Strategy for RF Breakdown Protection of the Linac4 RFQ

Rolf Wegner, Bartosz Bielawski

Outline

- Detection of Breakdowns and Breakdown Clusters
- Recovery from Breakdown Clusters
  - Beam inhibition
  - Recovery algorithm
    - Simulation examples
- Conclusions

RFQ Breakdown Detection

Detection:

- background: Endoscope inspection showed plenty of BD craters
  => current protection for RFQ is not sufficient (vacuum, klystron, modulator)
- breakdowns (BD) are discharges that are caused by strong EM fields
- plasma of electrons and copper ions acts as short circuit
  => feeding RF power is reflected
- **detection**: if this reflected power exceeds an adjustable threshold level
  => **fast interlock** is generated within the pulse (~50 µs / pulse ~1000 µs)
  => RF and Beam stopped (BIS –> Source RF)
- **auto-reset** for next pulse (isolated BD)
- if a **BD cluster** (consecutive BDs) or a **high** BD Rate (**BDR**) is observed
  => **no further auto-reset, Recovery is needed**
- **traceability**: alarms will be generated on interlocks + Timber logging
- **implementation ongoing** (RF section: CS, LRF, MK)

RFQ Breakdown Detection

BD cluster detection:

- BD clusters / high BDR will be detected using history and bins
  - 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)
- Monitoring of BDs on different time scales (per hour, per day) over several days in Inspector
- Monitoring of BDs in Timber
- Refinement during Linac4 startup

Recovery from Breakdowns

Recovery, general remarks, Beam inhibition:

- BDs can damage the surface and can leave craters / sharp edges
  => EM field enhancement, further discharges are provoked
- Recovery: edges can be smoothed by field emission
  => apply EM fields with lower strength (to avoid discharges)
  => slowly ramping amplitude up to nominal level
  => beam needs to be inhibited (lower transmission => losses)
- **RFQ needs to be pulsed without beam**
  => **BIS interlock will be kept active (RFQ BIS user_permit = FALSE)**
  => change of RF controls required to decouple BIS interlock and RF pulse permit (many thanks Jan for the clear recommendation)
  => implementation: BIS user_permit = AND (current logic, extra FESA bit) so that the **beam can be disabled while RFQ is pulsing**

Recovery from Breakdowns

Recovery algorithm, I:

- synergy with CLIC high gradient structure conditioning / BD recovery
  => many thanks to the CLIC team for helpful input (W. Wuensch, L. Millar)
- in Recovery Mode the LLRF Feed-back is opened (open loop).
- Level 1/2 shall quickly bring back the RFQ into operation, ~1/5 min.
- If more than a certain number of BDs are detected during recovery, the next, more sensitive Recovery Level is entered.
- On each entry into a Level, the amplitude is reduced by a defined factor and ramped-up in small steps over a number of pulses for each step.
- 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.

Recovery from Breakdowns

Recovery algorithm, II:

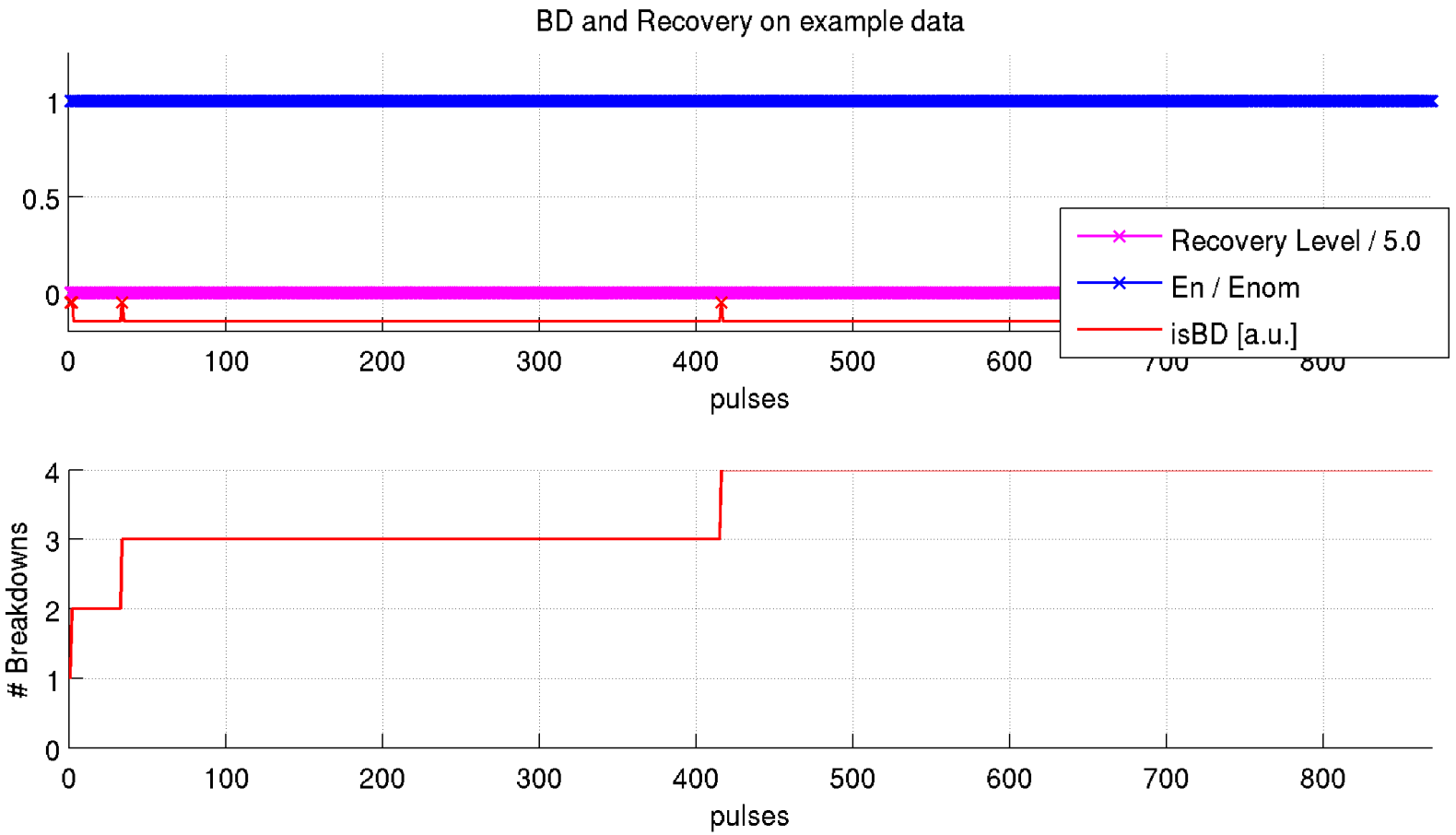
- Recovery Level 4 as most sensitive, “normal” Recovery Mode takes about 1 hour.
- If still not sufficient, the amplitude is further reduced and RF experts shall be contacted by the Operator while the RFQ is pulsing (Recovery Level 5).
- If still too many BDs occur, the RFQ is stopped (Locked state).

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	7
locked	emergency stop						

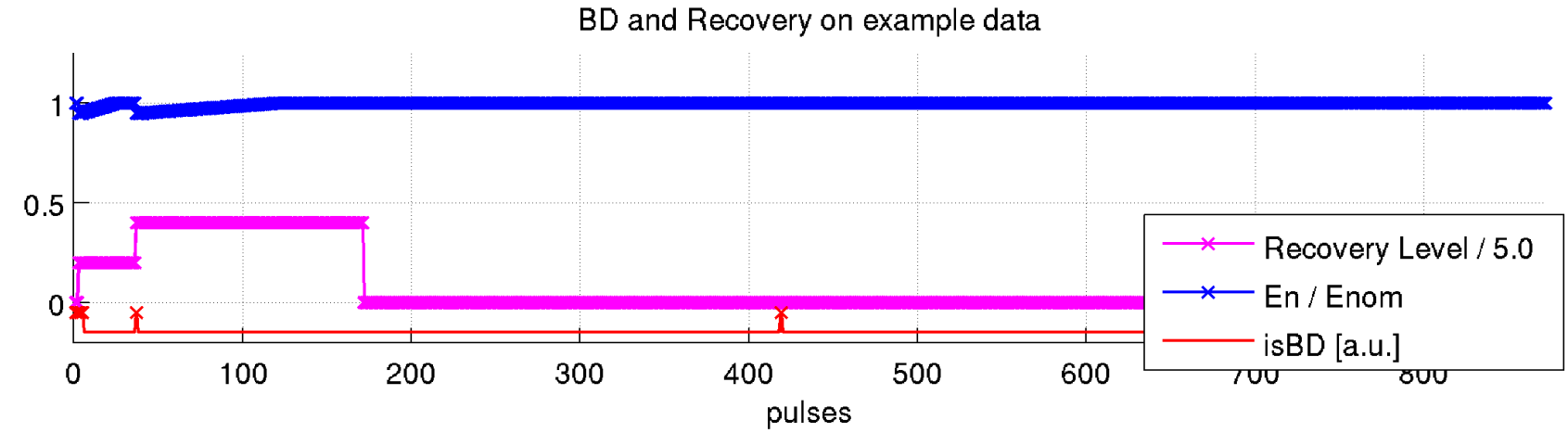
=> Refinement will be done during start-up for Run3.

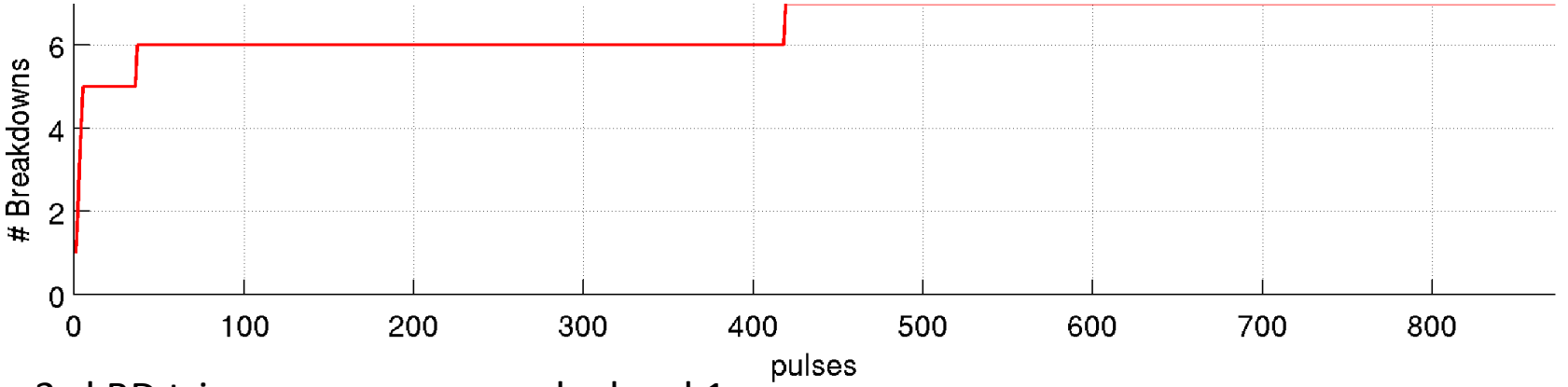
RFQ BD Recovery - examples



Single BDs are ignored if not too frequent.

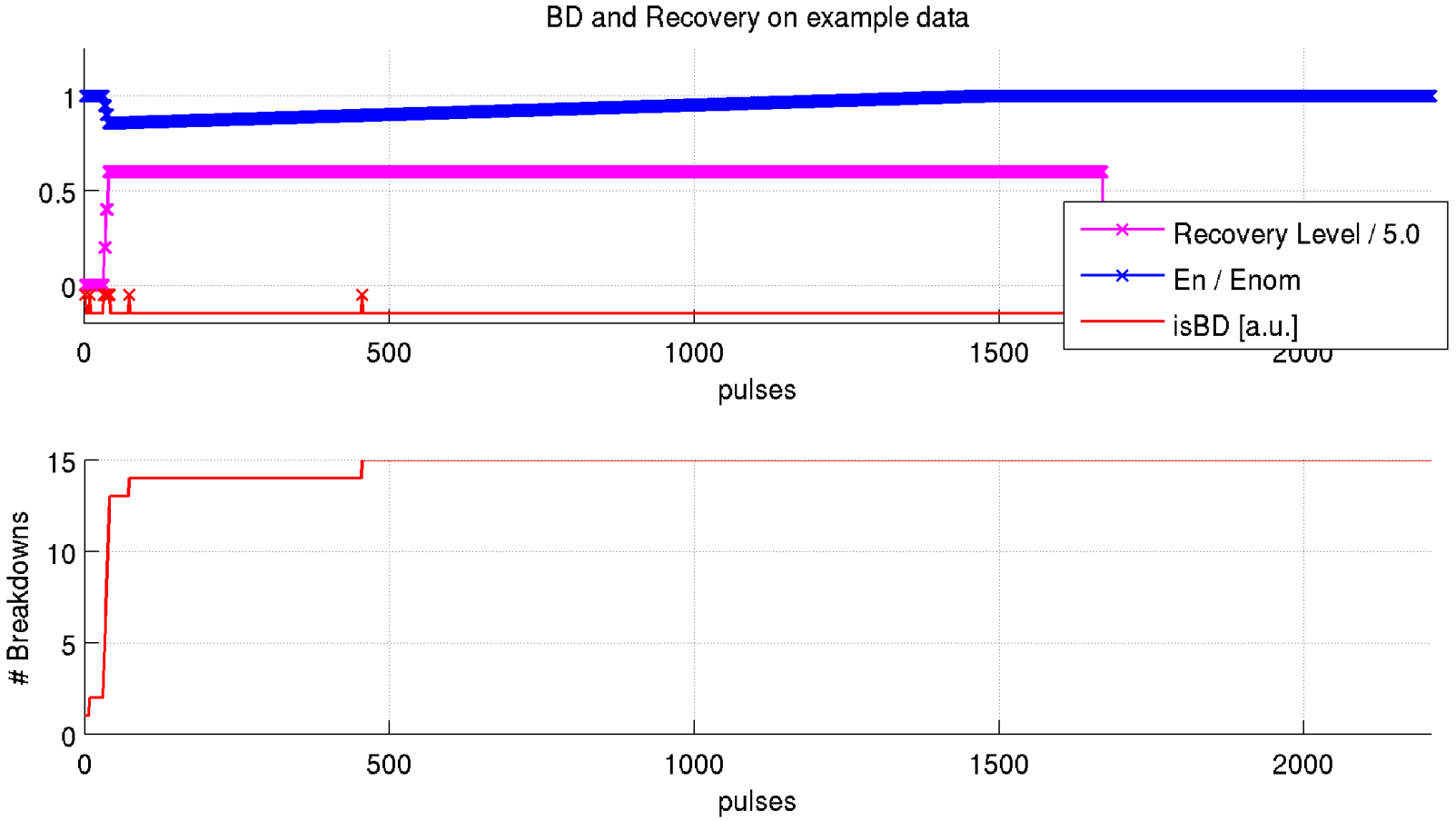
RFQ BD Recovery - examples





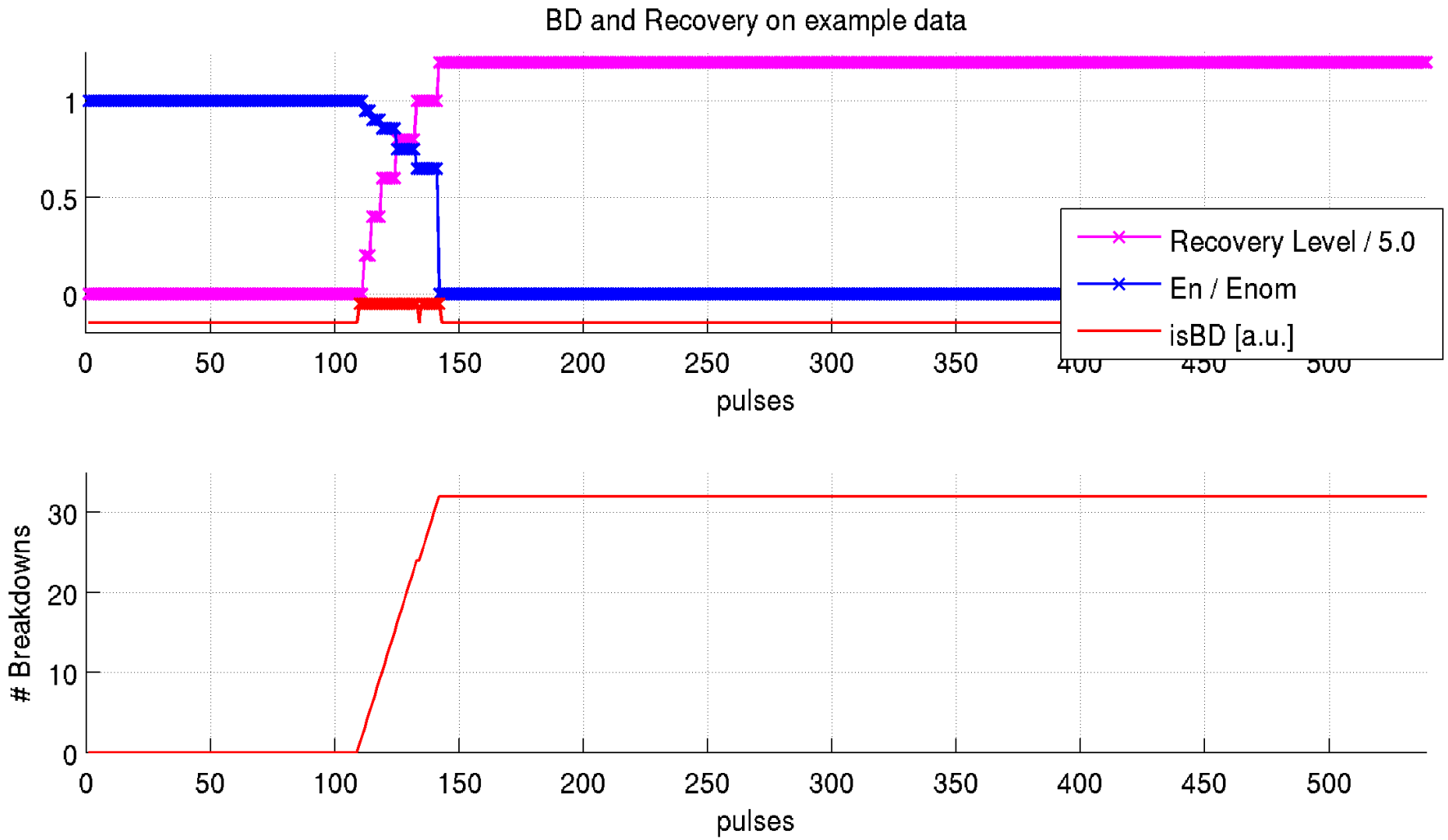
- 3rd BD triggers recovery mode, level 1
- E => 95%*E_nom, ramped-up in open loop followed by closed loop 100%*E_nom
- 6th BD (3rd within recovery level 1) triggers recovery mode, level 2
- no further BDs => ramp-up from 95%*E_nom to 100%*E_nom and closed loop
- back to normal operation. Next BD ignored as isolated BD.

RFQ BD Recovery - examples



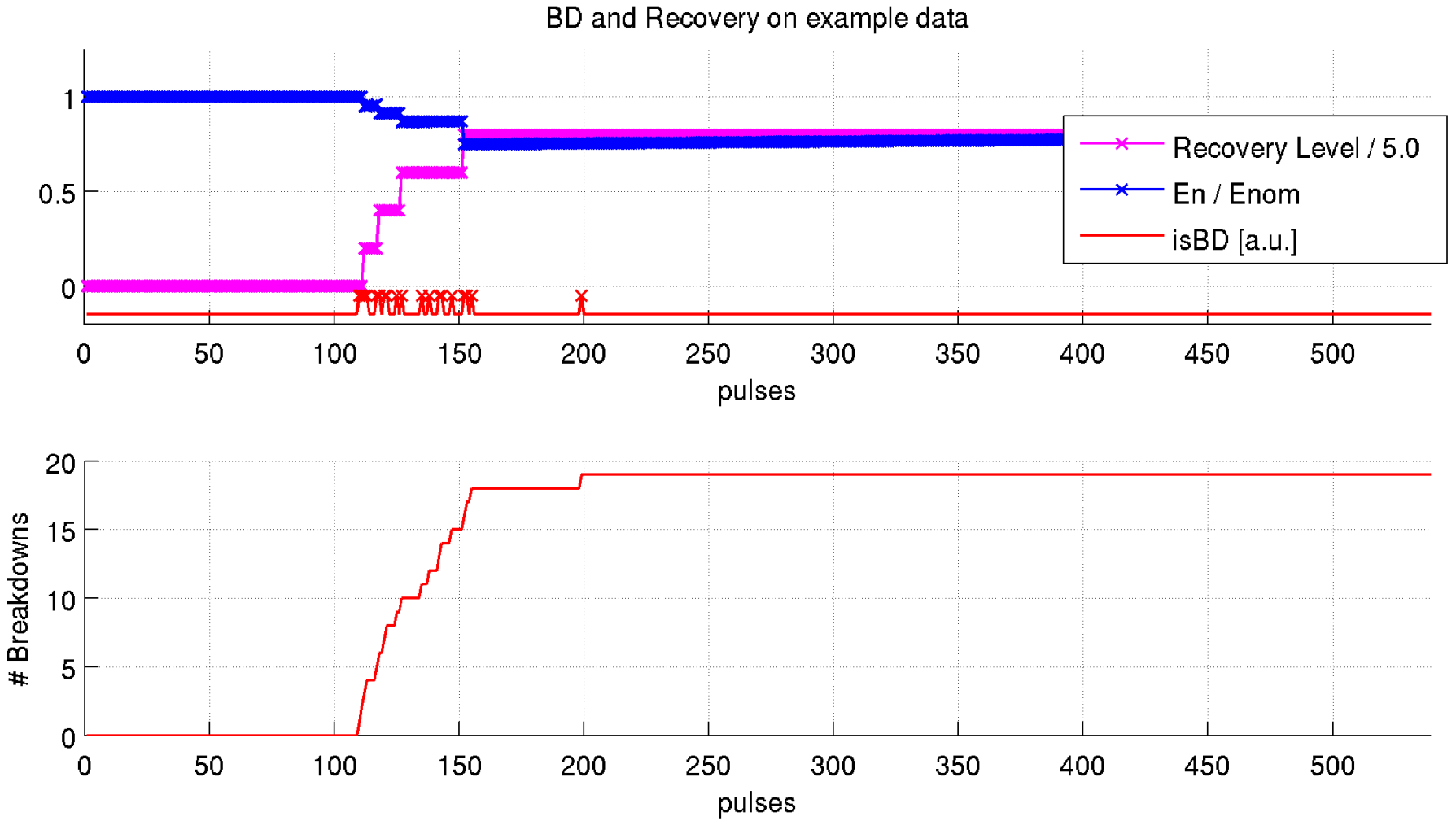
- 3rd BD triggers recovery mode, level 1
- 6th BD (3rd inside recovery mode, level 1) triggers level 2
- 11th BDs triggers recovery mode, level 3
- ramp-up from ~85% E_nom to 100% and Feed-Back loop closed
- back to normal operation after 1’700 pulses (34 min)

RFQ BD Recovery - examples



- 32th BD triggers recovery modes up to locked state = stop pulsing, something very wrong.

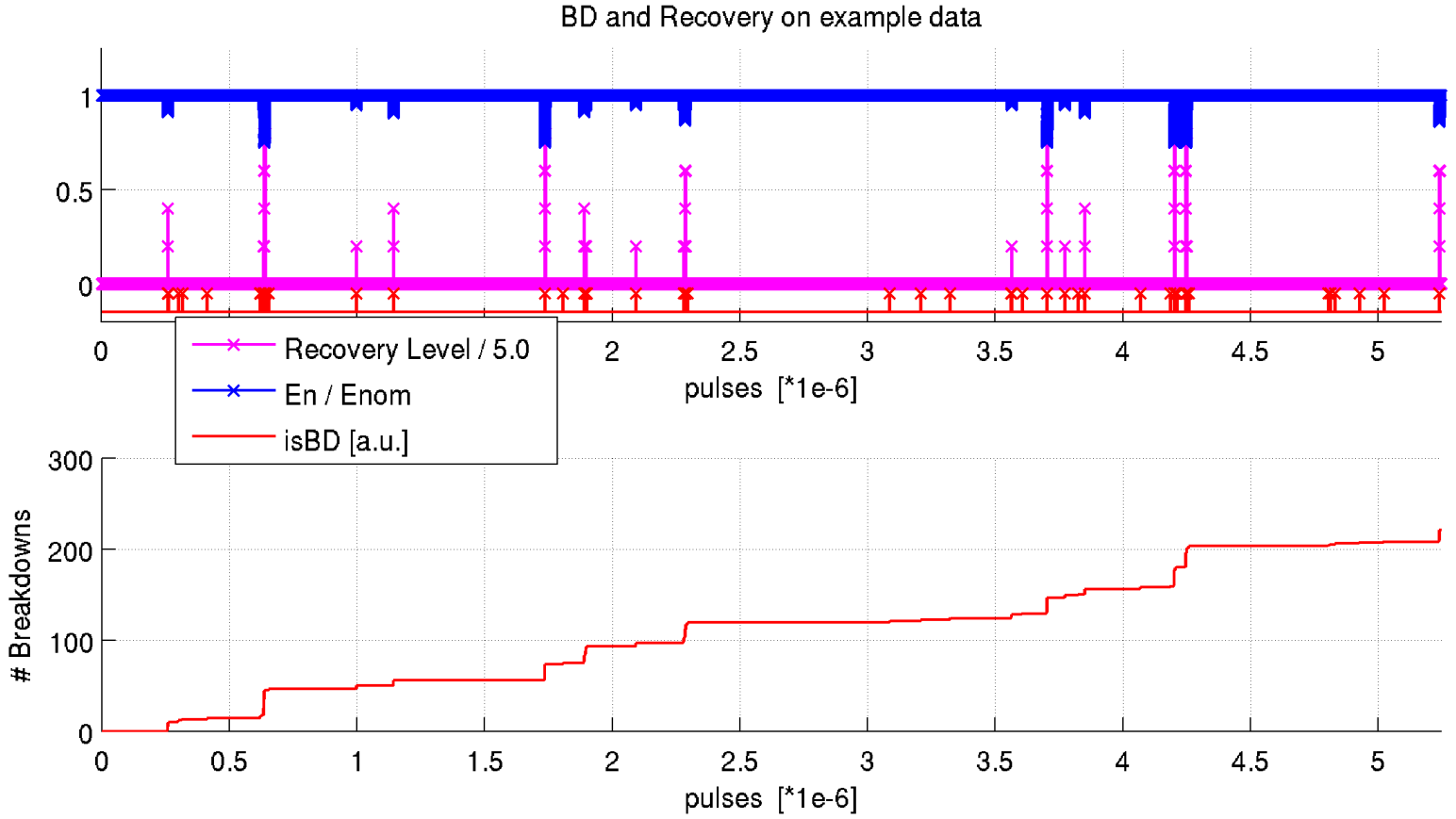
RFQ BD Recovery - examples



In reality a reduction in electric field will reduce the Breakdown rate strongly.

Assuming here a 10th power dependency BDR ~ (E/Enom)^10 (conservative).
=> the lower number of BDs leads the recovery mode only reach level 4 in this example.

RFQ BD Recovery – LBE data



- Simulating BD detection and recovery algorithm on the LBE run data
- assuming BDR ~ (E/Enom)^10 (conservative)

- **The presented algorithm will detect BD clusters, will protect the RFQ and will automatically recover its performance.**

Conclusions

- A system to detect Breakdowns (BDs) and to interlock within concerned pulses is being implemented.
- On isolated BDs the interlock will be automatically cleared to continue beam operation.
- When BD clusters or a high BDR are observed the RFQ will be switched to an automatic Recovery.
  - 2 bins will be used as primary trigger (first implementation).
  - Beam will be inhibited during Recovery via RFQ BIS user_permit=FALSE.
  - 4 Recovery Levels will treat “normal” cases with different amplitude reduction factors and ramp-up functions.
  - 2 additional Levels will cover special cases.
- Refinement will be done during start-up for Run3.
- The implementation is ongoing and will be presented by Bartosz.