Crab cavity failures: lessons learnt from SPS beam tests and consequences for HL-LHC

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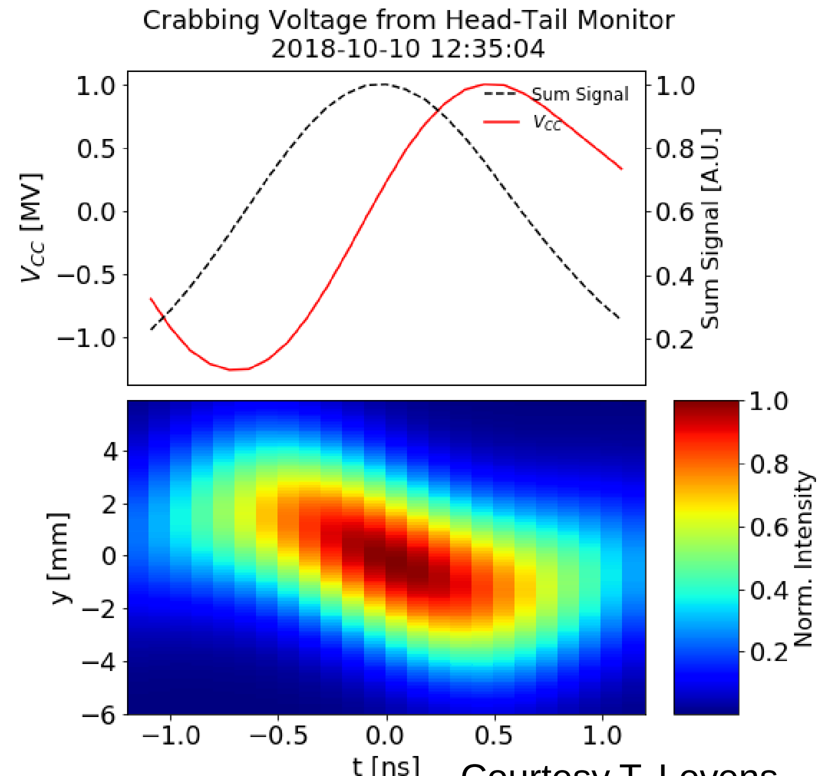
Crab Cavities in the SPS

Two vertical Crab Cavities (CC) installed in LSS6

Operational scenarios:

- Phased mode (crabbing outside the CC region)
- Counter-phased mode (transparent mode)



Courtesy T. Levens

Failure cases:

- Voltage drop (time constant 400 µs)
- Phase jump
- Detuning (continuous phase shift)

Normal operation

Maximum kick:

- 26 GeV: 1.12 σ/MV // 3.12 mm/MV
- 270 GeV: 0.35 σ/MV // 0.3 mm/MV

Aperture at 20.4 mm (7.3 σ at 26 GeV, 23.6 σ at 270 GeV)

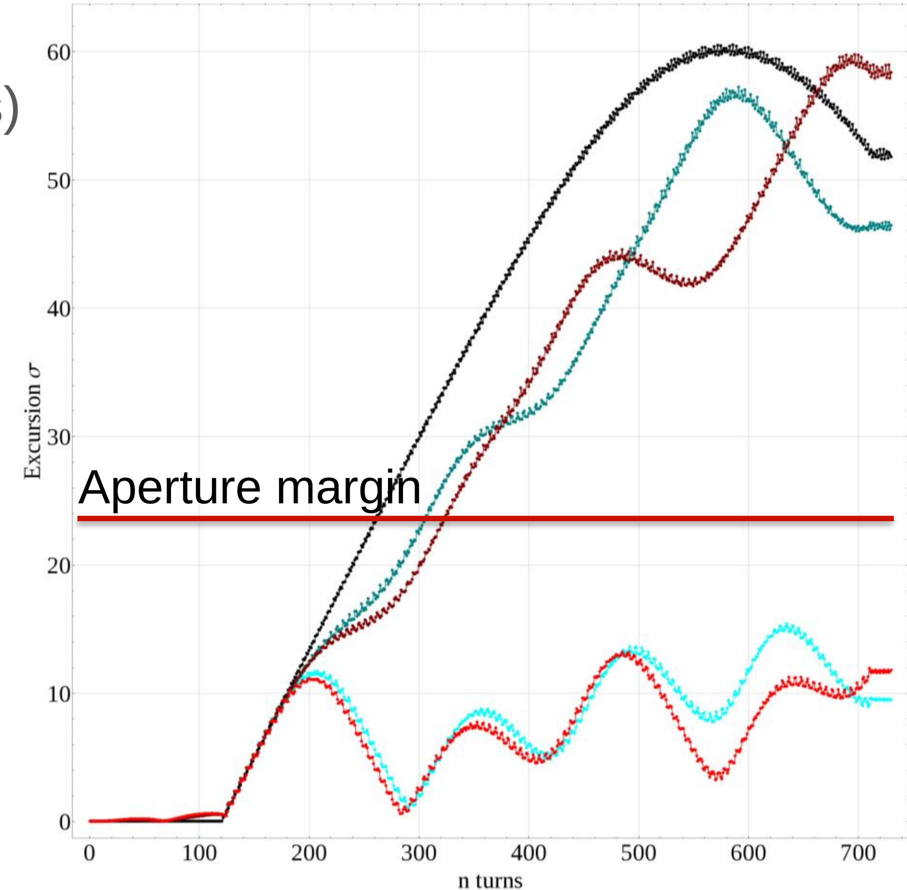
For ”slowly” ramping cavities, no significant losses expected. However, if fast voltage change occurs, oscillations up to ±7 mm/MV at 26 GeV are possible.

Detuning - resonance

- Worst case scenario (not observed in the SPS tests)
- A phase slip on resonance can lead to large orbit excursions within short times

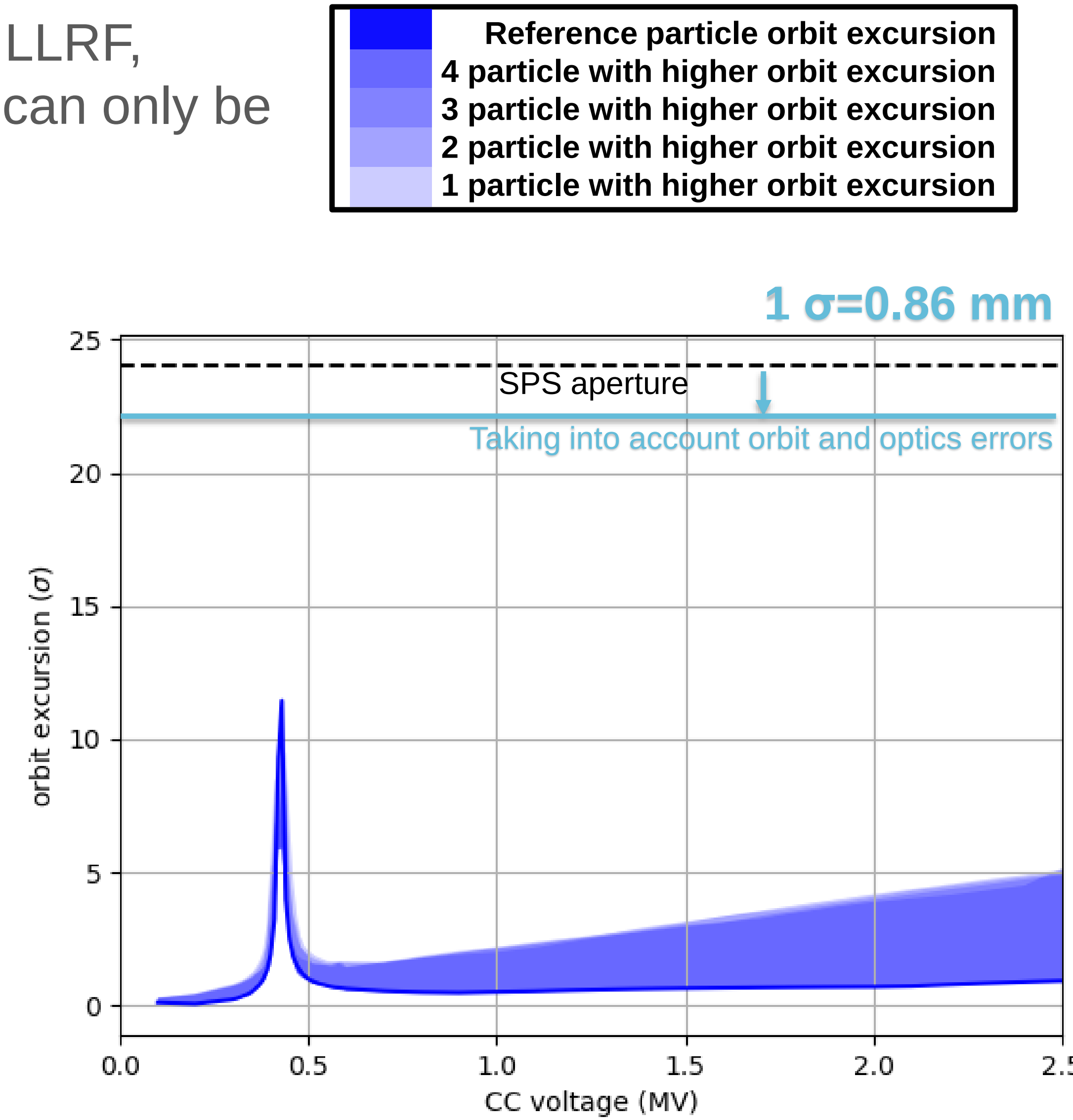
Example: 270 GeV with 2 MV total crabbing:

- Rise time excursion: ~100 turns
- Rise time losses: ~10 turns (~200 µs)



Detuning - resonance

If phase change is driven by CC LLRF, limited by power and resonance can only be reached for voltages < 0.5 MV



Up to ~12 σ excursion within **100 turns (2 ms)**

Rise time of losses is significantly shorter **(~10 turns)**

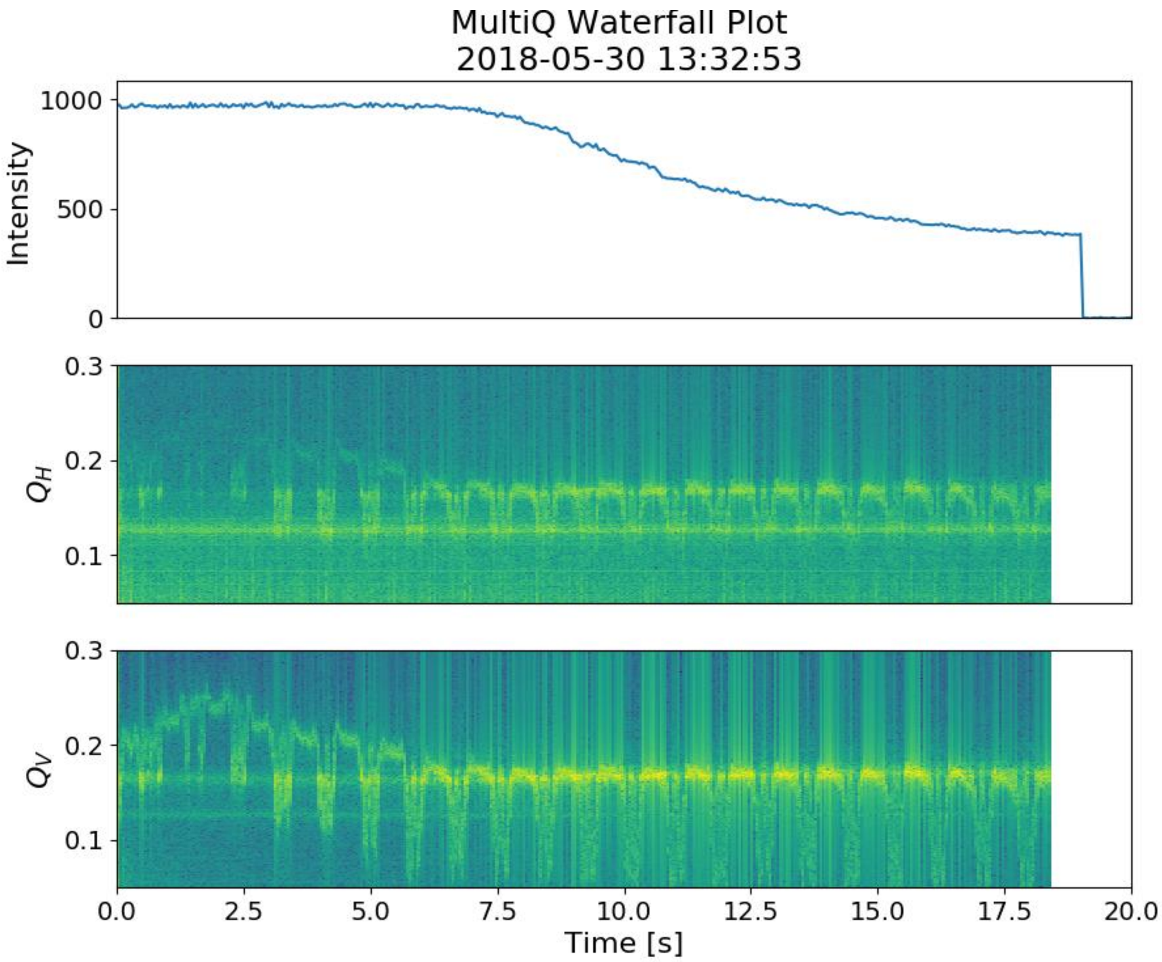
If CC detects failure and dumps, not a concern, but we can not rely on BLMs **(20 ms reaction time)**

Observed failures

- Two types of failures observed so far:
  - **Slow:** Beam lost over ~seconds due to CC tuner adjustment
  - **Fast:** Whole beam lost in **~1.3 ms** due to large voltage during ramp

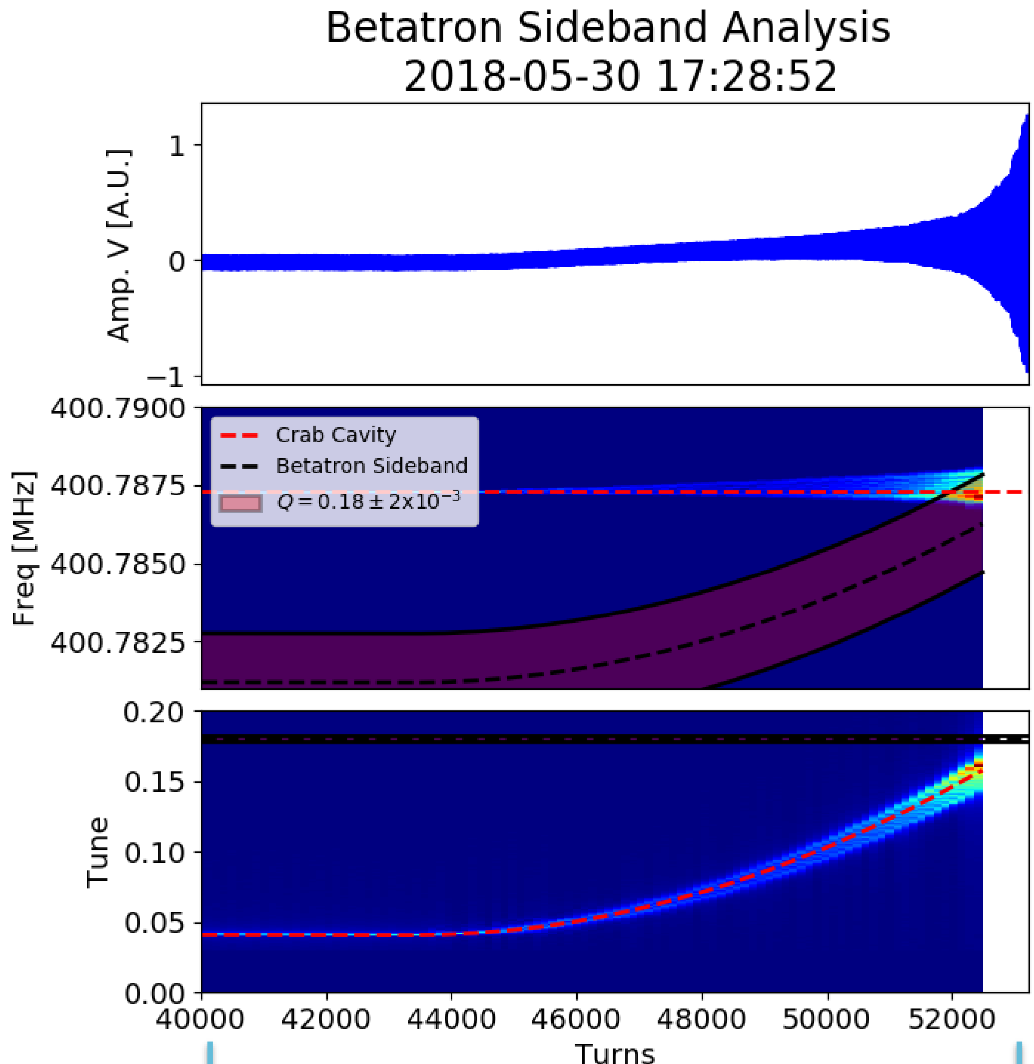
Slow loss failure

- Caused by CC1 tuner loop setup (<10 kV), crossing the vertical tune
- Slow failure, can be protected against by BLMs



Fast loss failure

- CC1 at 1 MV and 270 GeV frequency, with beam revolution frequency sweeping from 26 towards 270 GeV
- Effectively a change in the driving frequency of the beam by the CCs, leading to resonance at the tune (0.18); **full beam loss**.
- Lowering the voltage at start allowed proceeding through ramp.

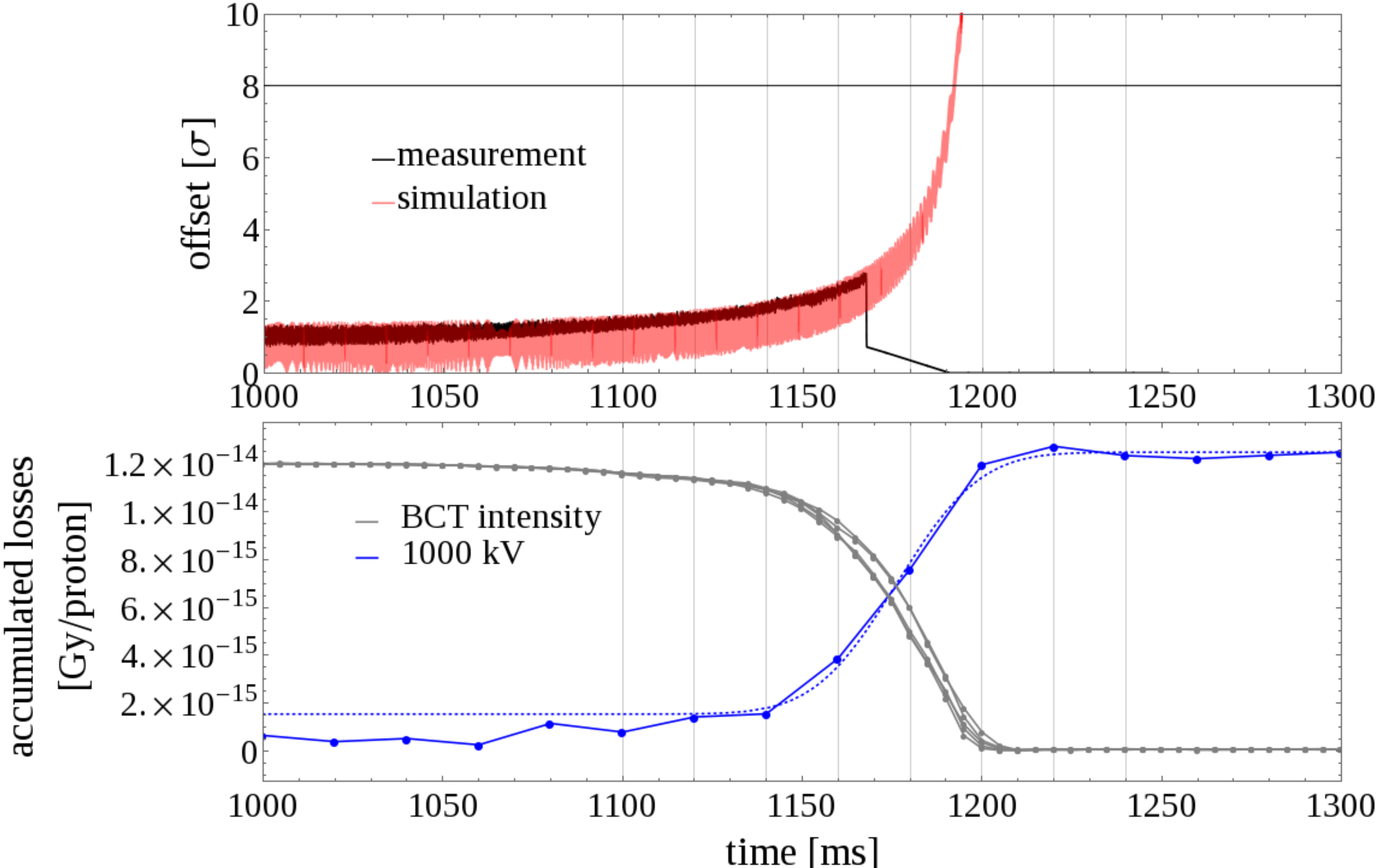


~280 ms

Courtesy L. Carver

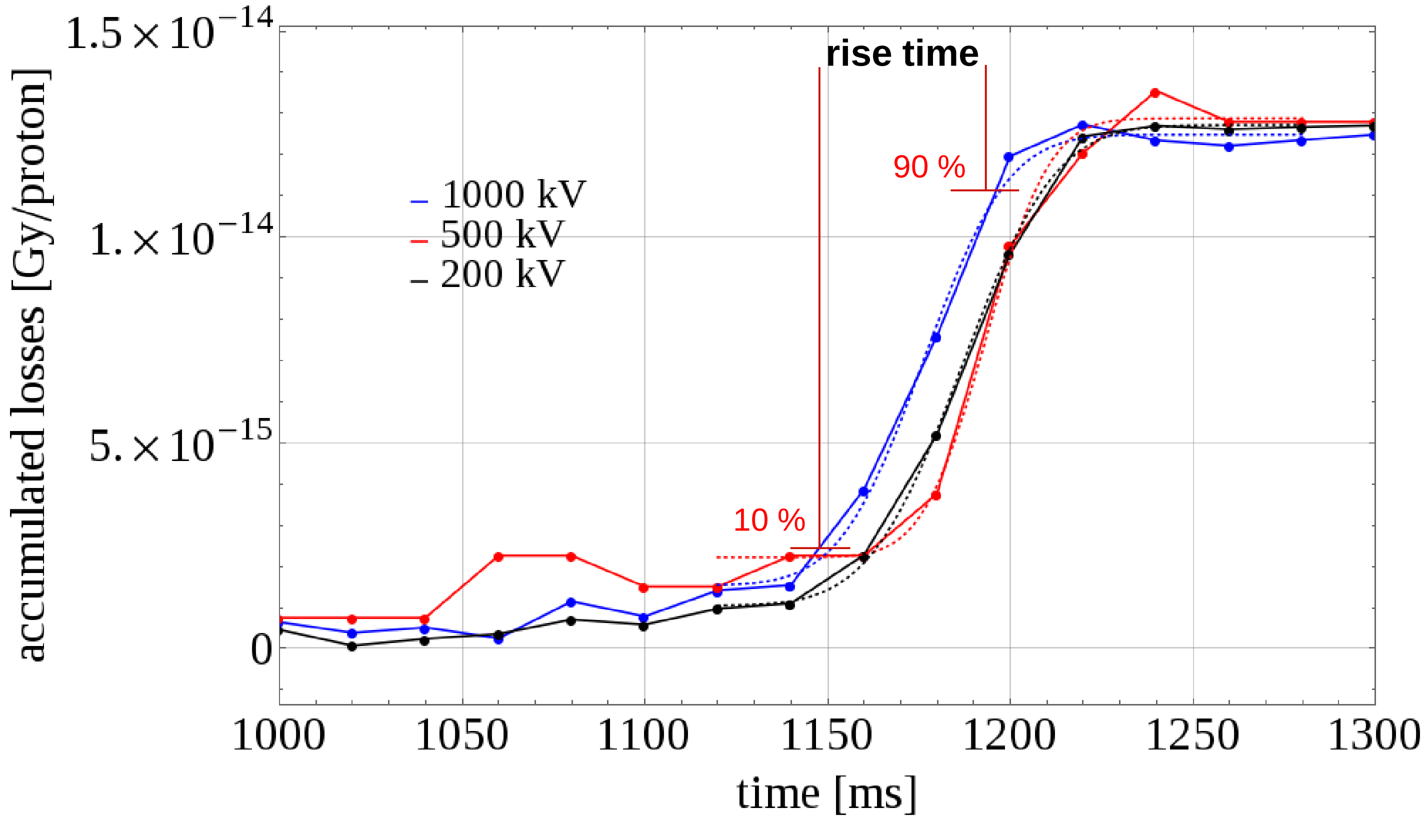
Fast loss failure – simulation

- Simulation of the ramp with 1 MV, using a linear model
  - Good agreement with measured bunch offset
- Loss rise time slower than rise time of offset due to tune spread



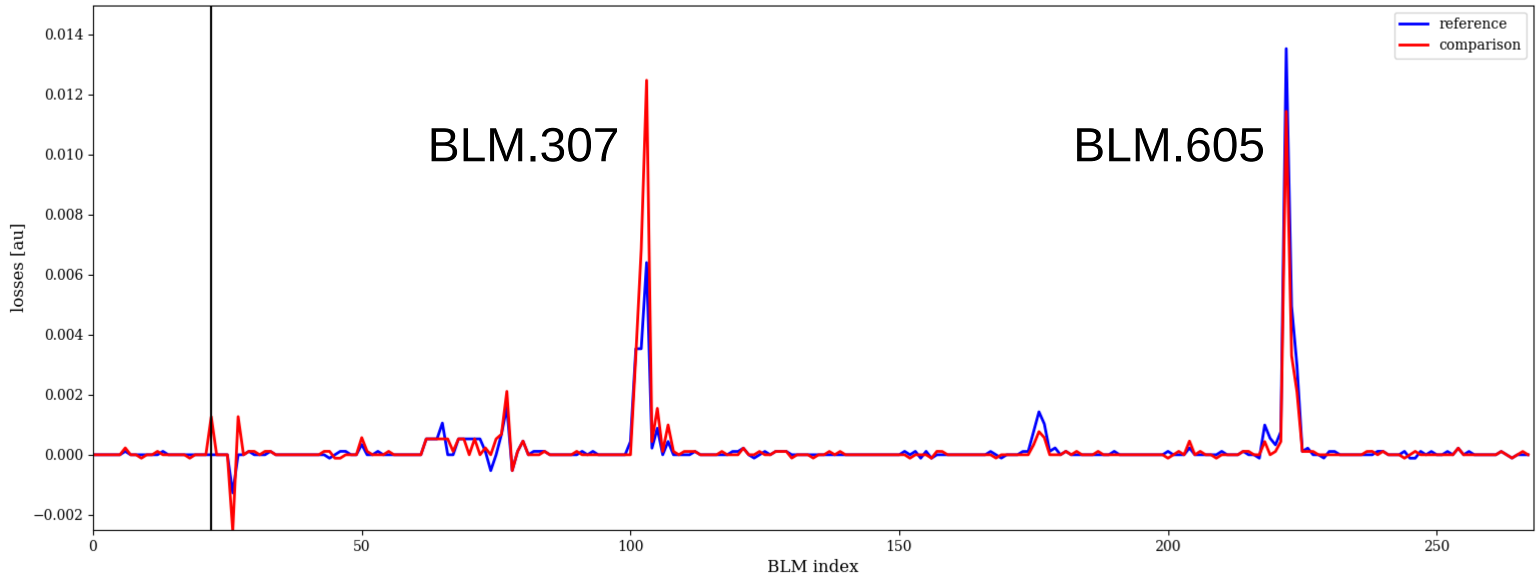
Rise time of losses

- Rise times at 26 GeV ~ 40 - 50 ms
  - Similar for 200, 500 and 1000 kV
- Reaction time of SPS BLM system, 20 ms
- Not measured yet at 270 GeV
  - More rigid beam -> slower rise of orbit offset
  - Less space charge-induced tune spread -> faster rise of losses



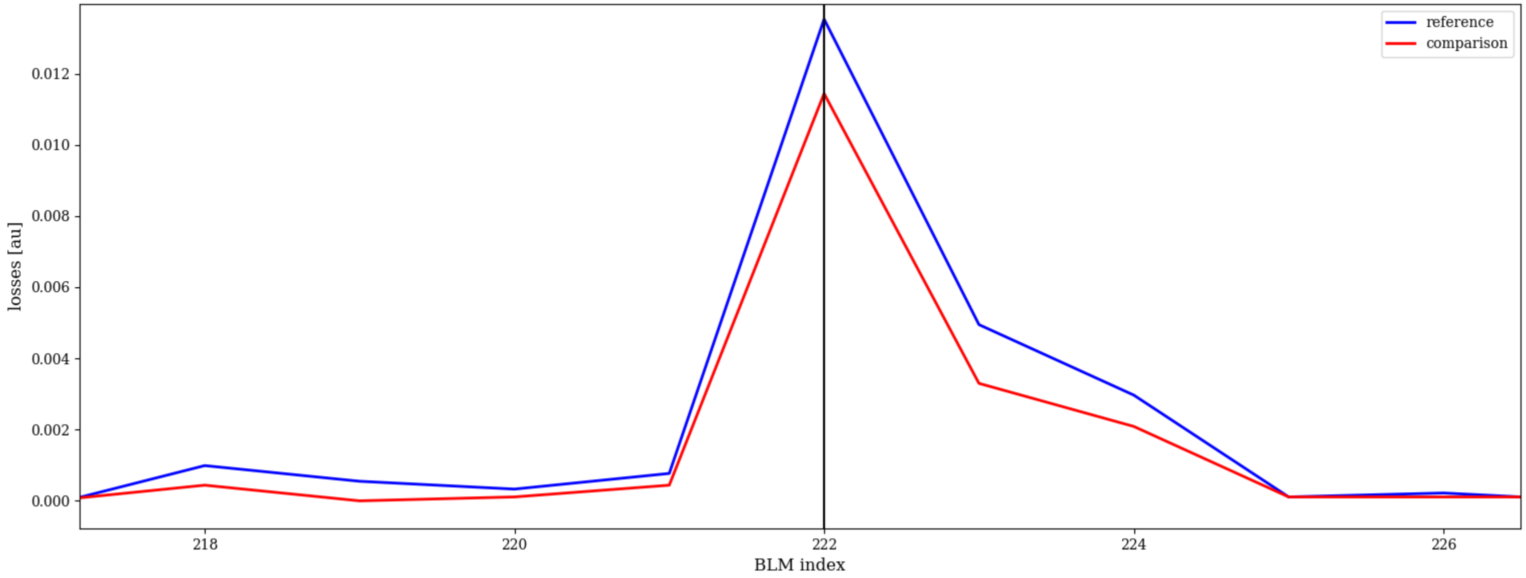
Loss locations

- No well-defined aperture in SPS
  - In LHC the TCPs are the bottlenecks
- Two locations saw losses consistently due to CCs for all failures (with no change to SPS orbit)



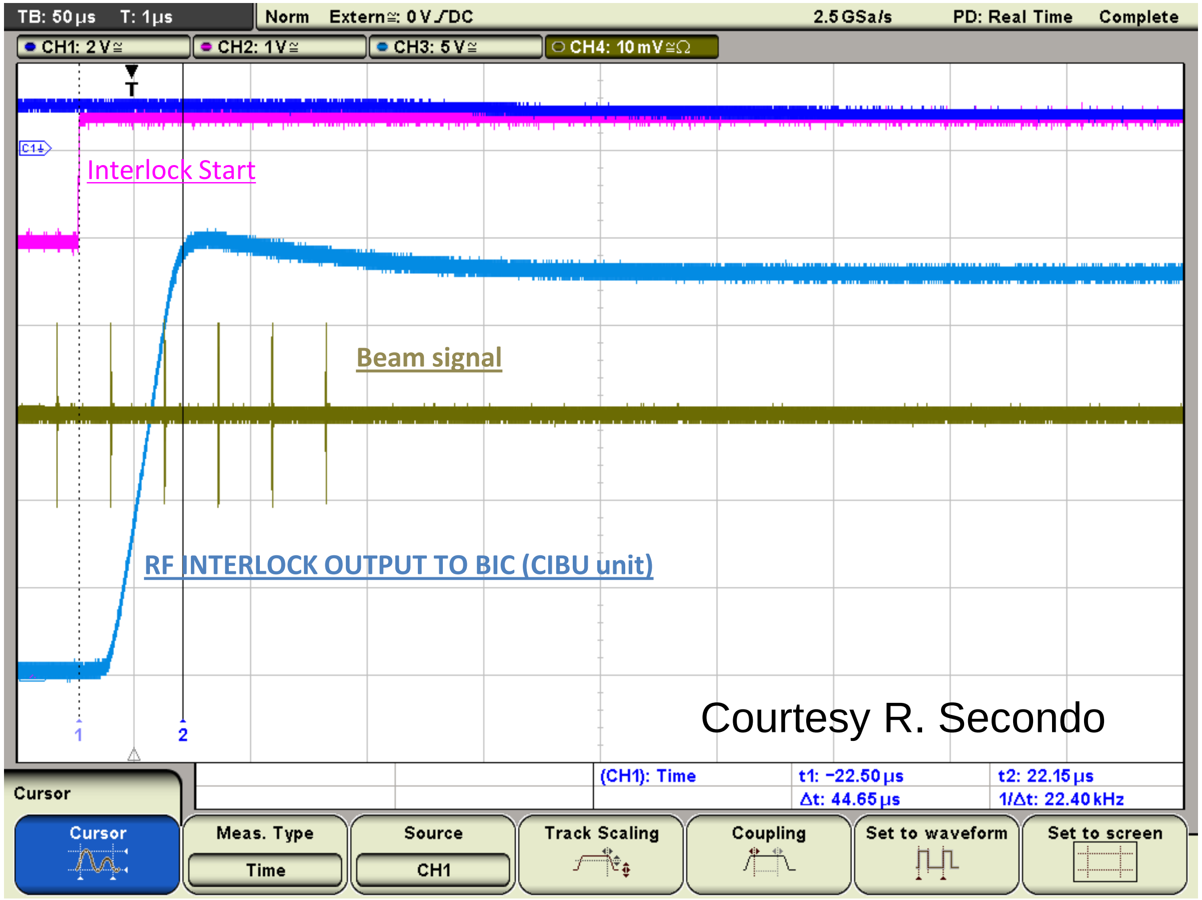
Loss locations - zoom

- A single BLM sees majority of losses, but SPS requires two adjacent BLMs above threshold to dump
- Must ensure that thresholds are set low enough at critical locations



Interlocks implemented and measured

- Fast RF interlock for phase difference between CC RF and SPS RF
- Successfully tested and dumped beam in ~60 µs



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Conclusions

Extra slides