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
Many thanks to SPS OP and Crab Cavity team

8th Annual HL-LHC Collaboration Meeting – 2018-10-18, CERN
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: $1.12 \, \sigma$/MV // $3.12 \, \text{mm}^*/\text{MV}$
- 270 GeV: $0.35 \, \sigma$/MV // $0.3 \, \text{mm}^*/\text{MV}$

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

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

Courtesy L. Carver, T. Levens
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
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

~280 ms

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 \(2 \text{ ms in LSS}\)
- At higher energy:
  - More rigid beam -> slower rise of orbit offset
  - Less space charge-induced tune spread \(~0.08 \text{ at 26 GeV}\) -> faster rise of losses
  - Measured during ramp 10/17/2018 – analysis pending

![Graph showing rise time and accumulated losses](image)
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
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)
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 \(~100 \mu s\) after phase difference above threshold

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

phase difference above threshold,

RF interlock output to BIC becoming false

BIS recognizes interlock and executes dump

Beam signal

beam dumped

Courtesy R. Secondo
High Luminosity LHC

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

- 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 \( \sim 1 \text{ kHz} \) (in SPS: \( \sim 130 \text{ kHz} \))
  - 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