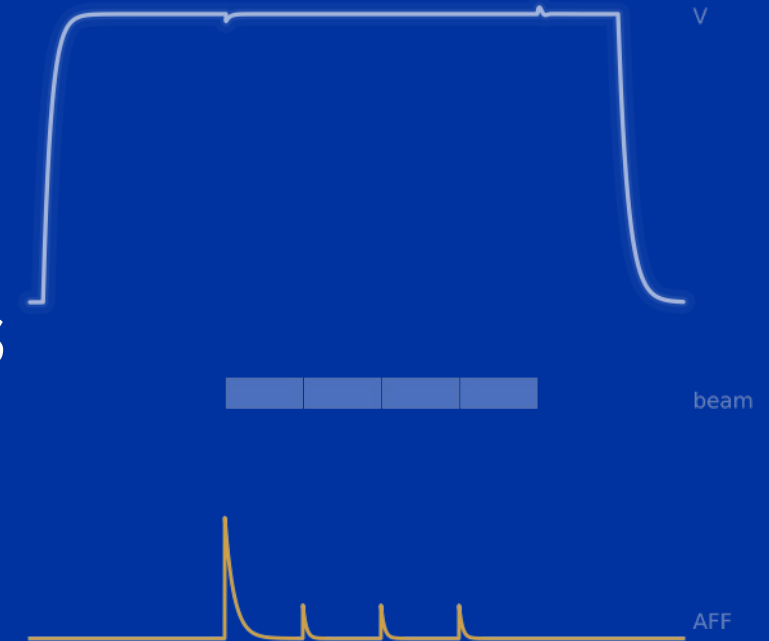


CCDTL5: modes at -0.93 / +1.02 MHz

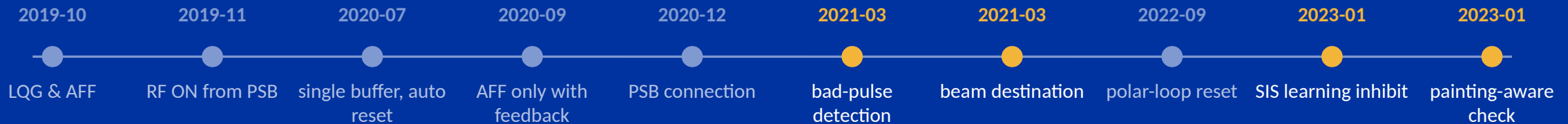


5 years

A learning loop learns whatever it sees

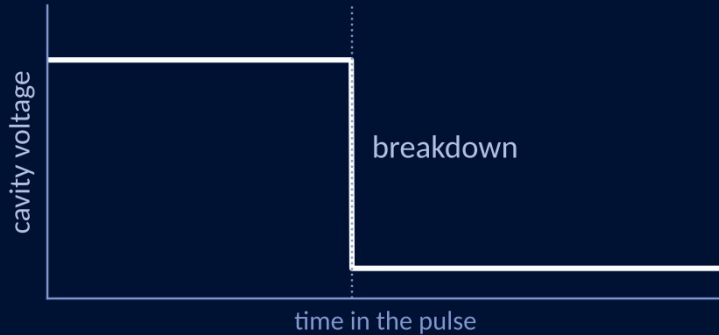


2019–2023: one fix at a time

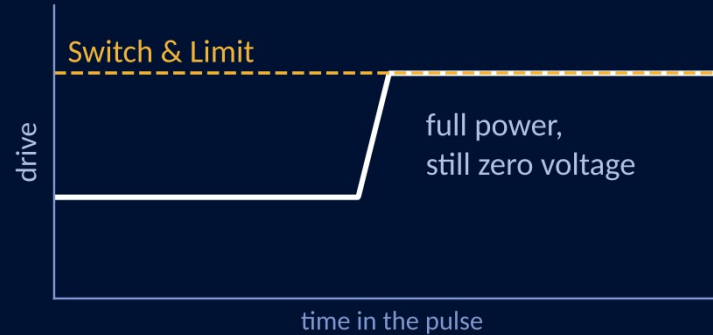


Breakdowns must never be learned

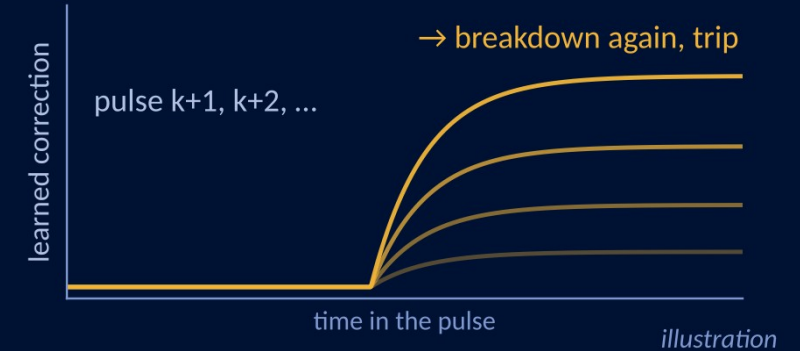
1 Breakdown: the voltage collapses



2 Feedback drives into the Switch & Limit



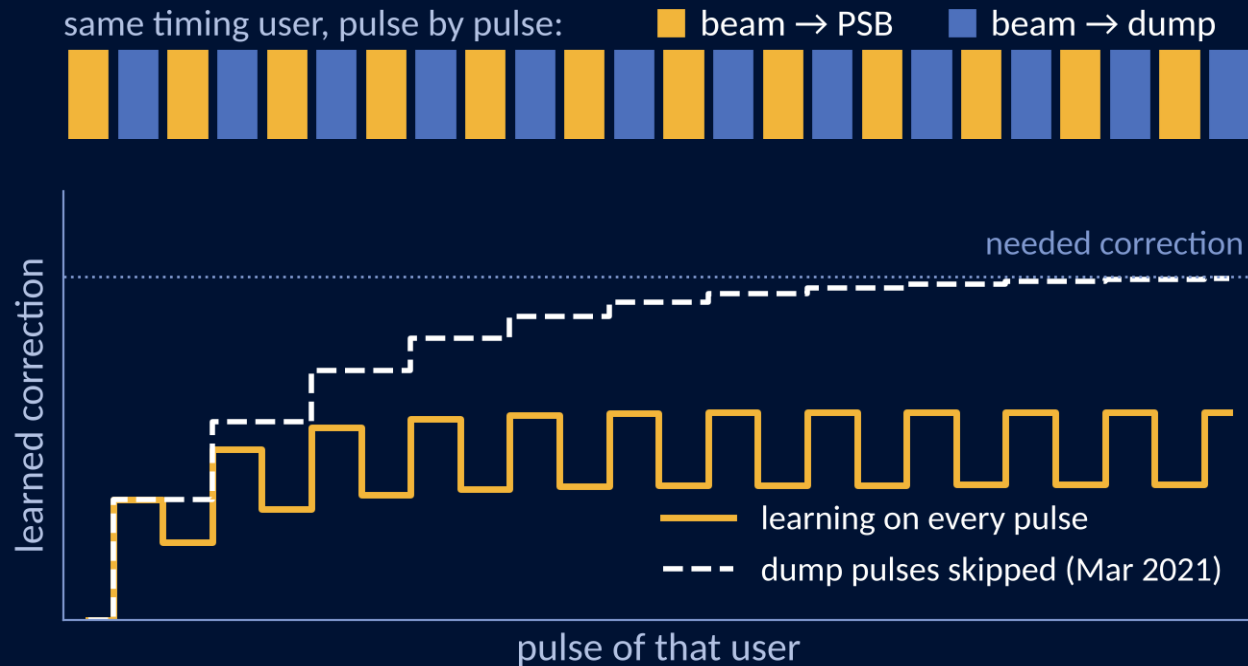
3 The AFF learns it → overdrive



Now

- Built-in pulse classifier: min · max · mean · std of the cavity voltage → no voltage · breakdown · unstable → not learned. The std catches oscillations that keep the same mean.
- Mean-error threshold → not learned
- Restart by the sequencer, AFF off until the end: open loop, tuners lock, set-point ramp → reset polar loop → close feedback → reset AFF history of all users → enable AFF from zero
- Switch & Limit card caps the drive → protects the klystron

One user, two destinations – the AFF never settled



illustration

Debuncher, 2021

The AFF never reached a stable state.

Every second pulse of the same user went to the dump – the destination is decided pulse by pulse.

No beam in the debuncher → the AFF unlearned what the previous pulse taught it.

Surprise: the same user can have two destinations.

Fix: destination = dump → no learning, no playback.

Related gates

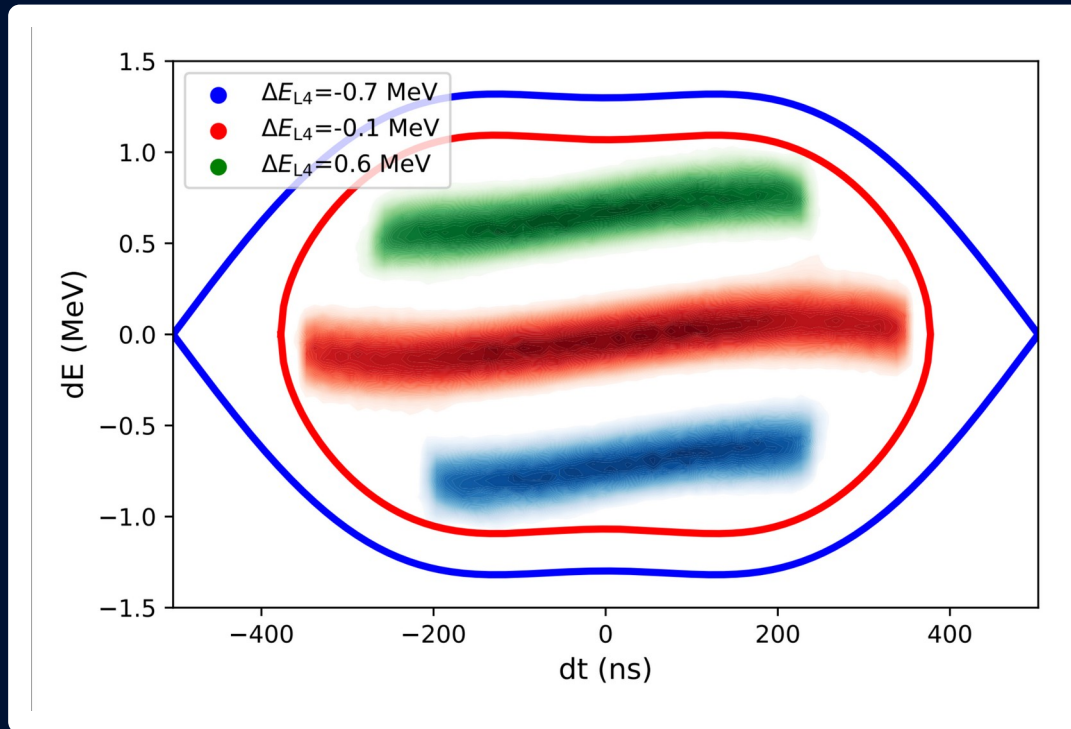
No ring played

known before the pulse → no learning, no playback

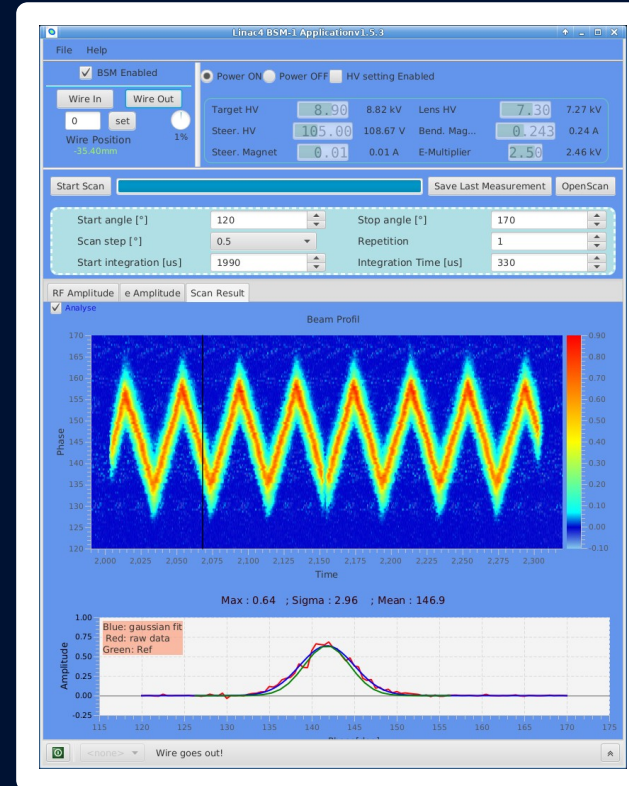
SIS inhibit (2023)

arrives after the pulse → played, not learned. Source or other line tripped, destination not ready

Painting: a modulated pulse can be a good pulse



PSB longitudinal phase space with painting



BSM measurement during painting tests
courtesy J. Tan, SY-BI

PIMS11-12 swing the energy, the debuncher swings the phase – on purpose.

The pulse classifier called it unstable → the AFF stopped learning on exactly the painted users.

Jan 2023: the classifier knows the painting waveform – min · max · mean · std relative to it.

Every failure mode now has an automatic answer

Condition	Detected by	Action
Feedback off	mode check	AFF off entirely
Beam to dump (debuncher)	timing: dynamic destination	no learning, no playback
No ring played	timing: PSB ring mask	no learning, no playback
Source / other line tripped, destination not ready	SIS learning inhibit (after the pulse)	skip learning
Breakdown / no voltage / unstable	pulse classifier: min · max · mean · std	skip learning
Painted pulse (modulated on purpose)	pulse classifier, relative to the painting waveform	learn as normal
Abnormal error	mean-error threshold	skip learning
User not played, or re-mapped	validity time per user	reset
Ring lengths or chopping changed	PSB Cruise Control writes ring settings	reset

Lesson 0: it works too well. *In 2020 a line ran on the AFF alone, with the feedback off – and held the voltage. Since then the AFF switches itself off without feedback.*

Outlook and thanks

Next – the AFF is stable today, but

- Tell the AFF the pulse current → a computed, not learned, correction from the first pulse
- The other way round: estimate the beam current from the learned correction
- High Current Mode: no problem so far, but at higher current the learning may become unstable

Thanks

Core team

P. Baudrenghien, R. Borner, B. Bielawski

Inspiration

K. Fong (TRIUMF)

Operations

P. Skowronski, G.P. Di Giovanni, B. Mikulec

High-power RF

R. Wegner

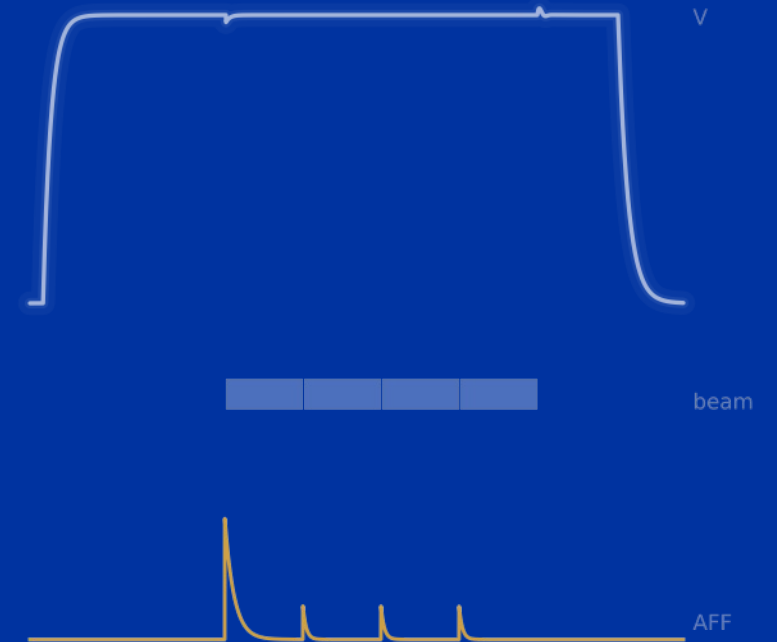
... and many colleagues in SY-RF, BE-OP and ABP



Thank you

Questions?

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Sources and image credits

Slide	Figure / content	Source
2	Linac4 layout · TDR quote	drawn for this talk · Linac4 Technical Design Report, CERN-AB-2006-084
3	Cavity voltage, PI vs LQG	P. Baudrenghien, B. Bielawski, R. Borner, LINAC'22 TH1AA06, Fig. 4
4	AFF principle	inspired by K. Fong (TRIUMF), LINAC'16 TUPLR009 · equations from the ALLL4CavityLoop FESA class
5	Beam phase along the batch (BSM)	R. Wegner, 2019 · LLRF'23 poster, B. Bielawski
6	Klystron power · energy at the Linac4 output	LINAC'22 TH1AA06, Figs 7 and 9 · energy: P. Skowronski
6	Linac4 availability	LLRF'23 poster, B. Bielawski
7	AFF panel · CCDTL5 spectrum	AFF application, B. Bielawski · LINAC'22 TH1AA06, Fig. 8
10	Two destinations	simulation for this talk (illustration)
11	PSB phase space with painting	S. Albright et al., HB'23 THBP38, Fig. 1
11	Phase sweep along the pulse	J. Tan, CERN SY-BI – BSM measurement during painting tests
5–6	Operation, High Current Mode	P.K. Skowronski et al., IPAC'25 THPS029

Code: ALLL4CavityLoop FESA class (aff.cpp, vcav.cpp) · ln4_rf_sequencer (aff_filter.py, turn_on.py) · FEC settings · CavityLoops firmware model

References

- [1] P. Baudrenghien, B. Bielawski, R. Borner, “*Low Level RF Control Algorithms for the CERN Proton Linac4*”, in Proc. LINAC'22, Liverpool, UK, 2022, paper TH1AA06.
- [2] M.P. Lavery, K. Fong, “*An Iterative Learning Feedforward Controller for the TRIUMF e-linac*”, in Proc. LINAC'16, East Lansing, MI, USA, 2016, paper TUPLR009, doi:10.18429/JACoW-LINAC2016-TUPLR009.
- [3] B. Bielawski, R. Borner, P. Baudrenghien, “*Insights and Conclusions from Operating the CERN Linac4 LLRF System*”, poster, 11th LLRF Workshop (LLRF2023), Gyeongju, Korea, Oct. 2023.
- [4] S. Albright, F. Asvesta, C. Bracco, B. Bielawski, R. Wegner, P. Skowronski, “*Two-Dimensional Longitudinal Painting at Injection into the CERN PS Booster*”, in Proc. HB'23, Geneva, Switzerland, 2023, paper THBP38, doi:10.18429/JACoW-HB2023-THBP38.
- [5] P.K. Skowronski et al., “*Experience with the CERN Linac4 and its Performance during the First Four Years of Operation*”, in Proc. IPAC'25, Taipei, Taiwan, 2025, paper THPS029, doi:10.18429/JACoW-IPAC2025-THPS029.
- [6] L. Arnaudon et al., “*Linac4 Technical Design Report*”, CERN-AB-2006-084, CERN, Geneva, 2006.

Unpublished CERN sources: ALLL4CavityLoop FESA class (aff.cpp, vcav.cpp) · ln4_rf_sequencer (aff_filter.py, turn_on.py) · CavityLoops firmware model · FEC settings · SY-RF e-mail and SVN history 2018–2023



Backup · LQG regulator, traced from the firmware

$$e[n] = y[n] - \hat{y}[n], \quad \hat{y}[n] = z_D[n]$$

$$\hat{x}[n+1] = a\hat{x}[n] + c u_m[n] + L e[n], \quad c = g(1-a)$$

$$z_0[n+1] = \hat{x}[n+1], \quad z_i[n+1] = z_{i-1}[n] + L_i e[n], \quad i = 1 \dots 46$$

$$u_{FB}[n] = I[n] - K(r_f[n] - \hat{x}[n]), \quad I[n+1] = I[n] + k_I(r[n-2] - y[n])$$

Per I and Q · traced from LQG_combined.slx (System Generator, 2022) · D = KalmanDelaySelect (22–46 samples) · r, f: setpoint low-pass, $\tau \approx 18 \mu\text{s}$ · K sign to confirm

Backup • AFF filter design (aff_filter.py)

A low-pass FIR filter, computed per line by the script: a fixed window (Hanning, exponential, rectangular) or, on some lines, the measured step response of the line – with or without DC. Long on purpose: the pre-driver amplifiers put a component close to 1 MHz into the drive:

1. AFF in EXCITATION mode, 4 rings $\times$ 150 μ s, RF $\rightarrow$ injection temporarily 250 μ s; average 16 pulses of the error
2. Delay: first sample where the median-filtered (25) derivative exceeds a threshold $\rightarrow$ look-ahead
3. Fit a polynomial (degree 21) to the step response
4. Differentiate $\rightarrow$ impulse response of the closed loop
5. Window with the falling half of a Hanning window
6. Optionally remove the DC component (“AC-coupled”, used since Sep 2020; --no-dc keeps it)
7. Normalise to $\sum |b| = 1$; write filter and look-ahead to the FESA class

Backup • Learning gates in code order

1. Mode OFF / EXCITATION, or ON with feedback off → no learning, no playback
2. Debuncher: DYN_LINAC_DEST = DUMP → no learning, no playback [INHIBIT_DEST]
3. PSB ring mask $\wedge$ AFF rings = 0 → no learning, no playback [INHIBIT_NO_BEAM]
4. SIS learn inhibit (arrives after the pulse, one cycle) → that pulse is not learned; it was already played [INHIBIT_SIS]
5. Cavity-voltage pulse status $\neq$ NORMAL → no learning [INHIBIT_BAD_PULSE]
6. Mean $|\text{error}| > \text{threshold}$ → no learning [INHIBIT_BAD_PULSE]
7. Otherwise: $s \leftarrow \beta \cdot s + (1-\beta) \cdot G \cdot \epsilon$, clipped, saturation flagged

Backup • AFF modes

Mode	Learning	Playback	Excitation	Use
OFF	no	no	no	–
ON	yes (feedback on, gates pass)	yes	no	operation
TEST	yes, also without beam	yes	fake beam-loading step	set-up without beam
EXCITATION	no	no	step from buffer start	delay → look-ahead, filter
INHIBIT_* / NOT_NEEDED	status only			why the last pulse was not learned

Backup • Timing: putting the window on the beam

- Window start = RF_ON → injection delay – advance; length = advance + Σ (ring length + distributor gap) + advance. Advance = 50 μ s: the long low-pass smears the sharp beam arrival, so the correction must start early and the amplifier is ramped up when the beam arrives
- Before Linac4 became operational, small timing shifts caused jitter → since Nov 2019 RF_ON is chained to the PSB (L4X.RFON), the same way as the chopper; the beam position in the pulse follows the PSB
- Aug 2020: beam arrived 243 μ s after RF_ON while the default assumed 300 μ s – the AFF missed the batch head; now computed from the master RF_ON
- Ring lengths and the chopping pattern come from PSB Cruise Control; writing them resets the AFF

Backup • AFF settings per line (FEC data)

Line	G	β	look-ahead
BU3	50	0.97	1.59 μ s
DTL1 / 2 / 3	97 / 90 / 50	0.97	1.75 / 1.77 / 1.59
CCDTL1 / 2	80 / 50	0.97	1.86 / 1.91
CCDTL3 / 4	79 / 20	0.97	1.95 / 1.86
CCDTL0506 / 7	80 / 80	0.97	1.45 / 1.59
PIMS0102 / 0304	50 / 70	0.97	1.65 / 1.54
PIMS0506 / 0708	40 / 70	0.97	1.64 / 1.55
PIMS0910 / 1112	35 / 68	0.97	1.59 / 1.59
Debuncher	45	0.97	2.00

Bunchers 1–2: tested, never activated. RFQ: no AFF.

Backup • A wrong correction can be stable – Buncher 3, 2021

Sunday 7 – Monday 8 March 2021

no trip – poor transmission for half a day

11:50

Tuner filter lets a bad sample through → cavity detuned, the AFF compensates

12:15

The AFF settles in a wrong but stable state

20:52

Supercycle change: users not played > 60 s are cleared – not the one still playing

05:07

All cycles removed → cleared

Now

Stricter tuner filtering • error threshold • validity time per user • reset on setting changes • sequencer “ON” resets all users

A user is only a slot in the supercycle: after re-mapping, the “same” user may be a different beam – so an old history is discarded, not trusted.