H. TIMKO, CERN BE-RF

BEAM INSTABILITIES AFTER INJECTION TO THE LHC

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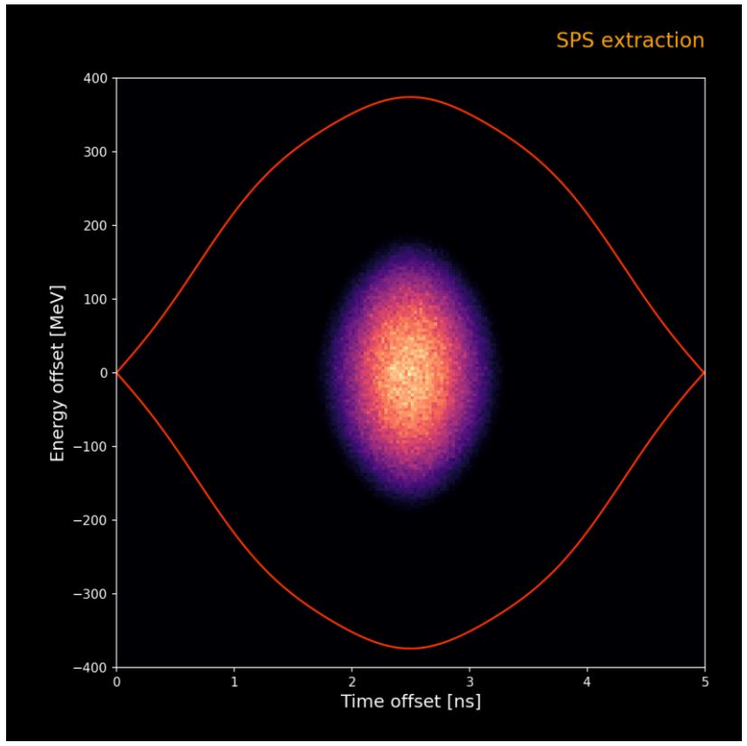
OUTLINE

INSTABILITIES AT LHC INJECTION

- MEASUREMENTS
- MECHANISM
- FIRST SIMULATION SCANS

NOMINAL INJECTION SCHEME

- Bunch parameters
  - 1.15×10^{11} ppb, 1.6 ns (4-sigma equivalent FWHM) at injection
- Extraction from the SPS bucket
  - 7 MV at 200 MHz and 1 MV at 800 MHz
- Injection into the LHC bucket
  - 6 MV at 400 MHz
  - 'Matched' would be ~2MV
  - Increased voltage to avoid losses

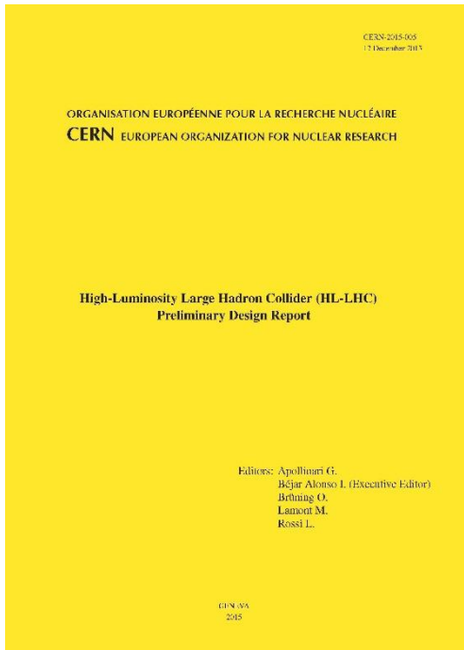


Simulated bunch
at SPS extraction

LIU & HL-LHC

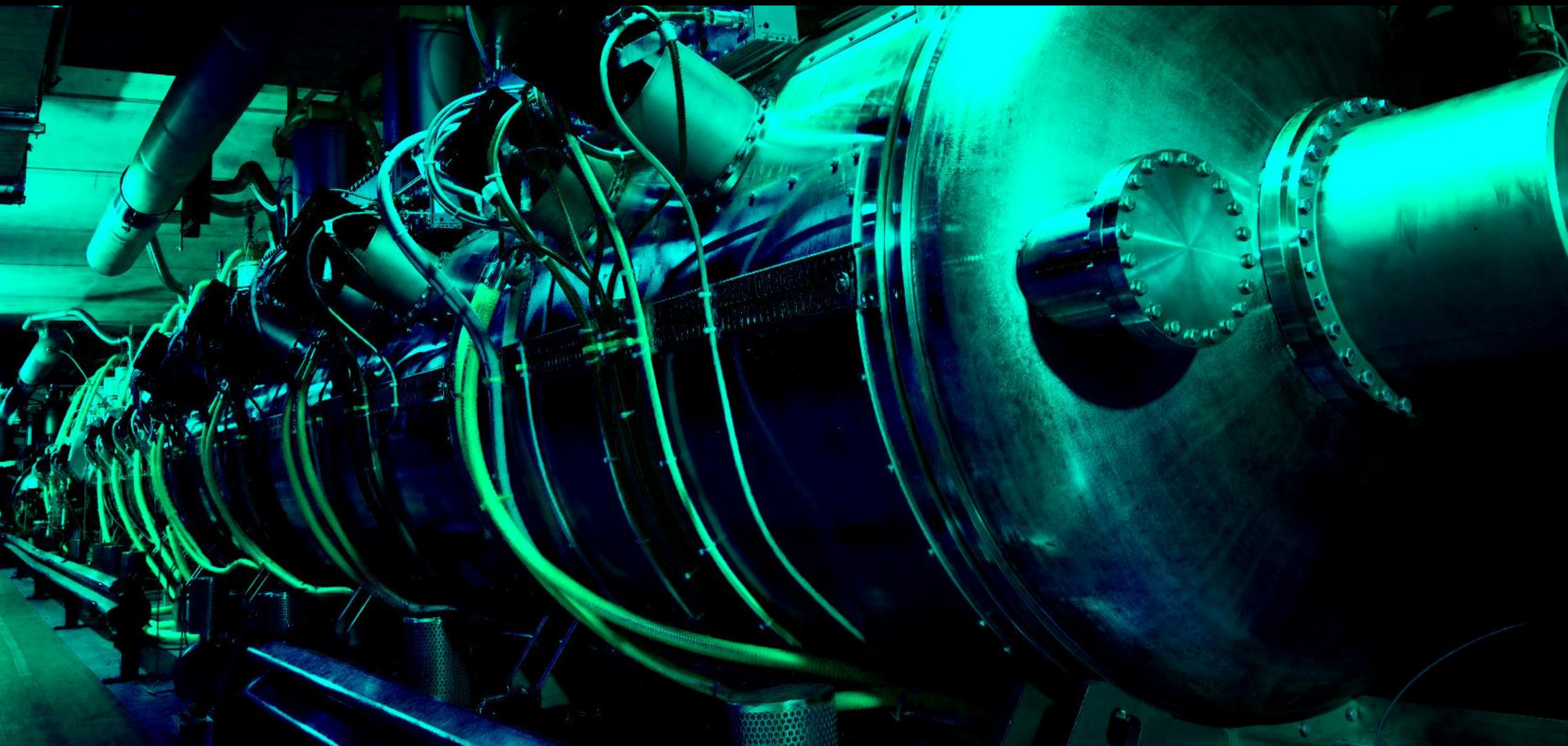
- LHC Injectors Upgrade (LIU): 2019-2020
  - Recommissioning: 2021
    - RF upgrade in SPS; up to 10 MV will be available
  - Gradual intensity increase: 2022-2023
    - Expect to increase also the intensity in the LHC

- High-luminosity LHC (HL-LHC): 2024-2025
  - Recommissioning: 2026
  - Targeted intensity: 2.3×10^{11} ppb at LHC injection



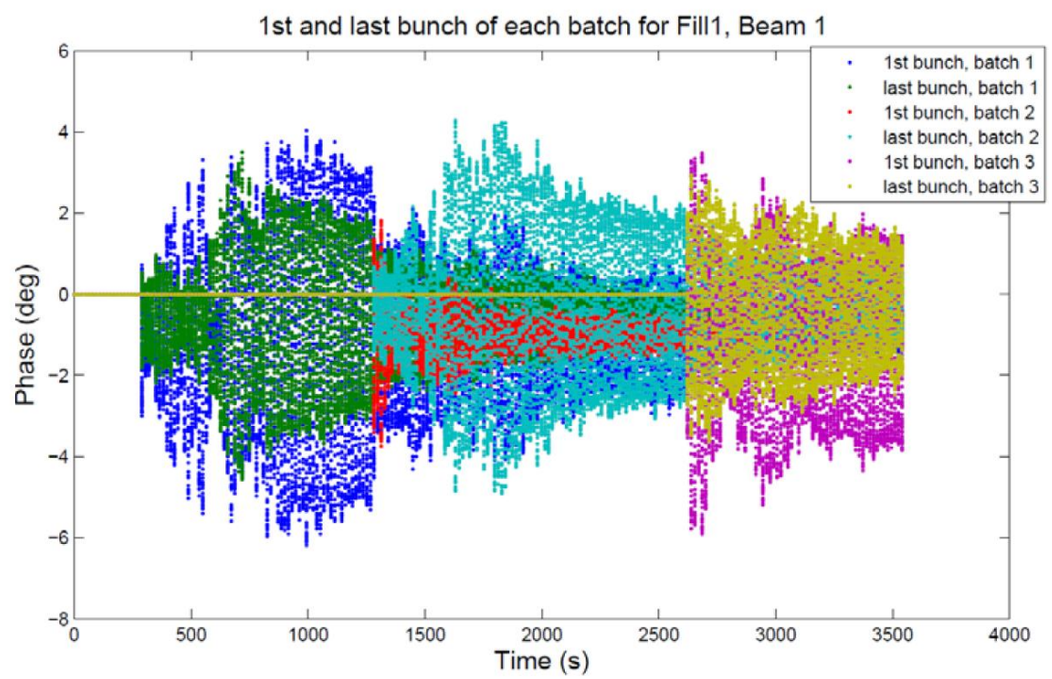
MEASUREMENTS

OBSERVATIONS IN THE LHC



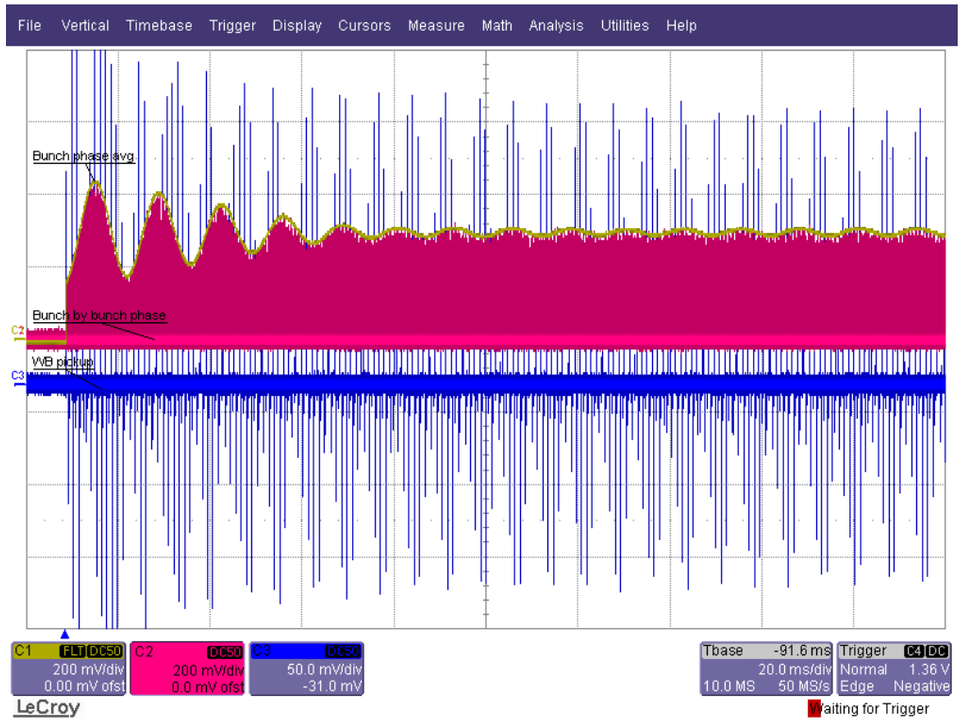
INJECTION OSCILLATIONS

- Long-lasting injection oscillations were seen since the first start-up with beam in the LHC
  - No harmful effect on the beam
  - Not studied in much detail back then



First dedicated studies of injection oscillations

8th May 2011

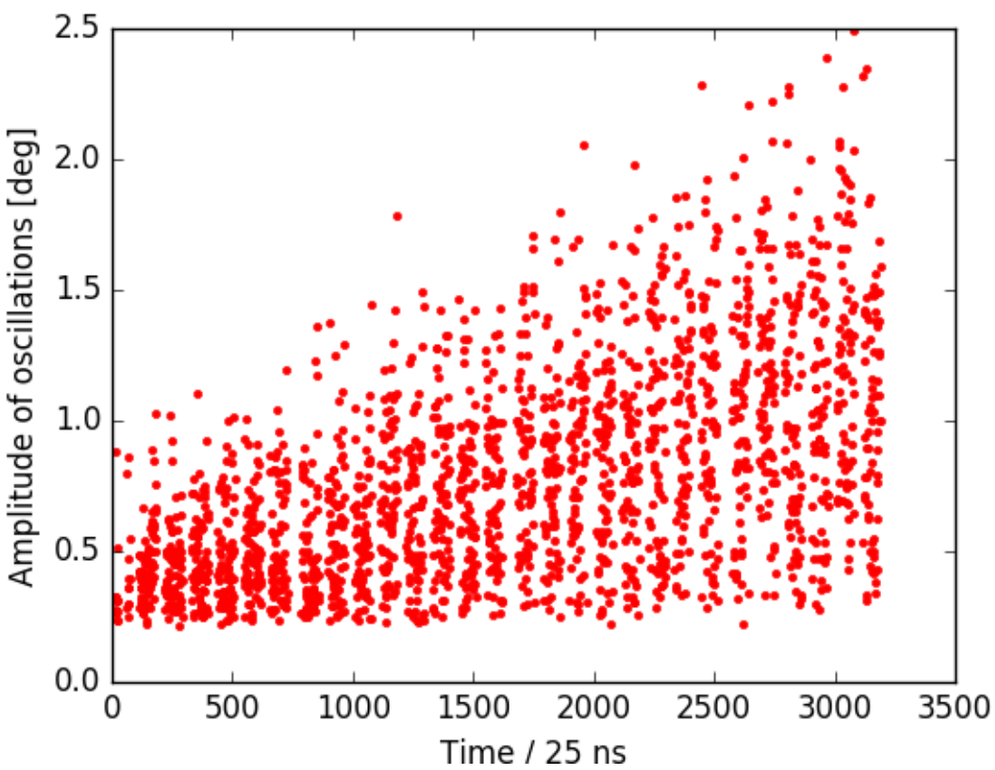


Injection transient signals during LHC beam commissioning

5th November 2009

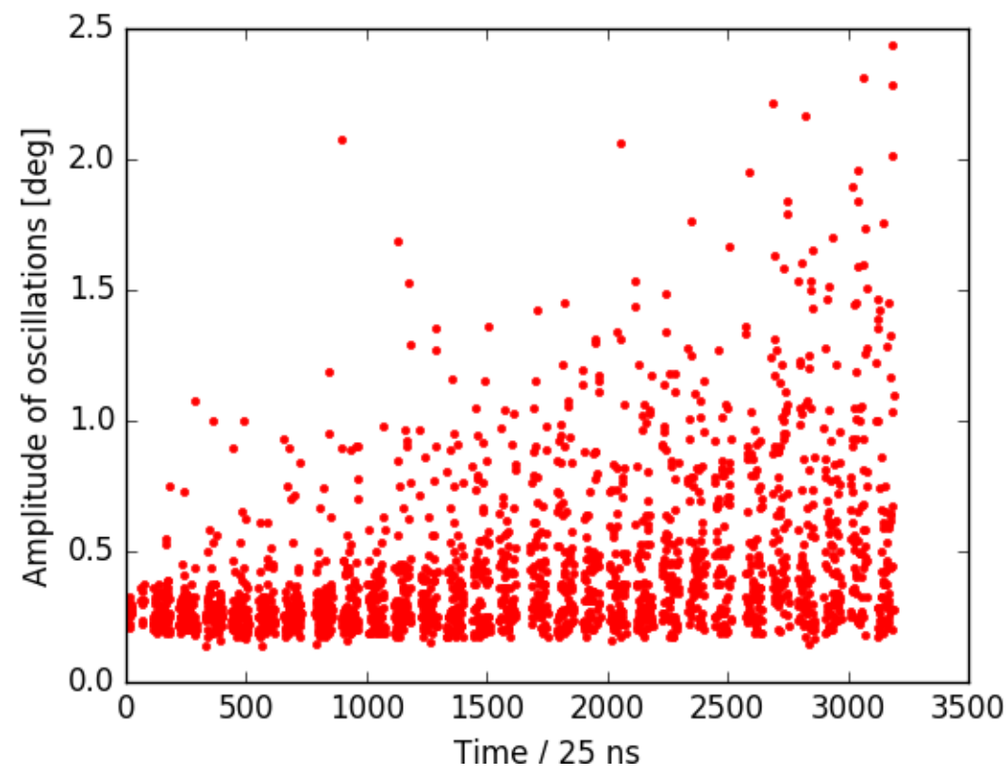
OSCILLATIONS THROUGH RAMP

- Observations in 2017 concerning injection oscillations
  - Patterns of dipole oscillations along the ring survive the ramp
  - Mystery: how can the oscillations remain after 13 million turns of phase noise injection for the controlled emittance blow-up?



Amplitude of dipole oscillations,
end of flat bottom

B2, October 2016

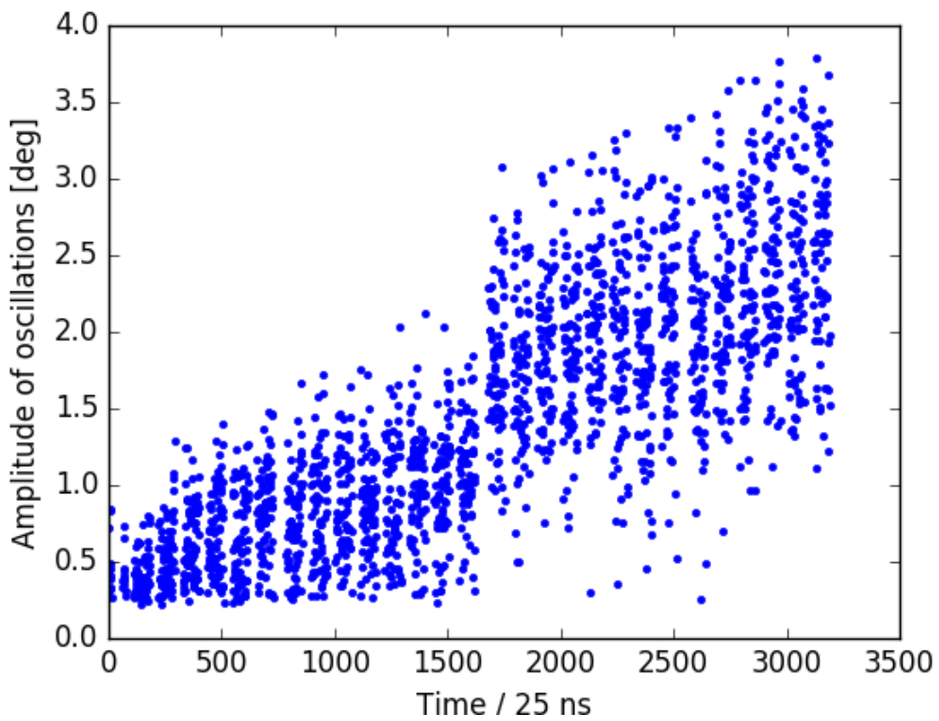


Amplitude of dipole oscillations,
arrival to flat top

B2, October 2016

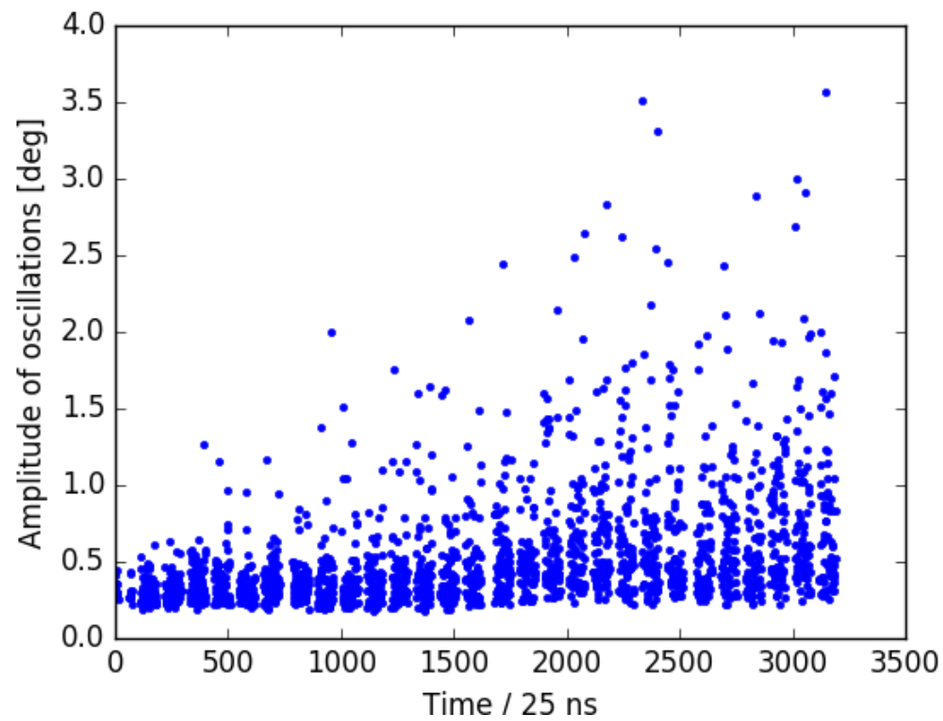
OSCILLATIONS THROUGH RAMP

- Correlation with the time spent on flat bottom
  - Batches injected later have a larger amplitude of oscillations, also at arrival to flat top
  - Full damping of oscillations requires about an hour at flat bottom



Amplitude of dipole oscillations,
end of flat bottom

B1, October 2016



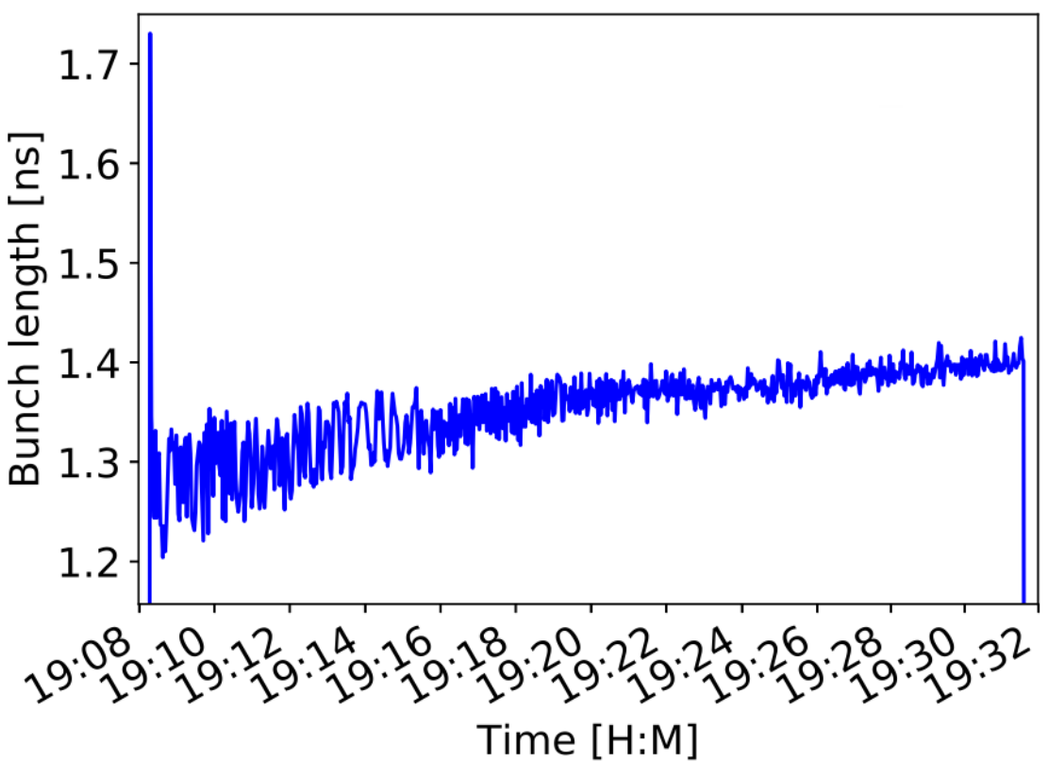
Amplitude of dipole oscillations,
arrival to flat top

B1, October 2016

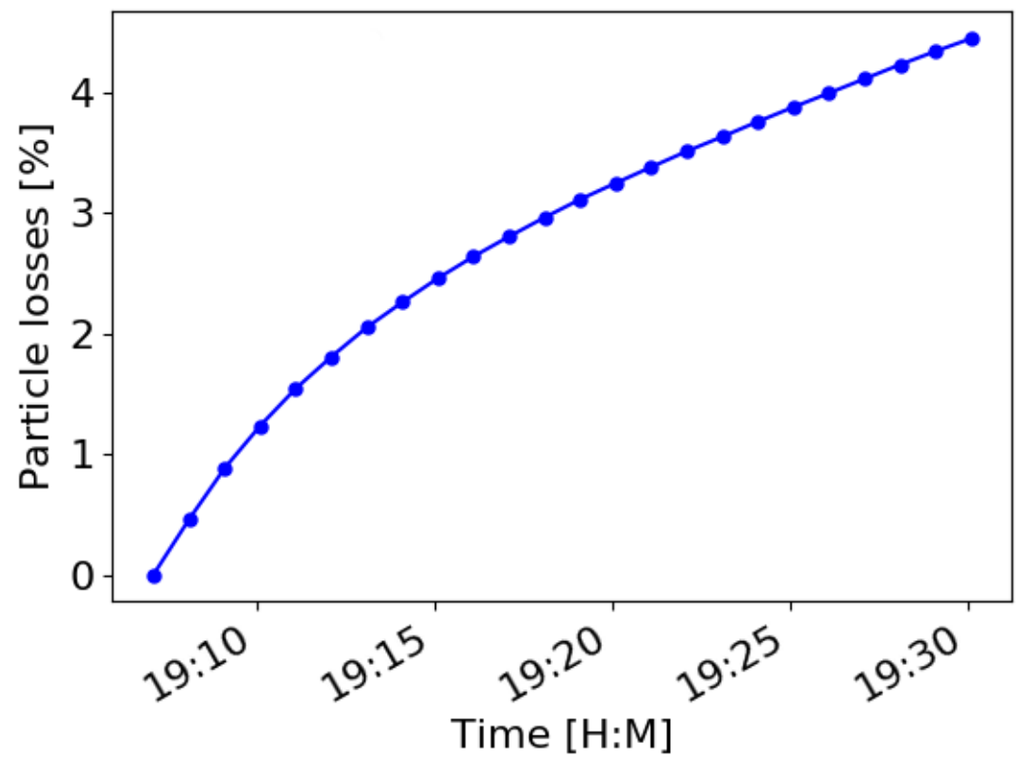
TOWARDS HL-LHC INTENSITIES

- Dedicated single-bunch measurements: (0.8-2.2)×10^{11} ppb
  - Using the nominal injection voltage of 6 MV
  - Instability develops after injection, leading to flat bottom losses

Single bunch of 1.9×10^{11} ppb



Bunch length increase: 10 %
(IBS only 3 %)

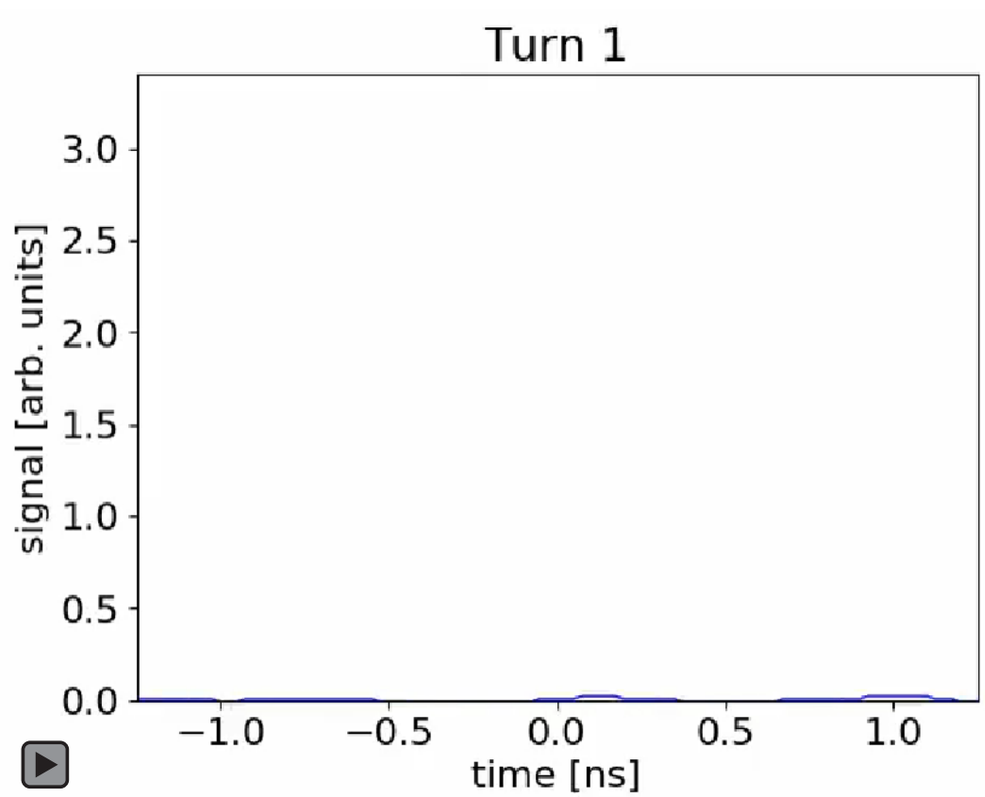


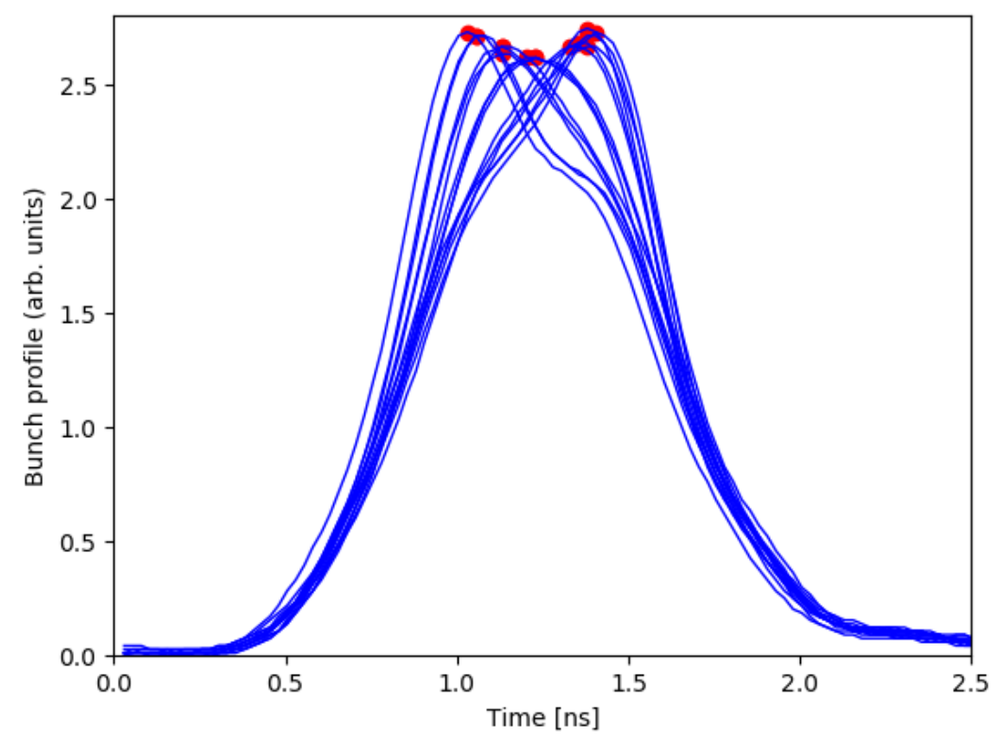
Bunch losses: 4 % over 20 minutes

AMPLITUDE OF OSCILLATIONS

- Stable phase measurements show only 10° phase oscillations peak to peak; 400 MHz RF component
  - Misleadingly small…

- Non-rigid dipole oscillations are seen on the bunch profiles
  - Peak oscillates with 50° pk-pk



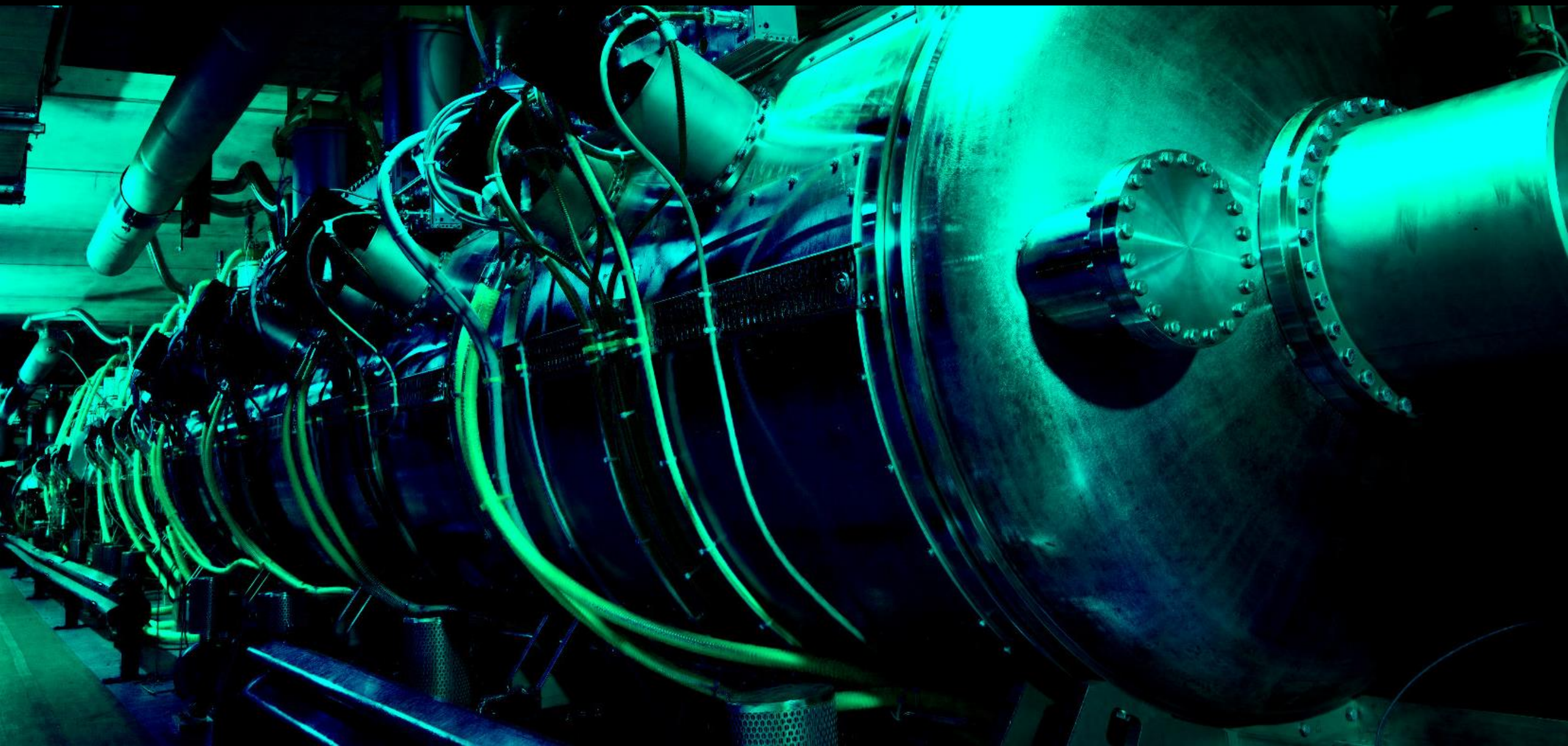


Oscillations of bunch profile peak

Single bunch of 1.9×10^{11} ppb, injection voltage of 6 MV

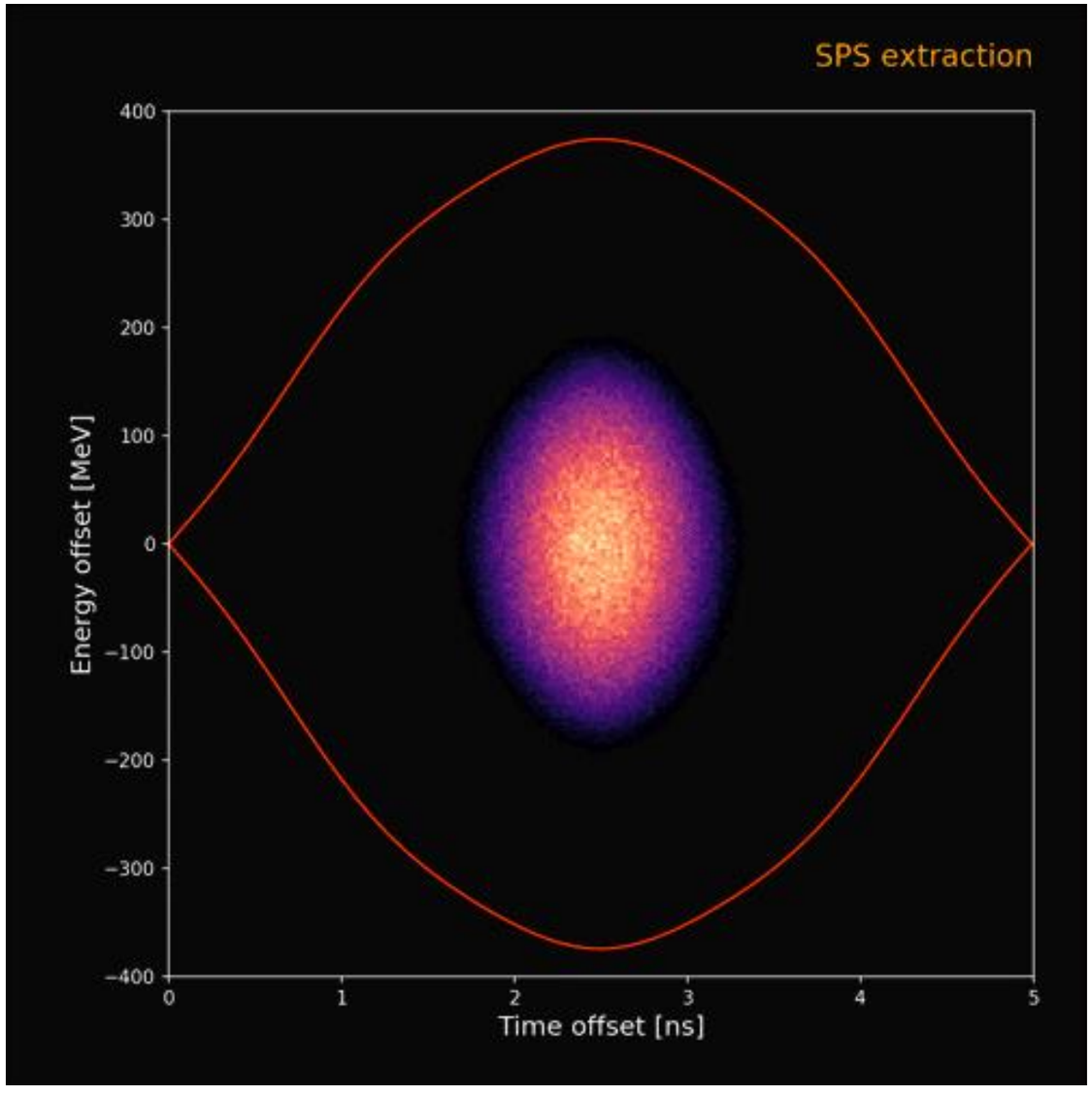
INSTABILITY FORMATION

SIMULATION STUDIES



MECHANISM

- Large mismatch at injection → island formation
  - Local loss of Landau damping



INSTABILITY FORMATION

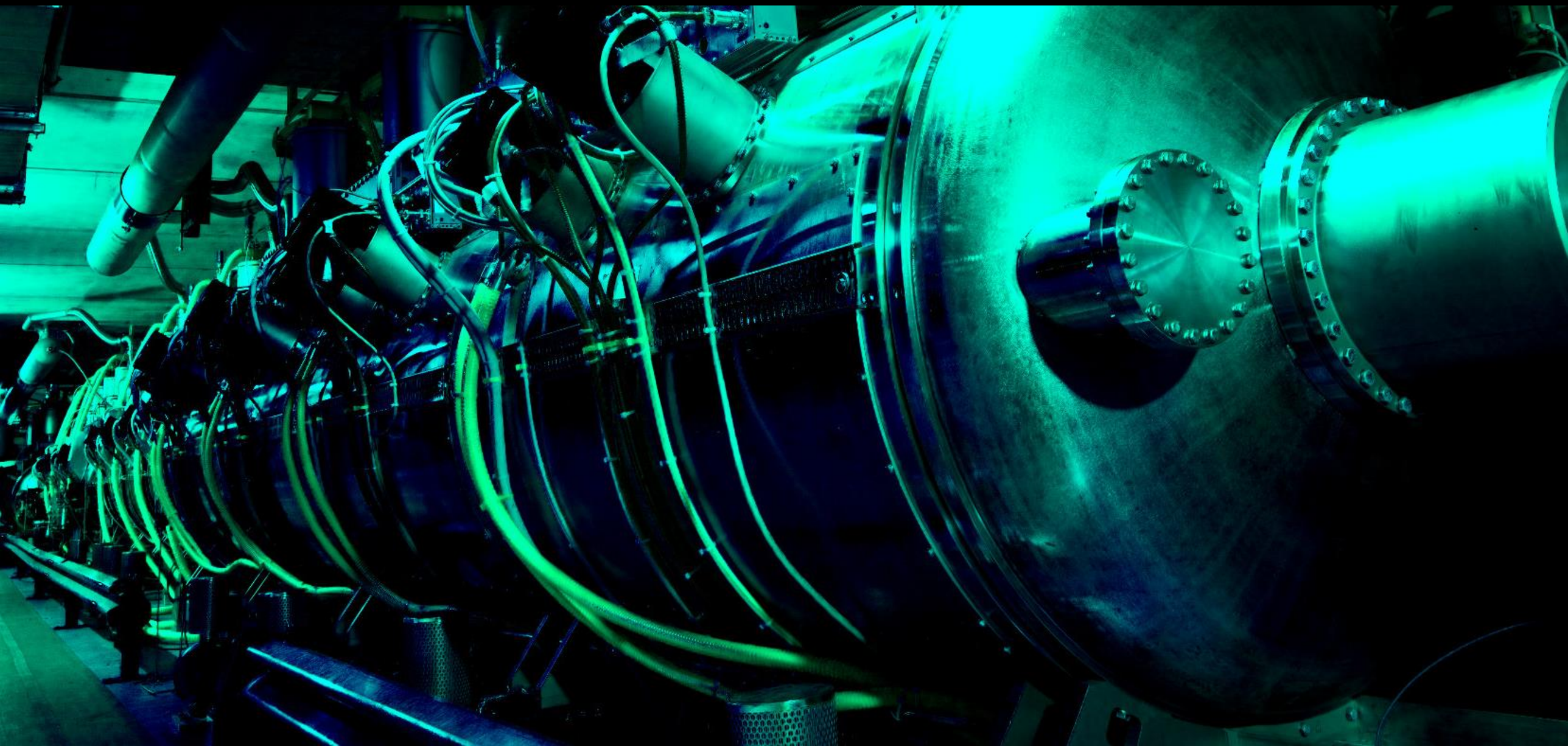
- Mismatch between bucket height and momentum spread
- In simulations with 1.15×10^{11} ppb, the instability occurs:
  - For a nominal bunch length (1.6 ns at injection), occurs with increased injection voltage (10 MV)
  - For shorter bunches (e.g. 1.4 ns) at nominal RF voltage (6 MV)
- In measurements, the instability occurs aready for the nominal bunch length and injection voltage, at an intensity of 1.9×10^{11} ppb injected

OPTIMUM INJECTION VOLTAGE?

- Best working point for the RF voltage in Run 3 and HL-LHC?
  - To keep SPS-LHC transfer losses low, prefer higher voltage
    - In the future, up to 10 MV at 200 MHz might be used for SPS extraction
    - Scaling the nominal LHC voltage, this would call for 8.6 MV
  - To prevent from instabilities and subsequent flat bottom losses, a lower voltage is desirable
- Other factors that play a role in the choice of the voltage
  - RF power consumption
    - Close to or beyond its limits with 8.6 MV and 2.3×10^{11} ppb
  - Controlled emittance blow-up during the ramp
    - Indispensable for operation
    - Difficulties with controlling the bunch length expected at high intensities
    - Interaction with flat-bottom instabilities to be studied

PARAMETER SCANS

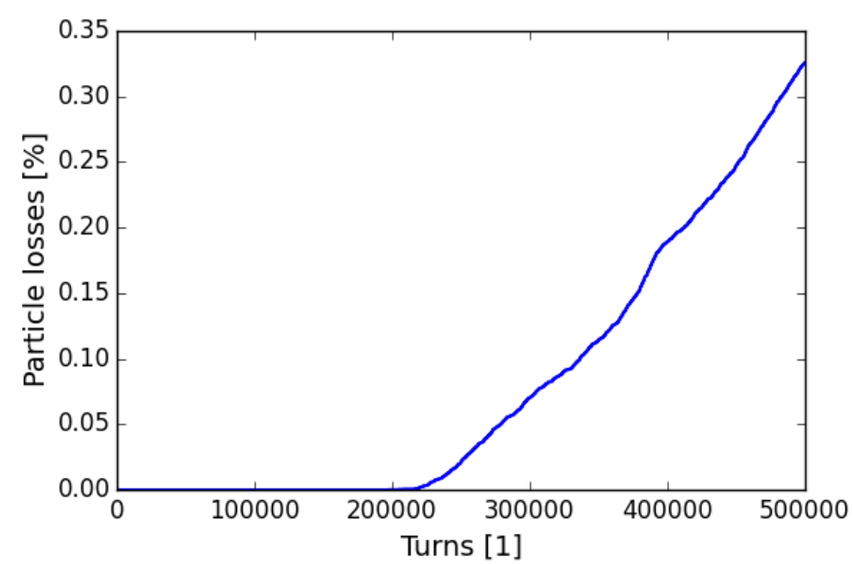
FIRST SIMULATION STUDIES



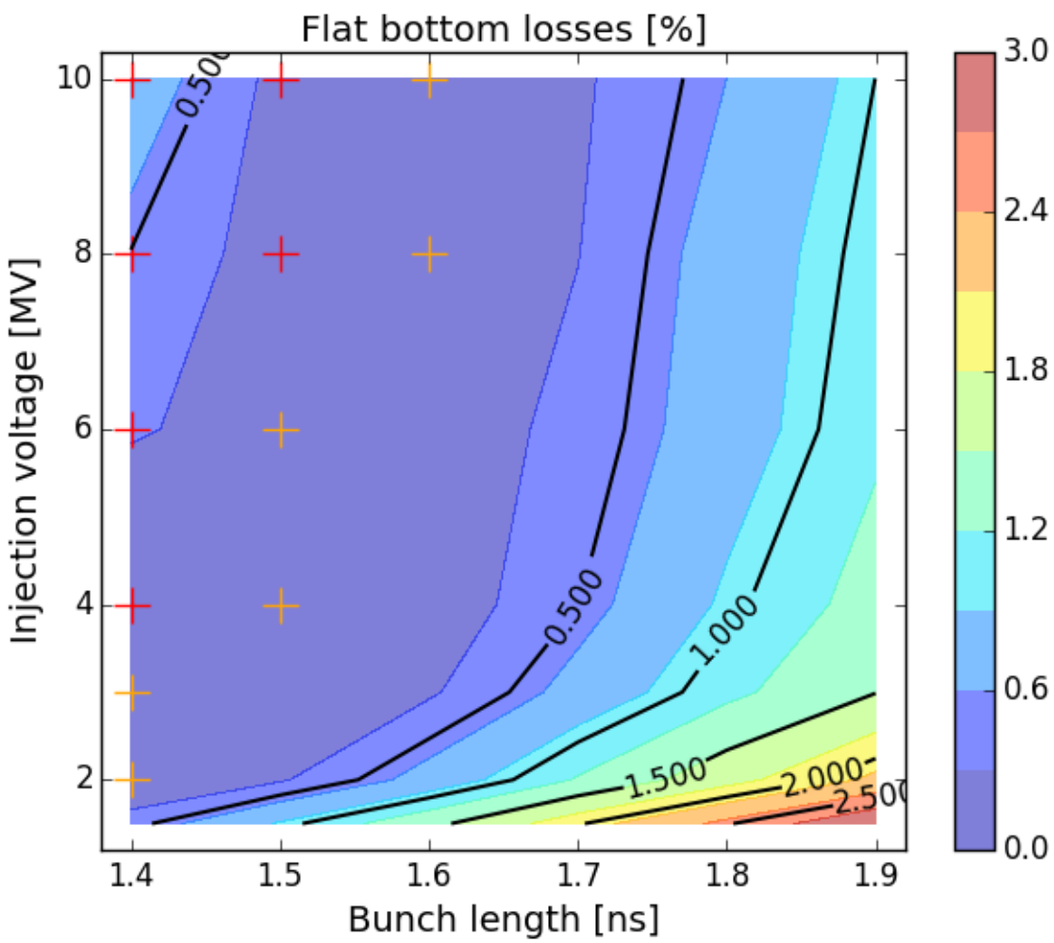
SIMULATION SETUP

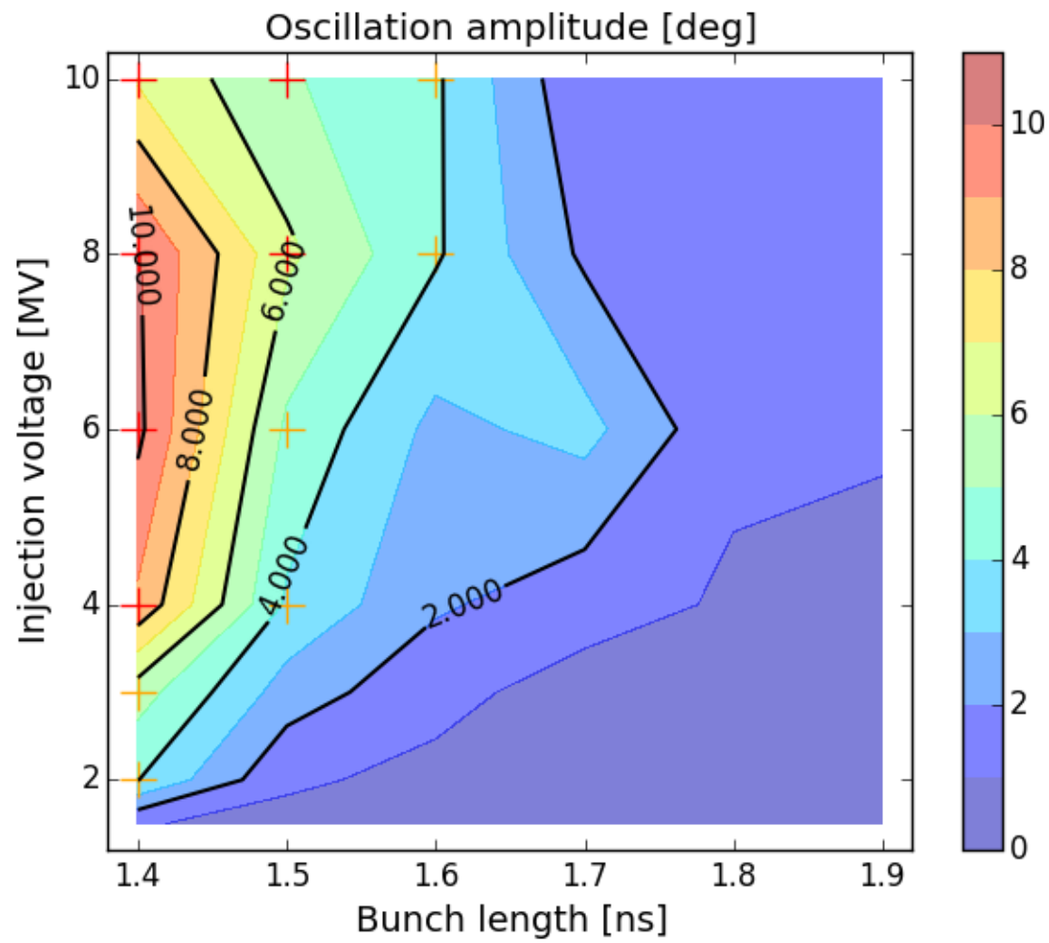
- The ‘optimum’ voltage is thus a compromise between acceptable losses (at injection and flat bottom) and sufficient damping of injection oscillations

- Simulations at nominal intensity
  - Using present LHC impedance model at 450 GeV
  - Flat bottom losses were determined from the separatrix, after first-turn capture losses
  - Oscillation amplitude from average bunch position after damping of the initial injection errors



OPTIMUM VOLTAGE SCANS (1)

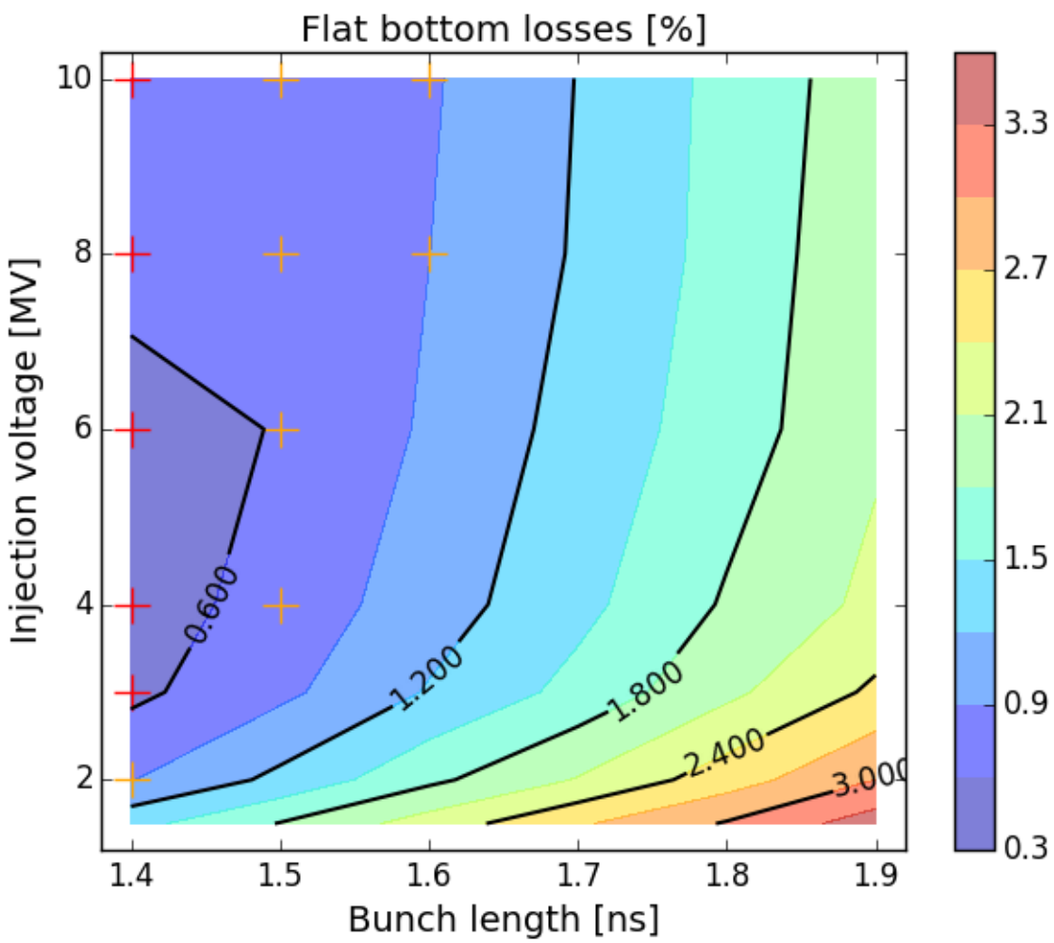


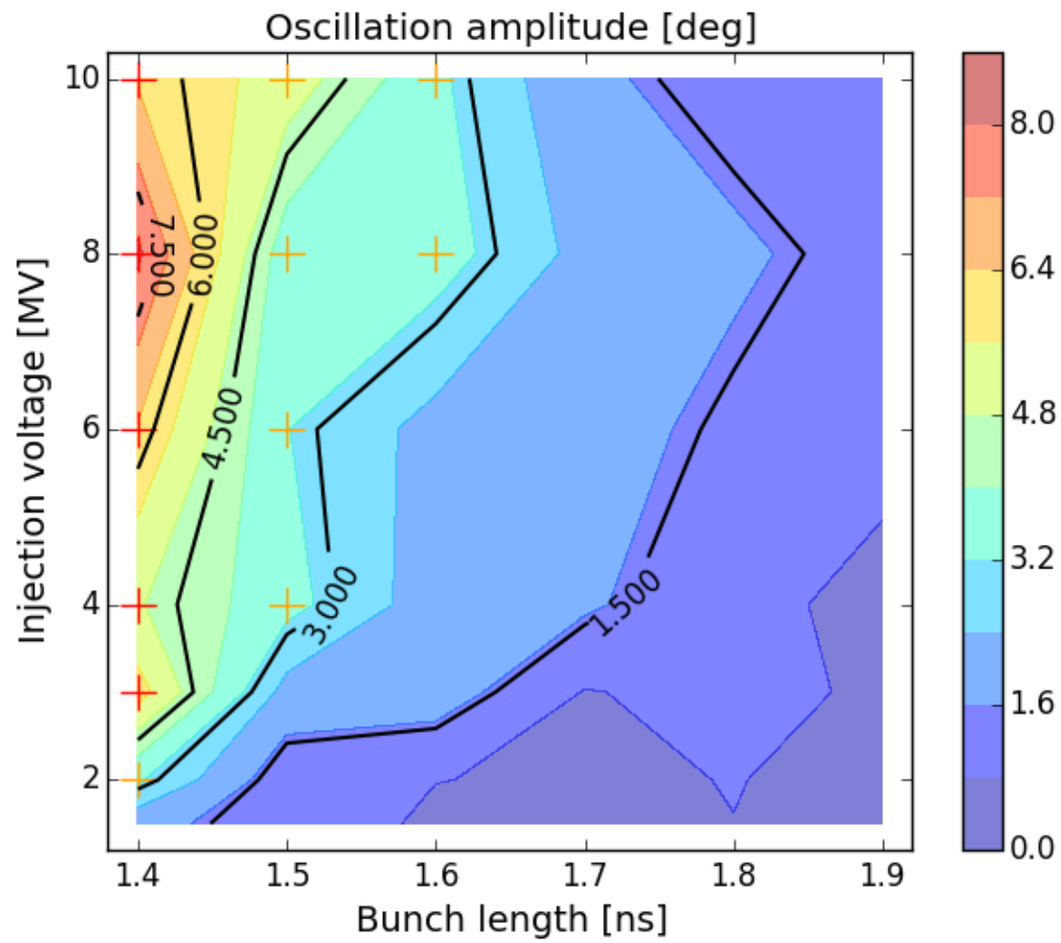


Using a binomial distribution function of action with exponent 1.5; fitted from measurements

Orange crosses = undamped cases
Red crosses = growing oscillation amplitude

OPTIMUM VOLTAGE SCANS (2)





Using a binomial distribution function of action
with exponent 5.0; to enhance the tail population

Orange crosses = undamped cases
Red crosses = growing oscillation amplitude

PRELIMINARY CONCLUSIONS

- Injection voltage: 4 MV could be a good compromise for nominal bunch intensity and bunch length
  - More stability margin
  - Would be beneficial also for reducing the RF power consumption

- To be verified experimentally

BEAM PHASE LOOP

- Presently operational scenario: averaging the phase error measurements of all bunches
  - Efficient RF noise reduction for physics
  - Concerning injection errors, however:
    - Only the first batches are efficiently re-centred; for batches injected later, the phase loop is less and less efficient
    - Batches already circulating in the machine get kicked at new injections
  - Phase loop not taken into account in simulations

- If necessary, injection oscillations could be damped by applying a batch-by-batch correction on individual batches

CONCLUSIONS

- Injection oscillations can develop into instabilities and can lead to losses
- Need to determine optimum voltage considering losses, stability and RF power consumption
- First simulation studies performed; experimental verification underway

감사합니다.