Experience with the Linac4 RFQ Breakdown Protection and Automatic Recovery System

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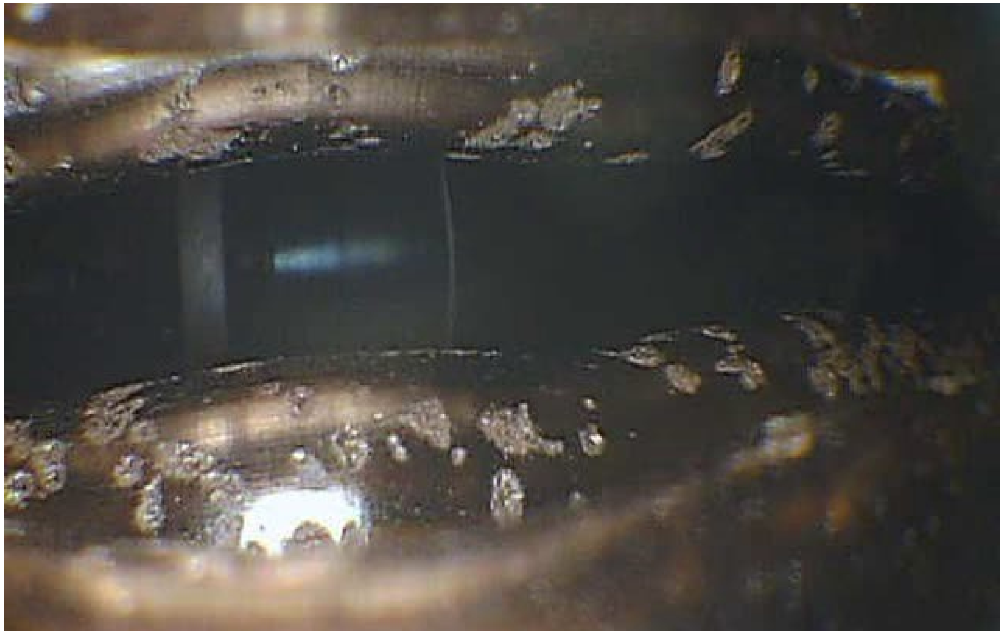
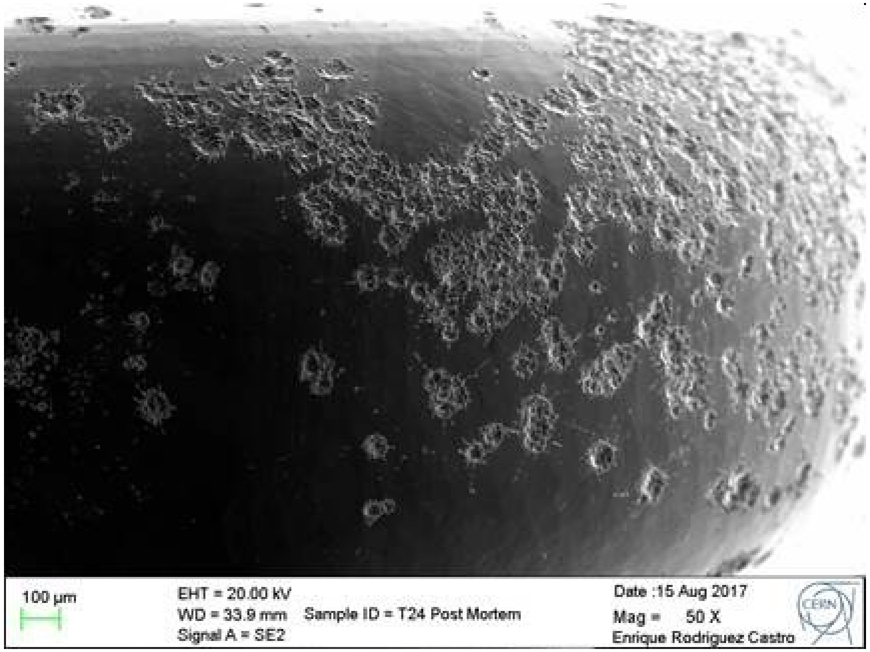
Outline

- Introduction
- Implementation of Protection and Automatic Recovery, adjustments made
- Illustration of Inspector panels and typical events
- Comparison of accumulated Breakdowns 2019 to 2021
- Interlocking RFQ on Tuning faults
- Conclusions

Introduction





Plenty of craters from RF discharges = breakdowns (BD) seen in the **L4 RFQ** endoscope inspection.

Picture from CLIC high gradient study (**T24**).

Discharges occur in high gradient RF structures. They can be isolated in time (single BD) or occur in clusters.

A BD protection system has been developed to intervene on BD clusters.

BD Detection and Protection

Detection and Protection:

- **detection**: reflected power > adjustable threshold level (100 kW)
  => fast interlock stops the RF pulse within ~60 µs (pulse ~1000 µs)
  => RF and Beam stopped
- **Software auto-reset** of interlock for the following pulses - assuming an isolated BD

BD cluster detection:

- **Bin 1 (BD cluster)**: 3rd BD within 25 pulses
  => **Recovery** Level 1 (trying a quick recovery ~1 min)
- **Bin 2 (high BDR)**: 8th BD within 9’000 pulses (3 hours, BDR ~ 1e-3)
  => **Recovery** Level 3 (sensitive recovery ~30 min)

Traceability

- alarms are generated on interlocks (LASER) + Timber logging

Recovery from Breakdowns

General remarks, Beam inhibition:

- **Recovery:** RF field in cavity lowered and slowly ramped-up to nominal level
- **RFQ needs to be pulsed without beam** to avoid beam loss
  BIS interlock is kept active during recovery (**RFQ BIS user_permit = FALSE**)
  => a small but important change was required to separate the RF pulse permit and BIS interlock (both were linked originally)
  implementation: RFQ BIS user_permit = **AND** (original logic, extra FESA bit)
- In recovery beam stopper is automatically activated to keep source pulsing

Recovery from Breakdowns

Recovery algorithm:

- synergy with CLIC high gradient structure conditioning / BD recovery
- in Recovery Mode the LLRF Feed-back is opened (open loop).
- 5 normal levels with different amplitude reduction factors and ramp-up speeds.
  Level 1 / 2 shall quickly bring back the RFQ into operation, ~1 / 5 min, deeper levels ramp-up slower from lower amplitudes.
- If more than a certain number of BDs are detected during a Recovery Level, the next, more sensitive Recovery Level is entered.
- When the nominal amplitude is reached, LLRF feedback is closed and the RFQ is pulsed for a certain time before going back to operational mode.
- If too many BDs occur, the RFQ is stopped (Locked state).

Recovery from Breakdowns

Level	new amplitude	# pulses hold	ΔA / A ramp-up	# pulses FB closed	sum pulses	approx. time	allowed BDs
1	95% * $A_{nominal}$	2	0.5%	20	40	1 min	2
2	95% * $A_{current}$	4	0.25%	50	130..210	~5 min	3
3	95% * $A_{current}$	10	0.1%	200	700..1700	15 to 35 min	5
4	75% * $A_{nominal}$	10	0.1%	500	3000	60 min	7
5	to keep RFQ pulsing while expert is contacted						
	65% * $A_{nominal}$	10	0.1%	1000	4500	90 min	11
locked	emergency stop						

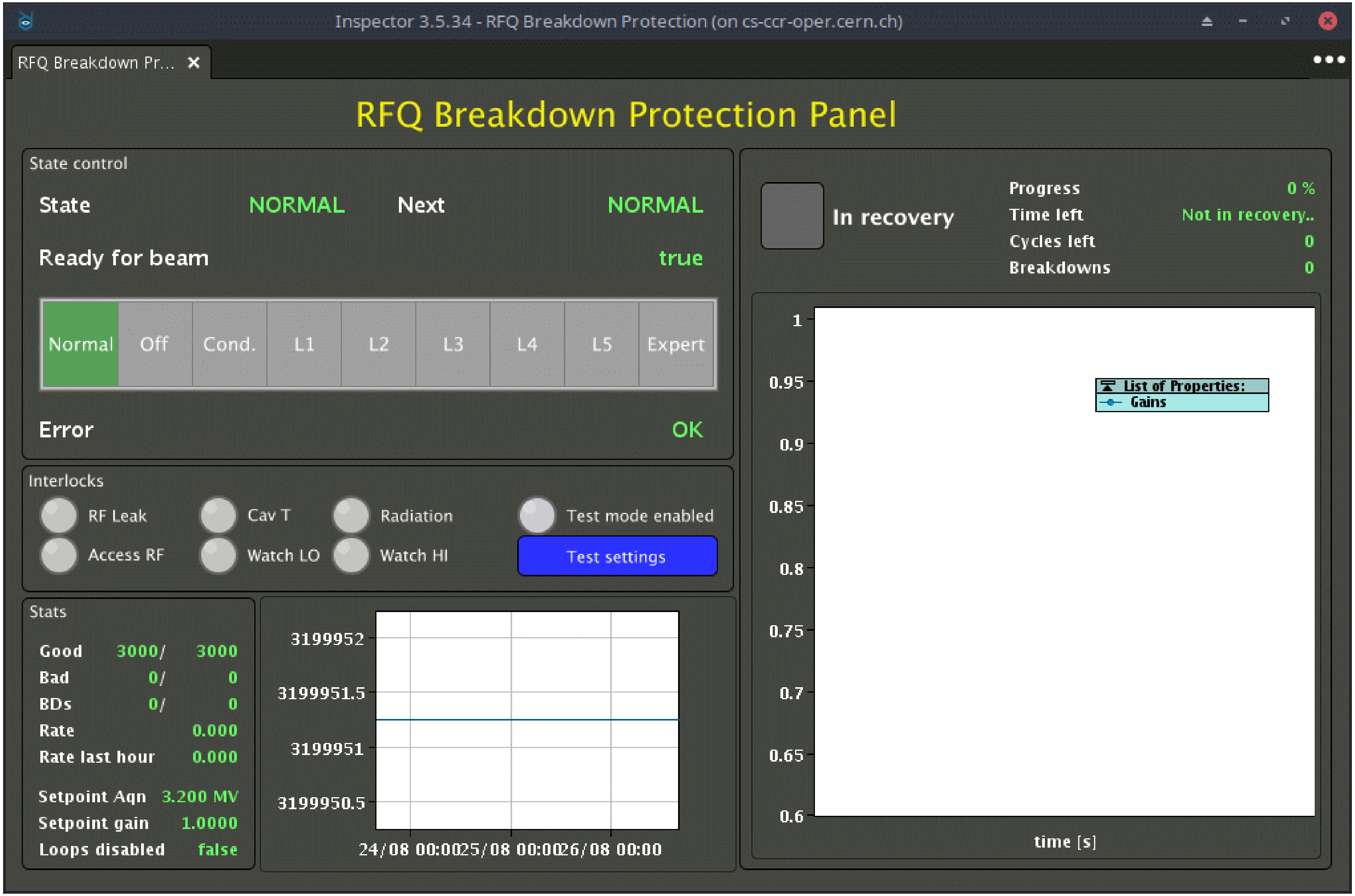
=> Refinement intended after first experience in operation

Recovery from Breakdowns

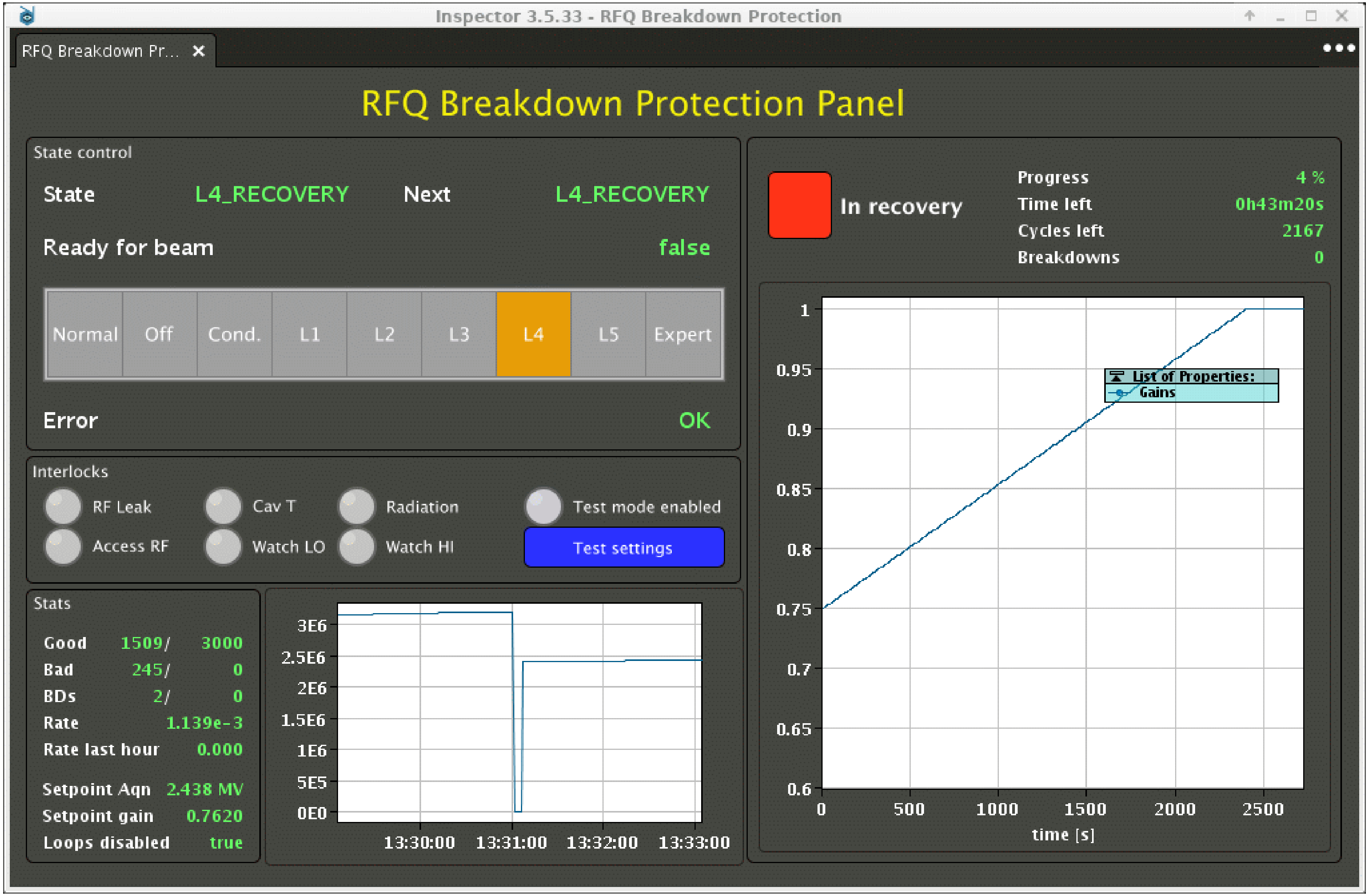
Level	new amplitude	# pulses hold	ΔA / A ramp-up	# pulses FB closed	sum pulses	approx. time	allowed BDs
1	95% * $A_{nominal}$	2	0.5%	20	40	1 min	2
2	**90%** * $A_{current}$	4	0.25%	50	210..280	4..6 min	3
3	**90%** * $A_{current}$	**6**	0.1%	200	800..1600	16 to 32 min	5
4	75% * $A_{nominal}$	**8**	0.1%	**250**	2250	45 min	7
5	to keep RFQ pulsing while expert is contacted						
	65% * $A_{nominal}$	10	0.1%	1000	4500	90 min	11
locked	emergency stop						

=> 1st Refinement, 11.12.2020

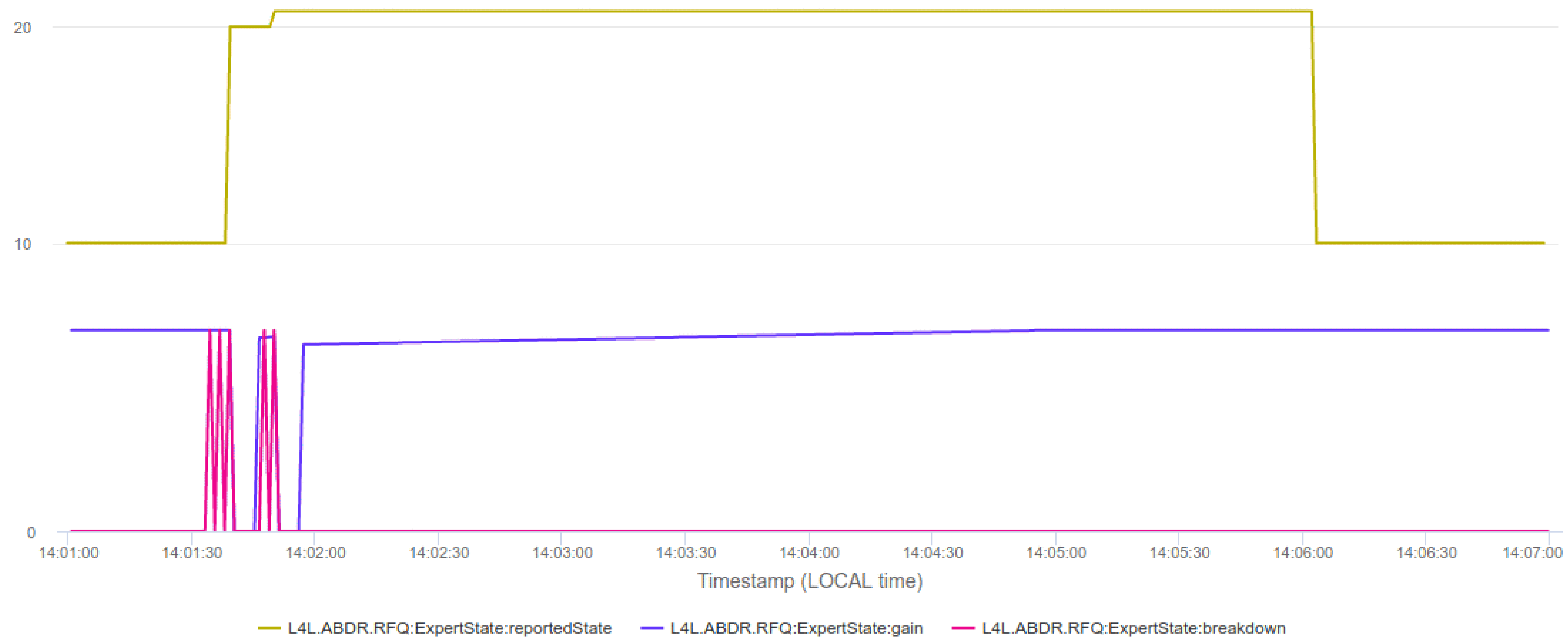
Inspector Panel, normal operation



Inspector Panel, in Recovery



Illustration



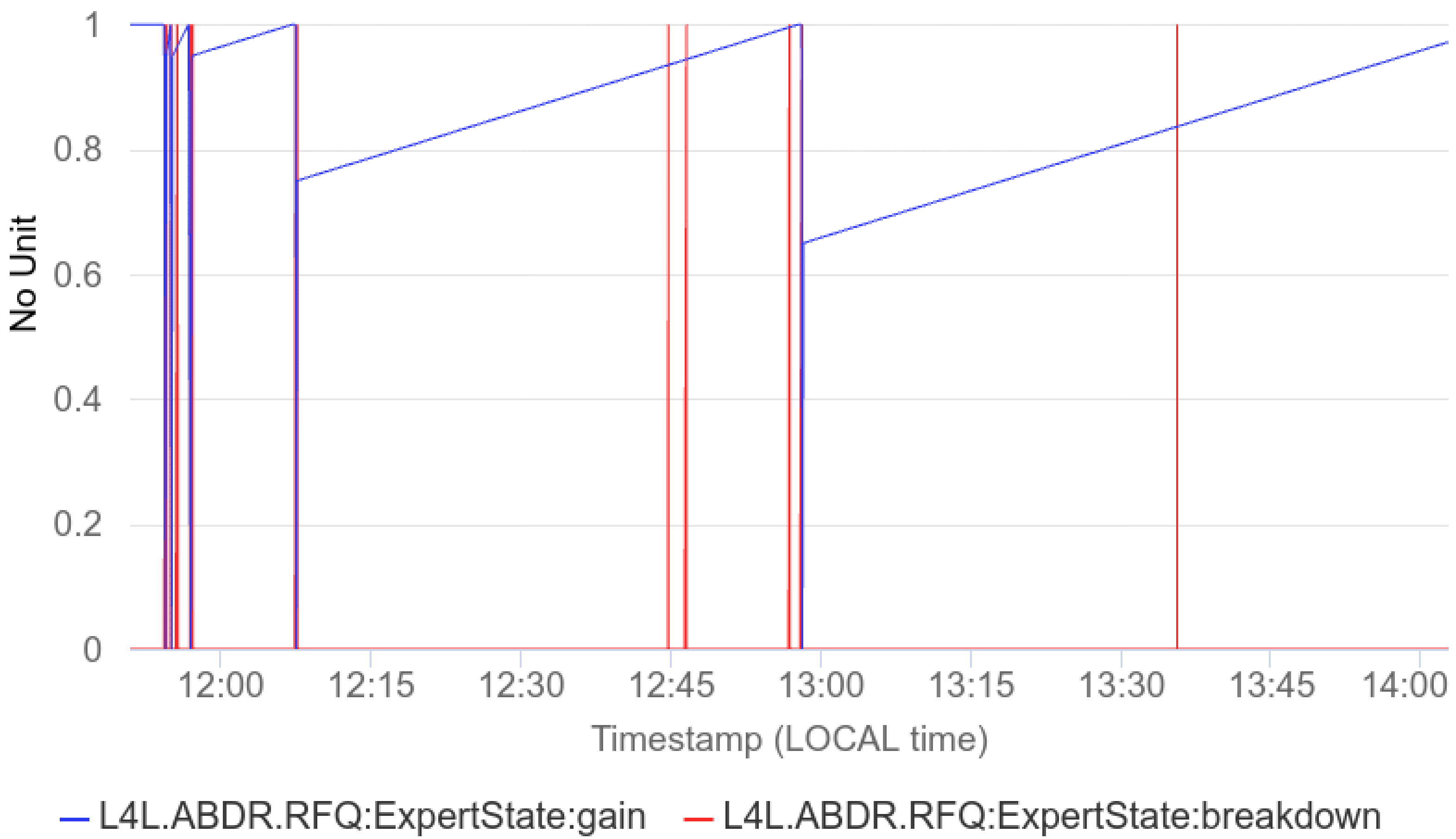
normal operation => 3 BDs => Recovery Level 1

2 BDs in Level 1 => Level 2 (early implementation error ≥ 2 BDs instead of > 2 BDs)

~14:05 feed-back closed, ~14:06 back to normal state = ready to accelerate beam

[blue curve: amplitude factor (gain), red spikes: BDs,
yellow curve: state of recovery class: 10 = normal, 20 = Recovery Level 1, 21 = Rec. Level 2]

Illustration

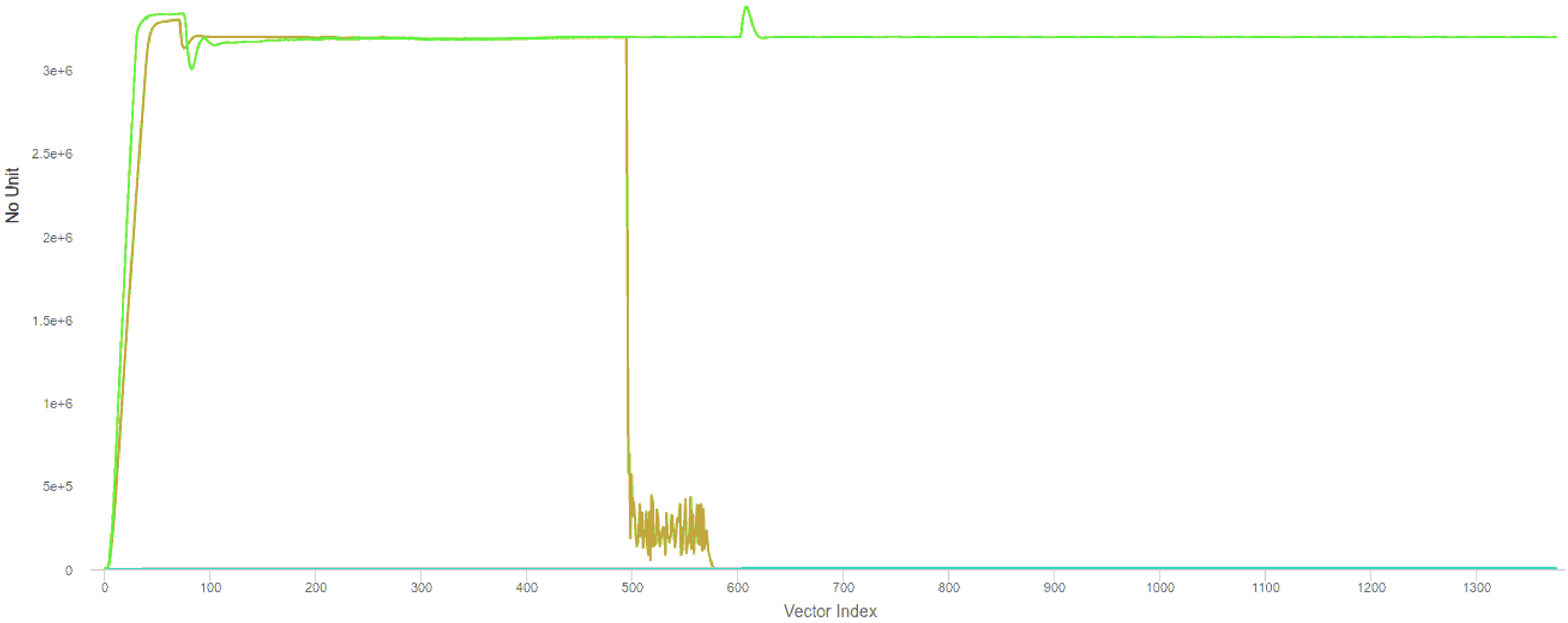


Sa 5 Sep. 2020: Operator increased pulse length by accident => many BDs

Recovery down to Level 5 (very short Level 1) [blue: amplitude factor, red: BDs]

29 BDs in total, 4 more and RFQ would have stopped pulsing (locked state)

Illustration

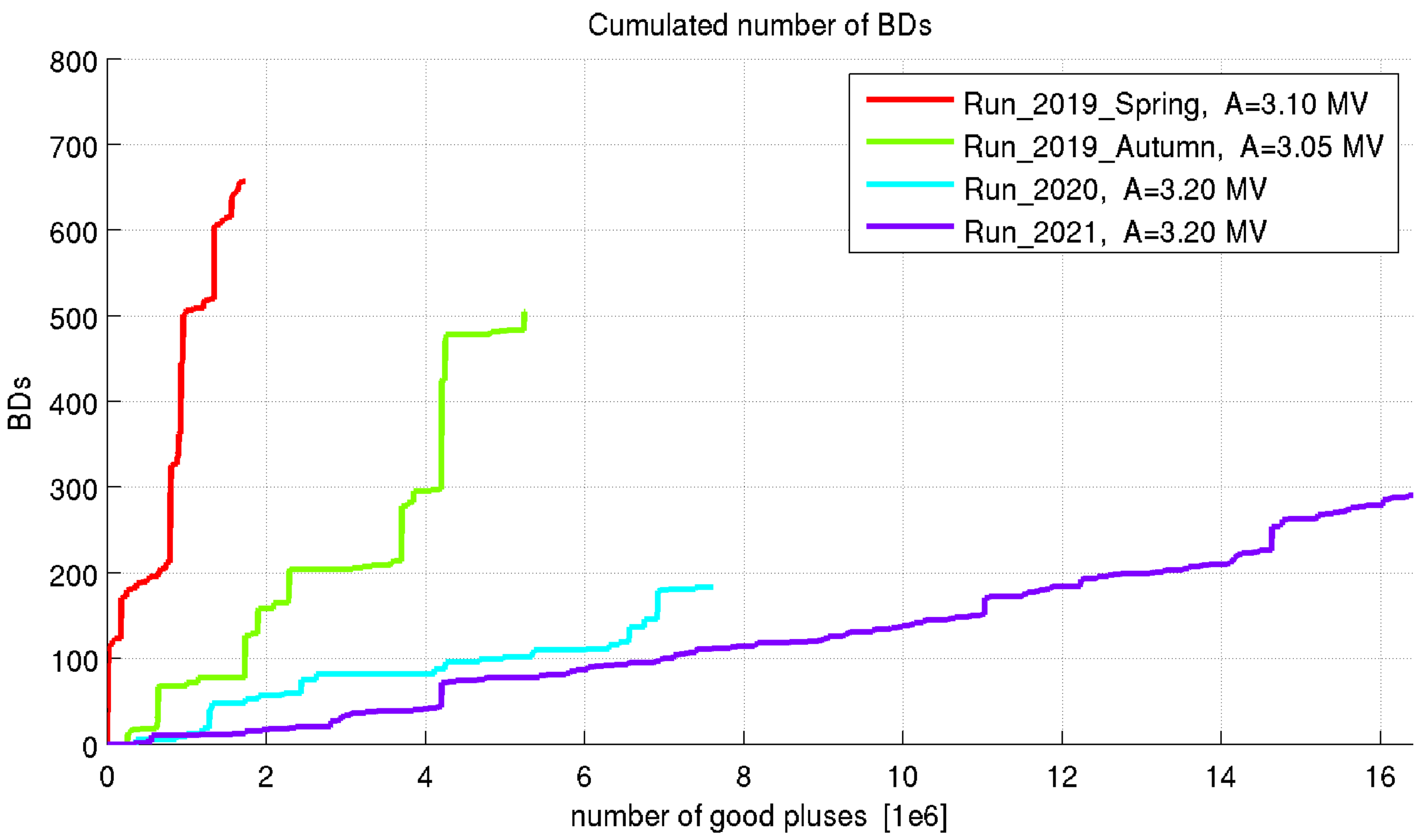


Waveform of a good pulse (green) and pulse where BD protection interlocks (yellow).

Time axis (abscissa) in sample number, 1’400 samples <=> 1’000 μs.

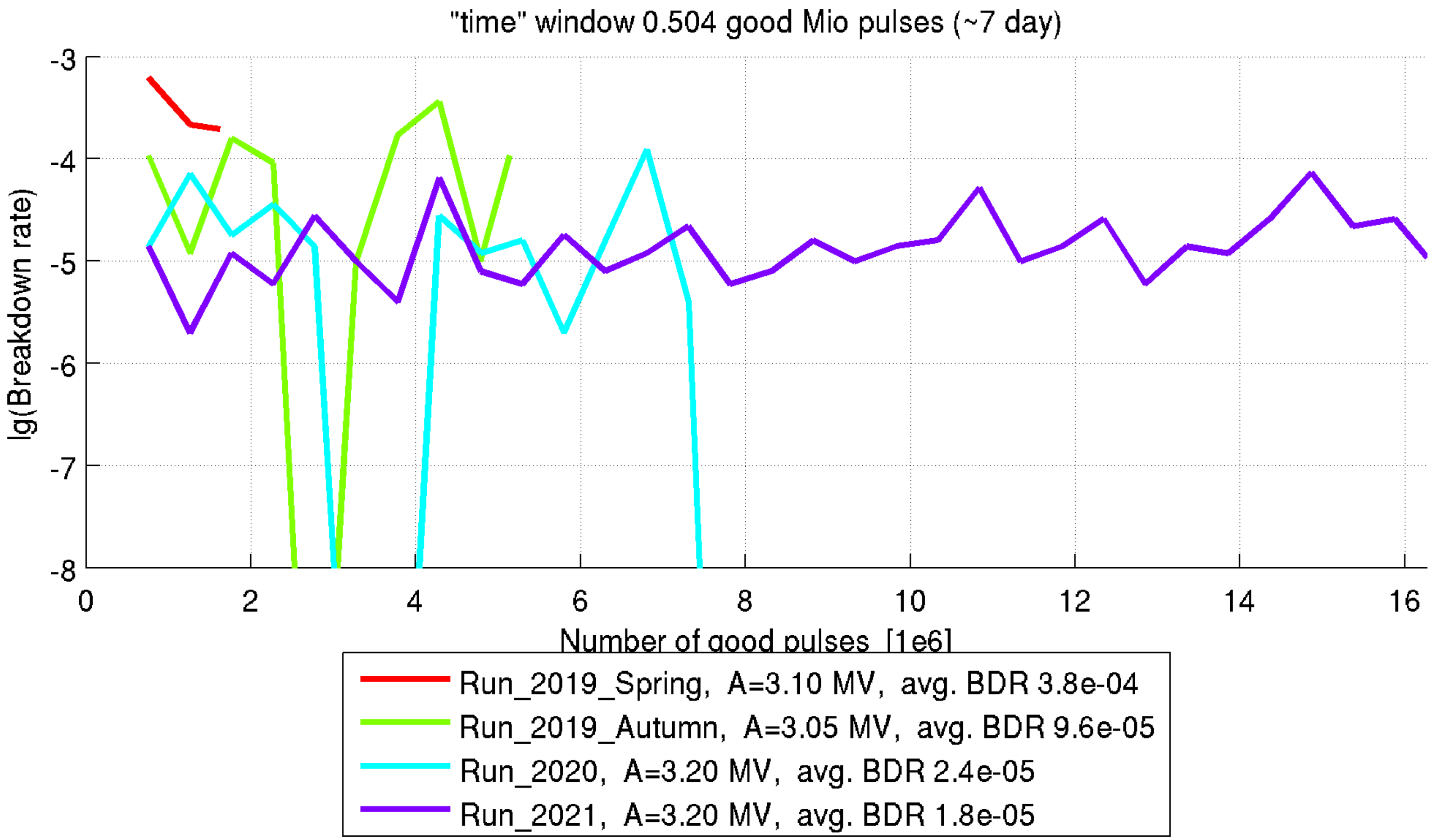
Interlock stops the feeding RF power in about 60 μs.

Breakdowns 2019 to 2021



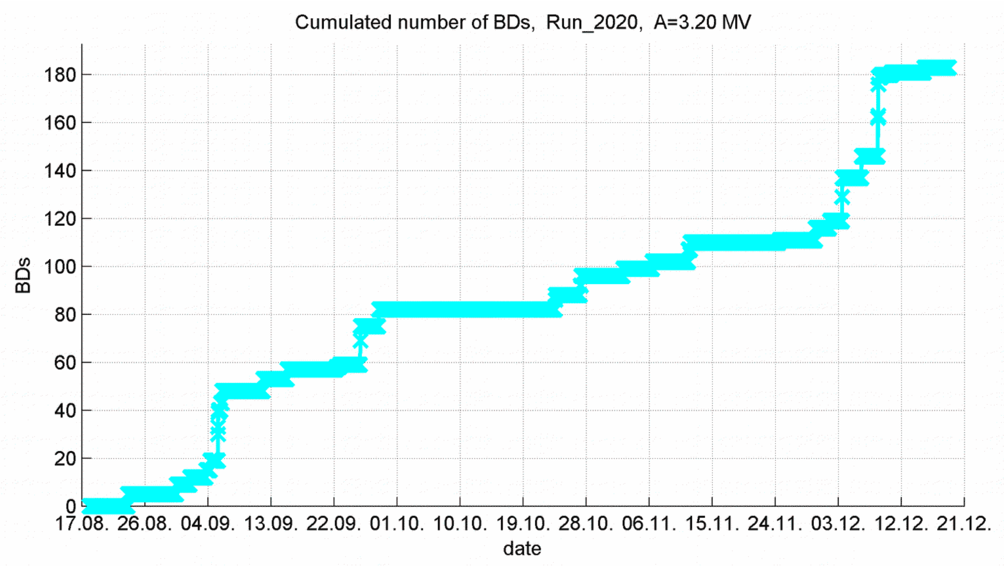
- 2019 **no BD protection**, nominal amplitude 3.03 MV
- 2020 **BD protection**, re-calibration, nominal amplitude 3.06 MV => **running above nominal**
  => **number of BDs significantly reduced by avoiding BD clusters - even with higher amplitude**
  BD clusters dominated by **external events** (RFQ tuning [glitches, water cut])

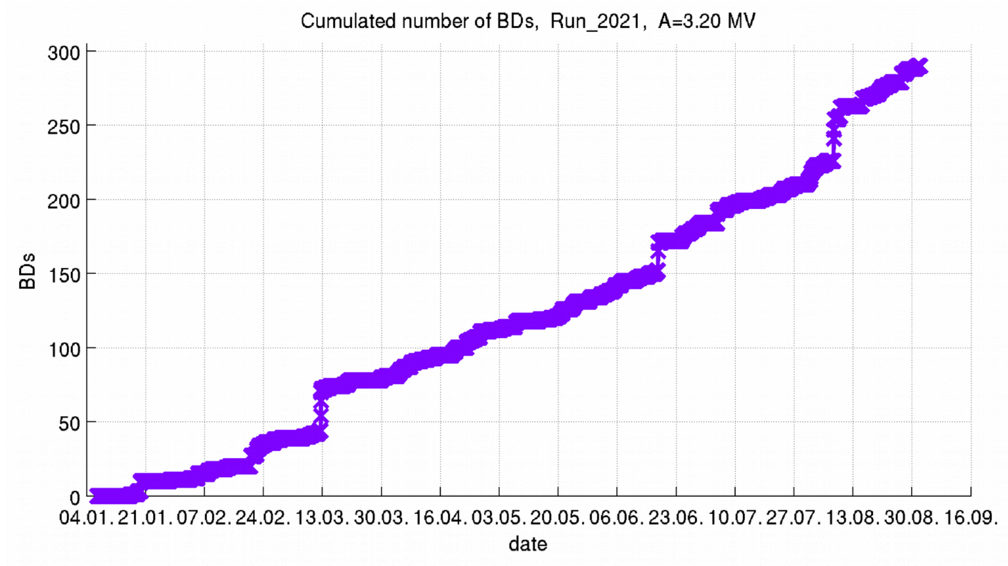
Breakdown-rate



The **BD Protection and Automatic Recovery system** was introduced before the start of the 2020 Run.
It worked so well that the decision could be taken to operate the RFQ above the design level (10% in power).
Despite the higher amplitude, the Breakdown-rate decreased by nearly 1 order of magnitude.

Breakdown Clusters





- 5. Sep. 2020 (Saturday): Operator by accident **increased pulse length** => very high BDR, protection went to Level 5 (a few BDs left to reach the emergency stop), 29 BDs in total
- 25. Sep. 2020 (Friday evening): **RFQ tuning stopped** => 16 BDs + 7 BDs when switching back on
- 23. Oct. 2020 (Friday evening): **RFQ tuning stopped** => 11 BDs + 6 BDs when switching back on
- 3. Dec. 2020: **“normal” BD** caused a cluster of 18 BDs, recovery down to Level 3
- 6. Dec. 2020: **“normal” BD** caused a cluster of 9 BDs, recovery down to Level 2
- 8. Dec. 2020: **“normal” BD** caused a cluster of 33 BDs, recovery down to Level 4

- 12. Mar. 2021: (undeclared) **CV intervention, tripped RFQ tuning** => a lot of BDs due to detuning, 28 BDs
- 17. Jun. 2021: **electric glitch, RFQ tuning tripped** => recovery down to Level 4, 19 BDs
- 4. July 2021: **“normal”** BD caused a cluster of 8 BDs
- 7. Aug. 2021: **electric glitch, RFQ tuning tripped** => recovery down to Level 4, 36 BDs

RFQ tuning - interlocking

The RFQ tuning consists of a **body circuit supplied by CV** and stabilised to ±0.1 K and a circuit for the vanes for each of the 3 segments. This later circuit is chilled by CV (stabilised to ±0.5 K) and precisely re-heated (to ±0.1 K) by a PLC system in responsibility of RF. This **precision system keeps the RFQ on tune**.

The design philosophy was to optimise the performance by the precision system but still be able to run without it as degraded, back-up solution.

However, increasing the RFQ amplitude above the design amplitude increases the risk of BDs and hence a deterioration in tuning can quickly cause BDs and BD clusters.

It is too much demanded from operators to survey the RFQ tuning on top of their other duties so that **interlocking the RFQ on interruptions of the tuning system** is seen as a good solution (RF + OP)

a) to protect the RFQ and
b) to make the operator aware of the issue (manual reset required for restart).

Feedback from OP

Feedback from OP (Piotr Skowronski):

- "In my view, the RFQ protection system works very well and it does not act too often. I believe the amplitude can stay like this."

  [amplitude 3.20 MV instead of 3.06 MV nominal (+5% in amplitude, +10% in power)]

- "I think beam operation should be blocked if RFQ is not tuned. I guess it would be safer if power would be limited until the tuner shows OK state."

Conclusions

- A system to detect Breakdowns (BDs) and to **interlock within concerned pulses** has been implemented.
  On isolated BDs the interlock is automatically cleared to continue beam operation.
  On BD clusters or high BDRs the RFQ is switched automatically into a **Recovery mode**.
  - Beam is inhibited during Recovery via RFQ BIS user_permit=FALSE.
  - 5 Recovery Levels with different amplitude reduction factors and ramp-up functions recondition the RFQ.
  - If still too many BDs occur, the RFQ will stop pulsing.
- During the 2020 and 2021 runs the Protection and Automatic Recovery system intervened several times and acted as designed.
  The RFQ is seen to be well protected, so that the decision could be taken **to run the RFQ about 10% above the nominal power level** in order to reduce the H^- beam loss inside the RFQ.
- **Despite the higher amplitude, the Breakdown-rate decreased by nearly an order of magnitude** compared to previous runs **thanks to the BD Protection and Automatic Recovery system**.
- In order to further decrease the Breakdown-rate, an **interlock mechanism on the tuning system state** is being implemented.

RFQ parameter

Parameter	Specified RFQ (2D)	Units	LINAC4 RFQ
RFQ frequency	352.2	MHz	352.2
Length	3.0	m	3.06
Electrical length	3.4		
Intervane voltage	84	kV	78
Average radius r_0	3.2	mm	3.256
/r_0 ratio	0.85		0.85
Stored energy	0.433	Joules/m	0.395
Capacitance	123	pF/m	
Power dissipation (Superfish)	91.8	kW/m	78.7
Quality factor	10400		6772
Shunt impedance (Superfish)	77	k -m	
Total power dissipation (1.2*Superfish, only cavity)	331	kW	390
Energy input	0.045	MeV	0.045
Energy output	3.0	MeV	3.0
Max RF duty cycle	5	%	10
Beam peak current during pulse	70	mA	70
Beam power (70 mA)	210	kW	210
RF total peak power	541	kW	600
Minimum aperture a	0.18	cm	0.18
Max field on pole tip	35	MV/m	34
Max surface field	1.9	Kilpatrick	1.84
Focusing parameter	6.0		
Acceptance at zero current	1.7	mm mrad	1.7
Transmission(*)	93	%	95
Input transverse emittance	0.25	mm mrad	0.25
Transverse emittance growth(*)	0	%	0
Longitudinal emittance(*)	0.14	deg MeV	0.13

"Linac4 RFQ Design, Contruction, Commissioning, and Operation"

(presentation, Carlo Rossi)

https://indico.cern.ch/event/754020/