Beam stability in the presence of electron cloud

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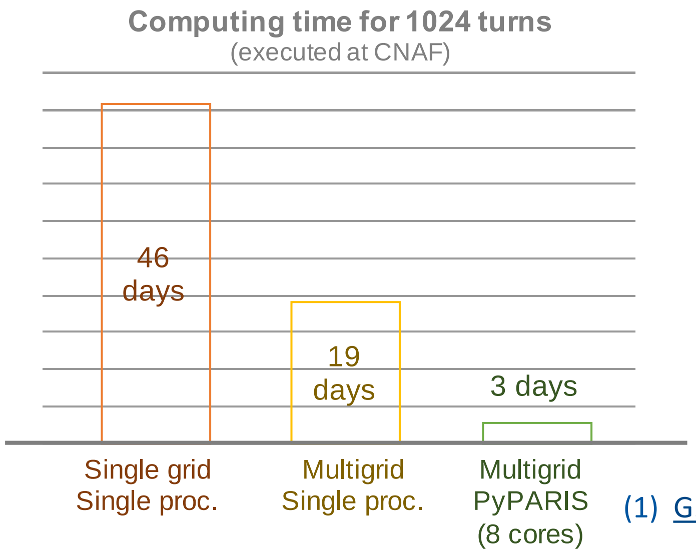
Many thanks to: G. Arduini, D. Cesini, K.Li, L. Mether, E. Métral and the INFN-CNAF institute in Bologna

PyECLOUD-PyHEADTAIL

Understanding of EC phenomena heavily relies on PyECLOUD-PyHEADTAIL simulations

- Simulations are very demanding in terms of time and computational resources → multi-scale problem
    - in space: small beam (~100 um) in a big chamber (4 cm)
    - in time: 1 ns for the e- motion, 1 to 10 s for instability development
- Recent work has been focused on increasing the performance of the simulation tools (1)
    - "telescopic" grid introduced in the Particle in Cell solver
    - exploit parallel computing through a new parallelization layer (PyPARIS)

→ Allowed gaining new insights on scenarios that were previously inaccessible!



(1) G. Iadarola et al, "THPAB043 (2017)

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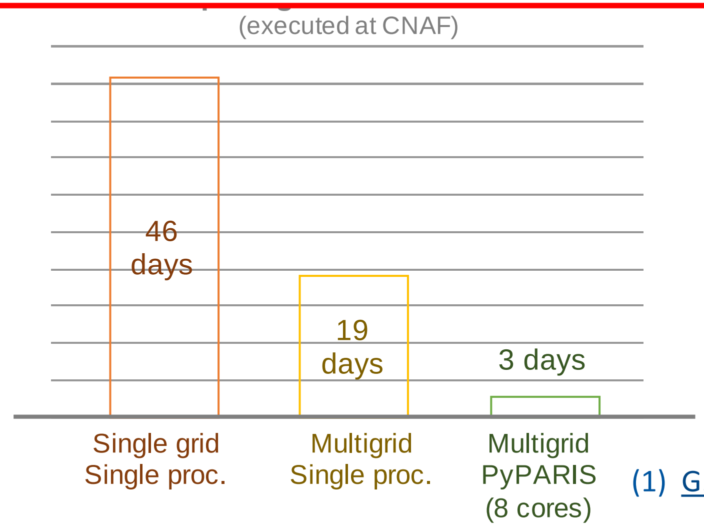
To approach the time-scale of beam observations in the LHC we need to simulate 10^4 turns

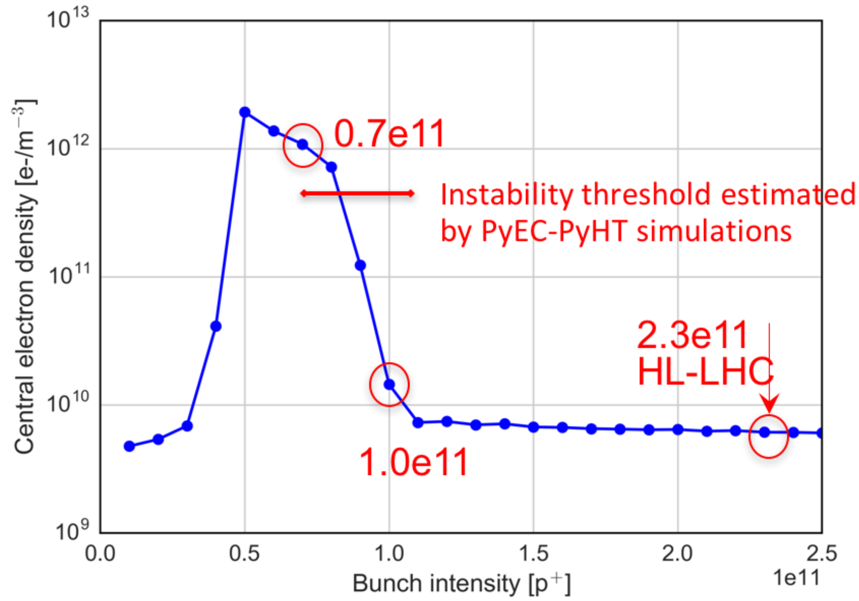
- 3-4 weeks of computing time and hundreds of CPUs (8-16 CUPs per job)
- HPC cluster at the INFN-CNAF in Bologna are extensively used for this purpose → simulations steadily running since June ☺



(1) G. Iadarola et al, "THPAB043 (2017)

Lessons learned from LHC

- EC in **dipoles** (~65% of the machine) is **not** expected to drive instabilities both at injection and top energy
    - ➢ the onset of instability development in dipoles depends on the electron density seen by the beam(1)→ in the present conditioning state of the LHC estimated density below the instability threshold
    - ➢ however the situation changes significantly when the bunch intensity decreases w.r.t. the nominal parameters → observations of instabilities in collisions consistent with our simulation studies (2) ☺

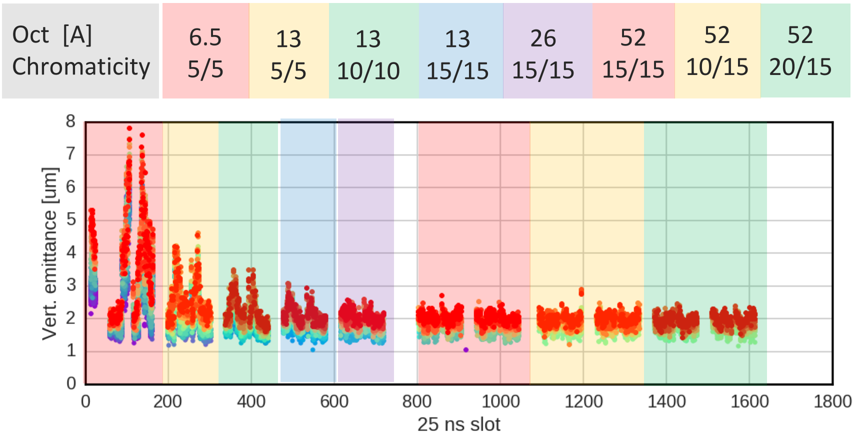


(1) H. Bartosik et al., "BENCHMARKING HEADTAIL WITH ELECTRON CLOUD INSTABILITIES OBSERVED IN THE LHC", ECLOUD12
(2) A. Romano et al., "Instabilities in stable beams", presentation at the ½ -day internal review of LHC performance limitations during run2

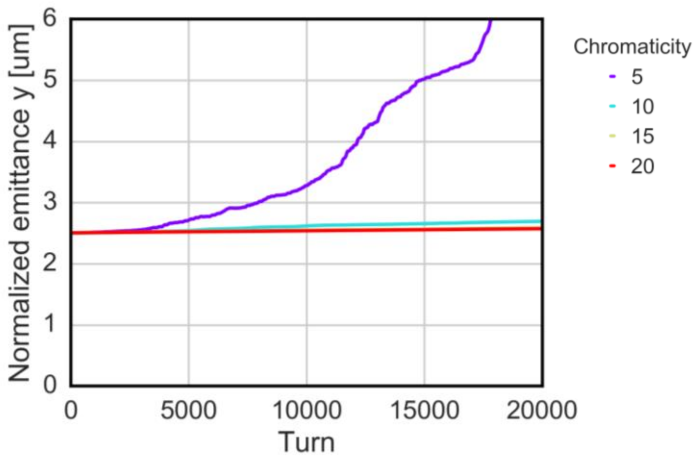
Lessons learned from LHC

- EC in **quadrupoles** (7% of the machine) alone is a key driver of instabilities at the LHC **injection** energy [1]
  - ➢ simulations allowed explaining instabilities observations → large chromaticity values, relatively high octupoles current and a fully functional feedback system were needed to reach a satisfactory emittance preservation
  - ➢ instability suppressed when increasing the beam energy up to 6.5 TeV due to the increased beam rigidity

Bunch-by bunch emittance measurements



PyECLOUD-PyHEADTAIL simulation studies



(1) A. Romano et al., "Electron cloud induced instabilities in the LHC", presentation at the Joint Ecloud-PyHEADTAIL Meeting

Instability simulations for HL-LHC

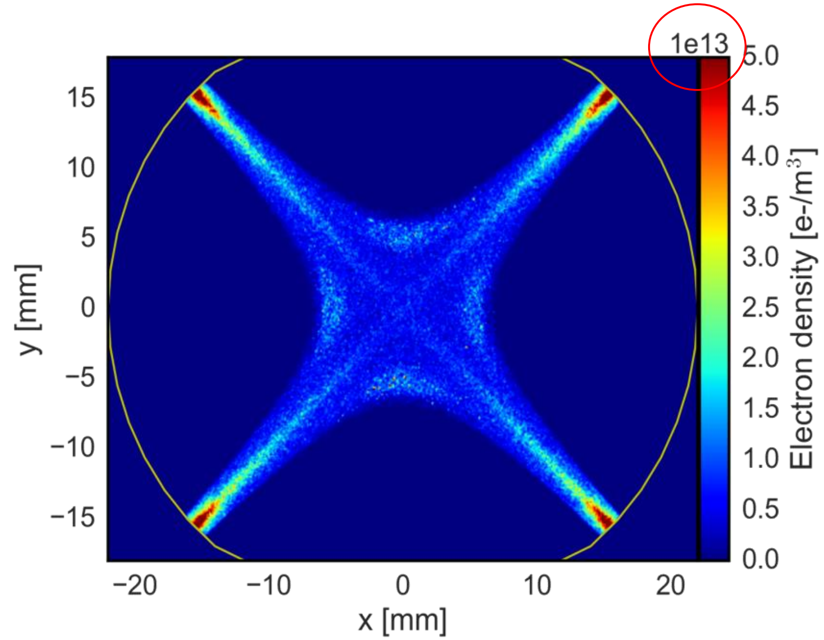
- The interaction of a single bunch with an EC has been simulated in the dipole and quadrupole magnets separately scanning the bunch intensity
  - the initial electron distribution is assumed uniform in the dipoles whereas in the quadrupoles, it is taken from build-up simulations (realistic e- distribution) → see next slides
- The simulation parameters are listed below

Parameters	Value @ 450 GeV	Value @ 7 TeV
N_b (p/bunch)	$0.6\text{-}2.4 \times 10^{11}$	$0.6\text{-}2.4 \times 10^{11}$
$\varepsilon_{x,y}$ (μm)	2.0	2.5
σ_z (cm)	10.4	9.0
B (T, T/m)	0.53, 12	8.3, 188.2
V_{400MHz}	8	16
$<\beta_x>$, $<\beta_y>$	92.7, 93.2	92.7, 93.2

Impact of e- distribution in the quadrupole magnets

- Due to electron trapping from magnetic field gradient
  - ➢ EC density at the beam location is very high
  - ➢ EC pinch dynamics can be very sensitive to the initial phase space distribution[1] → electrons trapped along the magnetic lines resulting in the attenuation of the pinch

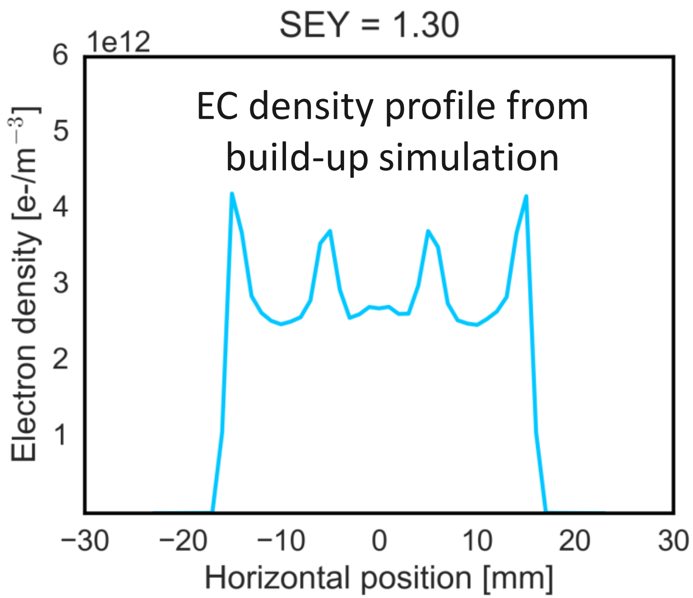
- For these reasons, a realistic initial distribution of electron in the quadrupoles from build-up has to be used to assess the threshold for the coherent instability (self-consistent simulations with the build-up)

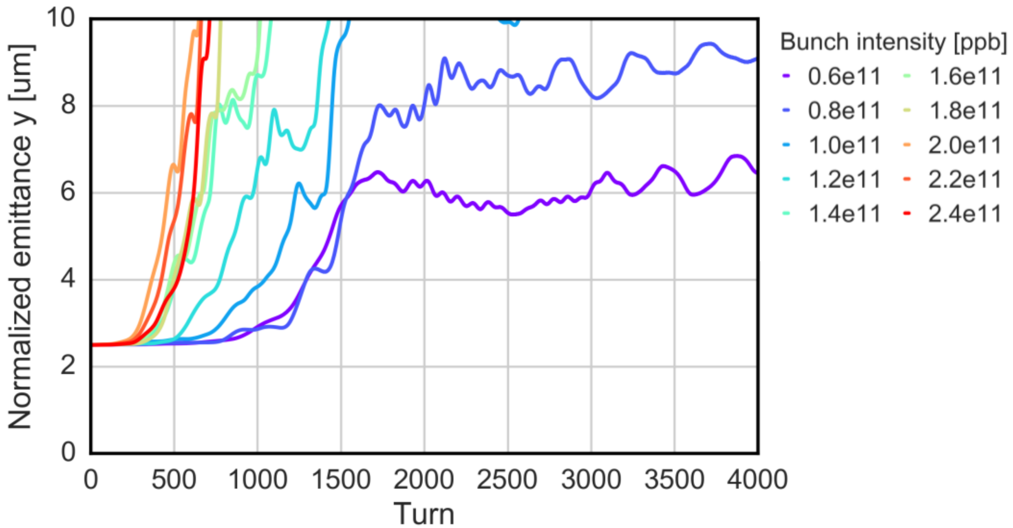


(1) G. Iadarola et al., "EFFECT OF ELECTRON CLOUD IN QUADRUPOLES ON BEAM INSTABILITY", IPAC15

Impact of e- distribution in the quadrupole magnets

- We want to study the impact of the beam intensity on the instability development
- At first we investigated separately the effect of the intensity increase on the instability mechanism by using the same initial EC distribution
  - EC distribution computed for N_b =1.0e11 and then used it as input for a set of instability simulations → realistic distribution from build-up but not self-consistent with intensity
  - Instability rise-time is much faster for higher beam intensities

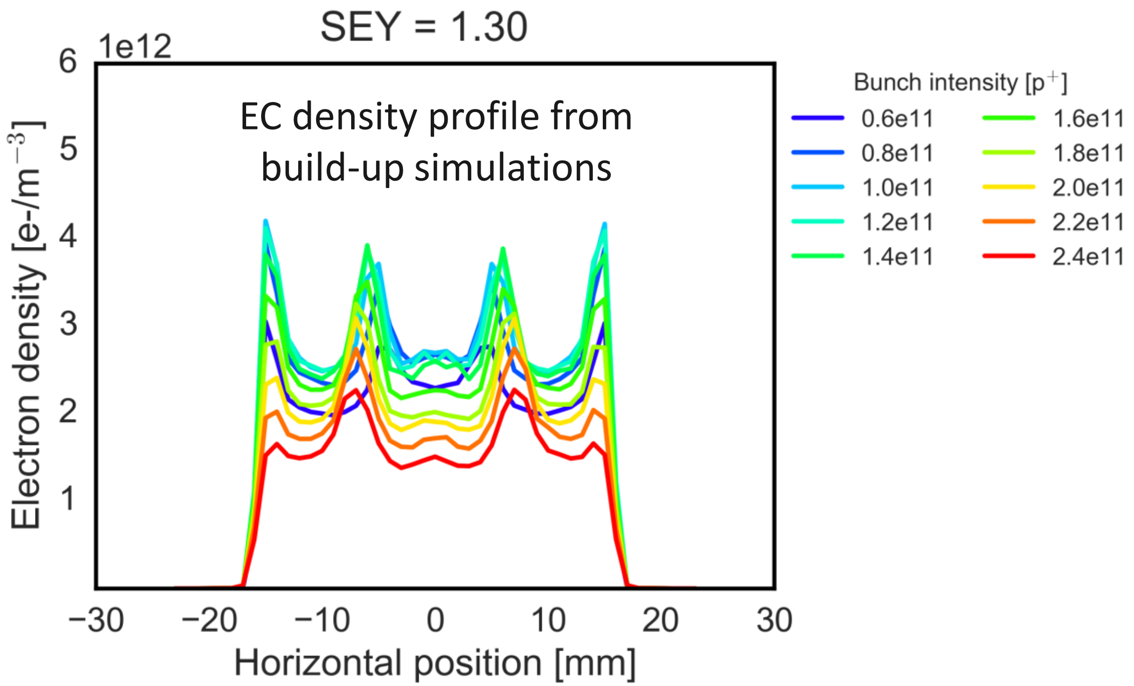




(Realistic total length of quadrupoles, NO chromaticity, NO octupoles, NO damper)

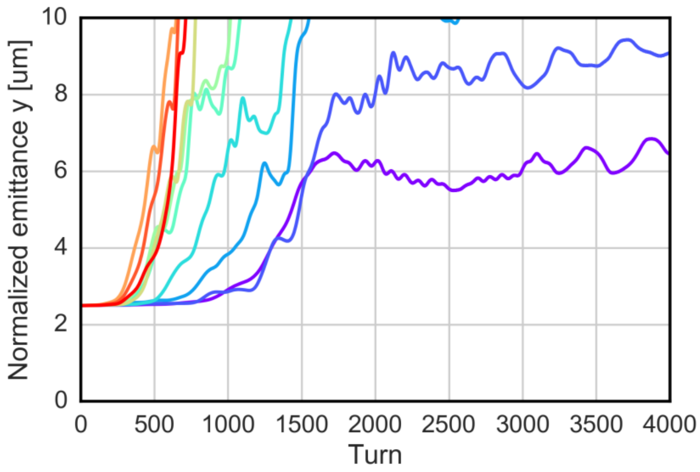
Impact of e- distribution in the quadrupole magnets

- We want to study the impact of the beam intensity on the instability development
- At first we investigated separately the effect of the intensity increase on the instability mechanism → for the same initial EC distribution instability rise-time faster for higher beam intensities
- However, the EC density profile estimated for different bunch intensity shows that for increasing bunch intensities, the electron density decreases significantly all over the chamber

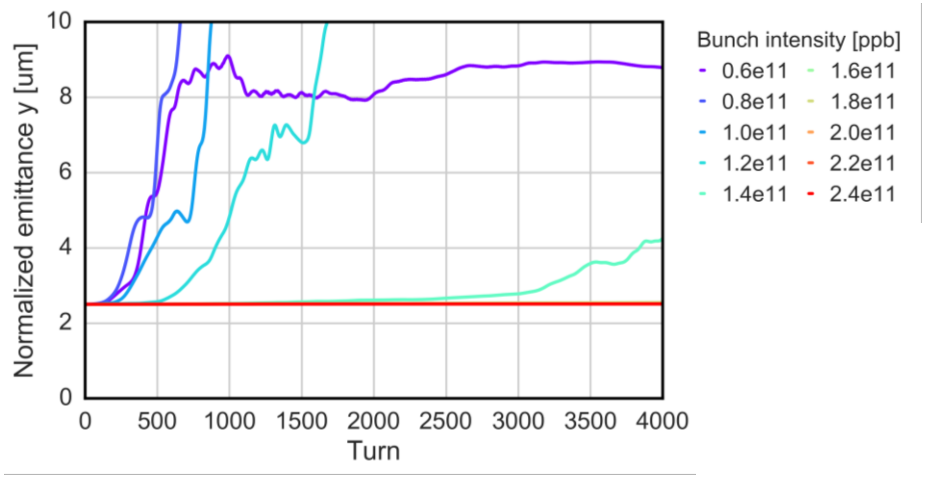


Impact of e- distribution in the quadrupole magnets

Initial distribution from build-up assuming N_b = 1.0e11 → same input for all cases



Initial distribution from build-up computed "ad-hoc" for each bunch intensity (self-consistent)



- The electron density is overestimated (up to a factor 2) when using the same EC distribution (computed for N_b =1.0e11) as input for a set of instability simulations
- Relying on self-consistent simulations
  - Instability observed for lower bunch intensity → larger EC density in the chamber
  - For higher bunch intensity the e- density is not sufficient to drive the bunch unstable

Impact of e- distribution in the quadrupole magnets

Initial distribution from build-up assuming N_b = 1.0e11→ same input for all cases

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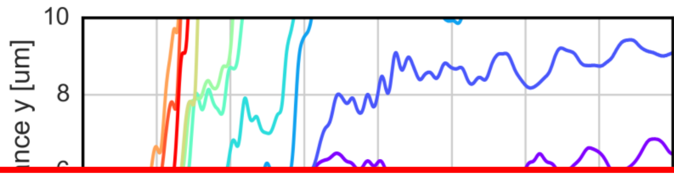
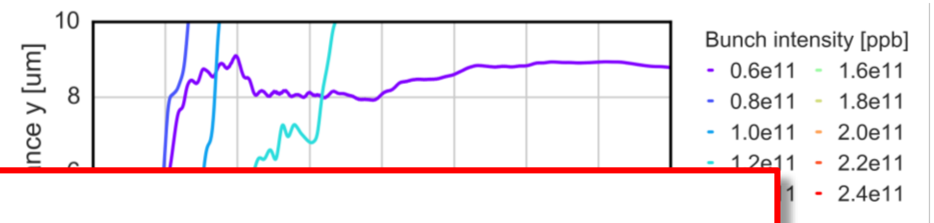




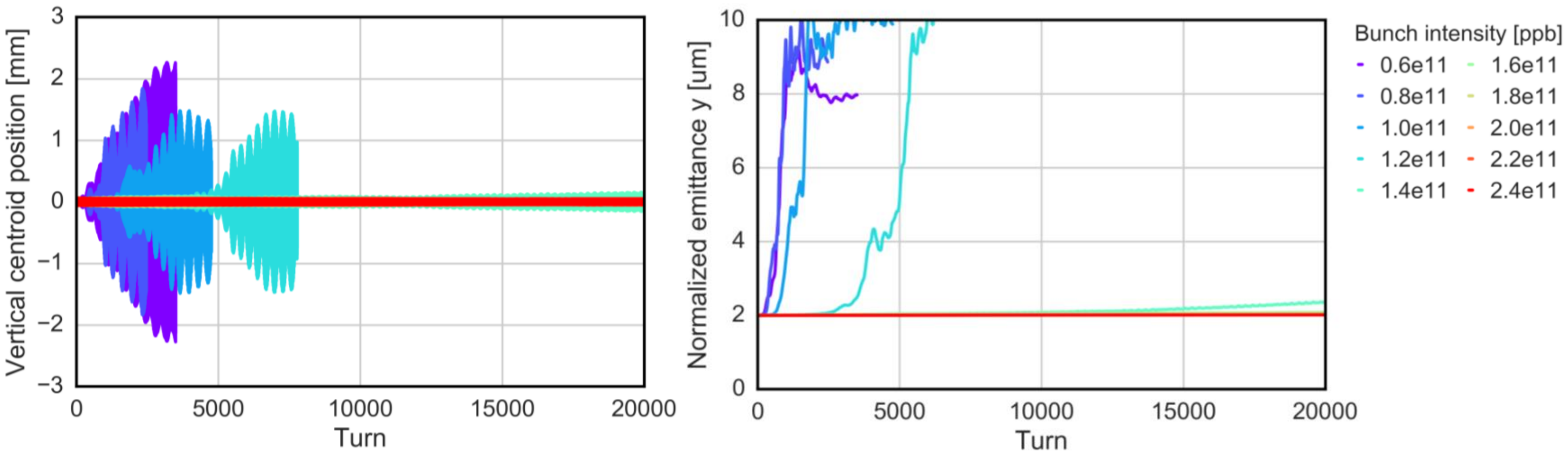
- To estimate correctly the instability threshold we need run self-consistent simulations with bunch intensity → initial EC distribution computed “ad-hoc” for different bunch intensities and used as input for instability simulations
- In these conditions the increase of the bunch intensity has a beneficial impact on the beam stability

- Relying on self-consistent simulations
  - Instability observed for lower bunch intensity → larger EC density in the chamber
  - For higher bunch intensity the e- density is not sufficient to drive the bunch unstable

Arc quadrupoles @ 450 GeV: only EC

- Instability observed in both planes, consistently with the symmetry of the e-cloud dynamics in the quadrupoles
- Unlike LHC, EC in quadrupoles is not expected to drive instabilities at injection within the beam intensity upgrade foreseen by HL-LHC (N_b=2.3e11 p/bunch) → provided that intensity dependence from build-up simulations is confirmed experimentally

EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3 (**after scrubbing**)	OFF	0/0	0

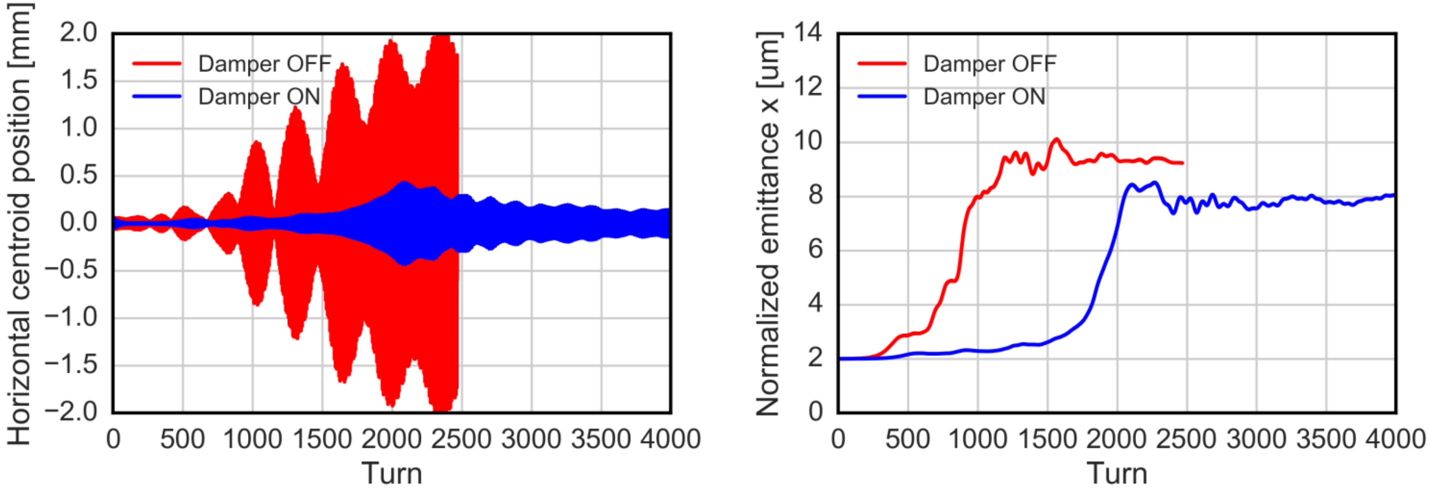


(similar behaviour in the horizontal plane)

Arc quadrupoles @ 450 GeV: transverse feedback effect

- $N_b = 8x10^{10}$ ppb → **unstable case**
- Feedback system helps in reducing the centroid oscillation but not the emittance growth

EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	ON	0/0	0

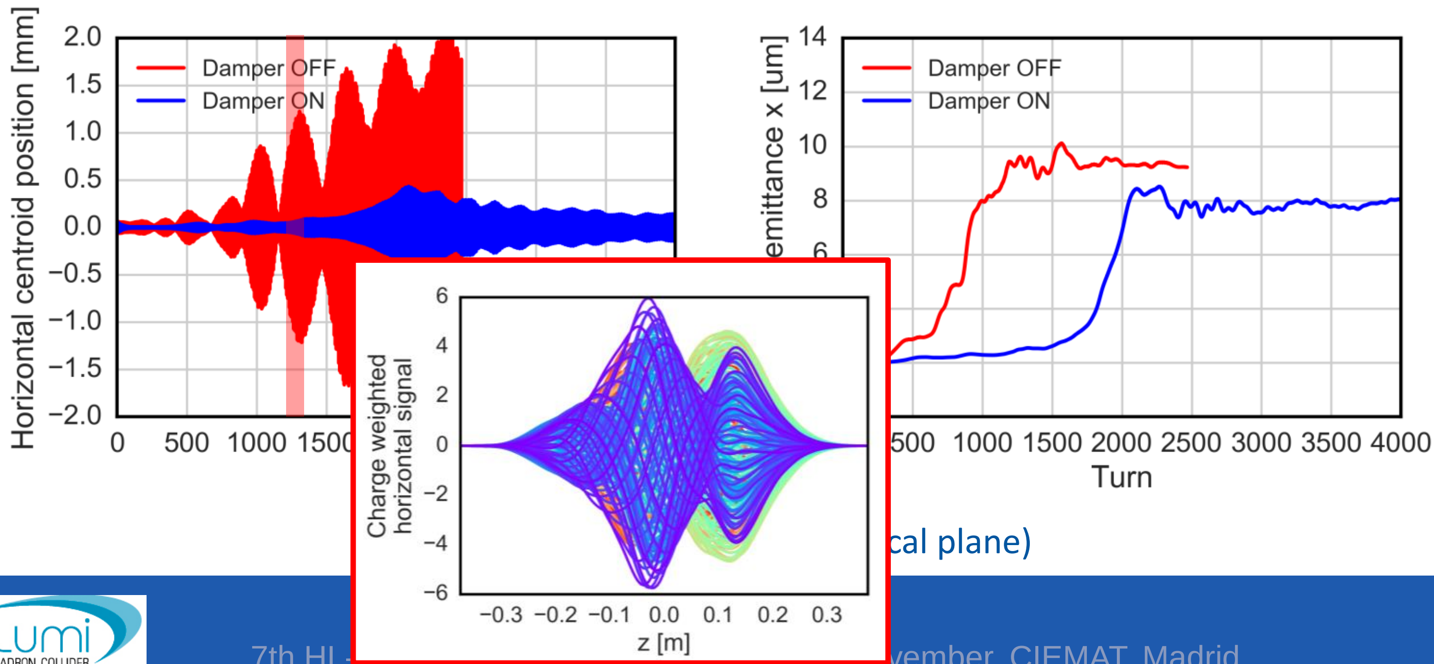


(similar behaviour in the vertical plane)

Arc quadrupoles @ 450 GeV: transverse feedback effect

- $N_b = 8 \times 10^{10}$ ppb → **unstable case**
- Feedback system helps in reducing the centroid oscillation but not the emittance growth
  - Higher order modes excited → cannot be damped by the traditional damper
- Consistent with the machine observation during the scrubbing run → higher damper gain helped to mitigate fast losses

EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	ON	0/0	0

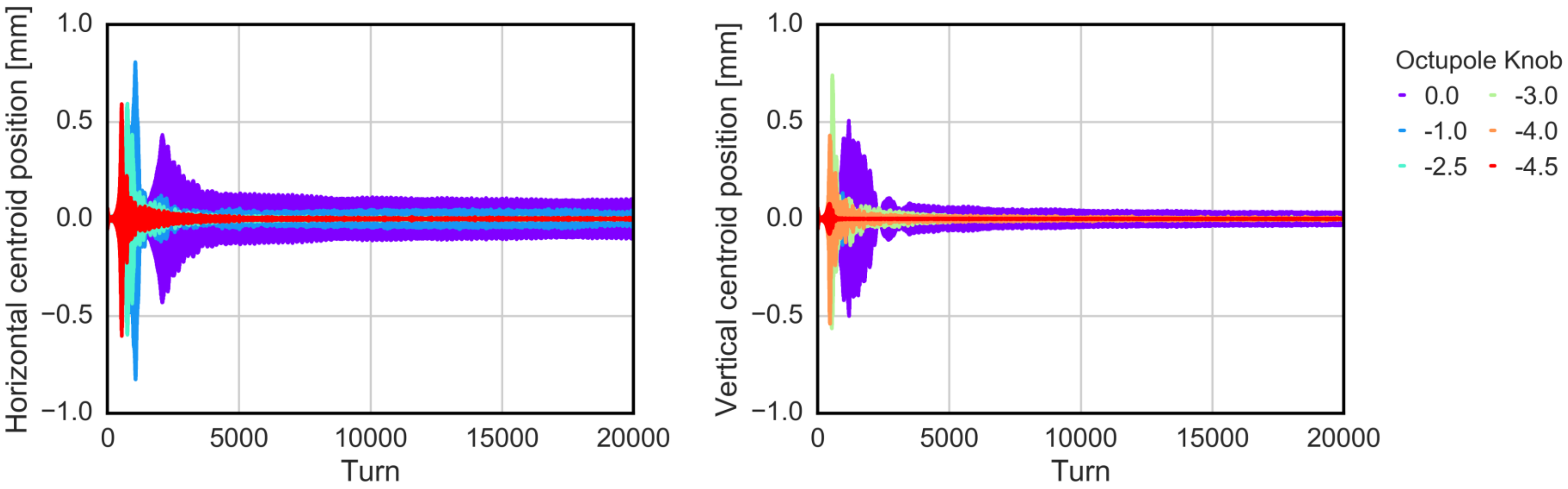


cal plane)

Arc quadrupoles @ 450 GeV: octupoles effect

- N_b = 8x10[10] ppb → **unstable case**
- Mild stabilizing effect of octupoles alone
  - attenuation of bunch oscillations in both planes

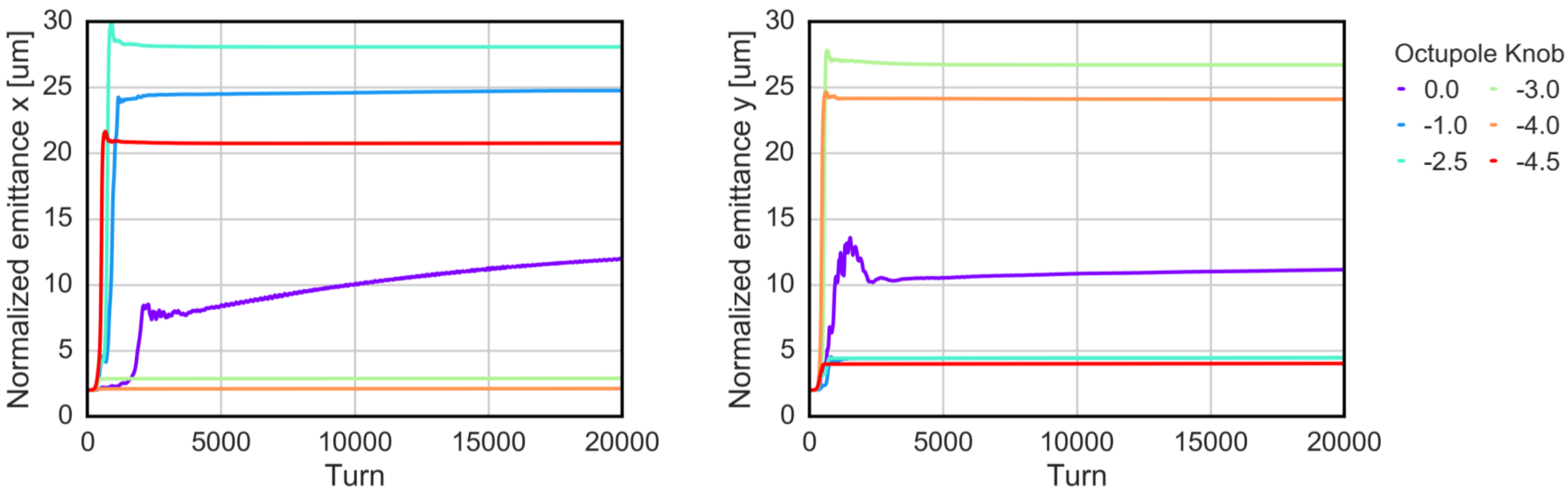
EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	ON	0/0	scan



Arc quadrupoles @ 450 GeV: octupoles effect

- $N_b = 8 \times 10^{10}$ ppb → **unstable case**
- Mild stabilizing effect of octupoles alone
  - attenuation of bunch oscillations in both planes
  - emittance growth still visible → instability randomly starting either from horizontal or from vertical plane

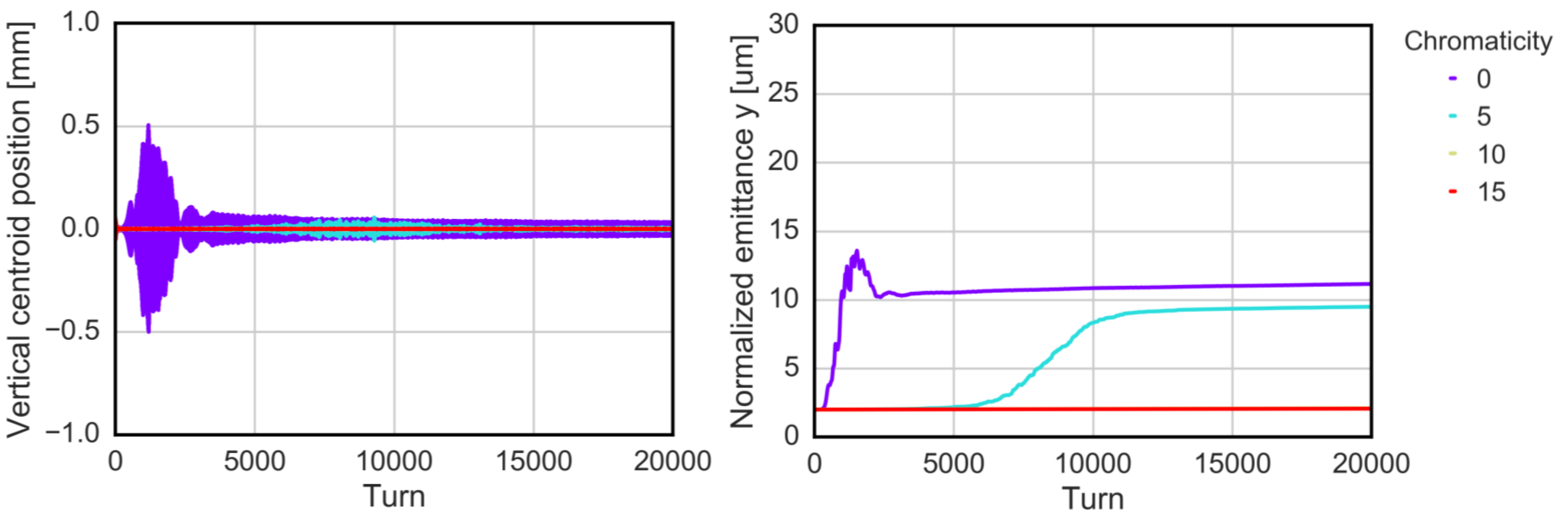
EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	ON	0/0	scan



Arc quadrupoles @ 450 GeV: chromaticity effect

- $N_b = 8 \times 10^{10}$ ppb → **unstable case**
- Strong stabilizing effect of chromaticity alone
  - Suppression of bunch oscillations
  - Rise time of the instability slower when increasing the chromaticity → for large chromaticity values no visible emittance blow-up

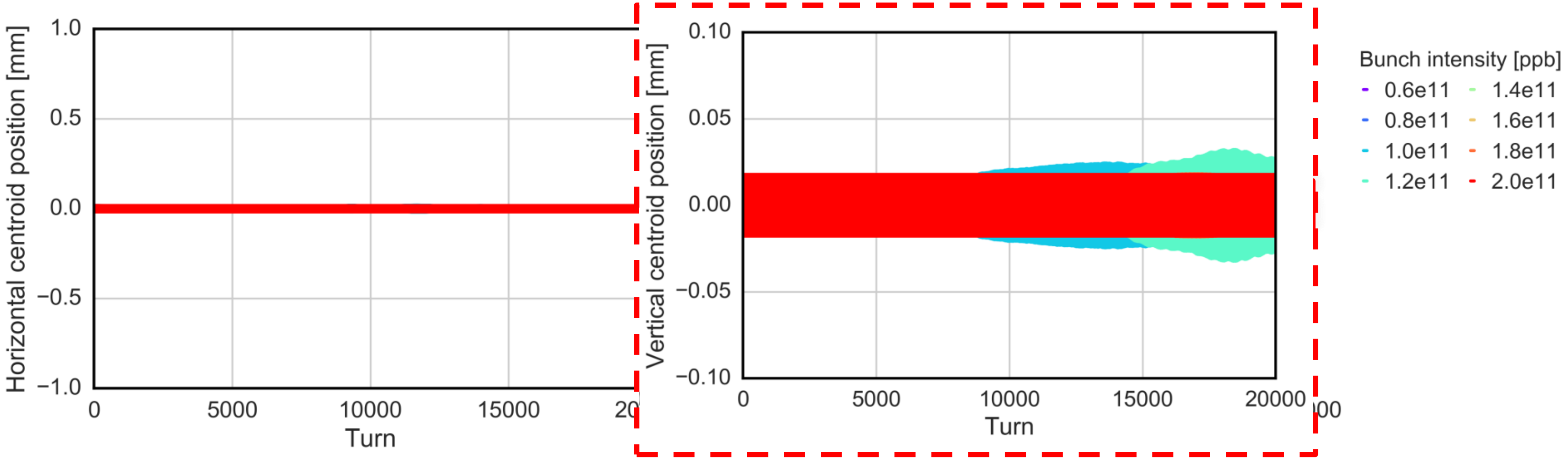
EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	ON	Scan	0



Arc quadrupoles @ 7 TeV: only EC

- For bunch intensities larger than 2.0e11 the multipacting process does not occur for SEY=1.30
- Strong stabilizing effects of the increased beam energy → effect of the increased beam rigidity
- Few unstable cases around LHC-like intensities can be observed in only the vertical plane, developing after 10k simulated turns

EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	OFF	0/0	0



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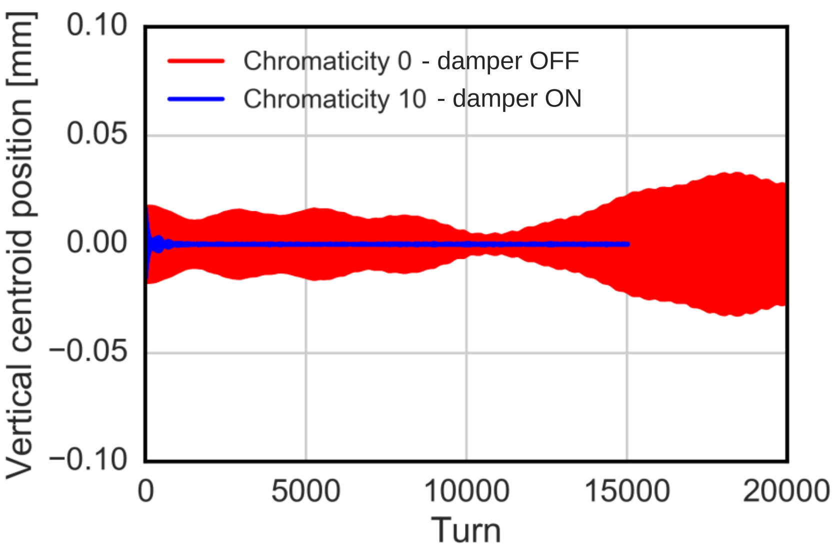
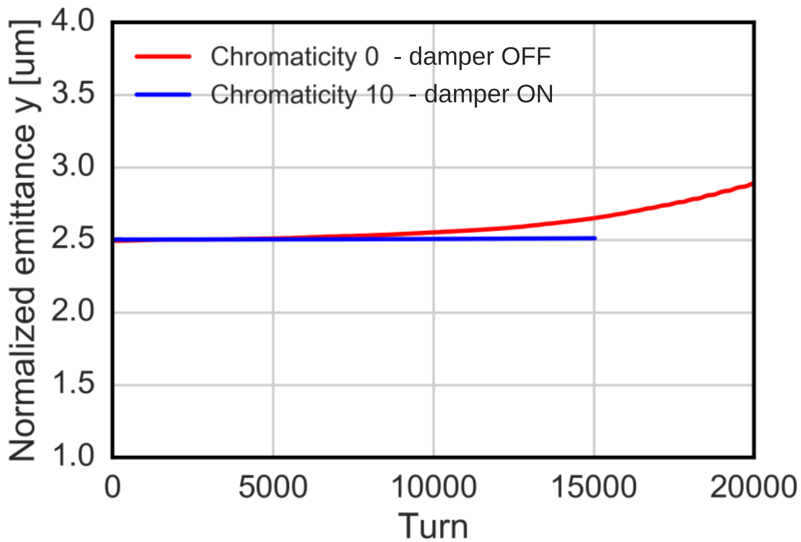
- Strong stabilizing effects of the increased beam energy → effect of the increased beam rigidity
- Few unstable cases around LHC-like intensities can be observed in only the vertical plane, developing after 10k simulated turns → stabilized by increasing the chromatcity

EC in quads	Damper	Chromaticity	Octupoles current
SEY 1.3	As labelled	As labelled	0





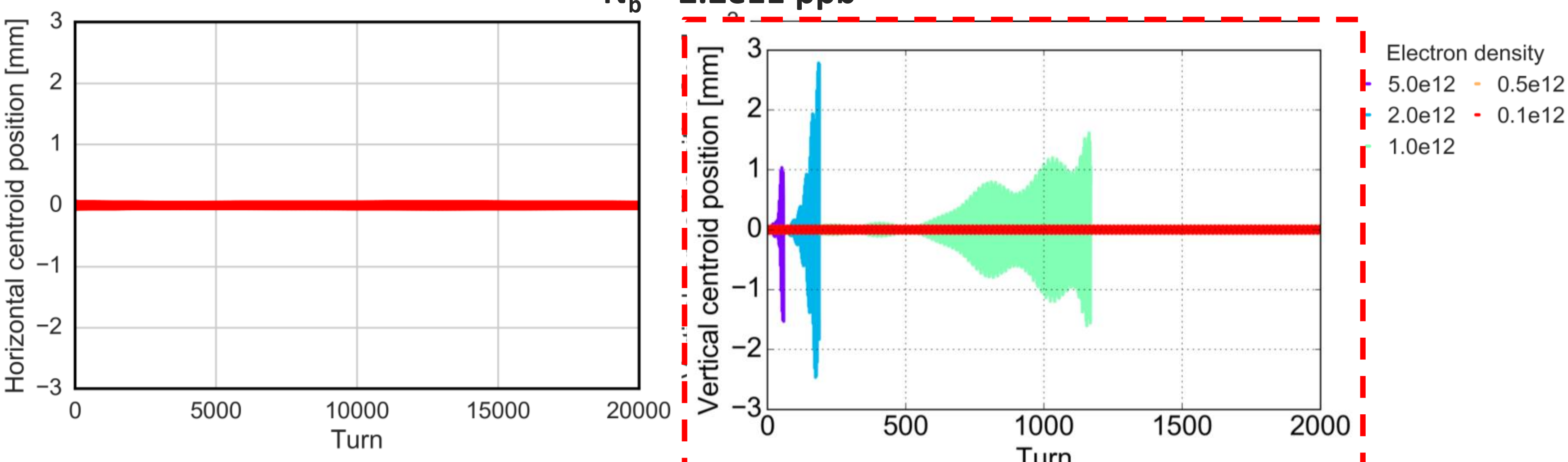
Arc dipoles @ 450 GeV: a first look

- EC distribution is initialized uniform within the dipole chamber and its density is scanned → good approximation[(1)]

- Instabilities observed only in the vertical plane
  - fast rise-time for large e- densities
  - instability threshold at around 1e12 e-/m^3

EC density in Dip	Damper	Chromaticity	Octupoles current
1e11-5e12	OFF	0/0	0

N_b = 2.2e11 ppb



(1) H. Bartosik et al., "BENCHMARKING HEADTAIL V ... HC", ECLOUD12

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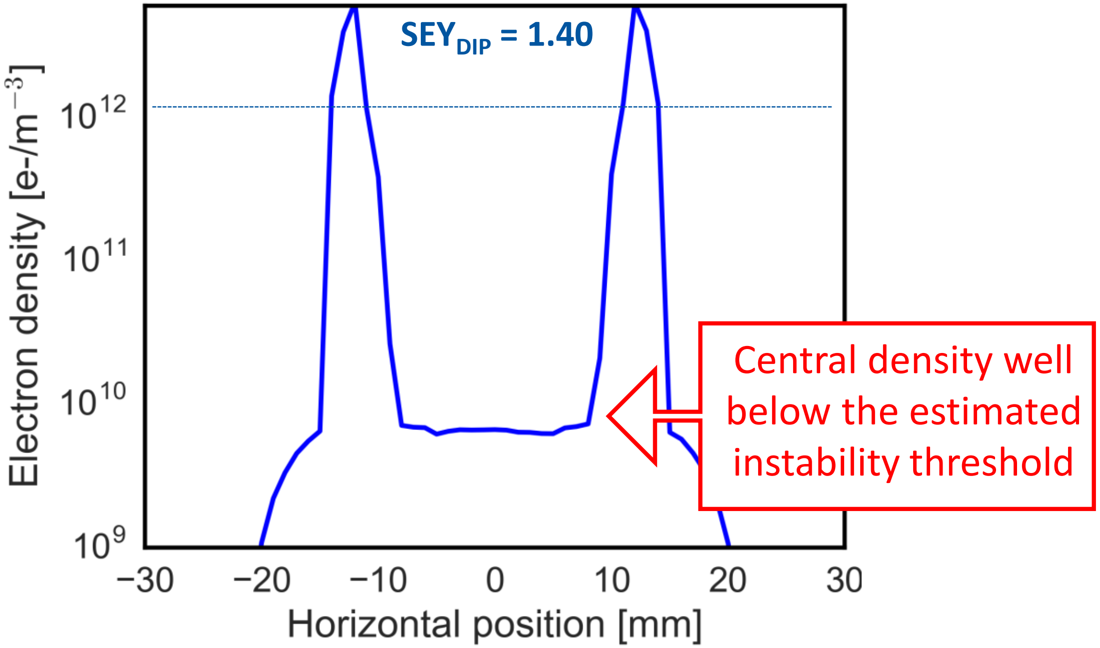
Estimated e- density from PyECLOUD build-up simulations



(1) H. Bartosik et al., "BENCHMARKING HEADTAIL WITH ELECTRON CLOUD INSTABILITIES OBSERVED IN THE LHC", ECLOUD12

Conclusions

- Simulation results show that the beam intensity increase foreseen by the HL-LHC has a beneficial impact on the beam stability

- Unlike LHC, the EC in quadrupoles in HL-LHC is not expected to drive the beam unstable both at injection and flattop energy after conditioning → provided that intensity dependence from build-up simulations is confirmed experimentally
  - However potential mitigation strategies have been investigated → strong stabilizing effect from large chromaticity values and mild effect from octupoles and damper

- Preliminary studies in dipoles show that the EC density in the beam chamber is well below the estimated instability threshold → EC induced instabilities at injection are not expected in HL-LHC

Thanks for your attention!