Electron cloud stability at injection: Coupled bunch effects

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Acknowledgements: G. Rumolo, CERN HPC Cluster team

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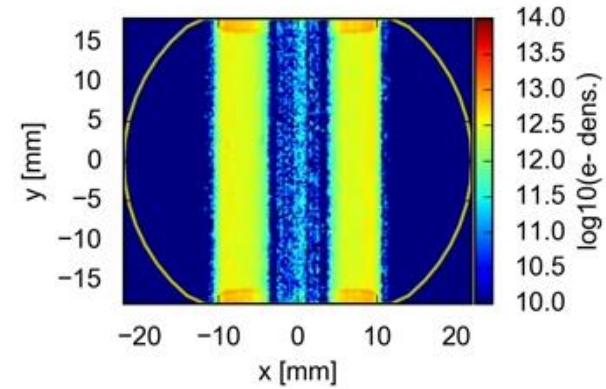
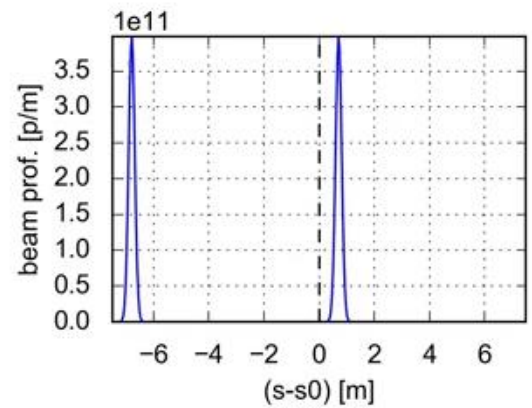
Introduction

Electron cloud can cause beam instabilities through the electromagnetic coupling of the motion of the electrons and the proton beam dynamics

- Since the electron cloud build-up process occurs over several bunch passages, electron cloud can, in addition to single bunch instabilities, be responsible for bunch-to-bunch coupling → coupled-bunch instabilities due to transverse offsets between bunches
  - This is particularly likely in dipole fields, where the electrons are constrained horizontally by the field lines, and the electron distribution is not fully reset from one bunch passage to the next





Coupled-bunch simulations

Although some analytical models exist, a comprehensive understanding of electron cloud effects relies on macro-particle simulations

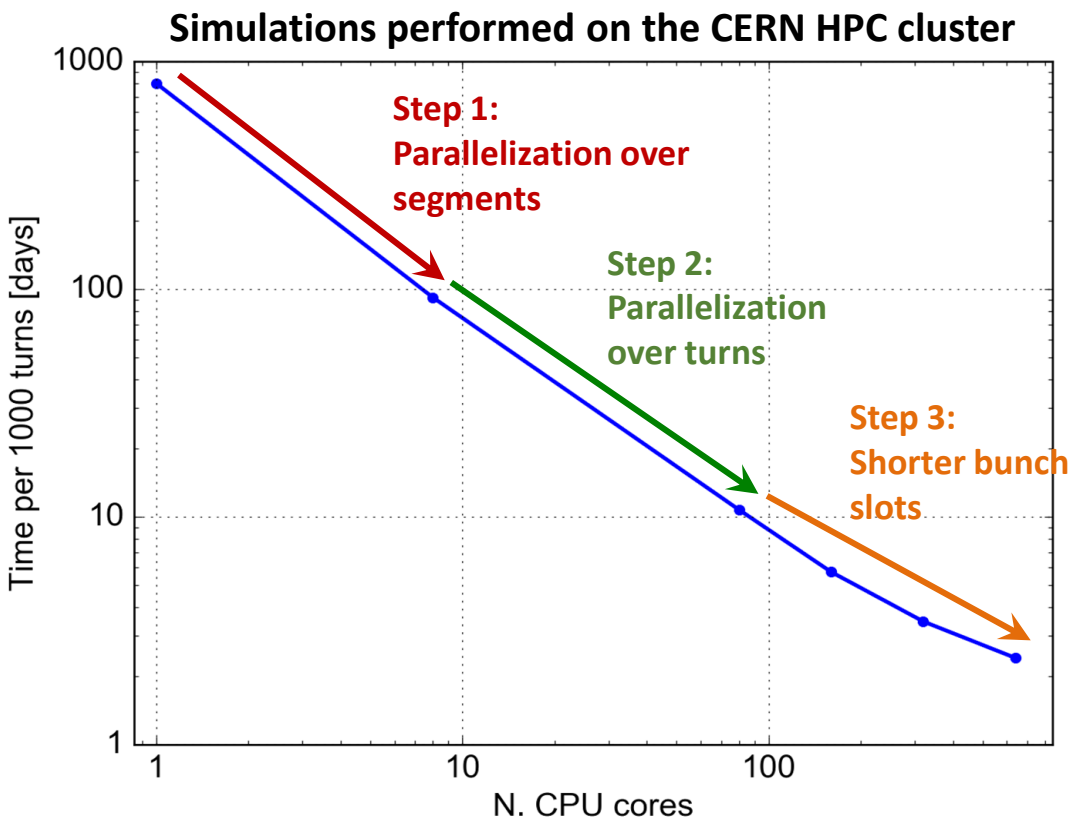
The simulation are computationally very heavy

- The entire chamber must be simulated, but the beam must be resolved very well
- The fast electron motion requires small time steps (~10^{-11} s), but the instability evolution can take up to several seconds
- Many macroparticles are needed to minimize numerical noise (~250k per e-cloud interaction)
- For coupled-bunch instabilities the e-cloud build-up must be simulated dynamically over the full bunch train to capture the instability

Coupled-bunch simulations

The PyECLOUD-PyHEADTAIL suite and its PyPARIS parallelization layer have been extended to exploit HPC clusters to perform coupled-bunch e-cloud simulations

- See *G. Iadarola, LMC, Nov 2018*
- Performance was boosted in three steps:
  1. Parallelization over accelerator segments
  2. Parallelization over different turns
  3. Smaller bunch slots



Recent developments

- Implemented options to enable or disable different MPI features and standard output
  - To diagnose problems encountered on HPC cluster

- Implemented possibility of saving and loading a pre-generated beam for simulations
  - Overcomes problem with bunch creation on cluster, where the simulation crashes if initialization (serial) lasts longer than an hour → 288 bunches possible

- Implemented the possibility of dividing the simulation into several consecutive runs similarly to single-bunch instability simulations
  - Overcomes the limit on job duration and allows continuing failed simulations

- Saving of slice data and selective saving of e-cloud data to keep output size reasonable

- Analysis tools for multiple simulations, slice data, etc

Simulation study

This new tool has for the first time been used for a comprehensive simulation study, investigating the coupled-bunch instabilities caused by dipoles in the LHC at injection

- The study is focused on
  - The effect of bunch intensity: LHC vs HL-LHC
  - The effectiveness of different mitigation strategies

The simulations have been performed on the CERN HPC cluster, with

- Trains of **144 bunches**
  (288 bunches require more resources, and the physics is captured with shorter trains)

- A total of **144 x 10^6 proton MPs** for the bunches and **200 x 10^6 electron MPs**
  ($2.5 \times 10^5 * N_{kicks} * N_{rings}$) → 350 million MPs

- **800 CPU-cores** per simulation (8 kicks, 100 parallel rings)

- Typical simulation time ~ **100 turns/day** (excluding queuing time)

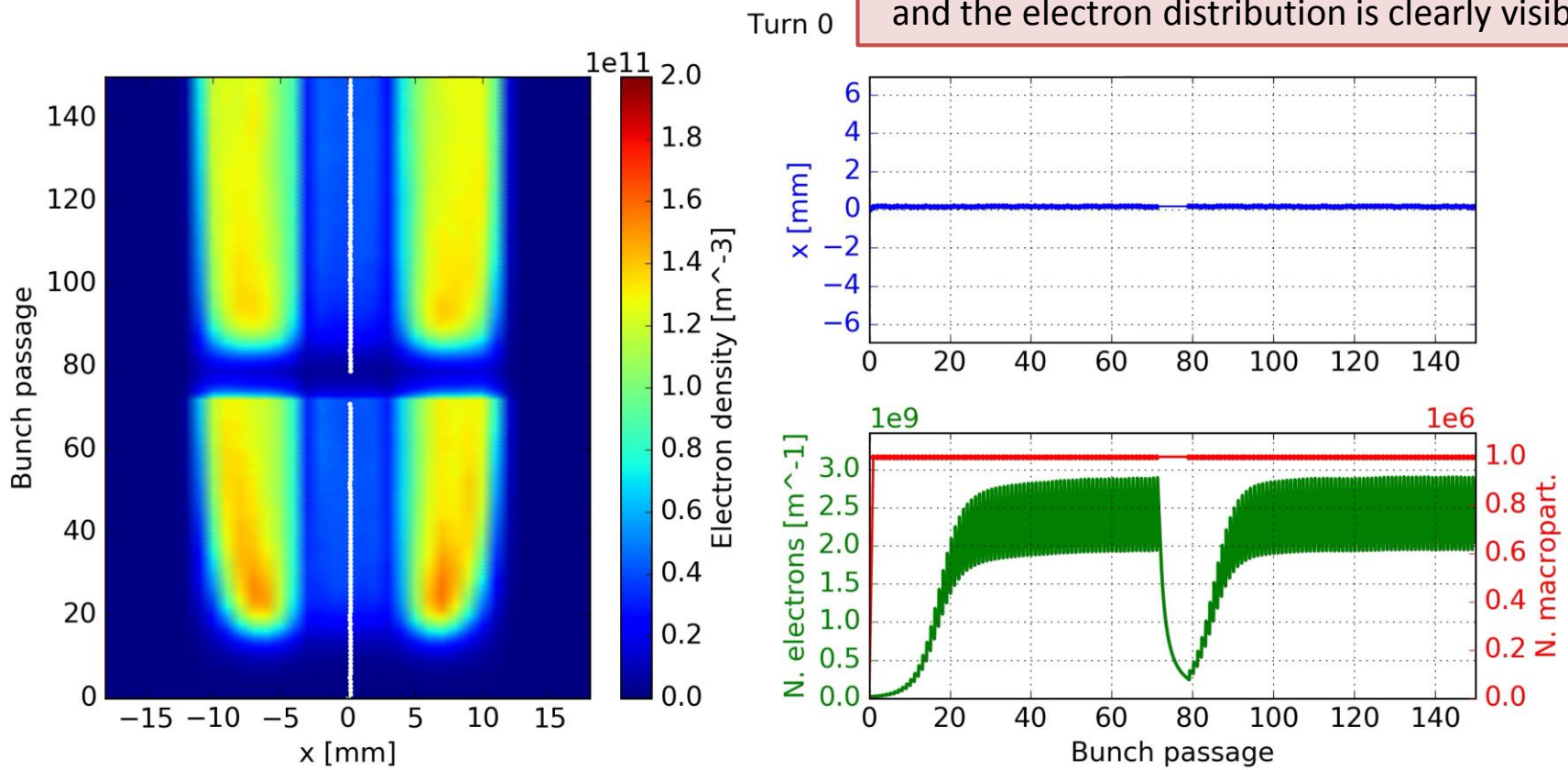
LHC simulation

An example simulation for LHC bunch intensity (1.1 x 10^{11} p/bunch)

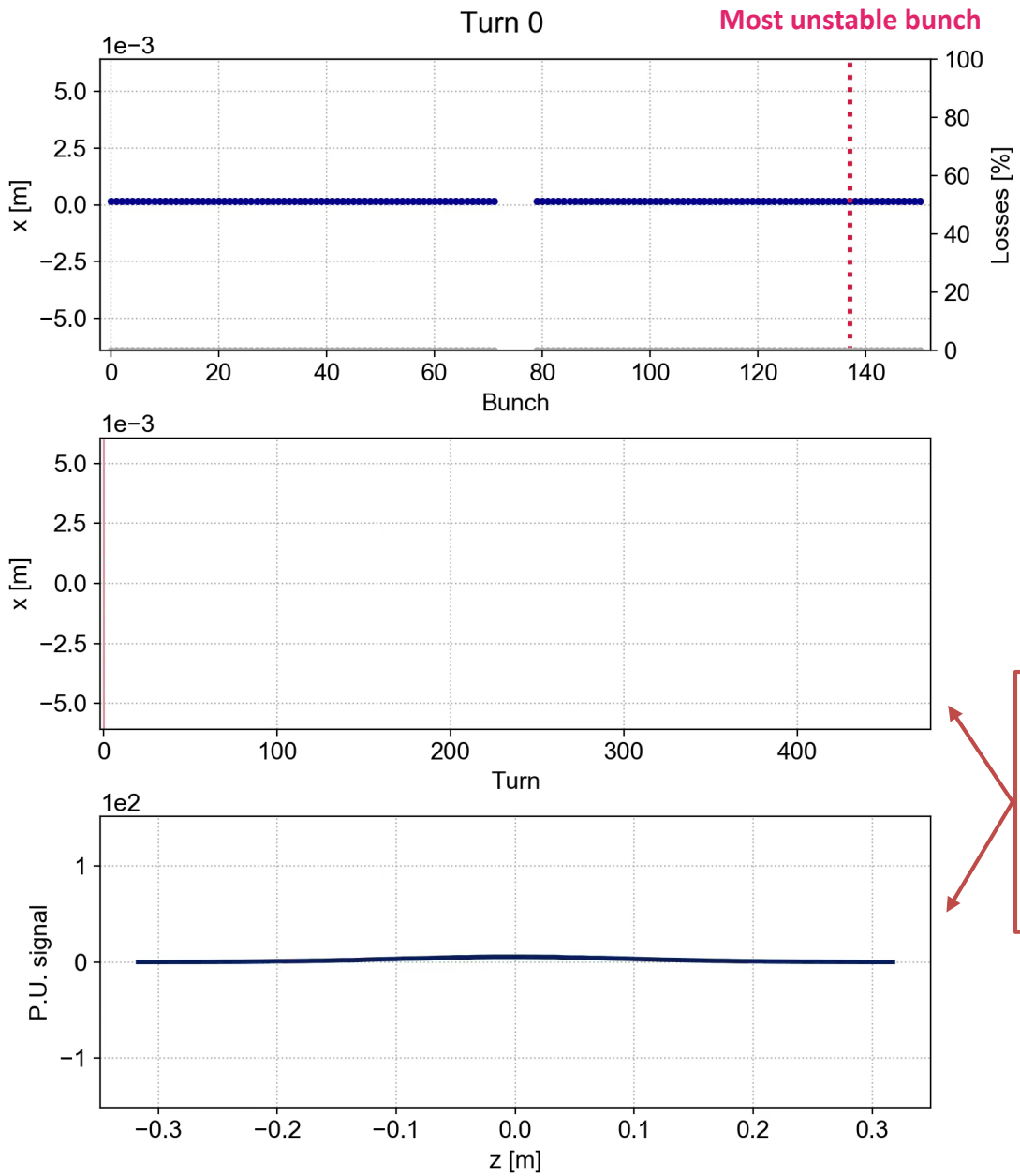
- SEY = 1.7 to observe the instability within an affordable simulation time
- Kick from e-cloud only applied in horizontal to avoid single bunch instabilities

Emittances	**2.5 µm**
Bunch length	**1.3 ns**
RF voltage	**8 MV**

Coupling between the motion of the bunches and the electron distribution is clearly visible



LHC simulation



Centroid and intra-bunch motion of the most unstable bunch (bunch 138)

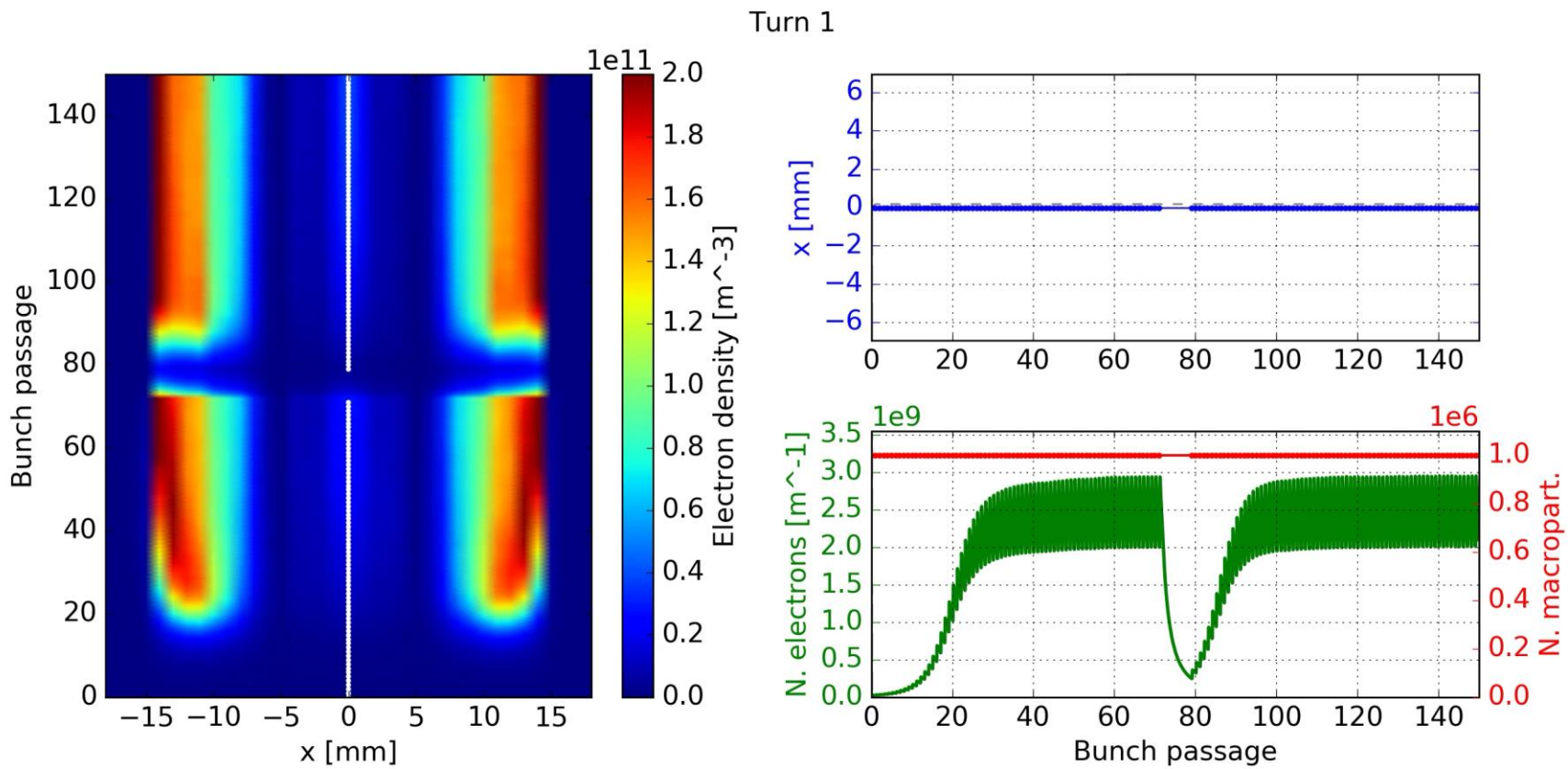
Very little intra-bunch motion, bunch oscillation is quite rigid

HL-LHC simulation

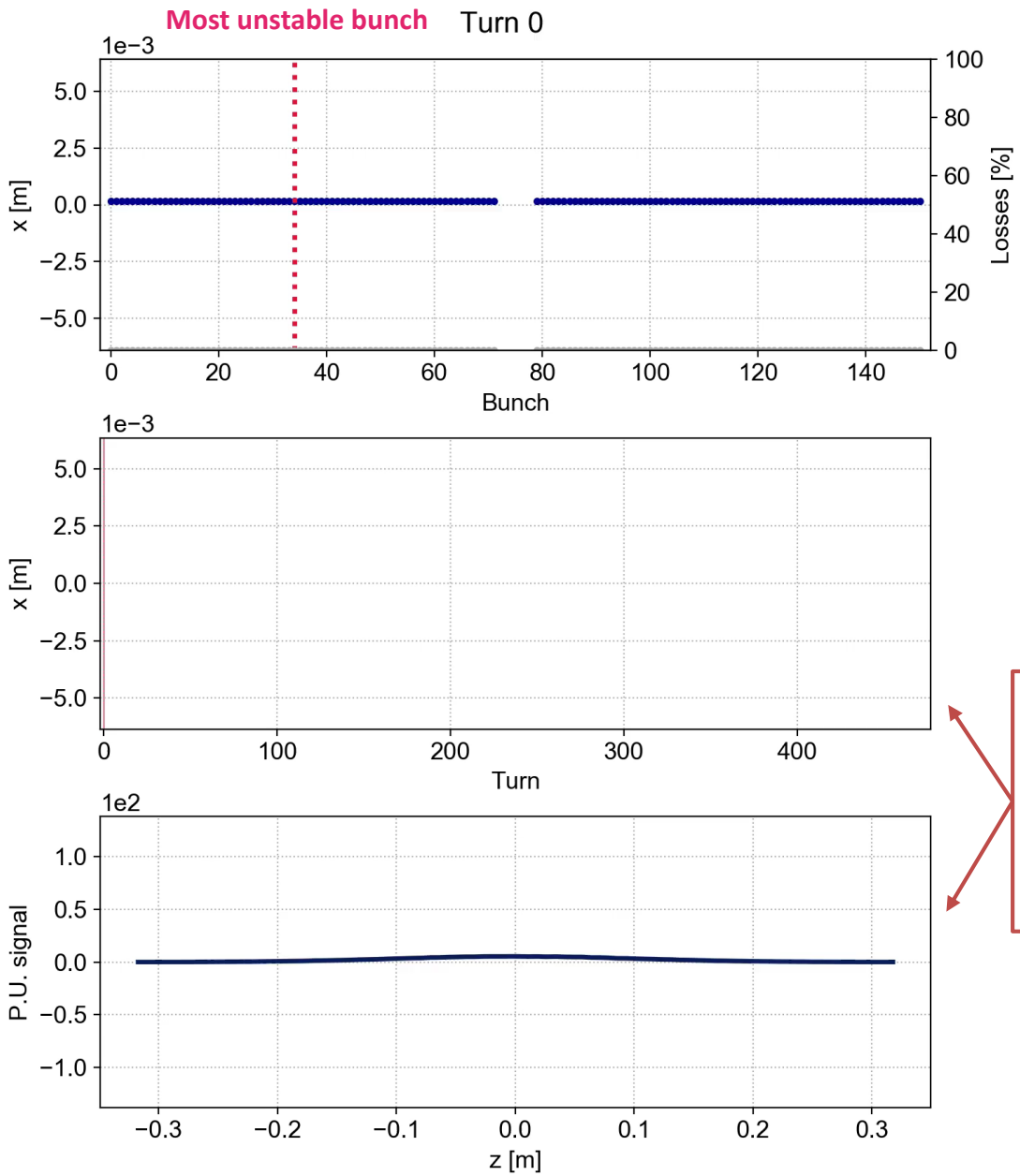
The corresponding simulation for HL-LHC bunch intensity (2.3 x 10^{11} p/bunch)

- Due to the larger bunch intensity, the electron stripes are further away from the beam
- The instability pattern along the bunch train is different
  - The most unstable bunches are in the middle of the first train

Emittances	**2.5 µm**
Bunch length	**1.3 ns**
RF voltage	**8 MV**



HL-LHC simulation

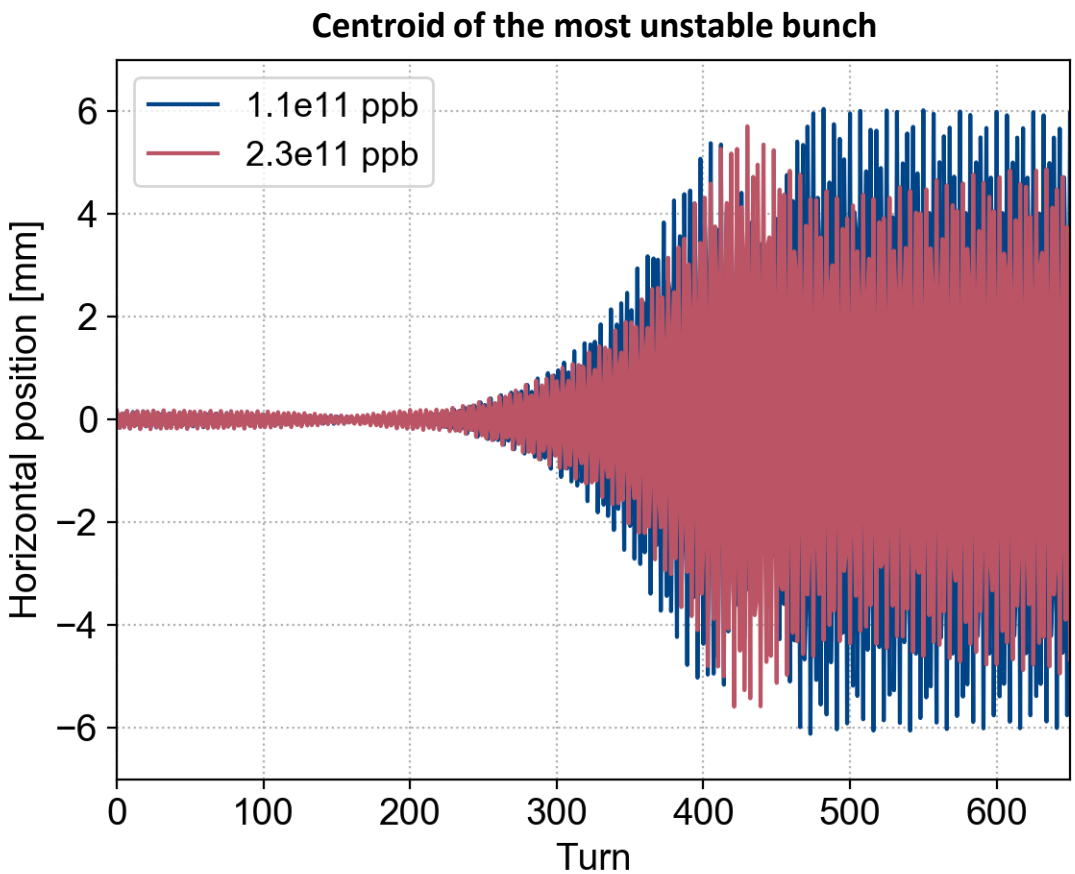


Centroid and intra-bunch motion of the most unstable bunch (bunch 38)

Very little intra-bunch motion, bunch oscillation is quite rigid

Effect of intensity

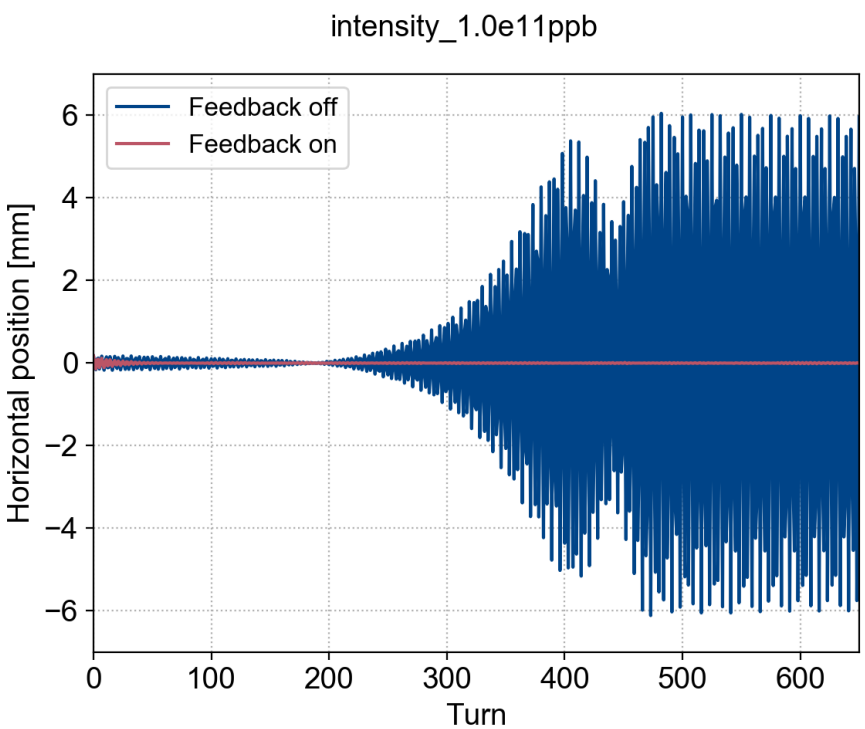
Although the instability develops in different locations along the train, the rise-time of the instability is very similar for the two values of bunch intensity

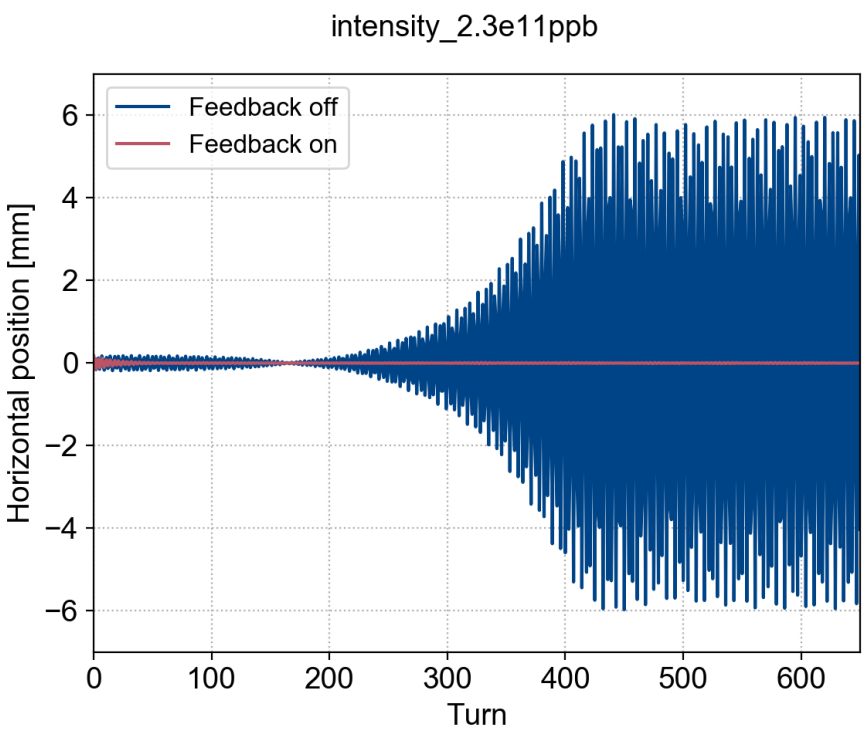


Effectiveness of feedback

Since there is not much intra-bunch motion, a transverse feedback should be effective in damping the instability

- The simulations have been repeated with an ideal transverse feedback active (20 turns damping time)
- In both cases the feedback fully suppresses the instability (over 3000 turns)

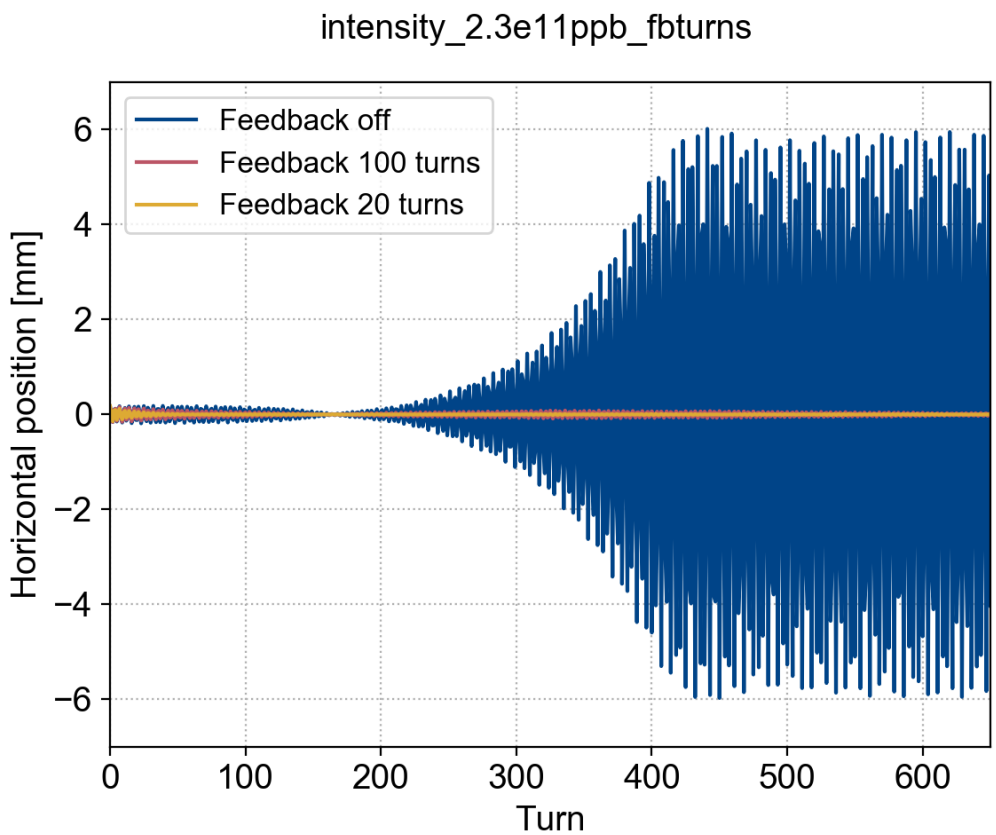




Effect of damping time

To investigate the effect of the feedback damping time, the simulation with HL-LHC intensity was repeated with a damping time of 100 turns

- The feedback is able to suppress the instability also with 100 turns damping time

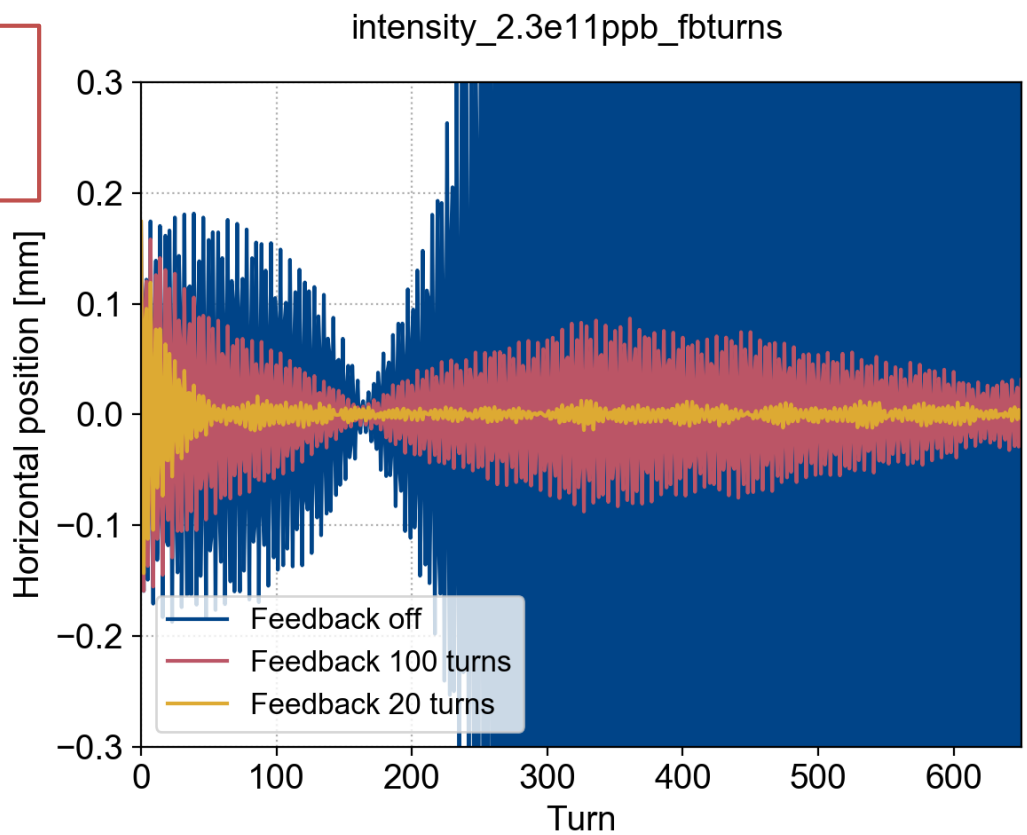


Effect of damping time

To investigate the effect of the feedback damping time, the simulation with HL-LHC intensity was repeated with a damping time of 100 turns

- The feedback is able to suppress the instability also with 100 turns damping time
- On a closer look, the beam oscillates considerably more with a larger damping time

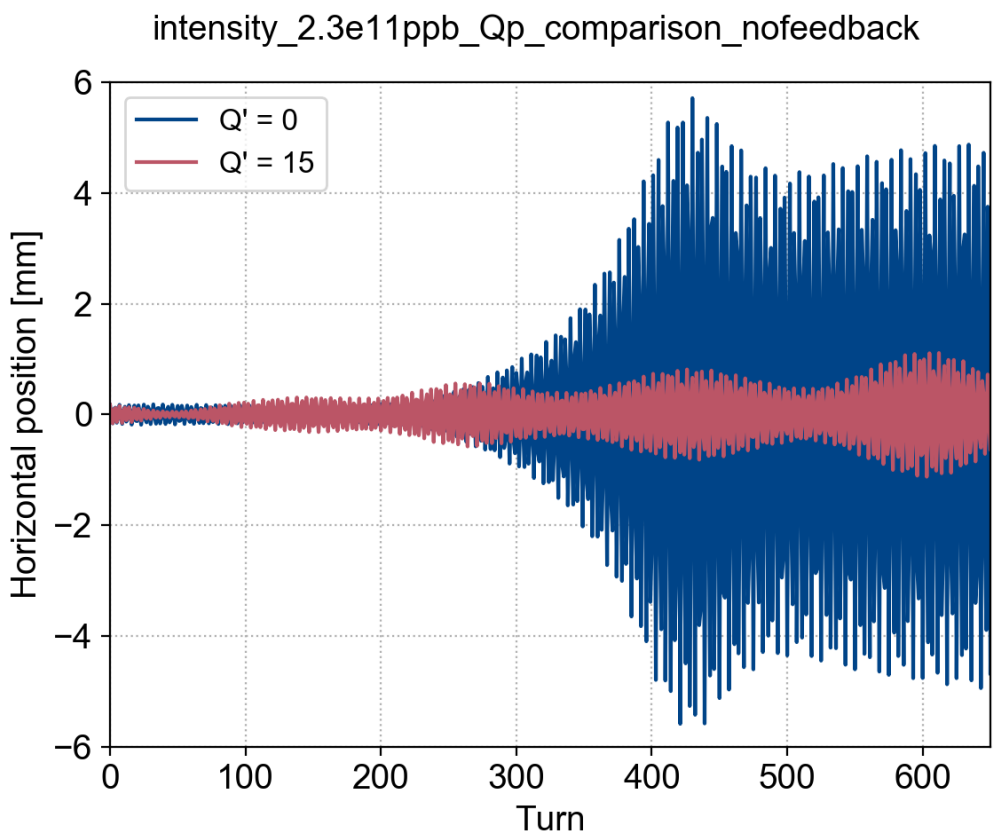
The simulation is initialized with a kicked bunch



Effectiveness of chromaticity

To investigate if the instability can be suppressed with chromaticity, the HL-LHC simulations were repeated with $Q'_x = 15$

- Chromaticity has a clear mitigating effect on the instability, but is not sufficient to fully suppress it



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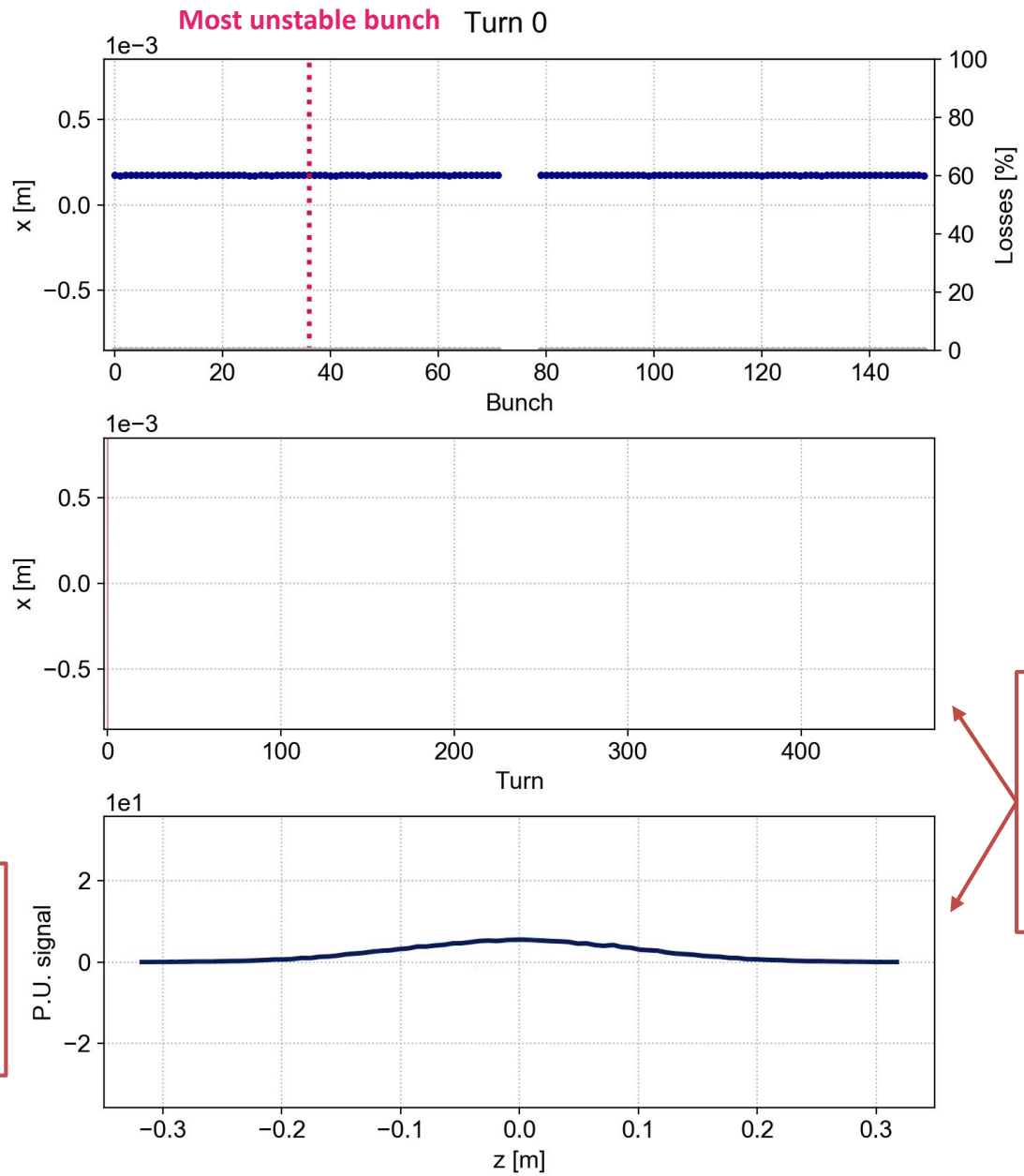

With chromaticity, a travelling wave intra-bunch motion is observed

Centroid and intra-bunch motion of the most unstable bunch (bunch 38)

Effectiveness of chromaticity

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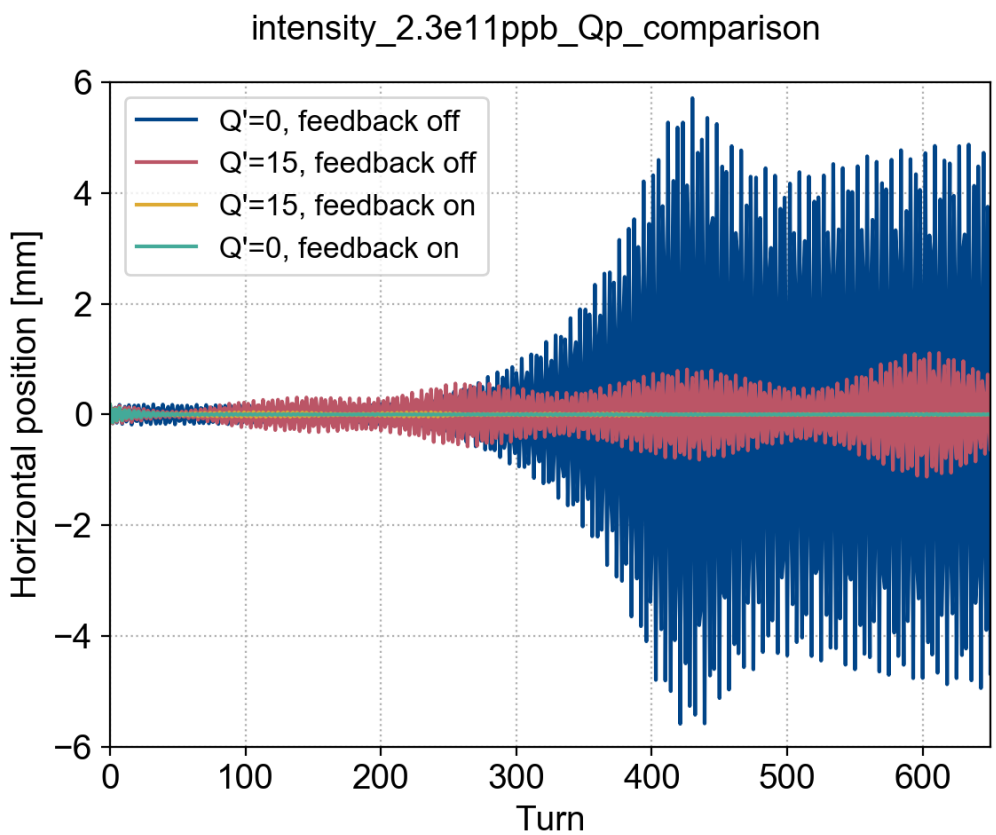

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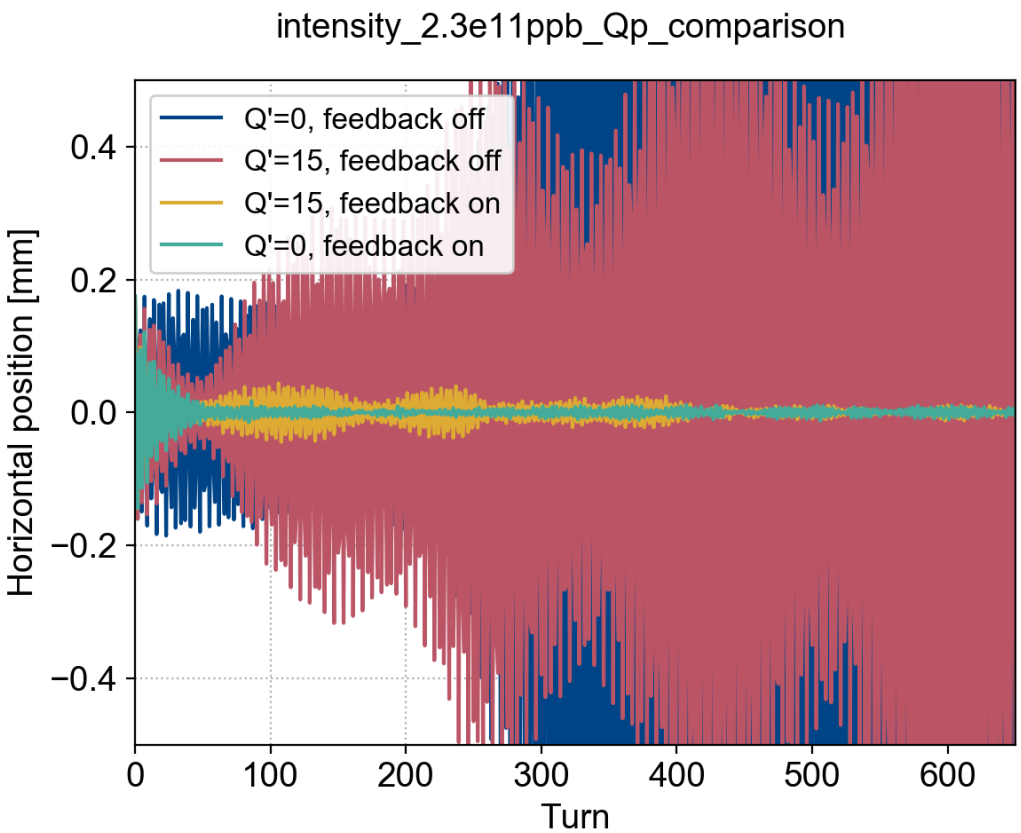
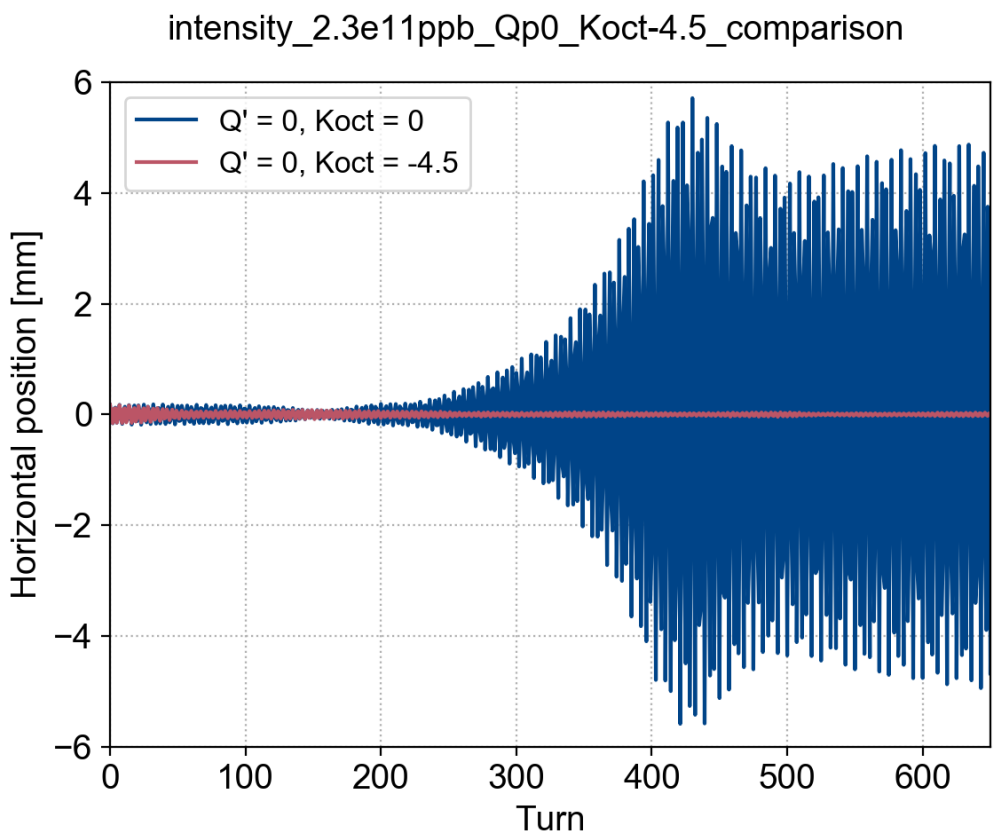
- Chromaticity has a clear mitigating effect on the instability, but is not sufficient to fully suppress it
- The damper suppresses the instability also in the presence of chromaticity, but a longer time is required to damp the oscillation



Effectiveness of octupoles

To investigate if Landau damping from octupoles can suppress the instability, the HL-LHC simulations were repeated with K_{oct} = -4.5, I_{LOF} = 59 A

- The instability can be suppressed with octupoles



Effectiveness of octupoles

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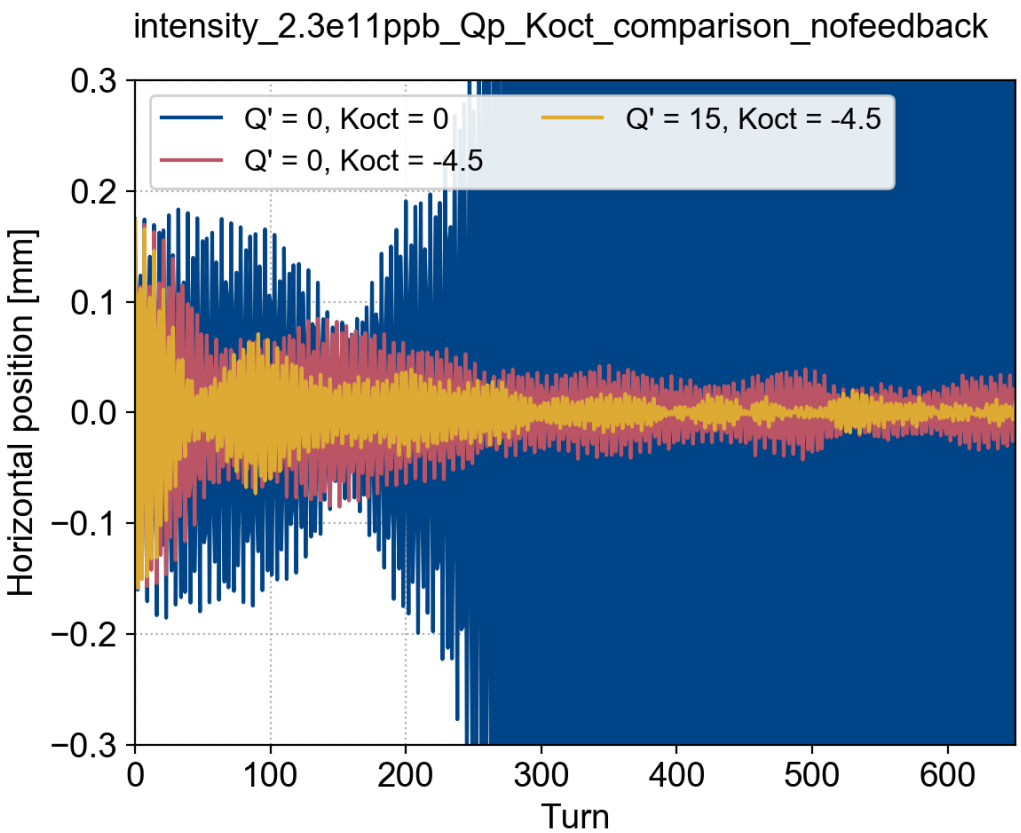
- The instability can be suppressed with octupoles
- Chromaticity and octupoles suppress the instability better than only octupoles



Effectiveness of octupoles

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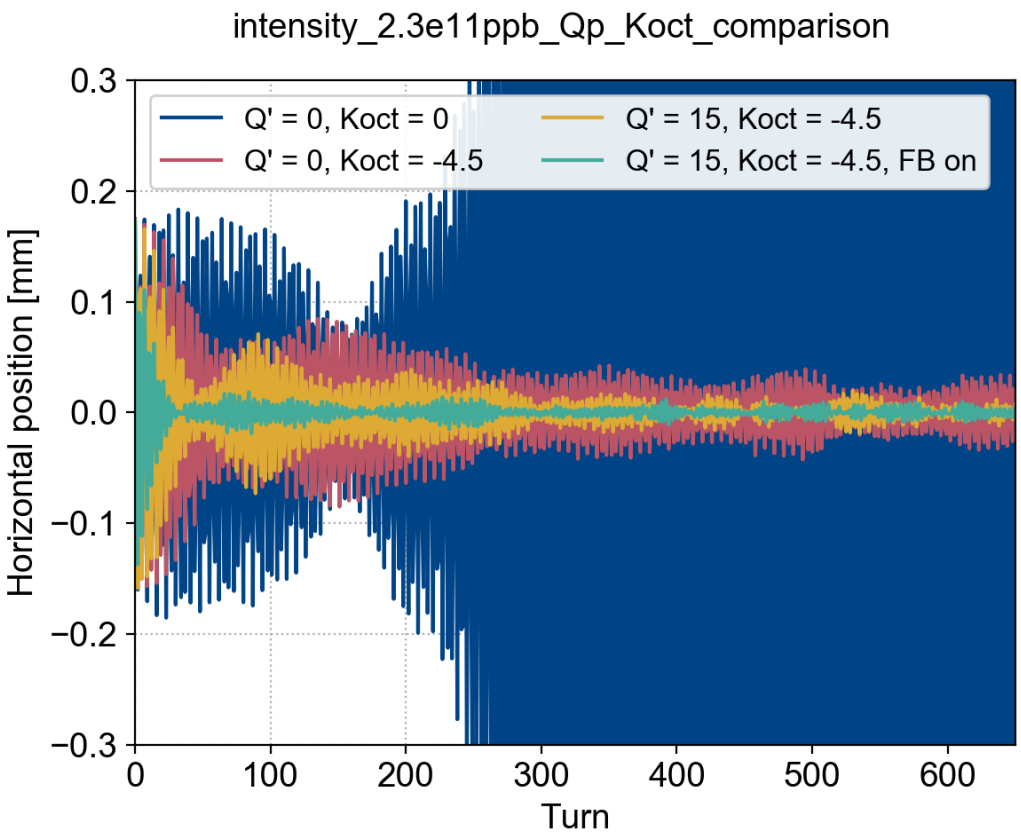
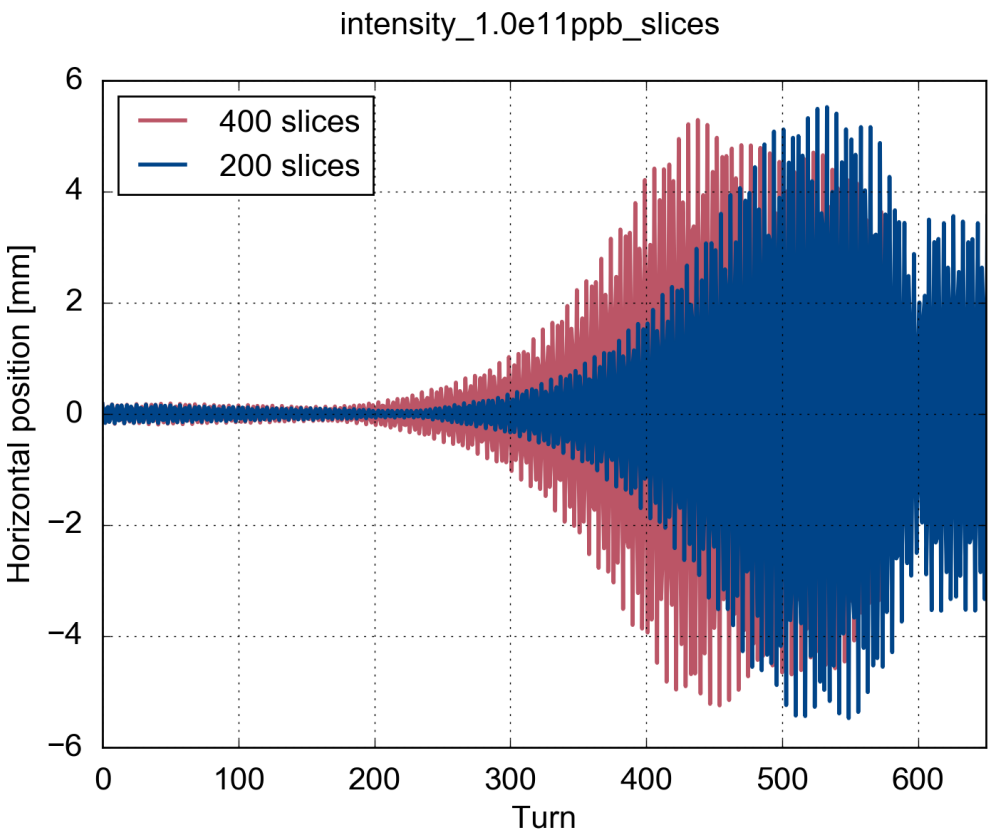
- The instability can be suppressed with octupoles
- Chromaticity and octupoles suppress the instability better than only octupoles
- The feedback remains effective also in the presence of chromaticity and octupoles



Convergence

Due to the large computing resources required for the simulations, extensive convergence scans are currently out of reach

- The convergence with respect to the number of slices the beam is divided into for the e-cloud interaction has been tested for the LHC simulation
  - There is not a significant difference in the instability rise time for the two cases → We could continue to run with 200 slices, to minimize the run-time



Conclusion

First comprehensive study of coupled-bunch e-cloud instabilities at 450 GeV in LHC

- The study in rough numbers:
  - 200 days of simulations on 800 cores → 3.8 million CPU hours
  - 600 GB of data produced
    (Transferring and post-processing of the data is very time-consuming and computationally intensive)

- Main conclusions
  - The instability develops in a similar time for LHC and HL-LHC intensities, but with a different pattern along the train
  - With 15 units of chromaticity, the instability is somewhat mitigated, but not suppressed
  - Both an ideal transverse damper and octupoles can suppress the instability over the simulated time span

Further studies

Some ideas for future studies:

- Further analysis on the presented simulation data sets (e.g. FFTs)
- Investigate why the instability develops in a specific region along the train (and why they are different for different intensities)
- Introduce quadrupoles in the simulations to investigate their effect on stability and mitigation techniques
- Introduce a more realistic transverse feedback (would require significant amount of development)