Conclusion on Machine Protection tests with Crab Cavities in the SPS

J. Uythoven, D. Wollmann

With input from:

H. Bartosik, T. Bohl, A. Butterworth, R. Calaga L.R. Carver, V. Kain, T.E. Levens, B. Lindstrom, G. Papotti, R. Secondo, M. Valette, G. Vandoni, J. Wenninger and M. Zerlauth

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Outline

- Introduction: crab cavities and machine protection
- Crab cavities in SPS in 2018
- Observed slow and fast losses
- Implementation and validation of HW phase interlock in the SPS
- SPS interlock requirements for the future tests
- Interlock requirements for HL-LHC
- Conclusions

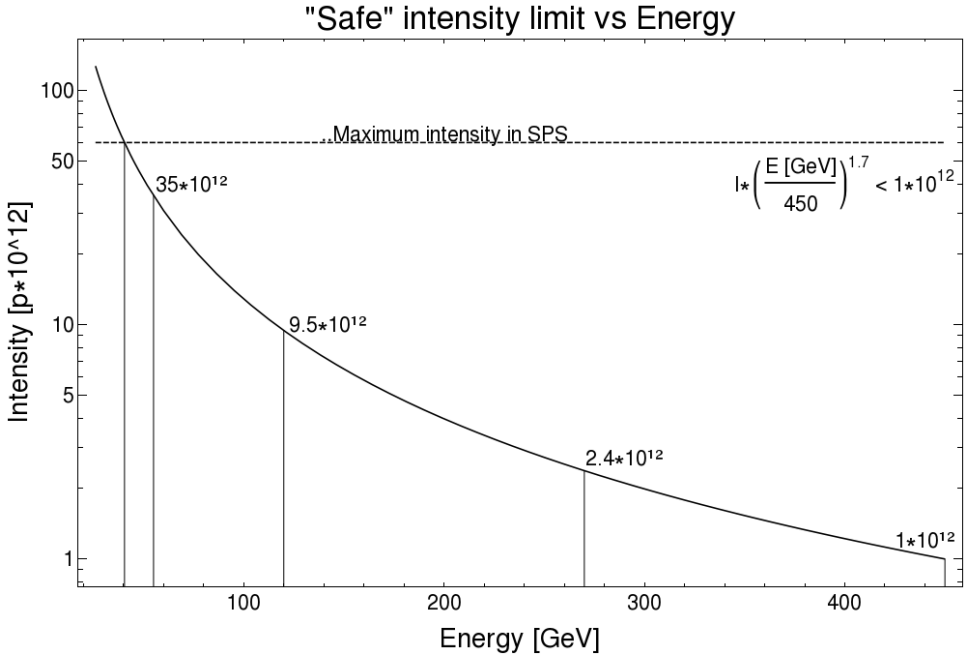
Introduction: crab cavities and machine protection

- Crab cavities can cause **fast transverse kicks** on the circulating beam leading to critical beam losses in the aperture within **tens of microseconds** in case of failures
- **Criticality of failures estimated** for HL-LHC by studying ‘corner cases’ (see A. Santamaria Garcia’s PhD thesis):
  - **Voltage drop**: sudden drop of crab cavity voltage
  - **Phase jump**: sudden change of crab cavity phase
  - **Detuning**: continuous change of crab cavity phase
- Criticality of **combined failures** has been studied (see IPAC18 paper by B. Lindstrom et al.), adding Beam-Beam kick.
- **Criticality** of crab cavity failures has also been studied **for the SPS**
- **First machine protection** tests with crab cavities and circulating hadron beam were **performed** in 2018 in the SPS

Crab cavity in SPS 2018 - Overview

- Two double quarter wave cavities in one cryo-module
  - Max 3.4 MV but only used up to ~1 MV in 2018
  - Operated mainly in single cavity mode
  - Maximum vertical kick:
    - @26 GeV: 1.12 σ/MV // 3.12 mm/MV
    - @270 GeV: 0.35 σ/MV // 0.3 mm/MV
  - SPS vert. aperture limited to 20.4 mm:
    - 7.3 σ @ 26 GeV,
    - 23.6 σ @ 270 GeV
  - CC frequency cannot follow change of SPS accelerating RF frequency during ramp (delta f = 130 kHz from 26 GeV to 270 GeV within 6 s)
- Interlock matrix to interlock table position, vacuum, RF (via PLC - slow) etc. well established and tested
- CC failures:
  - Voltage drop → not critical in SPS due to available aperture
  - Phase jump → not critical in SPS due to available aperture
  - Detuning → critical with high intensity beam, can lead to resonant excitation

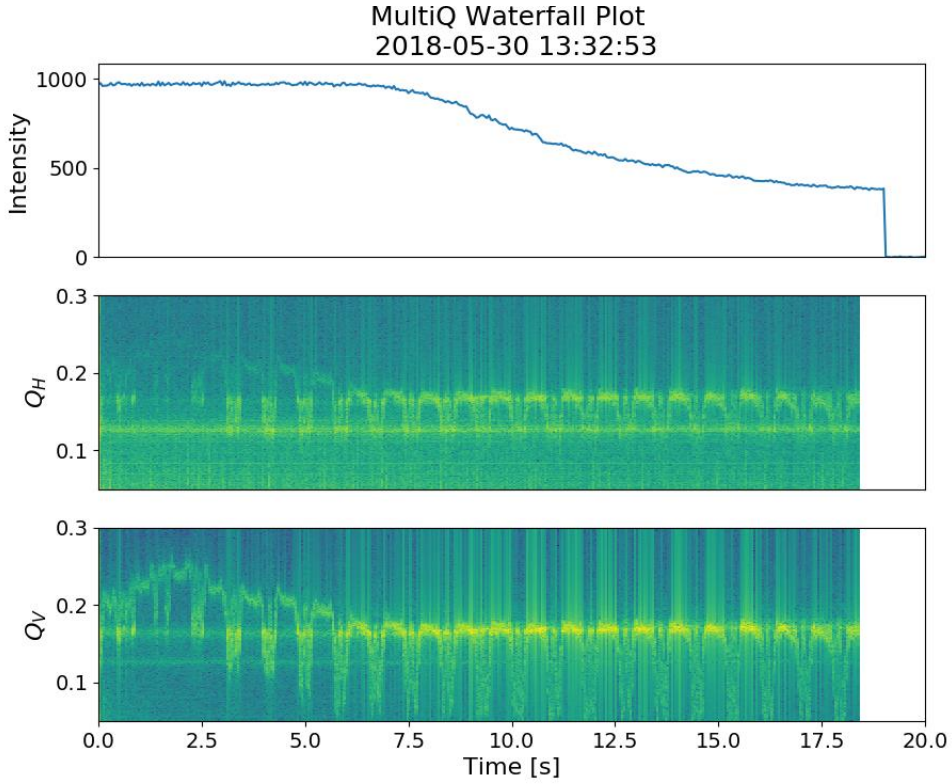
Safe intensity limits for Crab Cavity MDs in SPS



- Reaction time of SPS ring beam loss monitors too slow (20 ms) to interlock on fast critical beam losses
- Allowed intensity limits for crab cavity MDs without additional fast interlock (*including factor 10 safety margin*) :
  - @ **26 GeV: < 6 x 10^{12}** protons
  - @ **270 GeV: < 2.4 x 10^{11}** protons

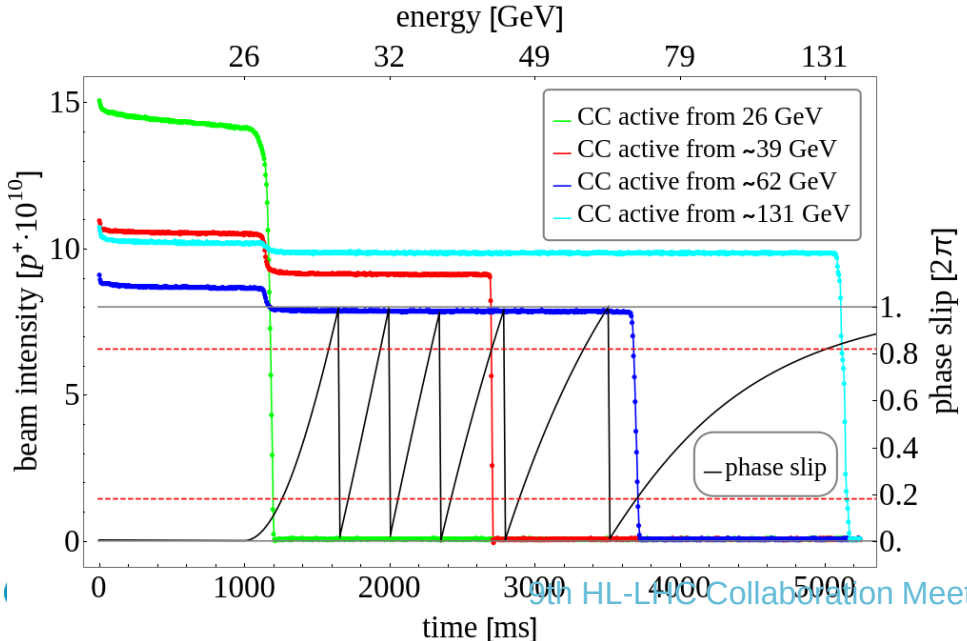
Observed slow losses

- Loss of significant parts of the beam within 0.5 to 19 sec
- Caused by issues with the tuner loop
  - < 10 kV applied on beam with varying frequencies
  - Crossing of vertical betatron tune
- Not critical for test setup as SPS BLMs can provide sufficient protection

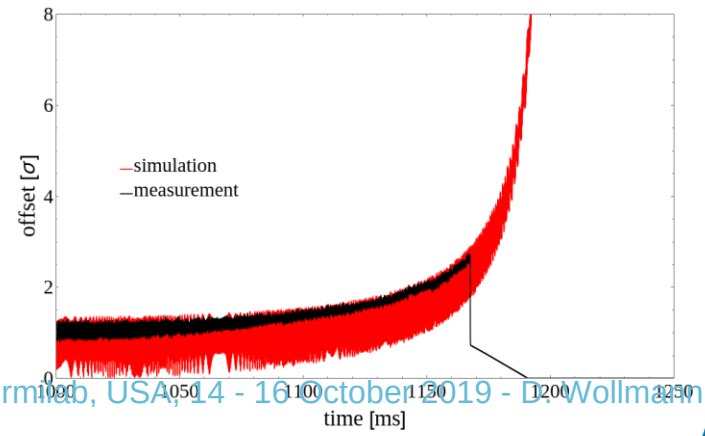


Observed fast losses

- 90 % of beam lost within 15 – 60 ms, due to resonant excitation of the beam by CC frequency crossing the betatron tune during ramp of main SPS RF
- Loss behaviour reproduced by simulations
- Loss speed affected by
  - Beam energy: slower losses at higher beam energies
  - Space charge induced tune depression: faster losses with reduced tune depression at higher beam energies; beneficial effect stronger when tune approached from below
- Could cause critical losses in case of unsafe beam → fast HW interlock of frequency / phase required

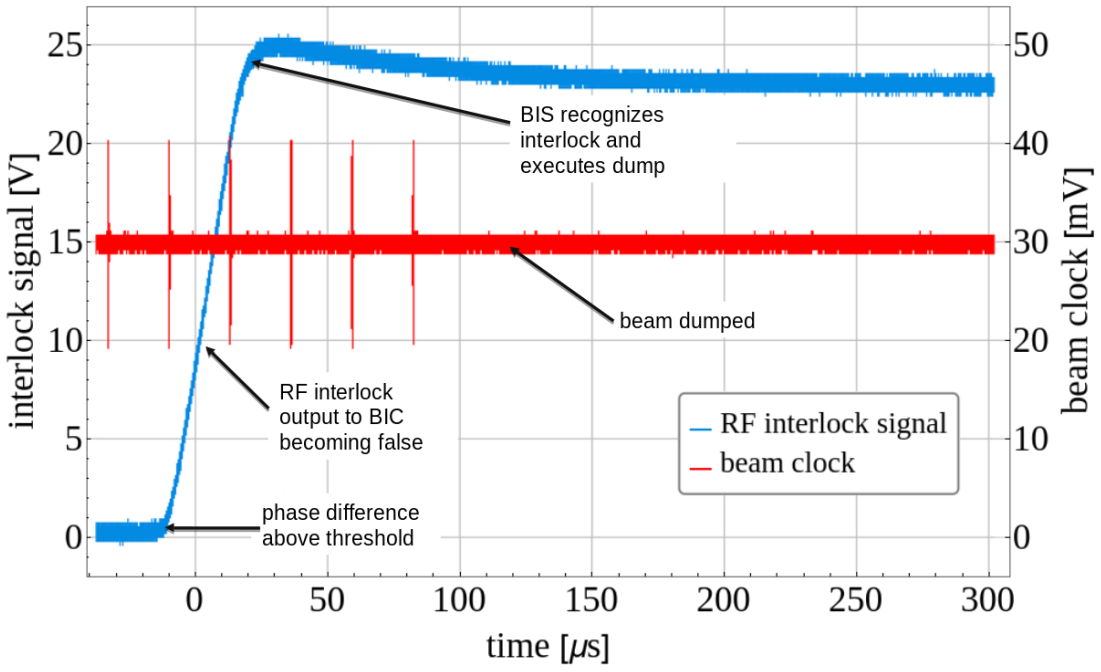


energy [GeV]	26	39	62	131
decay time [ms]	40	15	40	60



Fast phase interlock

- Hardware interlock of phase between SPS main RF and crab cavity RF was implemented and successfully tested in the SPS
- Beam was dumped five turns (< 120 us) after phase difference reached interlock threshold



Outlook to future SPS test, 2021 and beyond

- Crab cavity tests (setup of HW, RF controls etc.) with safe intensity can be performed without additional interlocks besides the existing interlock matrix
- Operation with high intensity beams requires:
  - Validated fast HW interlock of phase between main SPS RF and CC RF
    - Interlocking phase changes > +- 15 degree (for Q_h=0.13 and Q_v=0.18)
  - Ensuring that CC voltage < 50 kV before matching between main SPS RF and CC RF frequency:
    - Via HW interlock (strongly preferred) OR
    - Procedure/automatic sequence, which has been validated with low intensity: note that any change to the validated sequences requires a new validation

Requirements for HL-LHC

- Based on simulation results crab cavities can cause critical losses within less than ten LHC turns (< 1 ms)
- Dedicated hardware interlocks are required to interlock on
  - Phase drifts in one or multiple crab cavities (like tested in the SPS 2018)
    - This covers the interlocking against any frequency change
  - Sudden changes of voltage in one or multiple crab cavities (requested for SPS 2021)
    - Also needed for switching on cavities
- Correlated failures of multiple crab cavities need to be avoided, as they can lead to critical losses before a beam dump can be issued
  - Have independent cc systems, avoiding common hardware failures as much as possible

Conclusion

- For the first time machine protection experiments have been performed with crab cavities and low intensity proton beams
- Slow and fast losses were observed – loss scenarios seem to be understood
- Observed failures require HW interlock of crab cavity phase for the use with unsafe beam intensities in the SPS, also for 2021
- Voltage interlock is recommended for future SPS tests and to validate for future HL-LHC
- HL-LHC requires dedicated interlocks of voltage and phase.
- Common mode failures of multiple crab cavities need to be avoided by separating systems

References

- B. Lindstrom et al., ”Machine protection experience from beam tests with crab cavity prototypes in the CERN PS", Institute of Physics Journal of Physics: IPAC19
- A. Santamaria Garcia ”Experiment and Machine Protection from Fast Losses caused by Crab Cavities in the High Luminosity LHC", CERN thesis 2018
- B. Lindstrom et al., "Crab Cavity Failures combined with a Loss of the Beam-Beam Kick in the HL-LHC", Proceedings IPAC 2018.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