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

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Acknowledgements: H. Bartosik L. Carver, T. Levens
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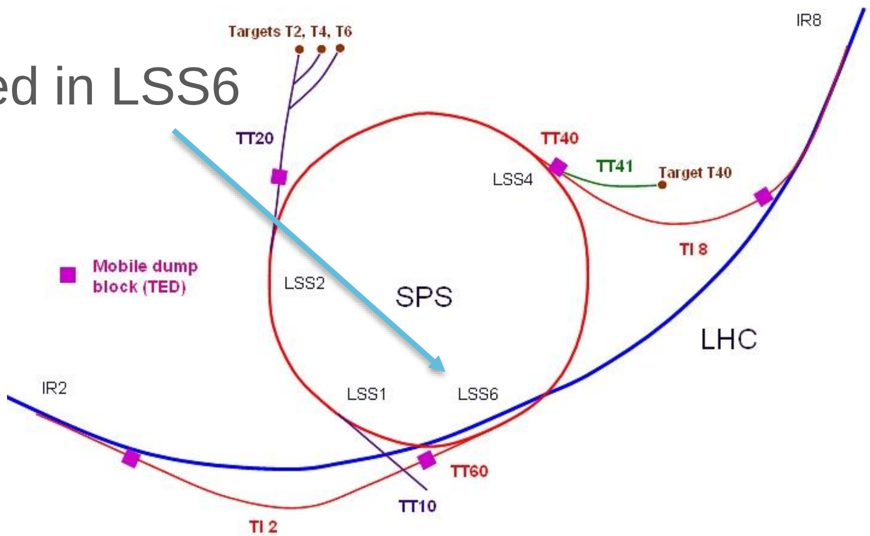
# Crab Cavities in the SPS

Two vertical Crab Cavities (CC) installed in LSS6

- Horizontal CCs to be tested in 2021




Operational scenarios:

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

Baseline failure cases:

- Voltage drop (not relevant for the SPS)
- Phase jump
- Detuning (continuous phase shift)
- Quenches (not observed, to be tested without beam)

# Normal operation in SPS

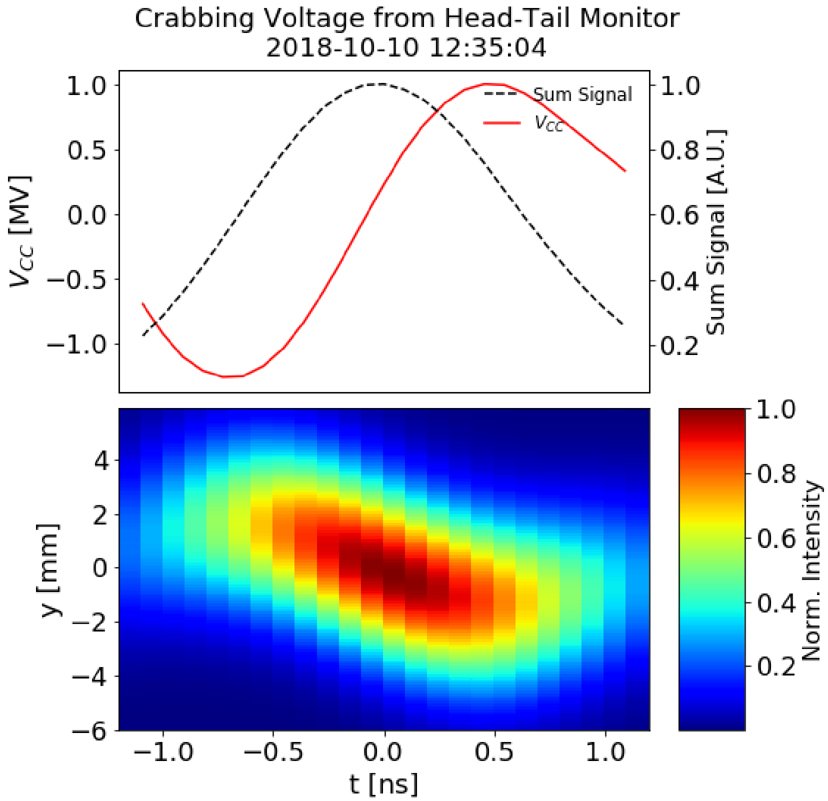
Maximum kick:

- 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

Oscillations up to ±7 mm/MV at 26 GeV are possible for fast voltage changes




Courtesy L. Carver, T. Levens

*values in mm at internal dump, TIDV, 86 m β, actual orbit not taken into account
εn 2.5 μm·rad

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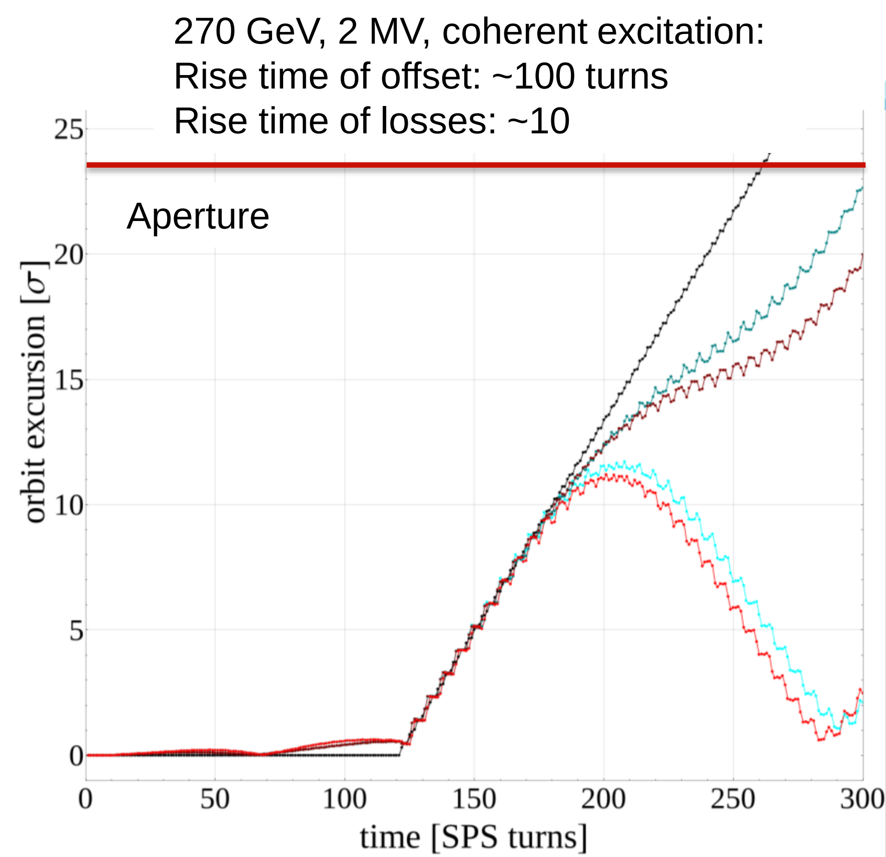
# CC Frequency errors

- Frequency errors in CCs can lead to significant kicks on beam
- Synchronization problems: If CCs not synchronized to main RF, there is a constant slip in the phase of the kick on the beam
- Change of the main RF during energy ramp: If CCs do not follow the main RF, loses synchronization, leading to phase slip
- LLRF driving the frequency/phase with main RF constant (e.g. operational error)

**→ if phase slip close to betatron tune, coherent excitation and very fast beam losses**

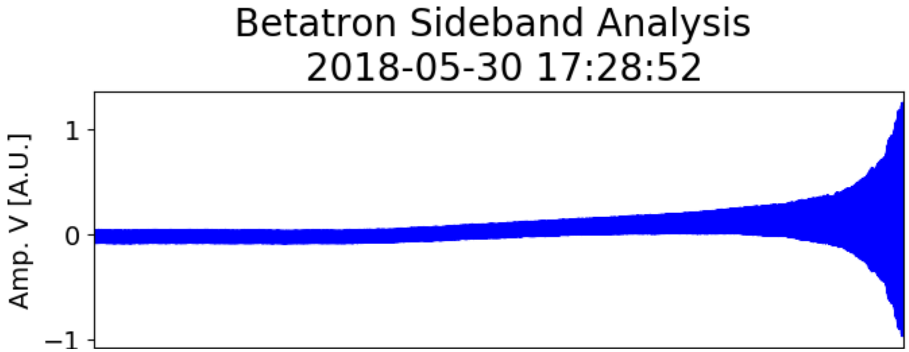



If LLRF detects failure and dumps, not a concern, but we can not rely on BLMs **(20 ms reaction time)**

→ RF frequency/phase interlock implemented and tested 5 Oct 2018

# Fast losses during ramp

- CC at 1 MV (total) and 270 GeV frequency, with beam revolution frequency sweeping from 26 towards 270 GeV
- **Full beam loss**
- Switching CCs on after reaching flat top allowed proceeding through ramp



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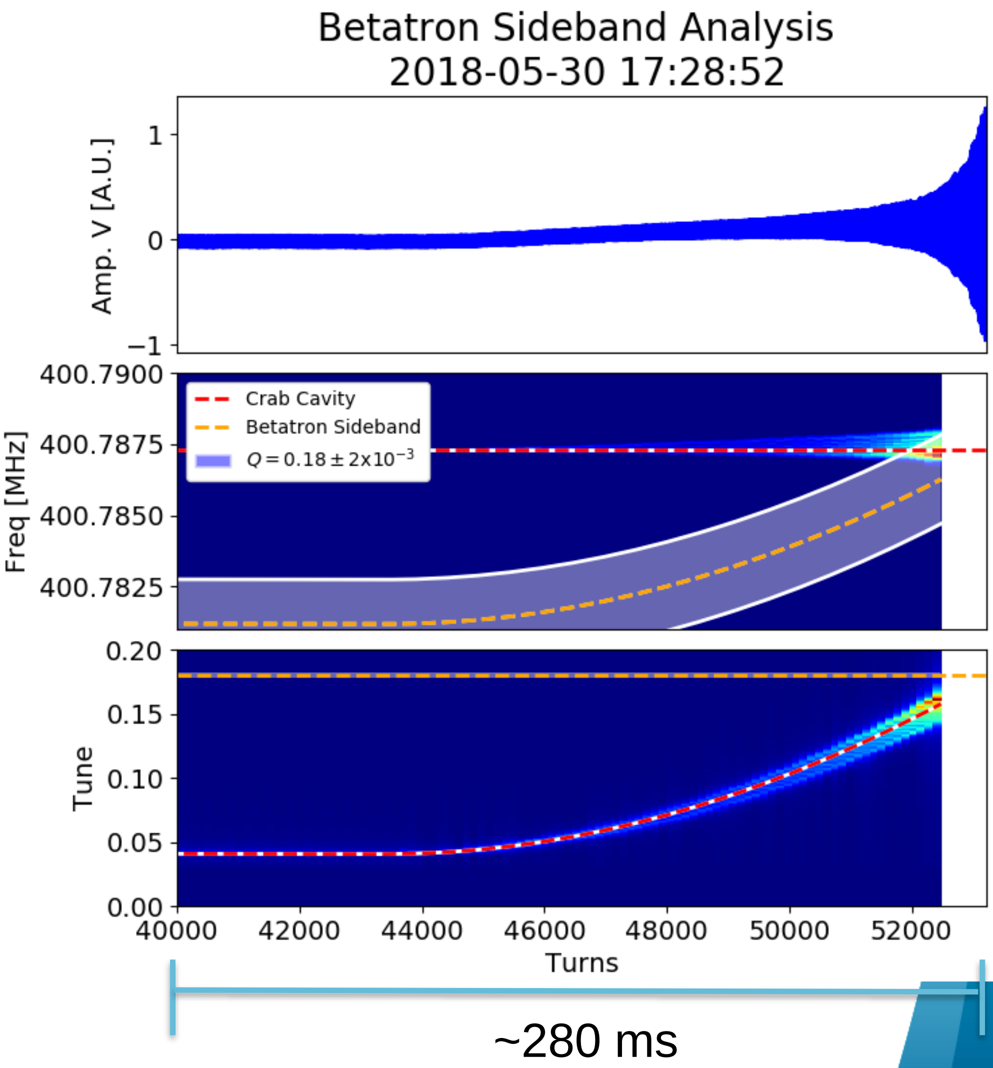
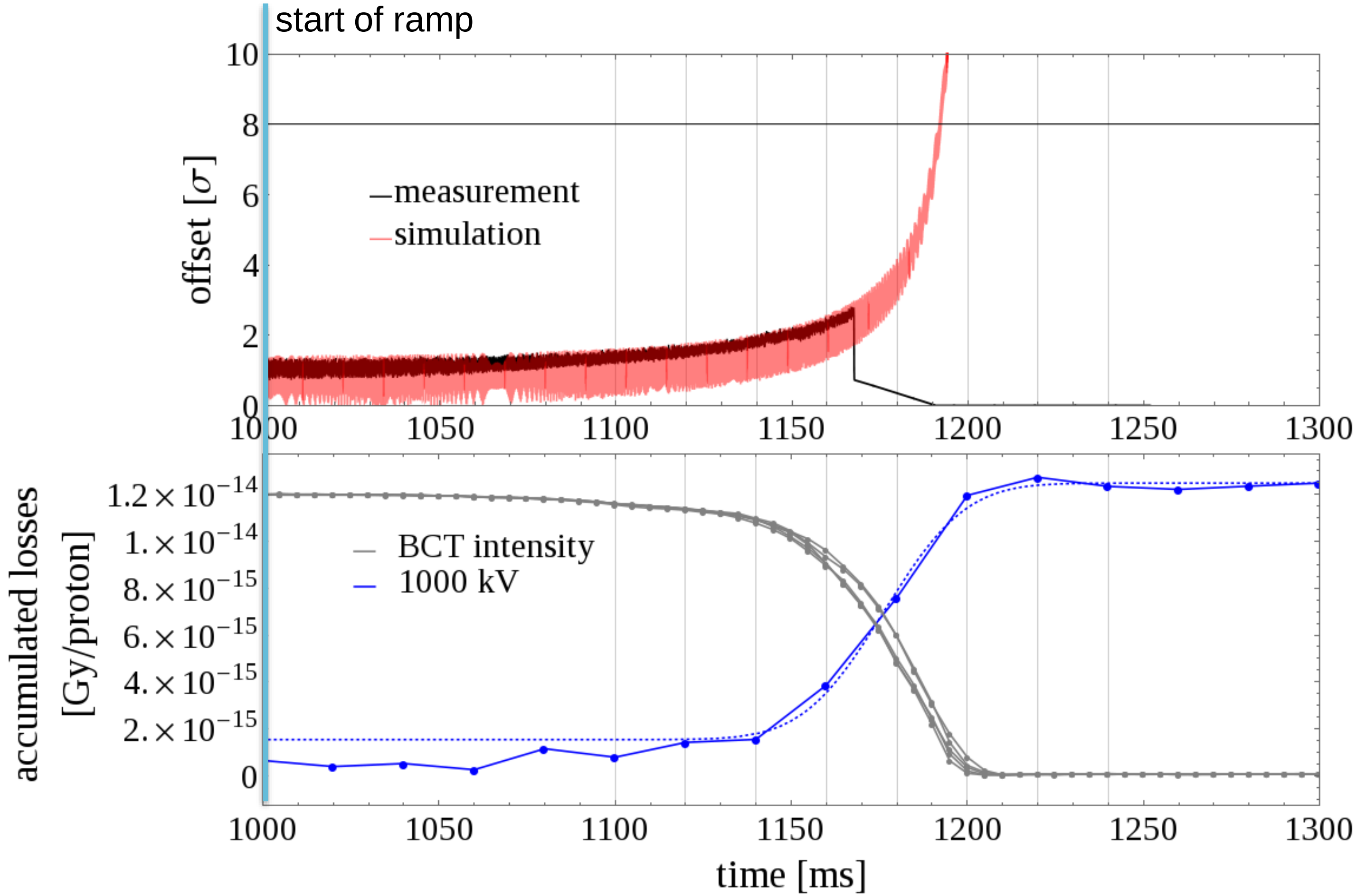



Courtesy L. Carver

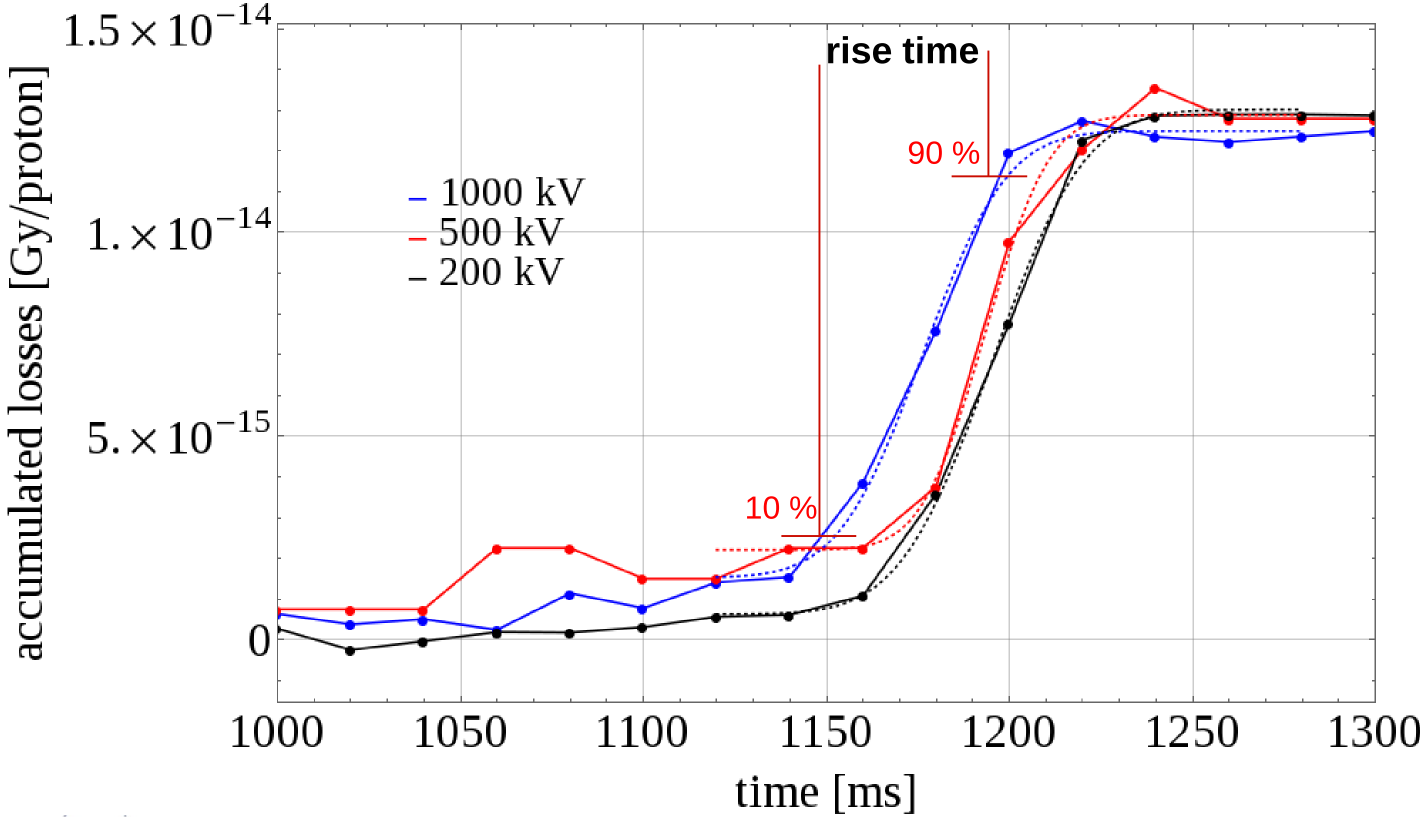
# Fast loss failure

- 26 GeV loss rise-times measured 09/28/2018 – 17:00-18:00
- Simulation of the ramp with 1 MV using simple linear tracking (transverse, longitudinal)
  - offset agrees with measurement
- Losses appear earlier than expected from offset due to betatron sideband / tune spread
  - → provides some ’protection’ (via the BLMs)



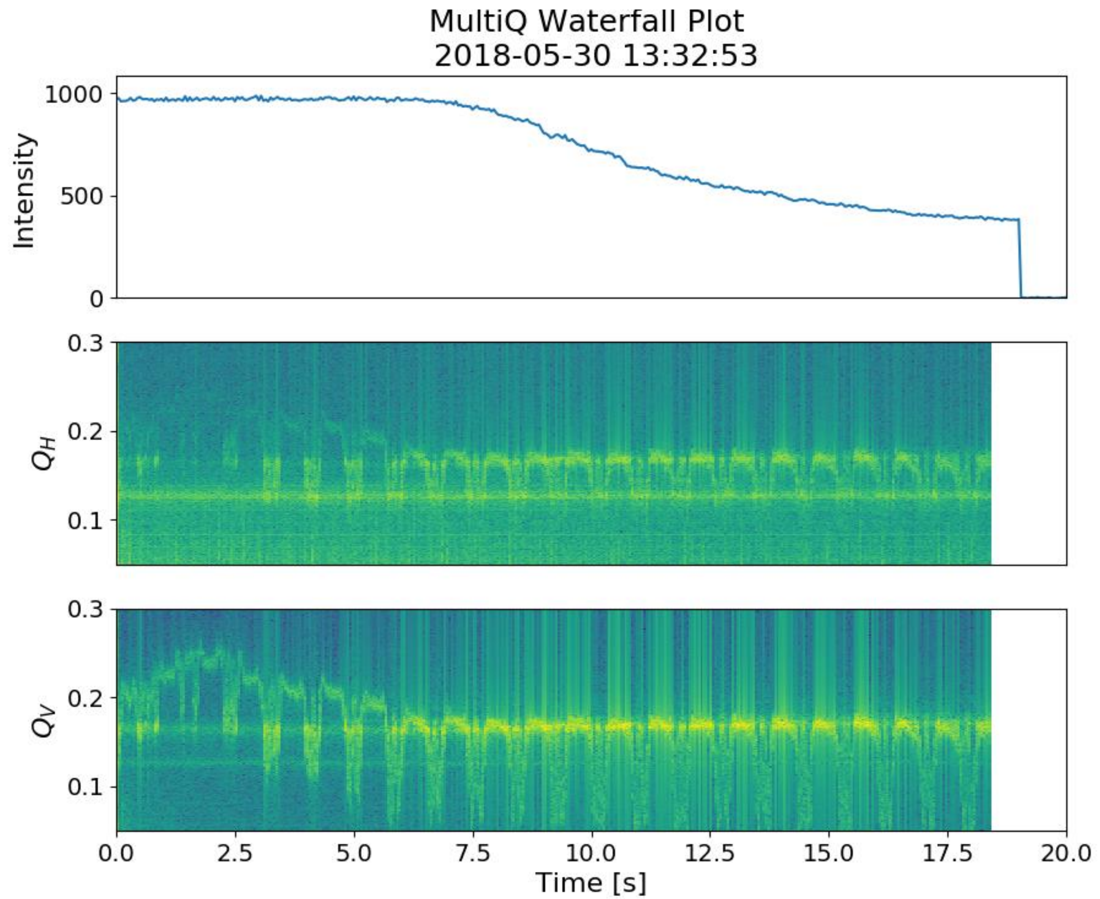
# Rise time of losses

- Rise times at 26 GeV ~50 ms (for high intensity beams, critical in **~10 ms**)
  - Similar for 200, 500 and 1000 kV
- Reaction time of SPS BLM system, 20 ms *(2 ms in LSS)*
- At higher energy:
  - More rigid beam -> slower rise of orbit offset
  - Less space charge-induced tune spread *(~0.08 at 26 GeV)* -> faster rise of losses
  - Measured during ramp 10/17/2018 – analysis pending



# Slow loss failure

- Caused by CC tuner loop setup* crossing the vertical tune
- Several tuner induced losses observed, e.g. on 10/10/2018
- Slow failure (> 0.5 s), can potentially be protected against by BLMs




* for more details, see presentation by P. Baudrenghien: indico.cern.ch/event/742082/contributions/3084929

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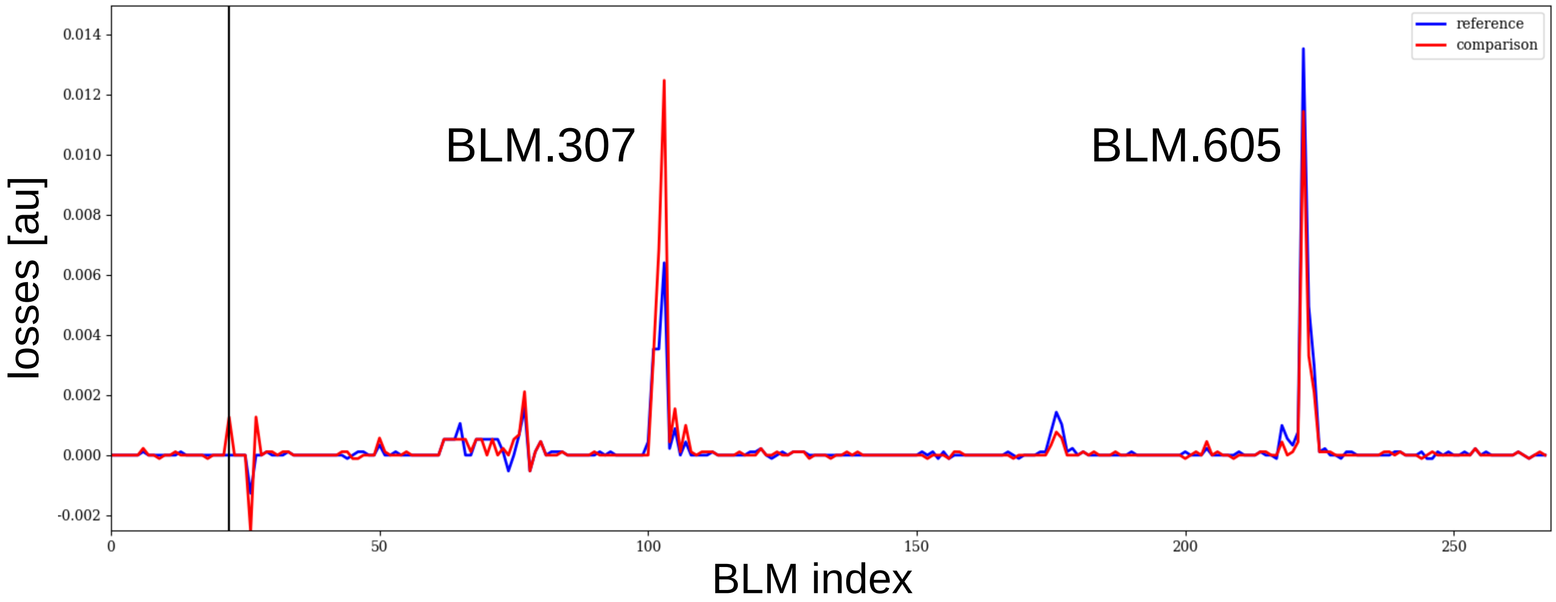
# Loss locations

- No well-defined aperture bottleneck in SPS, loss location depends on orbit and phase from CCs
  - In LHC the TCPs are the bottlenecks
- Two locations saw losses consistently due to CCs for all scenarios (with no change to SPS orbit)

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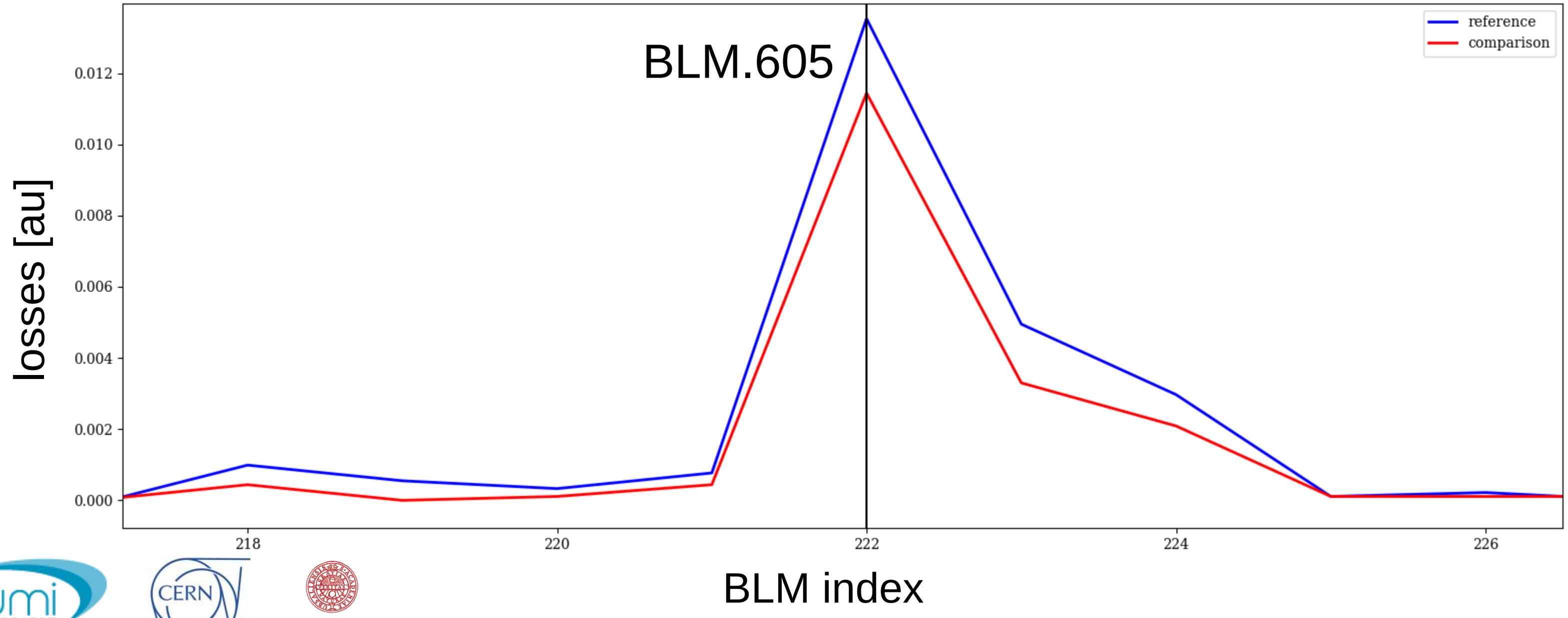
# Loss locations - zoom

- A single BLM sees majority of losses, but SPS requires two adjacent BLMs above threshold to dump (in the arcs)
  - In straight sections one is enough
- Ensuring thresholds are set low enough at critical locations successfully dumped the beam
  - Locations and thresholds to be validated for SPS Run III tests
  - Consider using a bump/horizontal collimators to define the location in Run III

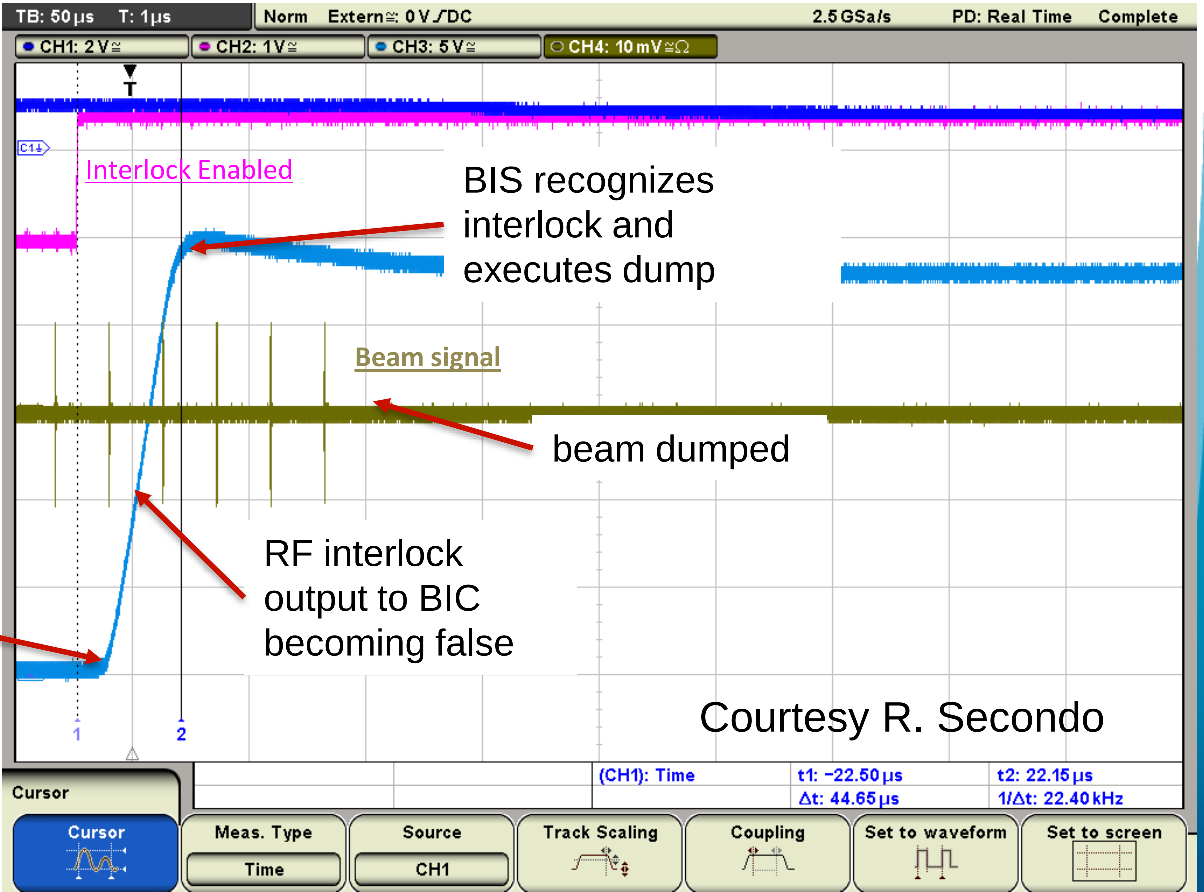


# Interlocks implemented and validated

- Fast RF interlock for phase difference between CC RF and SPS RF
- Successfully tested and dumped beam in **~100 µs** after phase difference above threshold

CC stability: ~1 kHz detuning over 12h, measured without feedback and no beam.
E. Yamakawa

phase difference above threshold,



# High Luminosity LHC

- Single CC failure, orbit offset at TCPs after 10 turns* (worst case):
  - Phase jump (60˚): **1.3 σ**
  - Detuning (60˚/turn) : **1.7 σ**

- SPS CCs perform as expected, no indications that failures might be slower than previously simulated
  - → **Fast RF interlock required**

- Tuner loop need be interlocked to not cross betatron resonance

- Frequency swing during ramp ~1 kHz *(in SPS: ~130 kHz)*
  - Impact on beam in case of non-synchronous CCs to be evaluated
  - No betatron resonance possible

* A. Santamaría García – Experiment and Machine Protection from Fast Losses caused by Crab Cavities in the High Luminosity LHC

# Conclusions

- CC have been tested successfully and safely even high intensities in the SPS, due to
  - implementation of an additional fast interlock
  - careful adjustment of BLM thresholds
  - detailed operational procedures
  - vigilant operation to mitigate risks
- Observed very fast as well as slow losses
  - Fast/significant losses only observed with safe beams
- For SPS CC operations in Run III, existing interlocks need to further mature

- SPS tests provide important input for interlock strategy and loss simulations in HL-LHC:
  - Need define max phase/frequency shift that can be tolerated
  - Need ensure RF synchronization or low voltage during ramp
    - No risk of betatron resonance, but HL loss margins much smaller
  - Fast RF interlock vital
  - Interlock on tuner loop