Electron cloud instability studies for the LHC

A. Romano, G. Iadarola, G. Rumolo

Many thanks to: X. Buffat, P. Dijkstal, K. Li, L. Mether, E. Métral

Outline

1. Overview on my PhD work
    - Topics studied
    - Ongoing studies
    - Activities and conferences

2. Electron cloud induced instability in the LHC during collisions at 6.5TeV
    - Instability observations: background and history
    - Simulations studies and challenges
    - Comparison of simulation results with the available experimental observations

3. Highlights from ongoing studies and next steps

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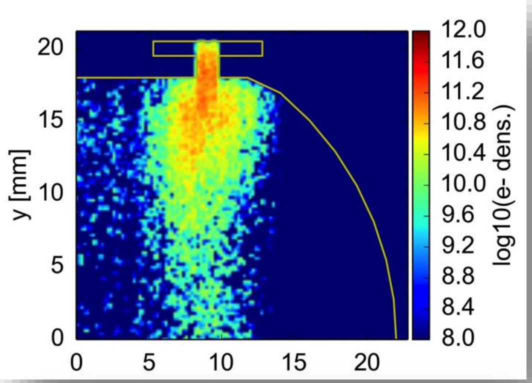
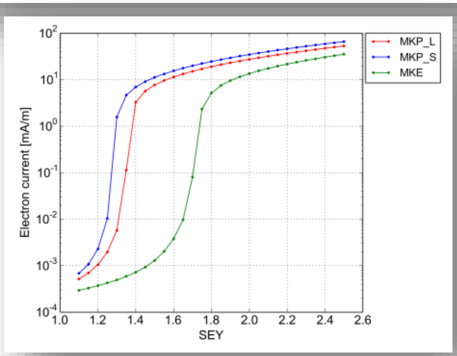
1. TOPICS STUDIED SO FAR

➢ ELECTRON CLOUD BUILD-UP

- Effect of the LHC beam screen baffle on the electron cloud buildup (Electron_cloud_Meeting_18.09.15, Proceedings_IPAC16)
- Electron cloud build up simulations in the SPS MKP and MKE (MKP_Strategy_Meeting_30.06.16, MKP_Strategy_Meeting_7.11.16)

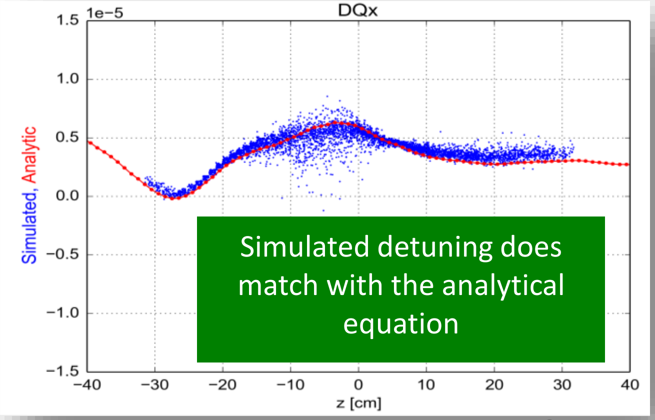




➢ ELECTRON CLOUD EFFECTS ON THE BEAM DYNAMICS

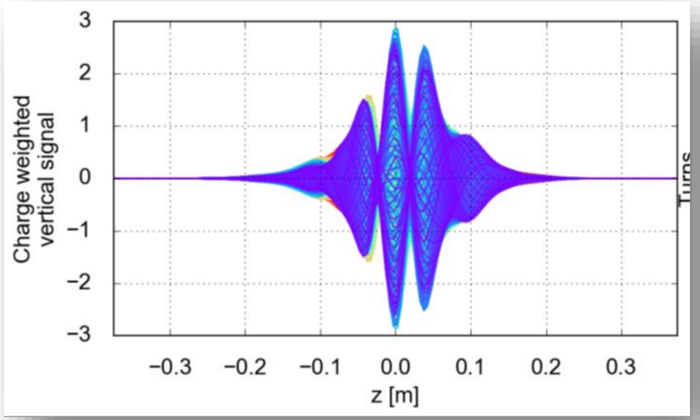
Incoherent effects

- Effect of the electron cloud on the tune footprint in the LHC arcs at injection energy (LBOC_Meeting_27.10.15)
- Effect of the electron cloud on the tune footprint in the LHC Interaction Regions at high energy (Electron_Cloud_Meeting_3.06.16)



My PhD work

Coherent effects



- Overview on the Electron cloud effect on the LHC beam dynamics (e.g preliminary results obtained using new developed tools) (Electron_Cloud_Meeting_30.09.16)
- Investigations on the electron cloud impact on the observed instabilities at high energy (1/2_Day_Internal_review_29.11.16)

Subject of this presentation and potential peer reviewed paper

2. ONGOING STUDIES

➢ **ELECTRON CLOUD EFFECTS ON THE BEAM DYNAMICS** *(coherent and incoherent effects)*

- Understanding of the EC driven instabilities in the arcs together with chromaticty, octupoles and transverse feedback → long simulations run to approach the time scale of machine observations

3. ACTIVITIES and CONFERENCES

- Experiment at LHC (MD, Scrubbing run)
- KWT (2015, 2016, 2017), IPAC '17, ICFA

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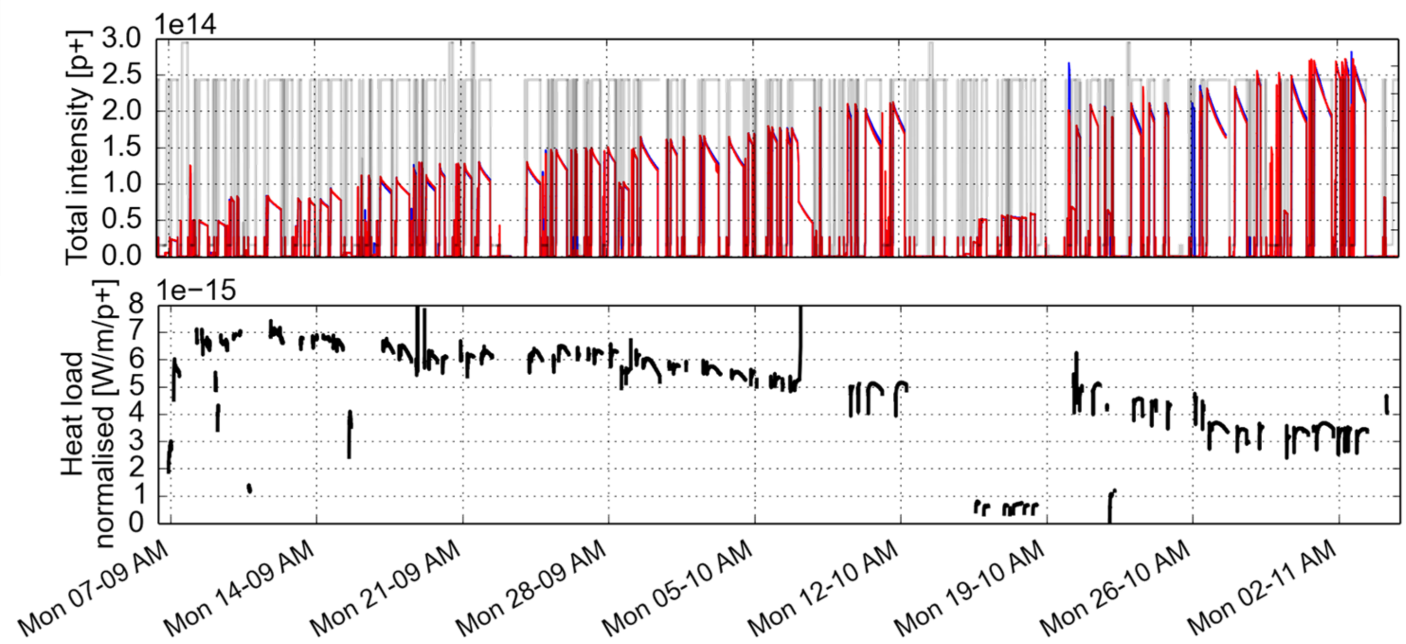
Key findings for instabilities in 2015

2015 was successful for LHC operation: deployment of the 25 ns beams and operation at 6.5 TeV → stable foundation for the 2016 physics run but the e-cloud remains still a challenge for the machine operation

- scrubbing is not sufficient to achieve a full e-cloud suppression → but conditioning effect throughout the year has been observed

2015



(See G.Iadarola_Chamonix2017 talk)

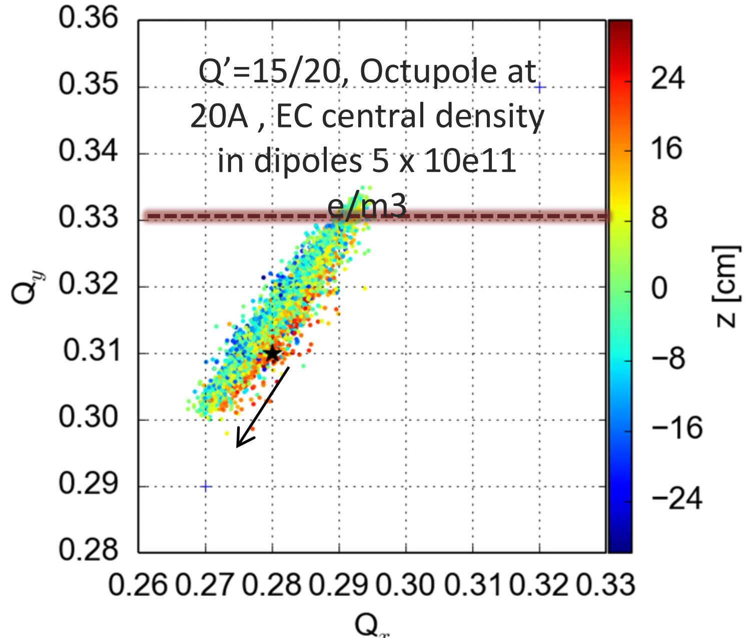
Key findings for instabilities in 2015

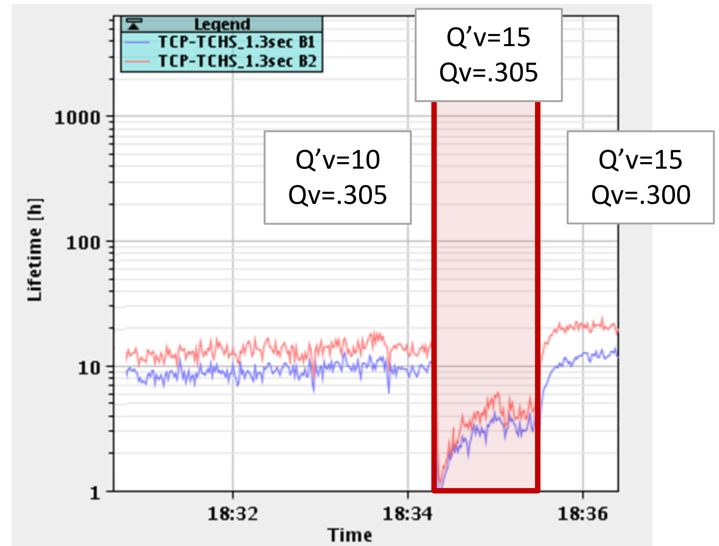
- **2015** was successful for LHC operation: deployment of the 25 ns beams and operation at 6.5 TeV → stable foundation for the 2016 physics run but the e-cloud remains still a challenge for the machine operation
  - scrubbing is not sufficient to achieve a full e-cloud suppression → but contiditiong effect throughout the year has been observed

- Establish operable machine settings to ensure the beam stability
  - **Chromaticity:** $Q'_{H,V} = 15/15$
  - **Octupoles** current: ~20 A → corresponds to $\Delta Q_{oct,spread}$ ~ 1×10^{-3}
  - **Transverse feedback:** high gain, maximum achievable bandwidth

- Further studies has been carried out in order to evaluate the contribution of these settings, together with the detuning induced by the e-cloud, on the tune footprint

Key findings for instabilities in 2015





Optimization of the working point to improve life time and avoid linear coupling

- Further studies have been carried out in order to evaluate the contribution of these settings, together with the detuning induced by the e-cloud, on the tune footprint

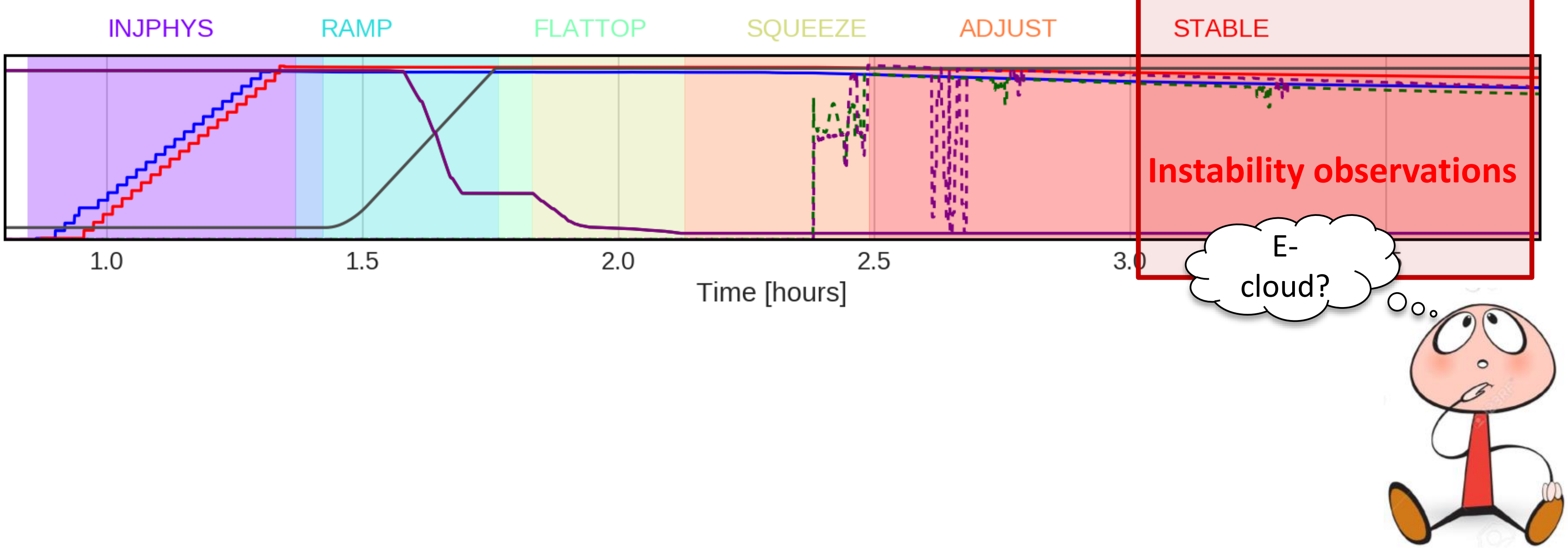
    → large tune footprint at injection which could reach the third order resonance

Moving from 2015 into 2016 LHC operation

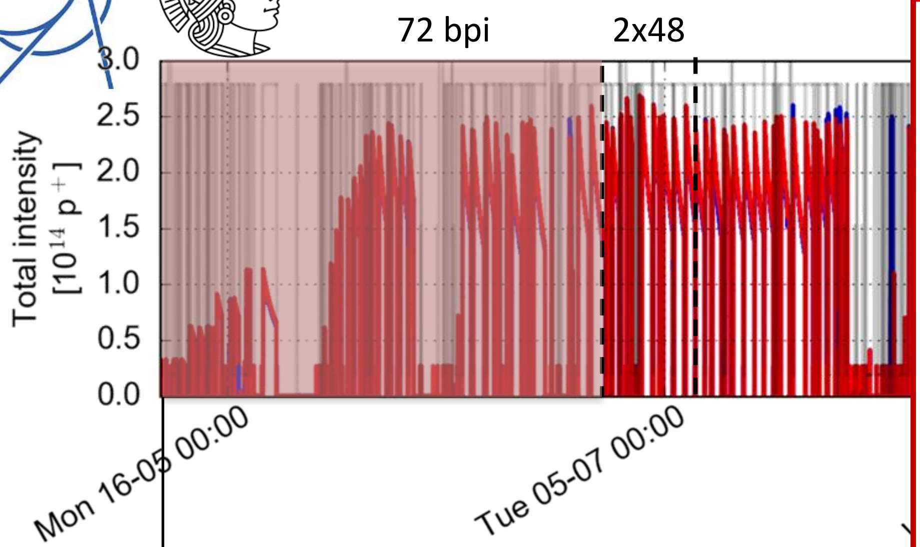
In **2016,** all performance optimizing measures worked out in 2015 have been applied

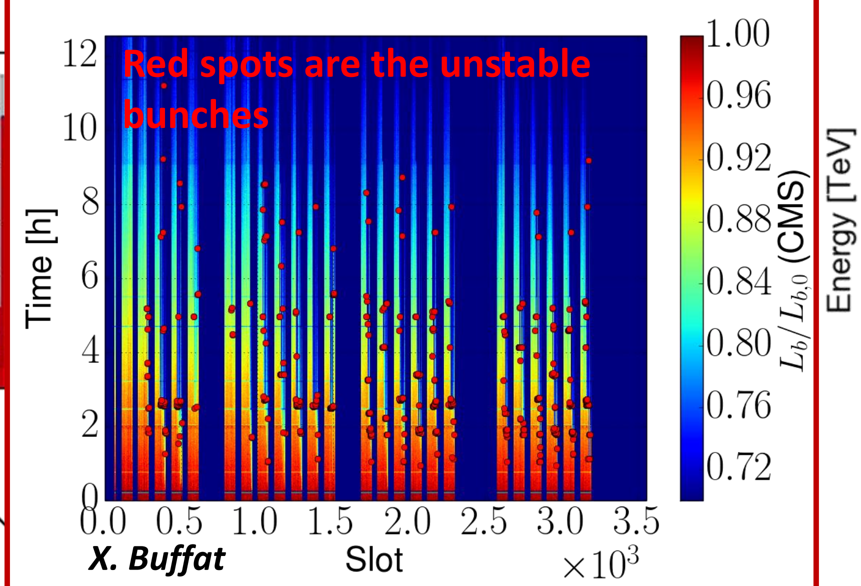
- Observations at the beginning of the run
  - ✧ in spite of high value of chromaticity (15 units in both planes) and high Landau octupoles current, a new type of instability was showing up after few hours in stable beam (i.e stable condition with collisions in the experiments)

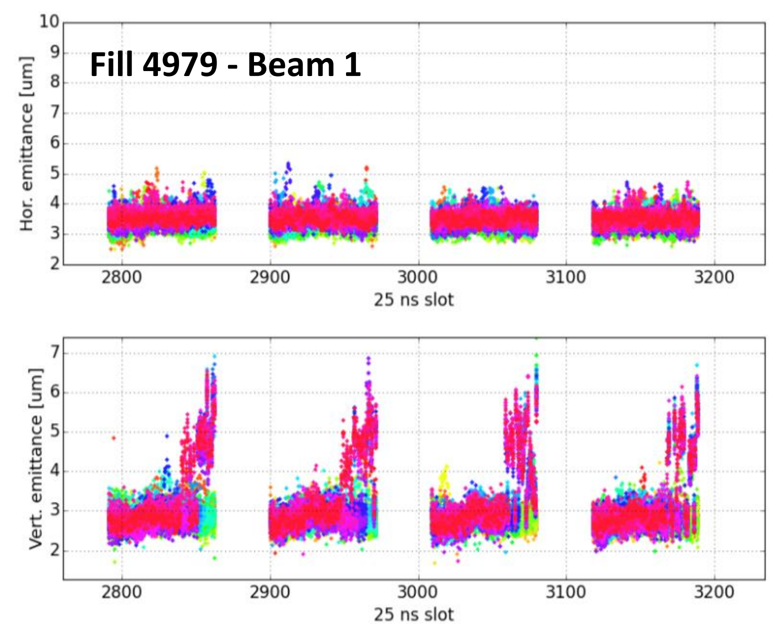
LHC beam mode:



Instabilities observation in stable beam - history



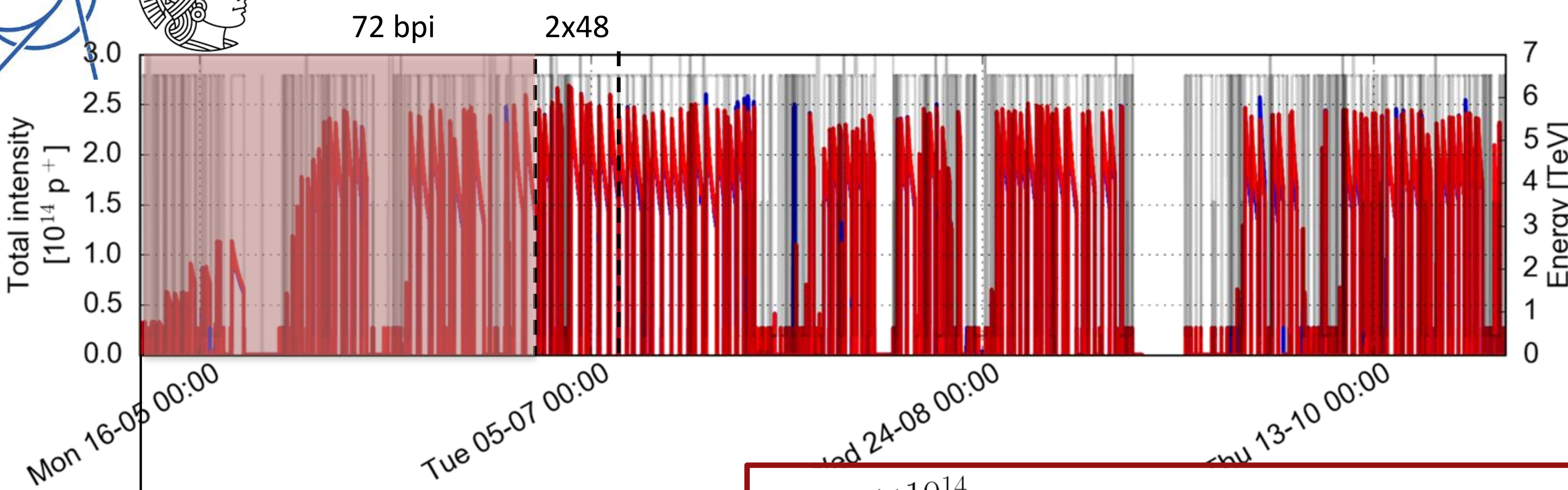




11/05/16

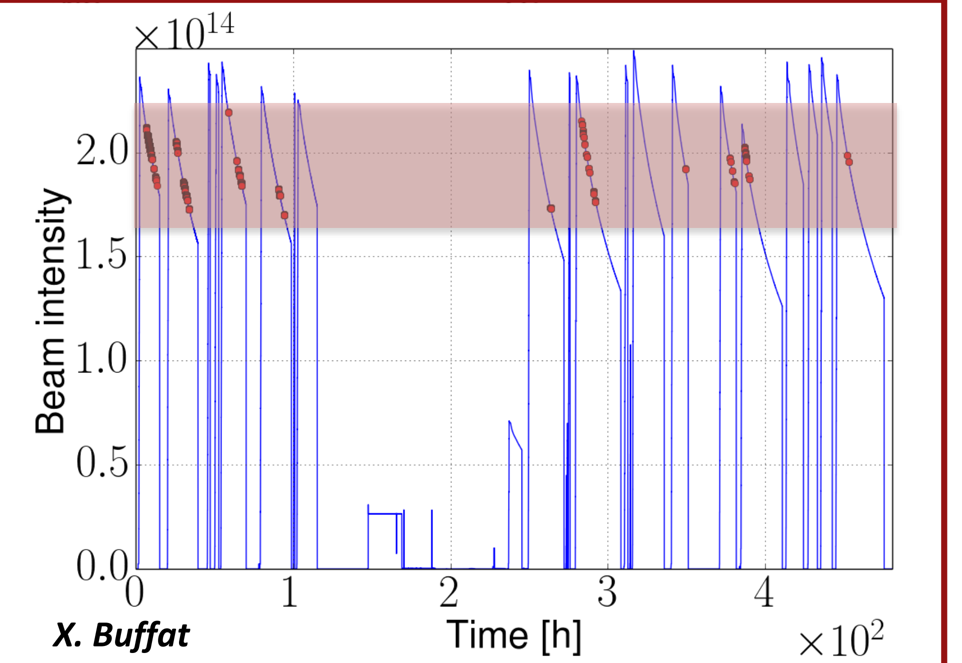
- Instabilities were observed in collisions at 6.5 TeV in most of the fills with trains of 72b.
- Several bunches blew-up in the vertical plane, as observed on bunch by bunch luminosity and BSRT data → affecting only bunches at tails of the trains (e-cloud?)

Instabilities observation in stable beam - history

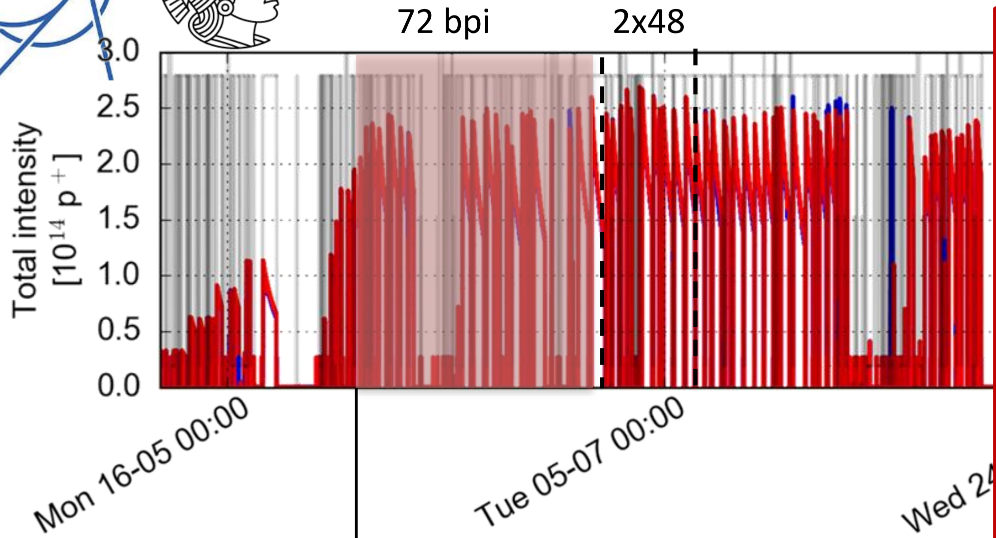


11/05/16

- Instabilities were observed in collisions at 6.5 TeV in most of the fills with trains of 72b.
- Several bunches blew-up in the vertical plane, as observed on bunch by bunch luminosity and BSRT data → ecloud?
- Data analysis showed that most of instabilities occurred for bunch intensities between 0.7e11 and 1.1e11

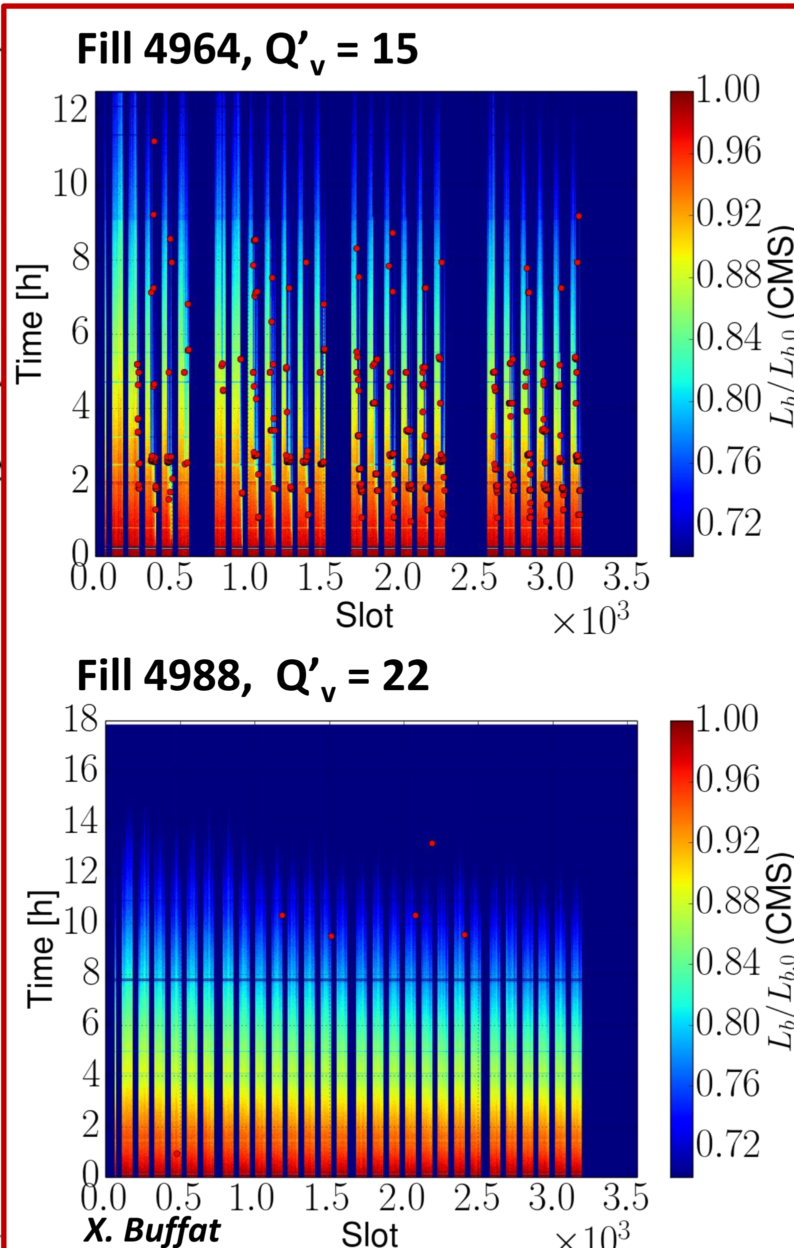


Instabilities observation in stable beam - history

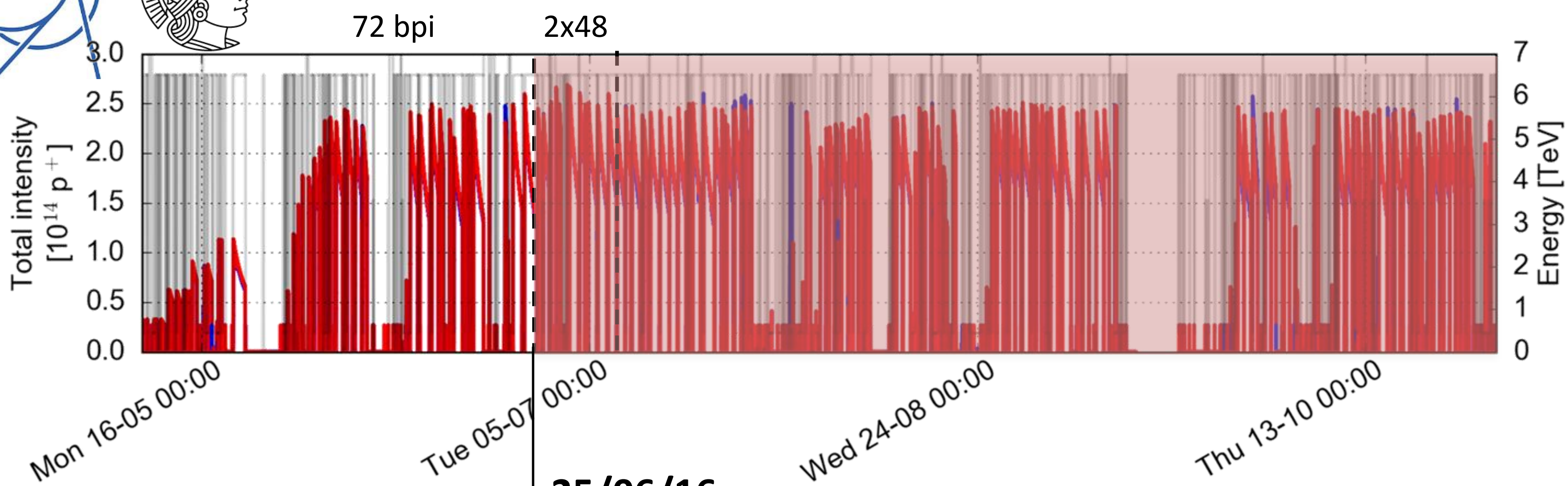


02/06/16

- Vertical chromaticity increased from 15 to 22 units after going in collision
  → blow-up mitigated, instability still sporadically detected on the bunch-by-bunch luminosity data
  → clear improvement on the number of unstable bunches



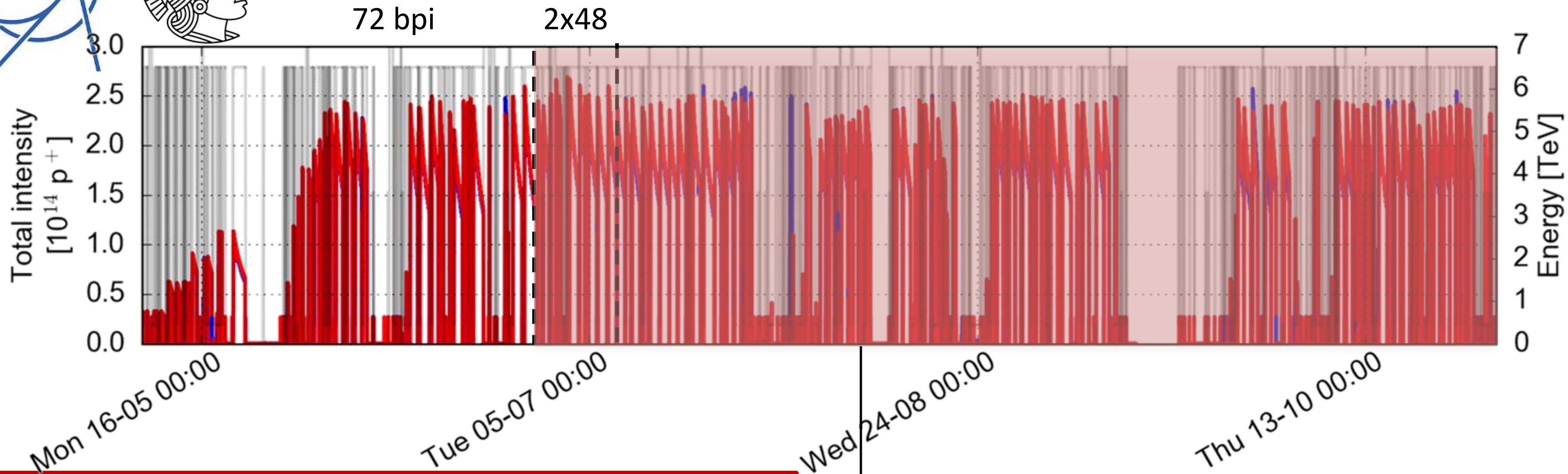
Instabilities observation in stable beam - history

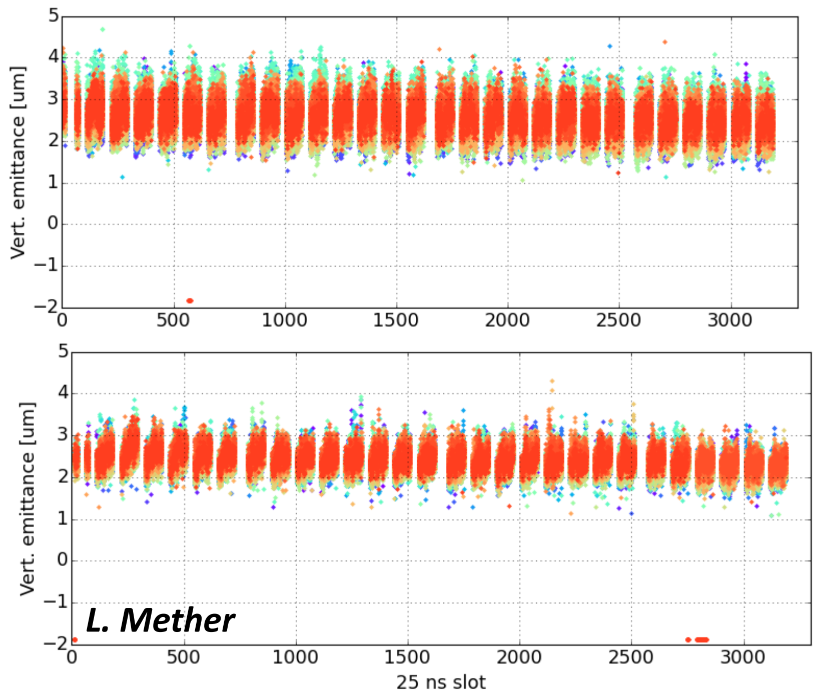


25/06/16 ...

- Physics fills with trains of 48b
  → No instability observed
  → Vertical chromaticity brought down to 15 units in collision still with no sign of instability

Instabilities observation in stable beam - history





19/08/16

- MD fills with trains of 72b. and bunch intensities 1.1e11, 0.9e11 and 0.7e11
- Chromaticity could be reduced to 5 units in stable beams without any sign of instabilities (scrubbing?)

Electron cloud driven instabilities

How the e-cloud can drive an instability?

- When a proton bunch passes through an e-cloud, electrons are attracted towards the transverse center of the beam

  → electron density increases within the bunch inducing coherent bunch oscillations, e.g transverse instability

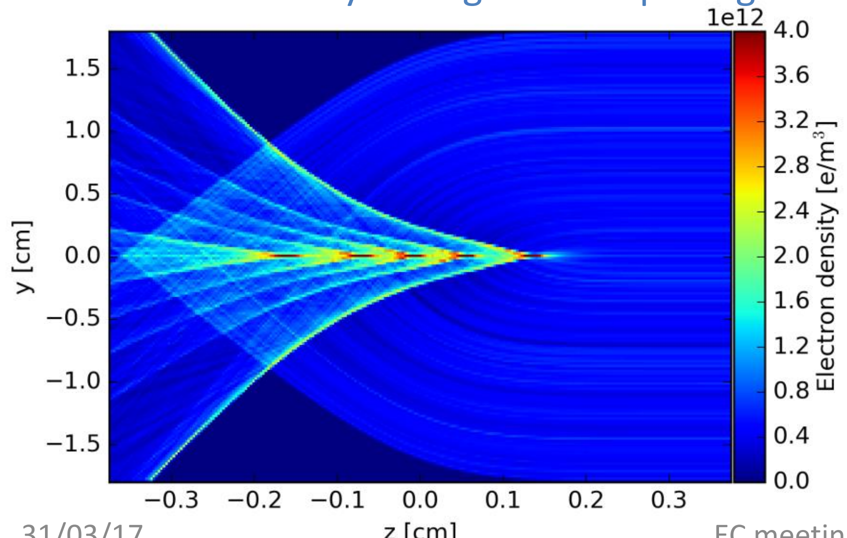
- Understanding of these phenomena relies on numerical simulations (PyECLOUD-PyHEADTAIL)

Multi-scale problem:

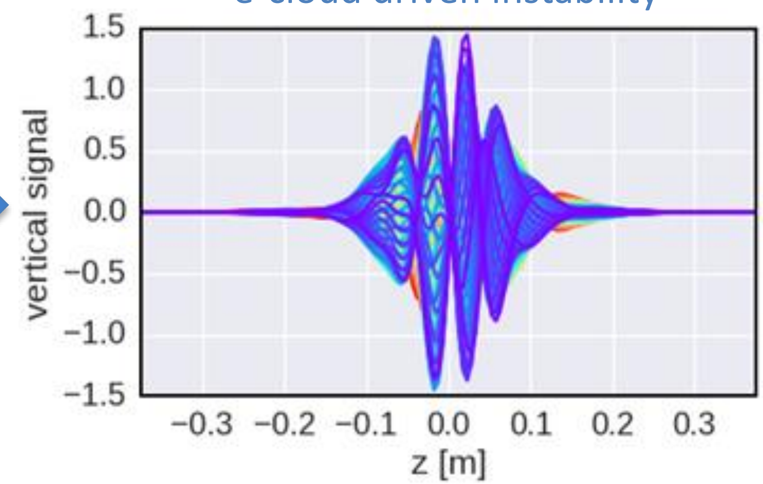
In space: small beam (~100 μm) in a big chamber (4 cm)

In time: 1 ns for the e^- motion, 1 to 10 s for instability development

Electron density during a bunch passage



e-cloud driven instability

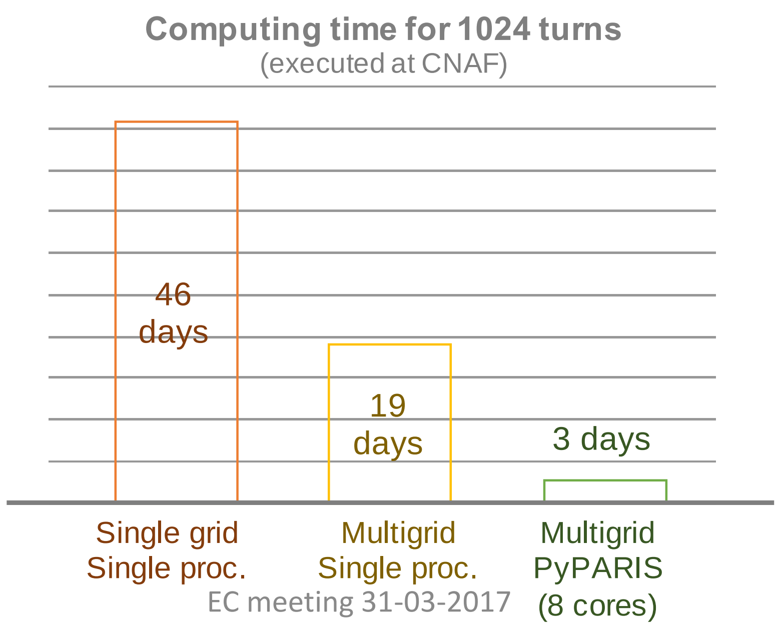


Simulation studies

- Recent work at CERN focused on increasing the performance of our simulation tools:
  - ✧ Introduced a " telescoping" grid in the Particle in Cell solver
  - ✧ Exploit parallel computing through a new parallelization layer (PyPARIS)

- Typical simulation study: ~400 CPU cores (8-16 cores per job)
  → Allowed gaining new insight on scenarios that were previously inaccessible (e.g. 10k turn simulations for LHC at 6.5 TeV)

- Long term effects, like incoherent emittance growth and interplay with other non-linearities, are practically unexplored in simulations (computationally very heavy)



Simulation studies

To check the potential role played by the e-cloud on the instabilities observed in stable beam, long simulation runs have been carried out → more than 10k turns (~1 s) to approach the timescale of the instabilities observations (~2.5s) → 3-4 weeks of computing time on the CNAF cluster

- Simulations were performed using realistic machine settings and a beam parameters

Machine and beam settings:

- Beam parameters: 1.0e11 ppb, 1 ns bunch length, 2.5 μm transverse emittance
- Octupole current set to 470 A → corresponds to $\Delta Q_{oct,sread}$ ~ 1 x 10^{-4}
- Chromaticity 15/15
- Transverse damper (100 turns of damping time)

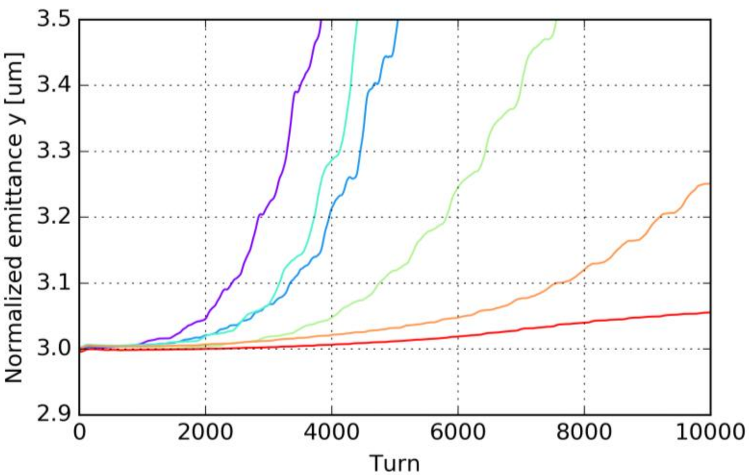
E-cloud configurations:

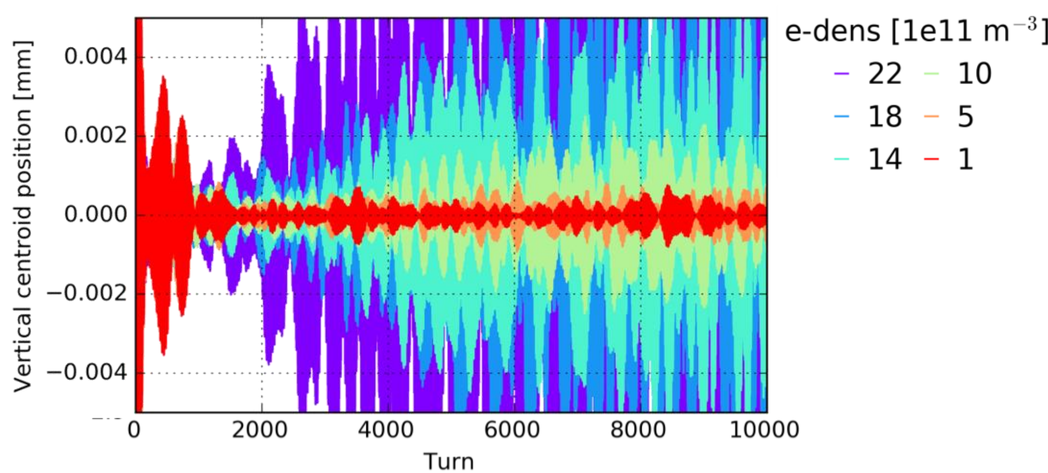
- e-cloud in dipoles: uniform electron density scan → good approximation*
- e-cloud in quadrupoles: self consistent simulation from buildup (SEY 1.30) → significant impact on the EC pinch dynamics **

* H. Bartosik, proceedings of the ECLOUD12 Workshop, Elba, 2012
**G. Iadarola, presentation at Joint HiLumi-LARP Meeting, Fermilab, 2015

Simulation studies: 1e11 p/bunch

- An electron density of 5×10^{11} p/m^3 in the central region of the dipoles is sufficient to induce a vertical instability (in spite of the high chromaticity and high octupole settings)

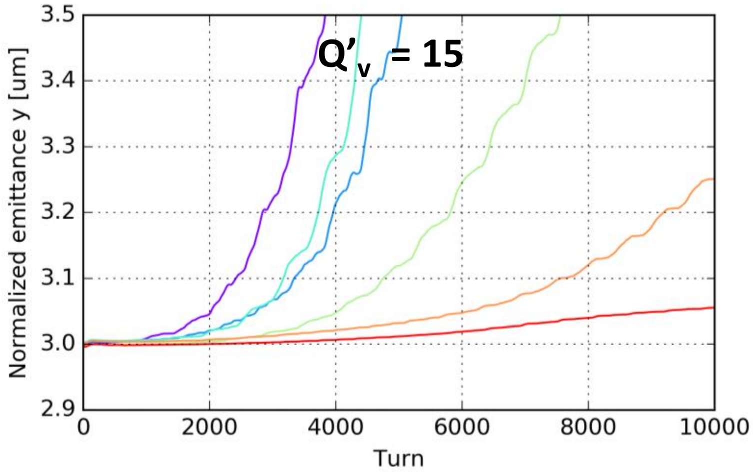


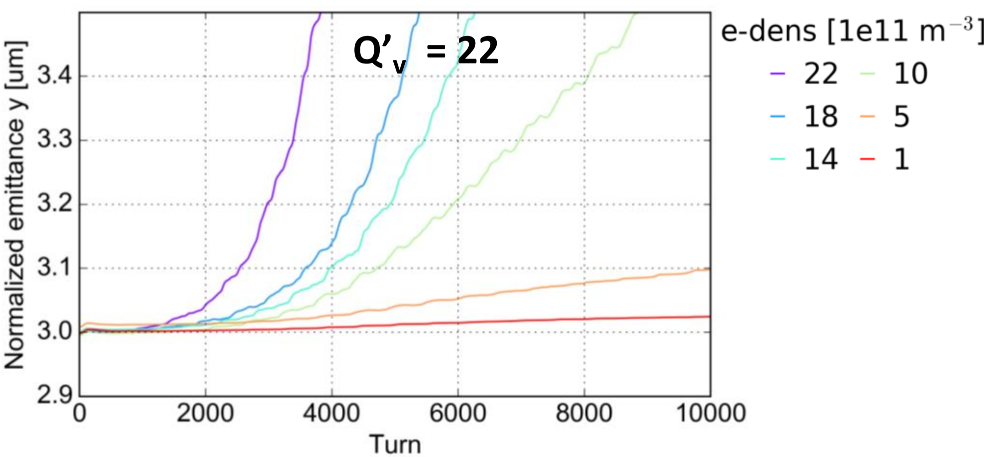


EC dipoles	EC quadrupoles	Chromaticity	Oct.	Damper	Sim.Turns
Density scan	SEY 1.30	15/15	470 A	100 turns	10k

Simulation studies: 1e11 p/bunch

- An electron density of 5×10^{11} p/m^3 in the central region of the dipoles is sufficient to induce a vertical instability (in spite of the high chromaticity and high octupole settings)
- Increasing Q'_v up to 22 units, the emittance growth becomes slower, expecially at low electron densities
- This instability could not be detected over our usual simulation runs of 500-1000 turns → we need run more than 10k turns for a better understanding of the instability process



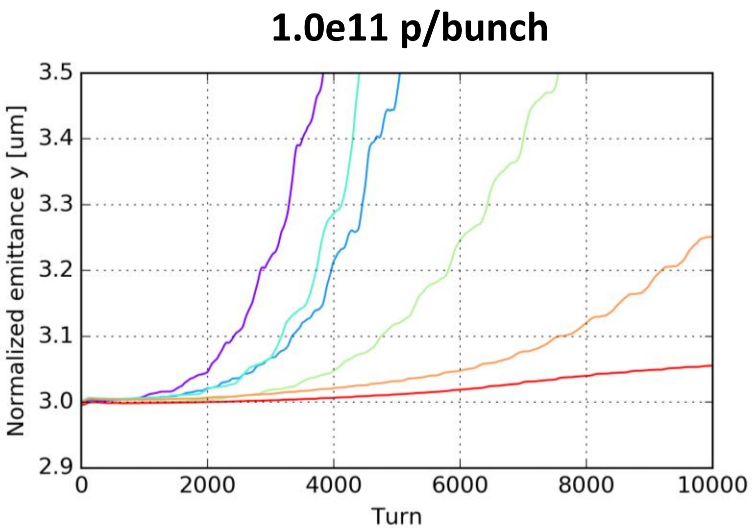


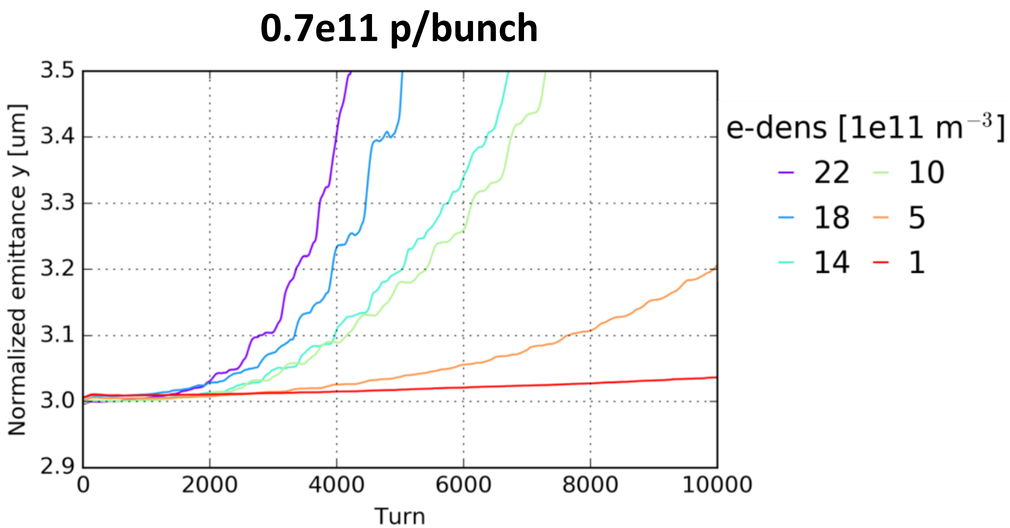
EC dipoles	EC quadrupoles	H Chromaticity	Oct.	Damper	Sim.Turns
Density scan	SEY 1.30	15	470 A	100 turns	10k

Simulation studies: different bunch intesity

- In the machine instabilities were observed for bunch intensities below than 1e11 ppb
- The impact of the beam intensity on the instability threshold has been investigated by running the same simulations with beam intensity of 0.7e11 ppb

  → Instability threshold basically unchanged!





EC dipoles	EC quadrupoles	Chromaticity	Oct.	Damper	Sim.Turns
Density scan	SEY 1.30	15/15	470 A	100 turns	10k

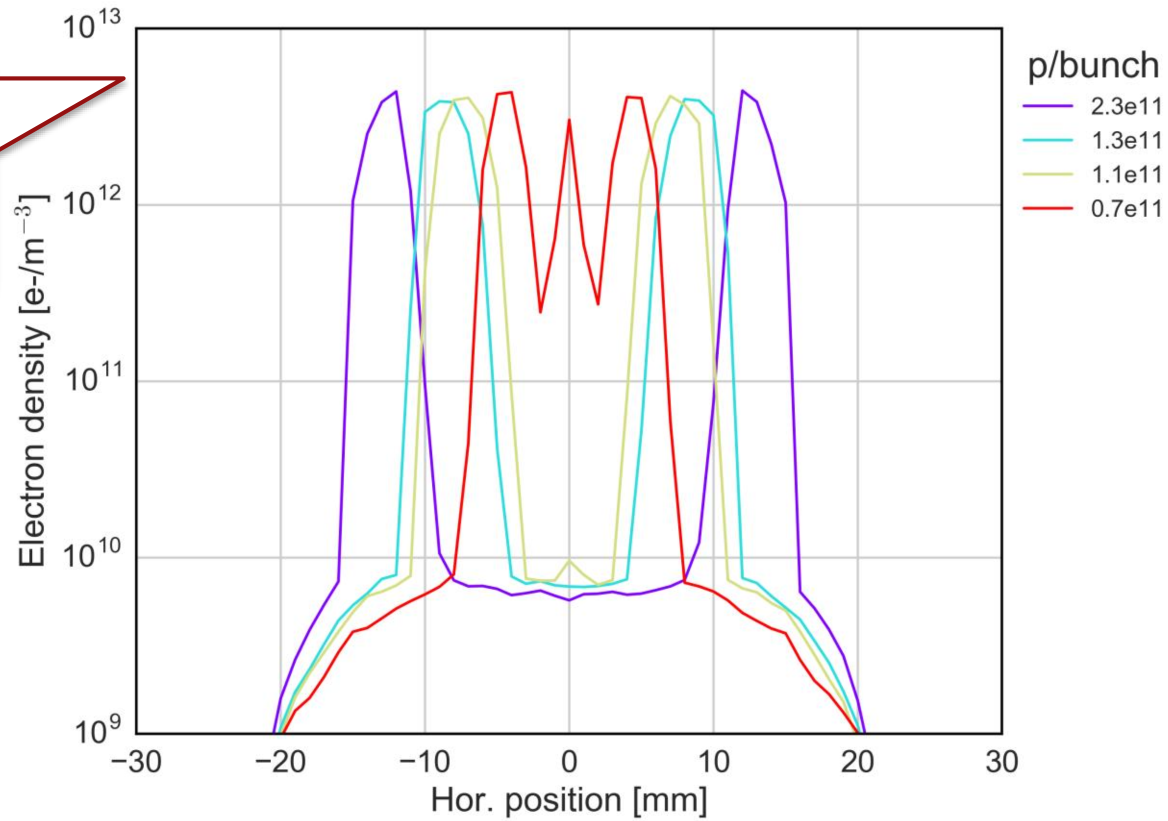
Central density from PyECLOUD simulations

- From PyECLOUD simulations we can estimate the electron density profile in the dipoles for different beam intensities

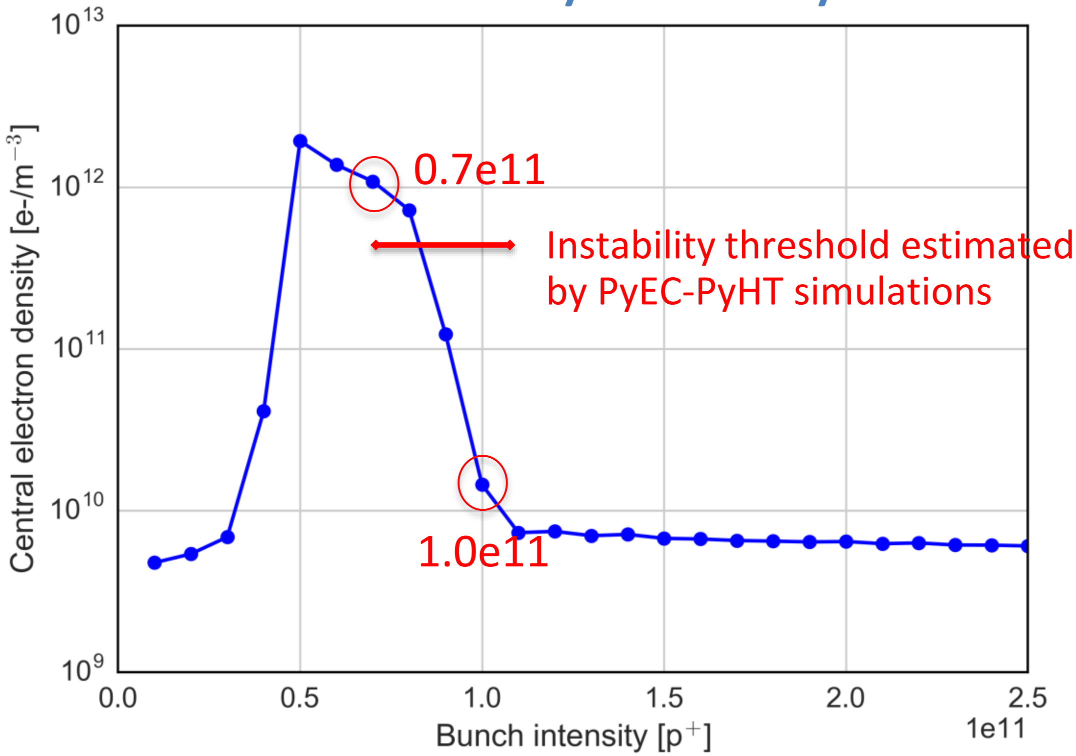
  → When the bunch intensity decreases, the central density increases significantly

Simulations settings

- $SEY_{DIP} = 1.4$
- 1 ns bunch length
- 2.5 um transverse emittance



Central density from PyECLOUD simulations

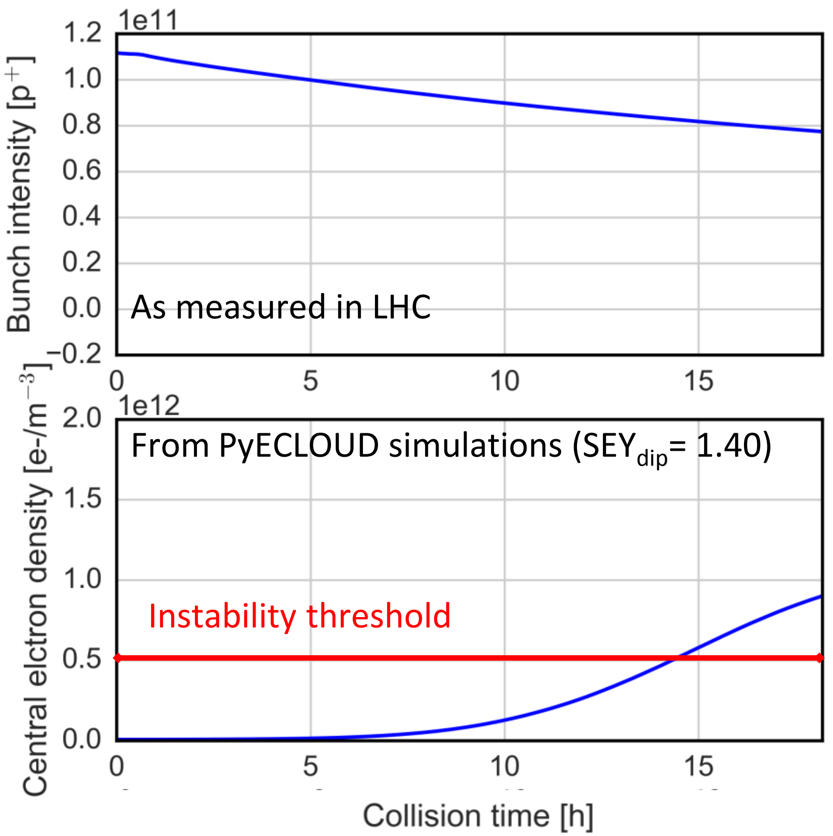


- For bunch intensities below than 1.0e11 ppb, the central density increases rapidly crossing the instability threshold

- For bunch intensities larger than 1.0e11 ppb, the estimated electron density is well below the instability threshold

Central density from PyECLOUD simulations

Fill 4980, started on Thu, 02 Jun 2016 04:32:03 → **Physics fill where we observed instabilities**



- **Average bunch intensity** (between B1 and B2) during the collisions has been used to infer the evolution of the central density

- **Evolution of the central electron density**: the central density increases over the fill time and crosses the instability threshold when the intensity has dropped to ~0.8e11 p/bunch

Good agreement between machine observations and simulations results

Summary and conclusions

- In spite of the high chromaticity and high octupole settings, a vertical emittance blow up of bunches at the end of the 72b trains was observed during the stable beam in most of the fills at the beginning of the year
  - An increase of the vertical chromaticities after going in collision was needed to avoid instabilities

- The potential role of the e-cloud has been investigated in simulation
  - According to machine observations, two different settings for the beam instensity were simulated showing a weak dependence of the instability thresholds on the bunch intensity

- Build-up simulation results showed that when the beam intensity decreases, the electron density in the center can become sufficiently high to drive an instability

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Ongoing studies

GOALS FOR ONGOING STUDIES:

1. check the impact of the EC in the LHC arcs (dipoles and quadrupoles) both at injection and flattop on the beam stability (e.g nominal LHC bunch)

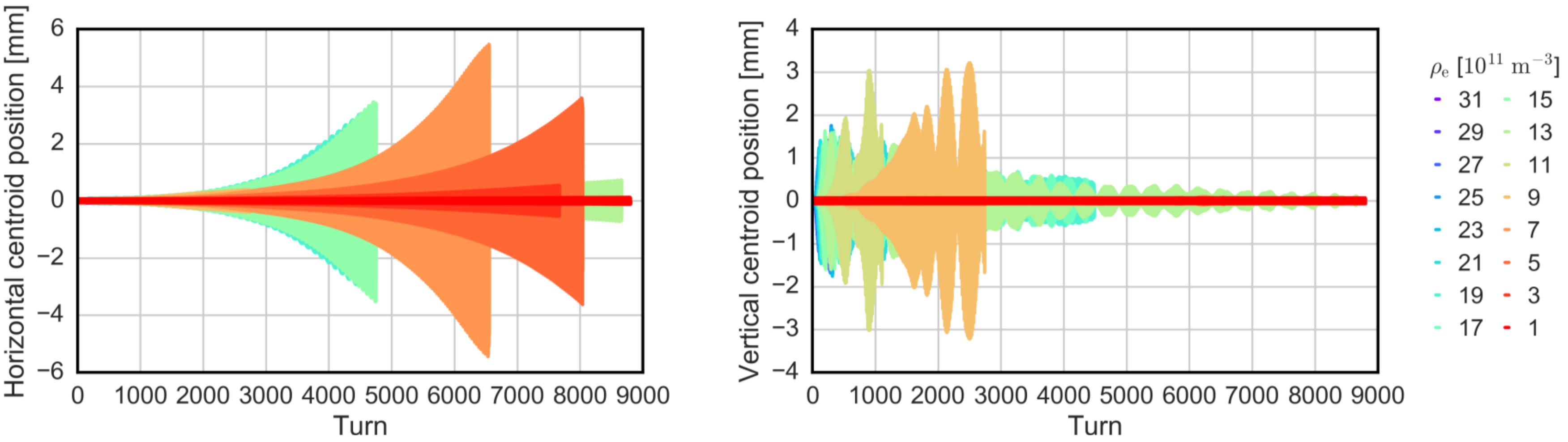
   → at injection, the work has been done in collaboration with Kevin Li

2. improve the understanding of machine settings on the instability threshold → chromaticity, octupoles and trasverse feedback are simulating together with the EC

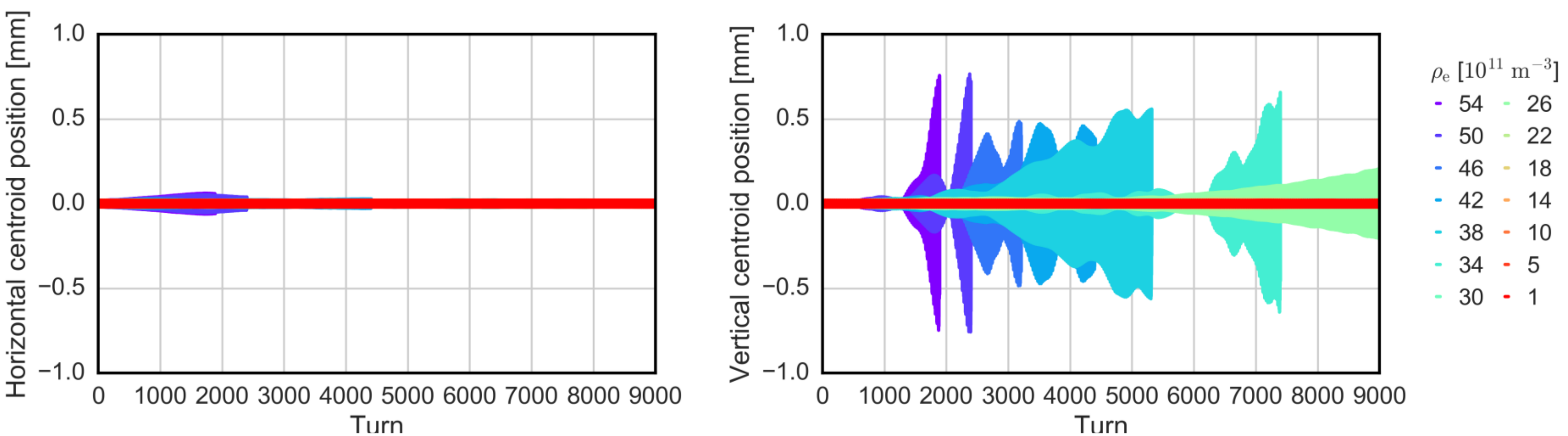
→ A full picture of the EC driven instabilities in the arcs and an optimiziation of machine settings to ameliorate LHC operation!

450 GeV *vs* 6.5 TeV: e-cloud in arc dipoles

INJECTION: both planes are unstable → H instabilities are much slower (~2000 turns)



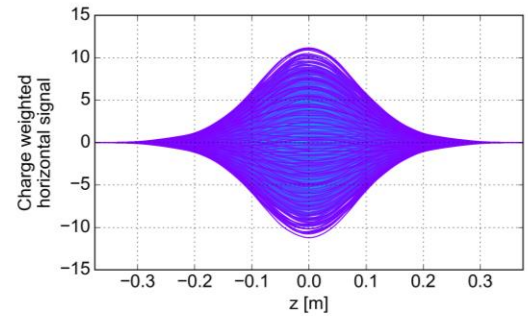
FLATTOP: vertical plane predomintly unstable



450 GeV *vs* 6.5 TeV: e-cloud in arc dipoles

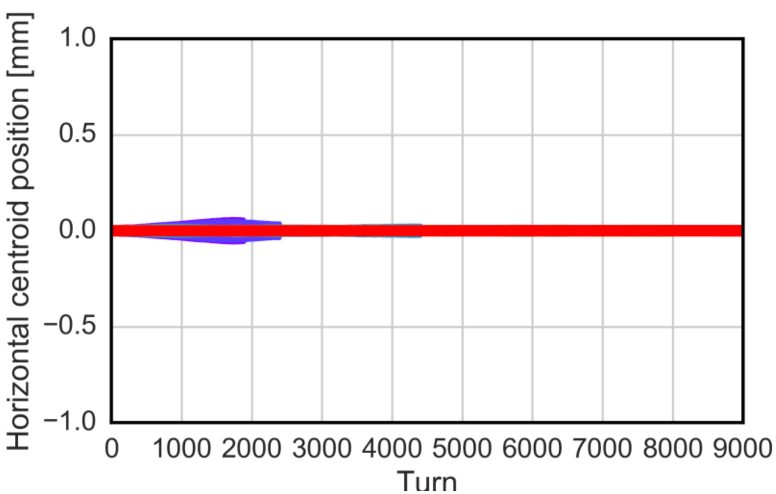
INJECTION: both planes are unstable → H instabilities are much slower (~2000 turns)

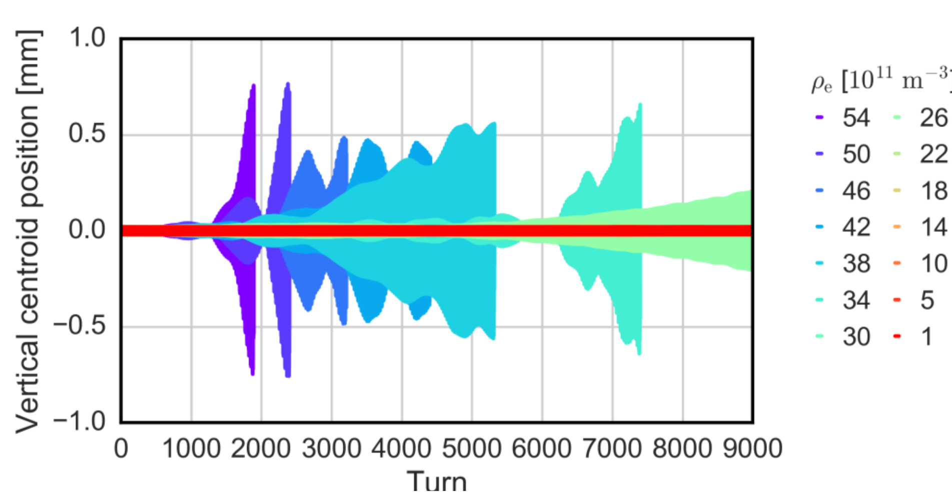
- **Horizontal instabilities** are mode-0 like → they are not observed in the machine because are damped by the transverse feedback



- **Vertical instabilities** develop for higher frequencies which can not be dealt by the stranverse feedback

FLATTOP: vertical plane predomintly unstable

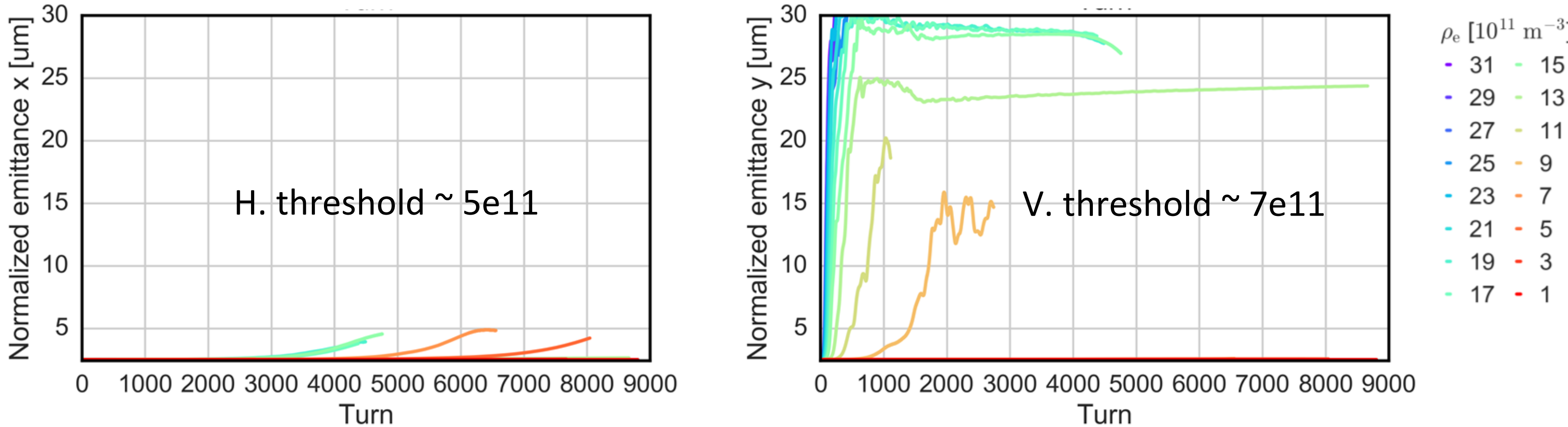




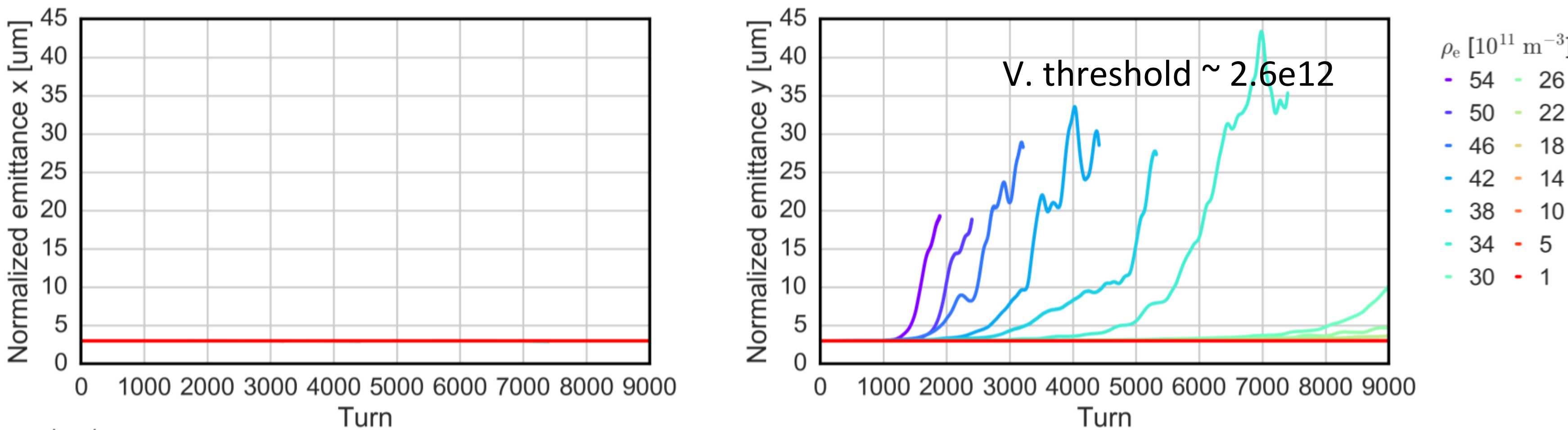
450 GeV *vs* 6.5 TeV: e-cloud in arc dipoles

EC instability threshold defined as density needed to generate 10% emittance growth over 9000 turns

INJECTION



FLATTOP



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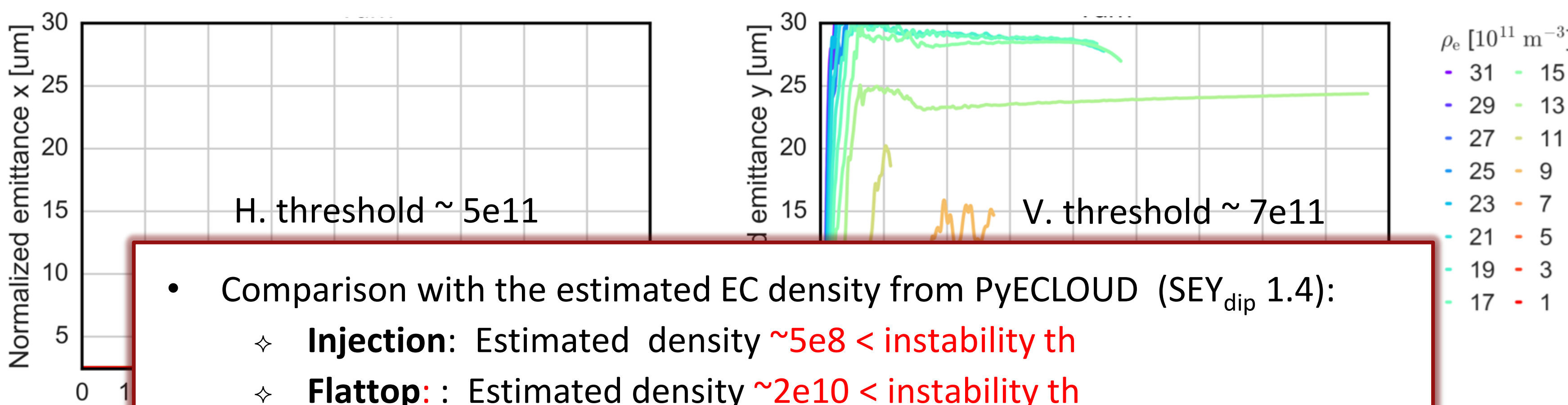
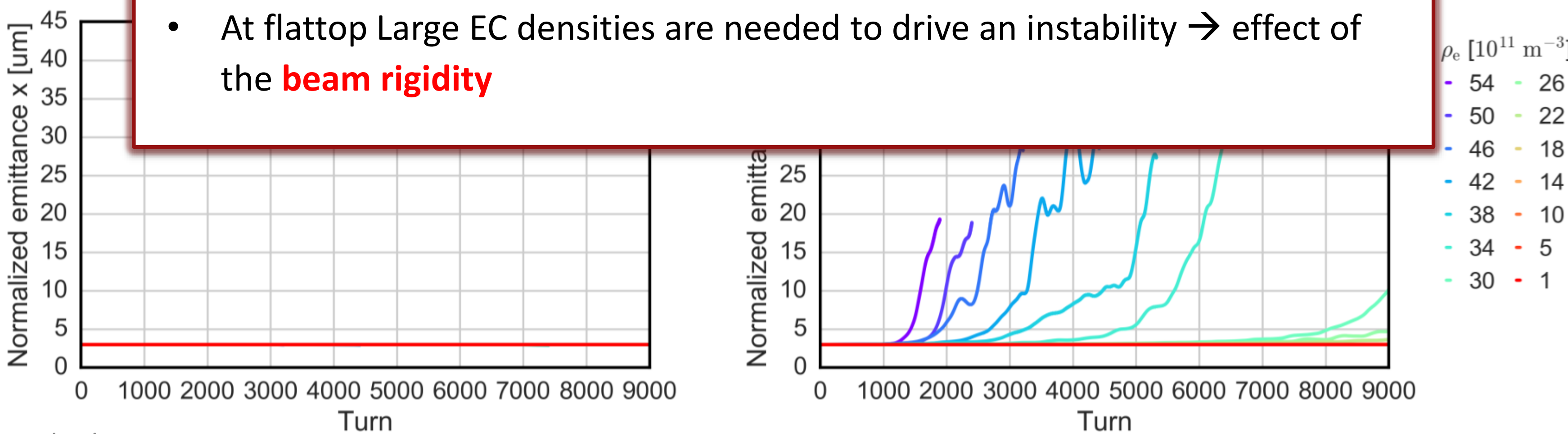
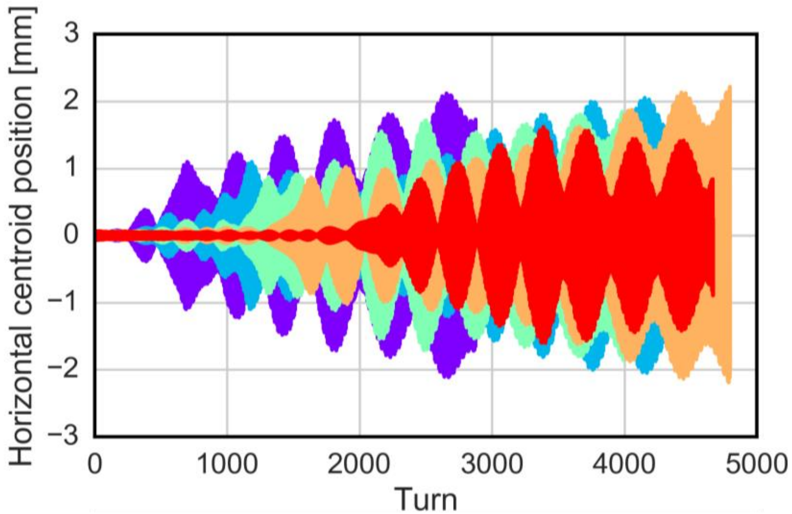


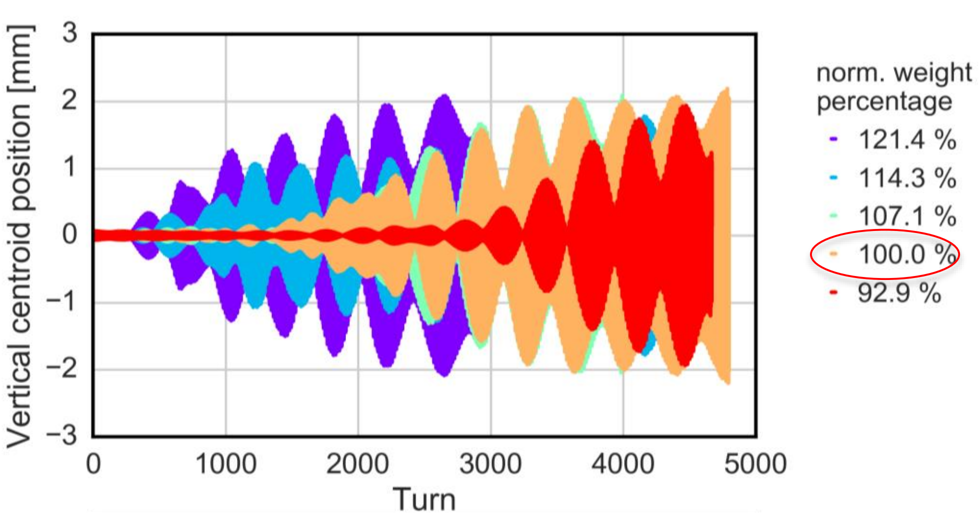
- Comparison with the estimated EC density from PyECLOUD (SEY$_{dip}$ 1.4):
  - ✧ **Injection**: Estimated density ~5e8 < instability th
  - ✧ **Flattop**: : Estimated density ~2e10 < instability th
  - → No EC induced instabilities can be explained over 9000 turns
- At flattop Large EC densities are needed to drive an instability → effect of the **beam rigidity**



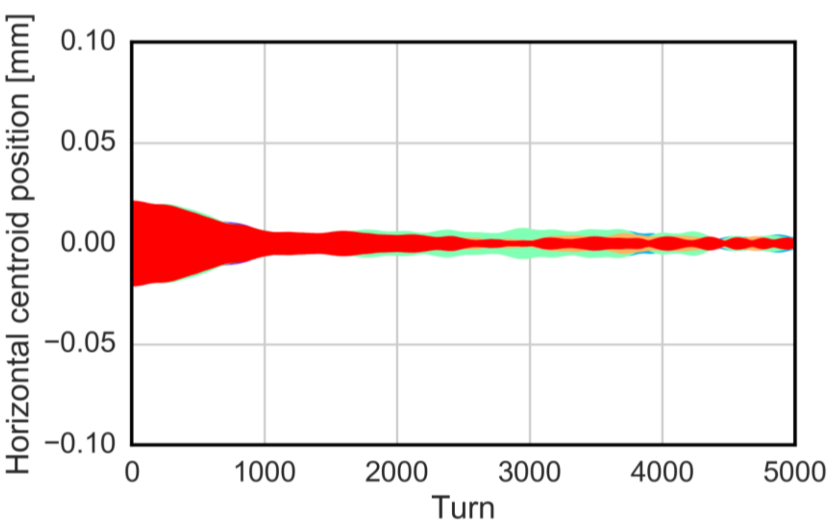
450 GeV *vs* 6.5 TeV: e-cloud in arc quadrupoles

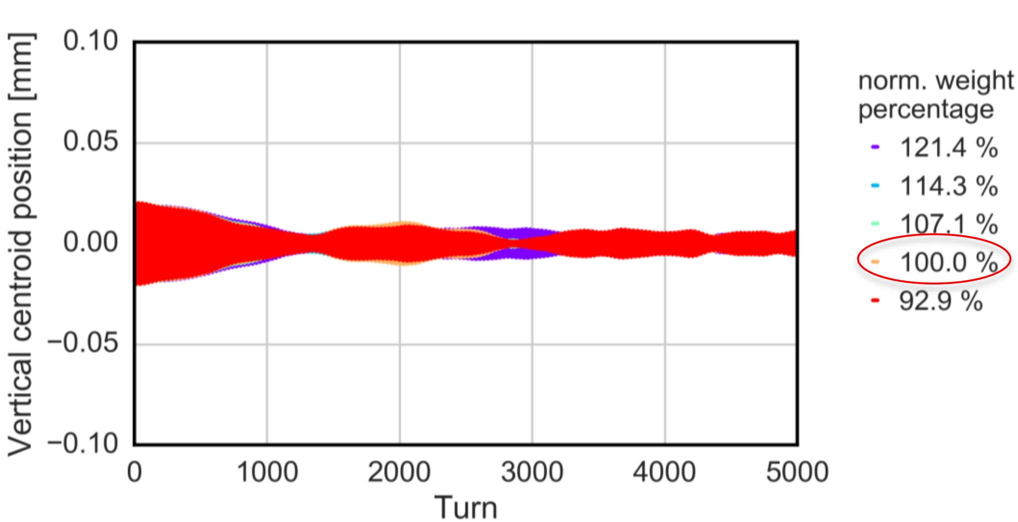
INJECTION: both planes are simmetrically unstable





FLATTOP: no clear instability can be detected

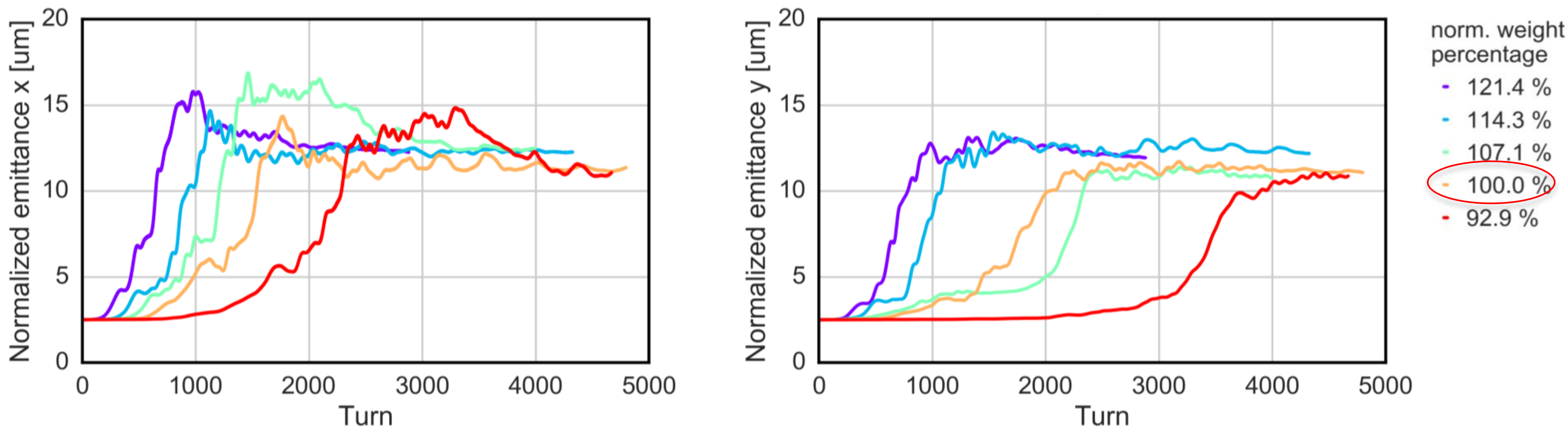




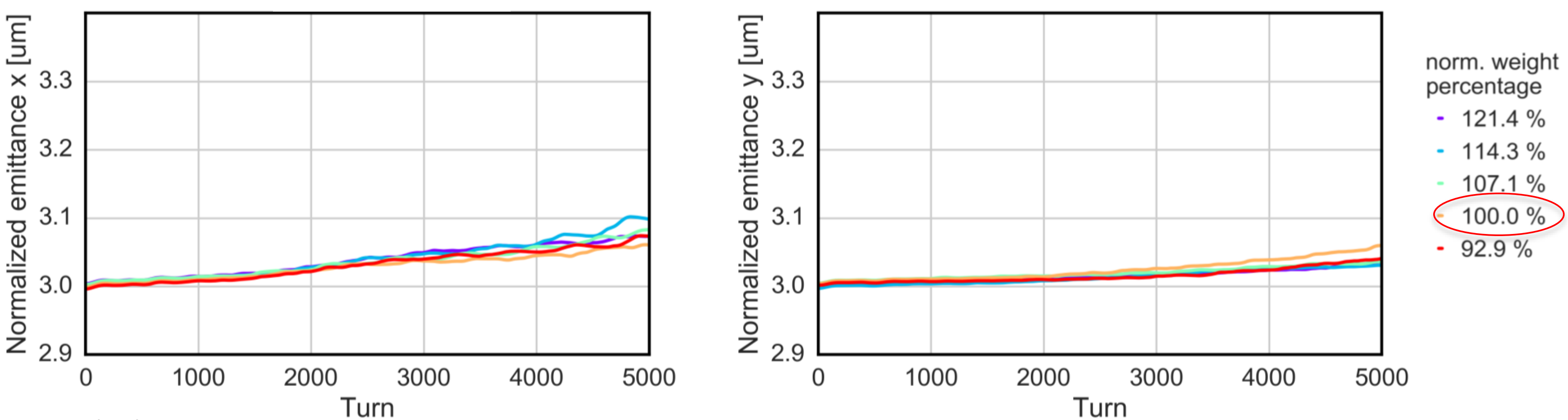
450 GeV *vs* 6.5 TeV: e-cloud in arc quadrupoles

EC instability threshold defined as density needed to generate 10% emittance growth over 5000 turns

INJECTION



FLATTOP



450 GeV *vs* 6.5 TeV: e-cloud in arc quadrupoles

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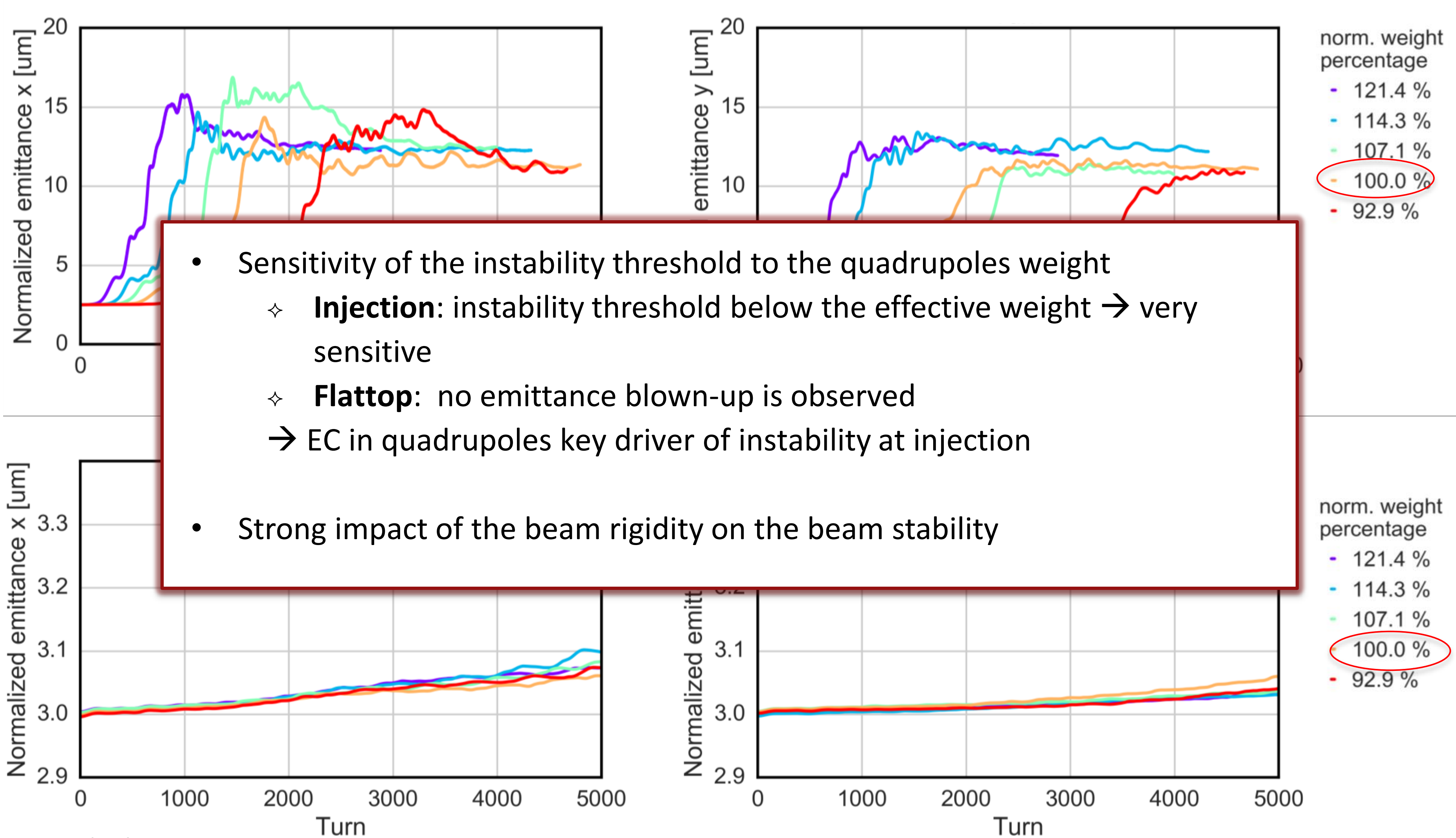
INJECTION



- Sensitivity of the instability threshold to the quadrupoles weight
  - **Injection**: instability threshold below the effective weight → very sensitive
  - **Flattop**: no emittance blown-up is observed

  → EC in quadrupoles key driver of instability at injection
- Strong impact of the beam rigidity on the beam stability

Summary and further studies

Electron Cloud

EC in **DIPOLES**
Estimated EC density < instability th
Instabilitiy observations cannot be explained (over 9000 turns) by the EC in dipoles alone → unless the beam intesity decreases

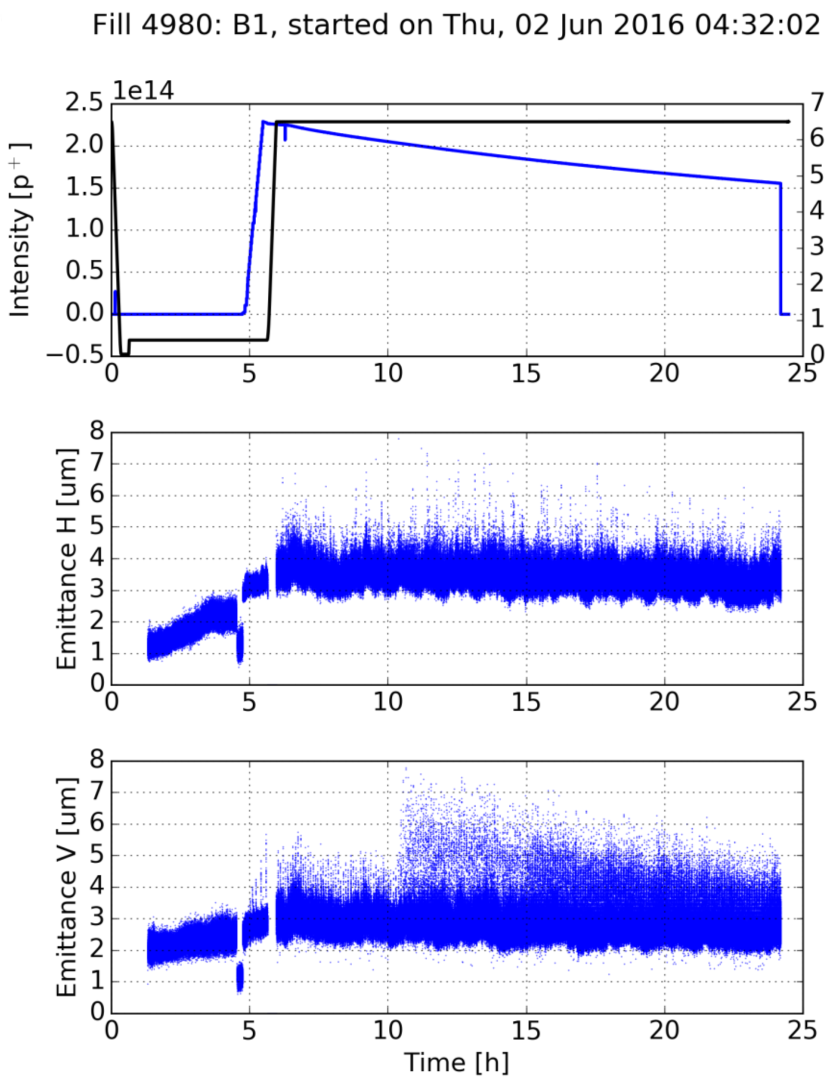
EC in **QUADRUPOLES**
key driver of instabilities at injection → at flattop due to the magnetic rigidity of the beam no clear instability can be observed

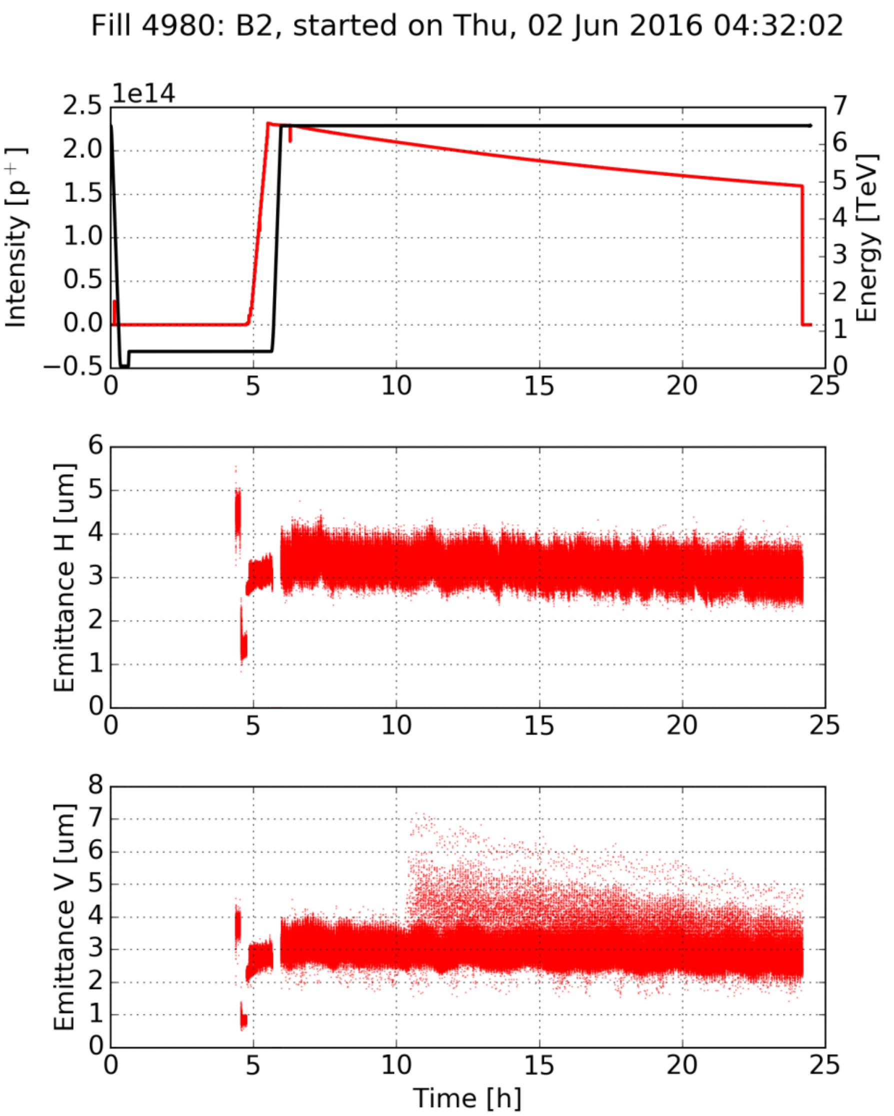
\+ Chromaticity + Landau octupoles + Transverse feedback

Next steps → How different machine settings together with e-cloud affect the beam stability?

Thanks for your attention

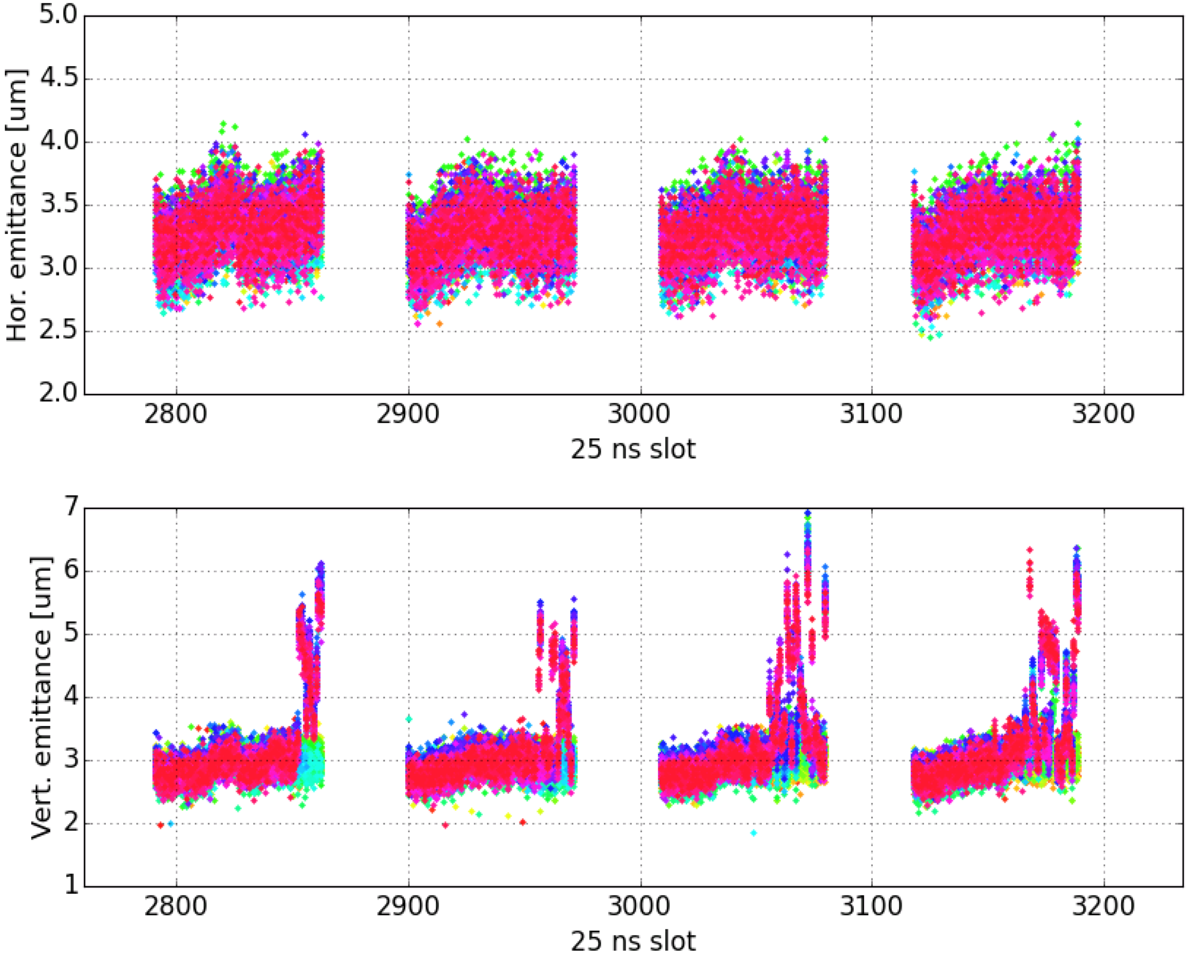
Instabilities in stable beam



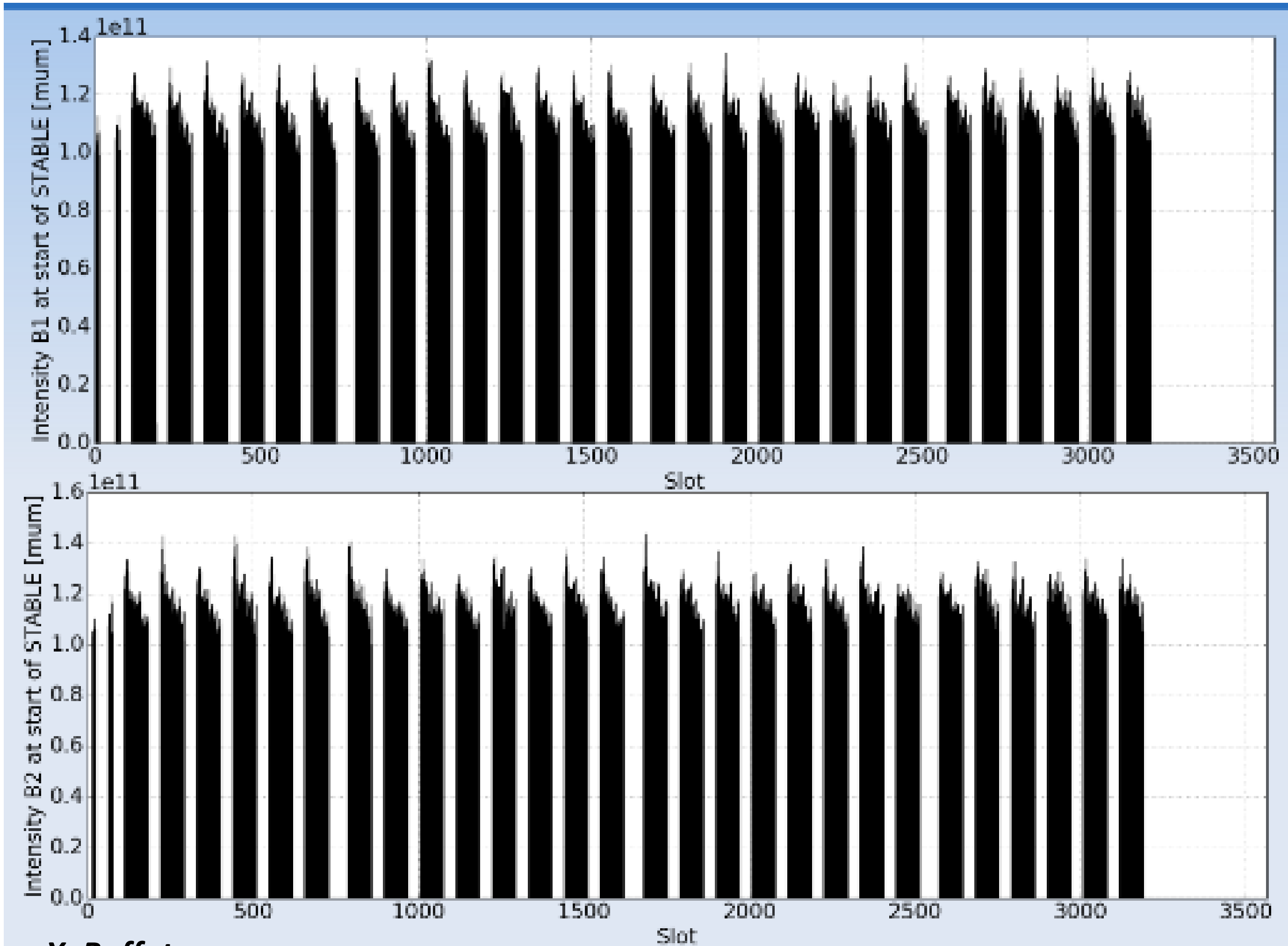


Instabilities in stable beam

Fill 4979 – Beam 2

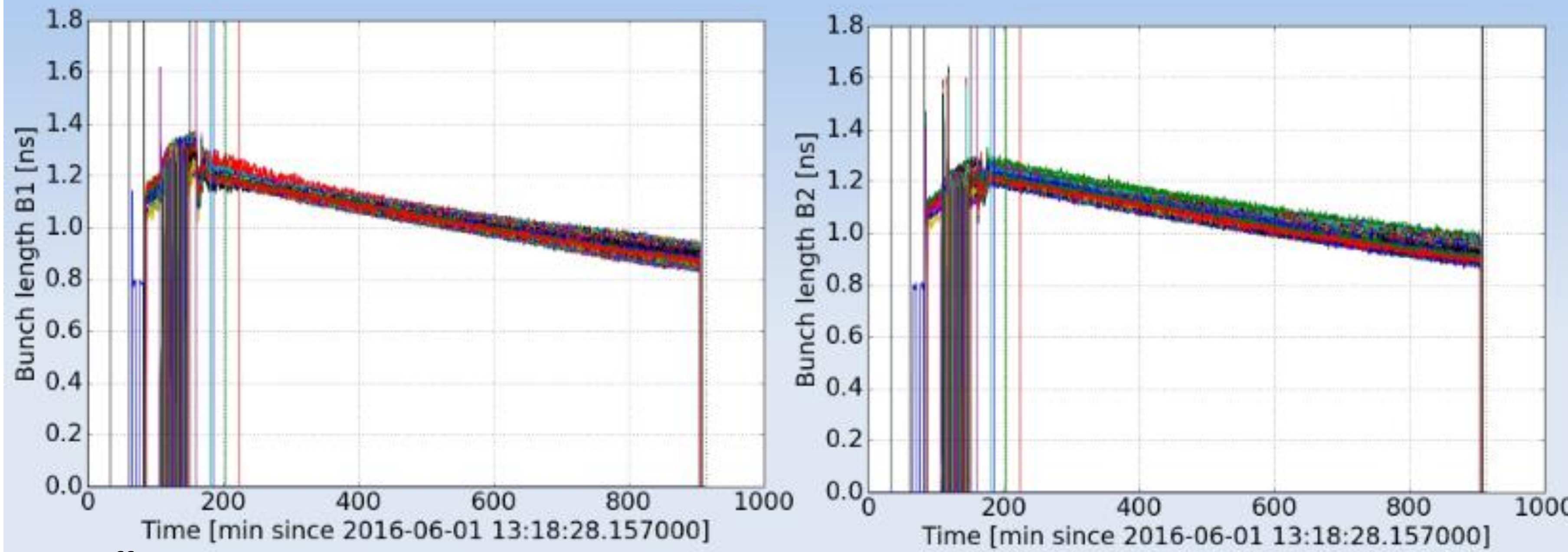


Instabilities in stable beam – beam intesity



X. Buffat

Instabilities in stable beam – bunch length



X. Buffat

HEADTAIL simulations

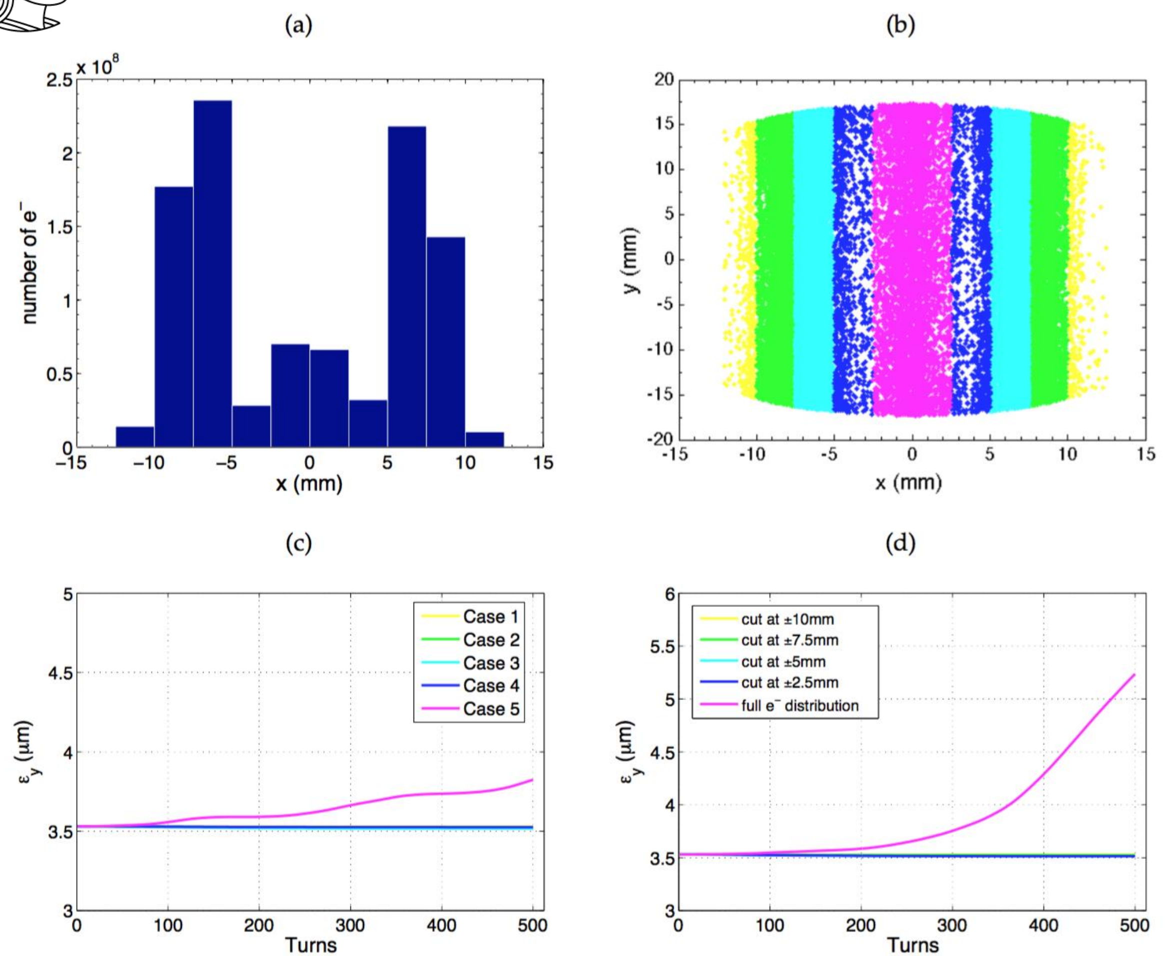


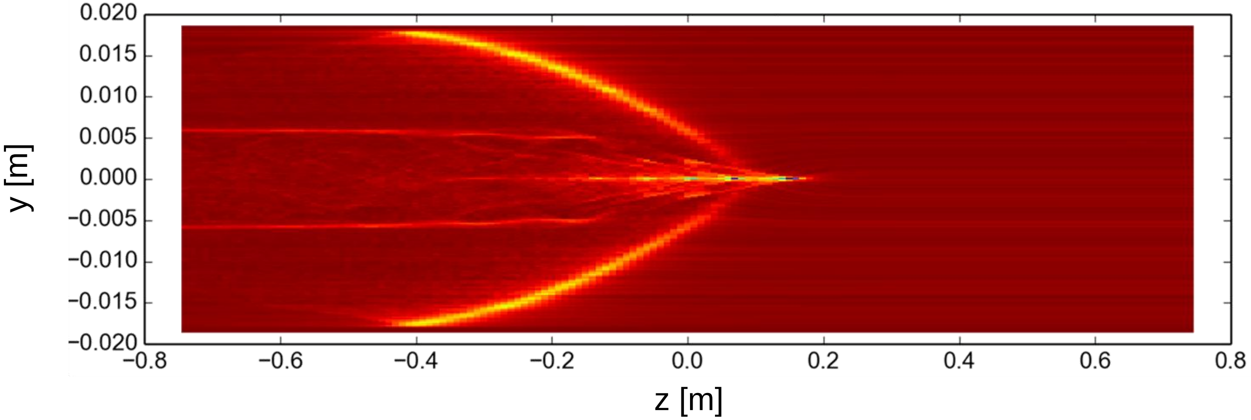
Figure 5.15: (a) Histogram of the horizontal electron distribution; (b) transverse electron distribution divided into colored regions; (c) evolution of the vertical emittance for the interaction with the electrons of the respective colored area; (d) evolution of the vertical emittance for different horizontal cuts of the electron distribution.

Fast vertical instability is driven by the central density of electron in dipoles

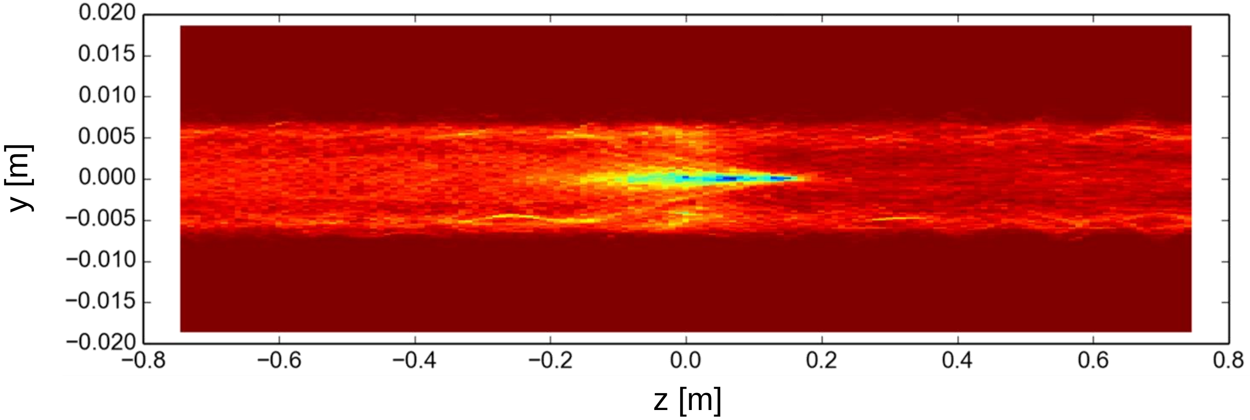
Arc Quadrupoles: realistic e⁻ distribution

- First test performed with **self consistent distribution from buildup simulation**
    - Electrons **trapped** along the magnetic lines → **pinch is attenuated**

Uniform initial distribution

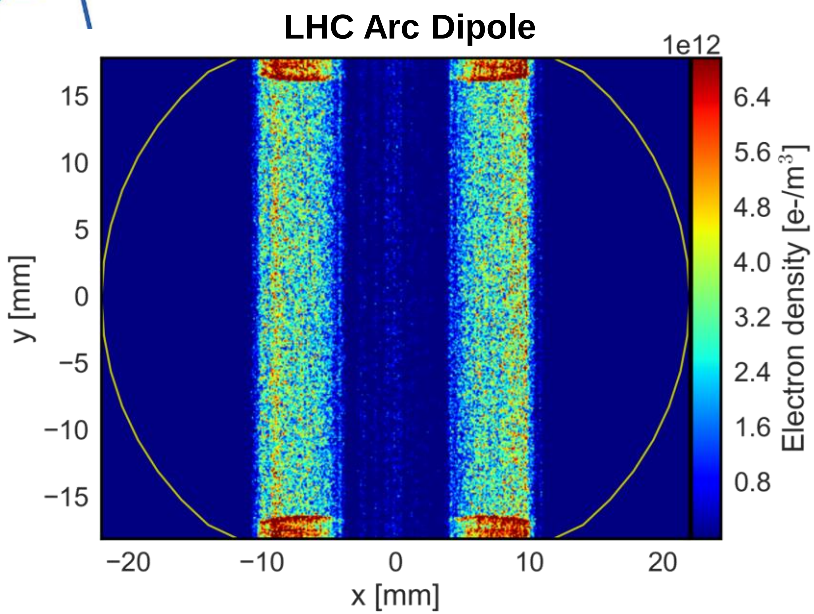


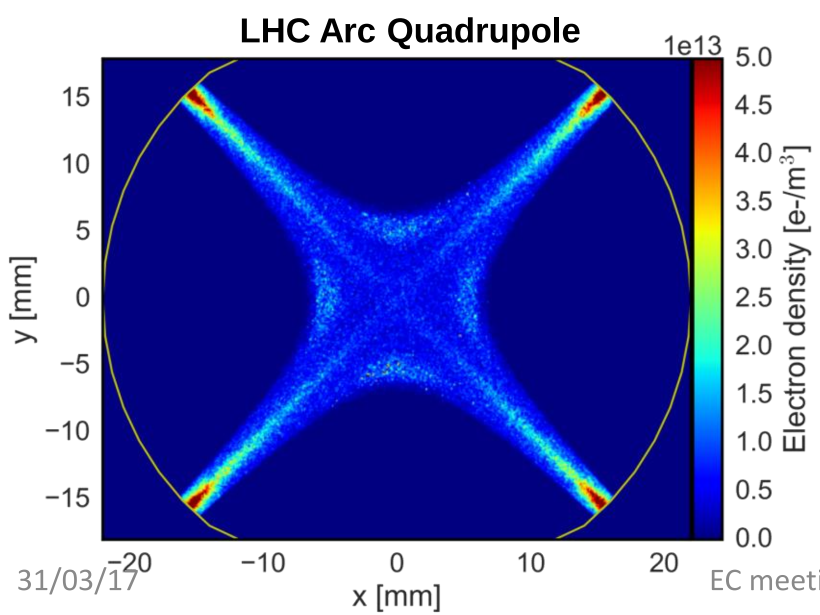
Initial distribution from buildup simulation

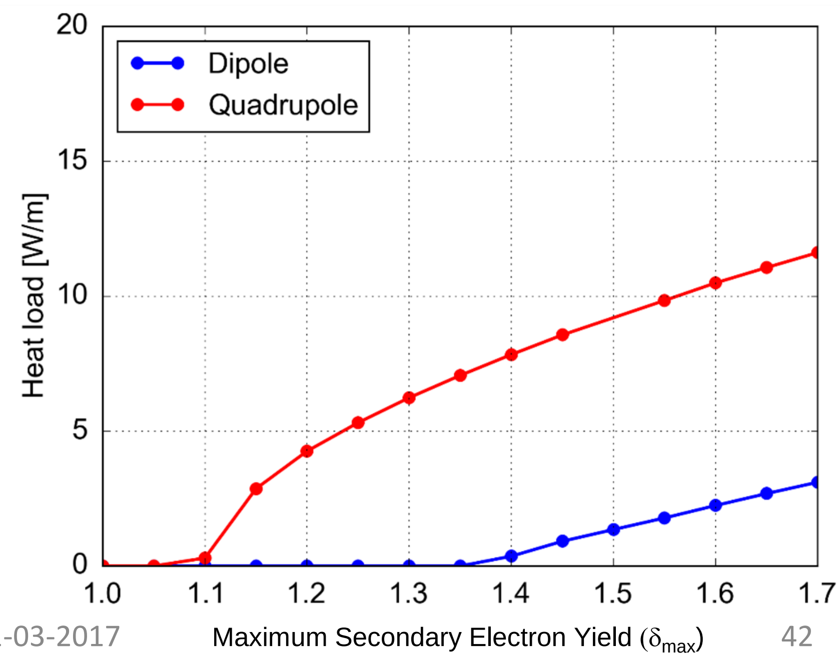


Electron trajectories are strongly influenced by externally applied magnetic fields

- Electrons **spin around the field lines**
- In **quadrupole** magnets magnetic **trapping** can occur with electrons surviving several bunch passages being accelerated up to a few keV
  → Much stronger heat loads compared to dipoles

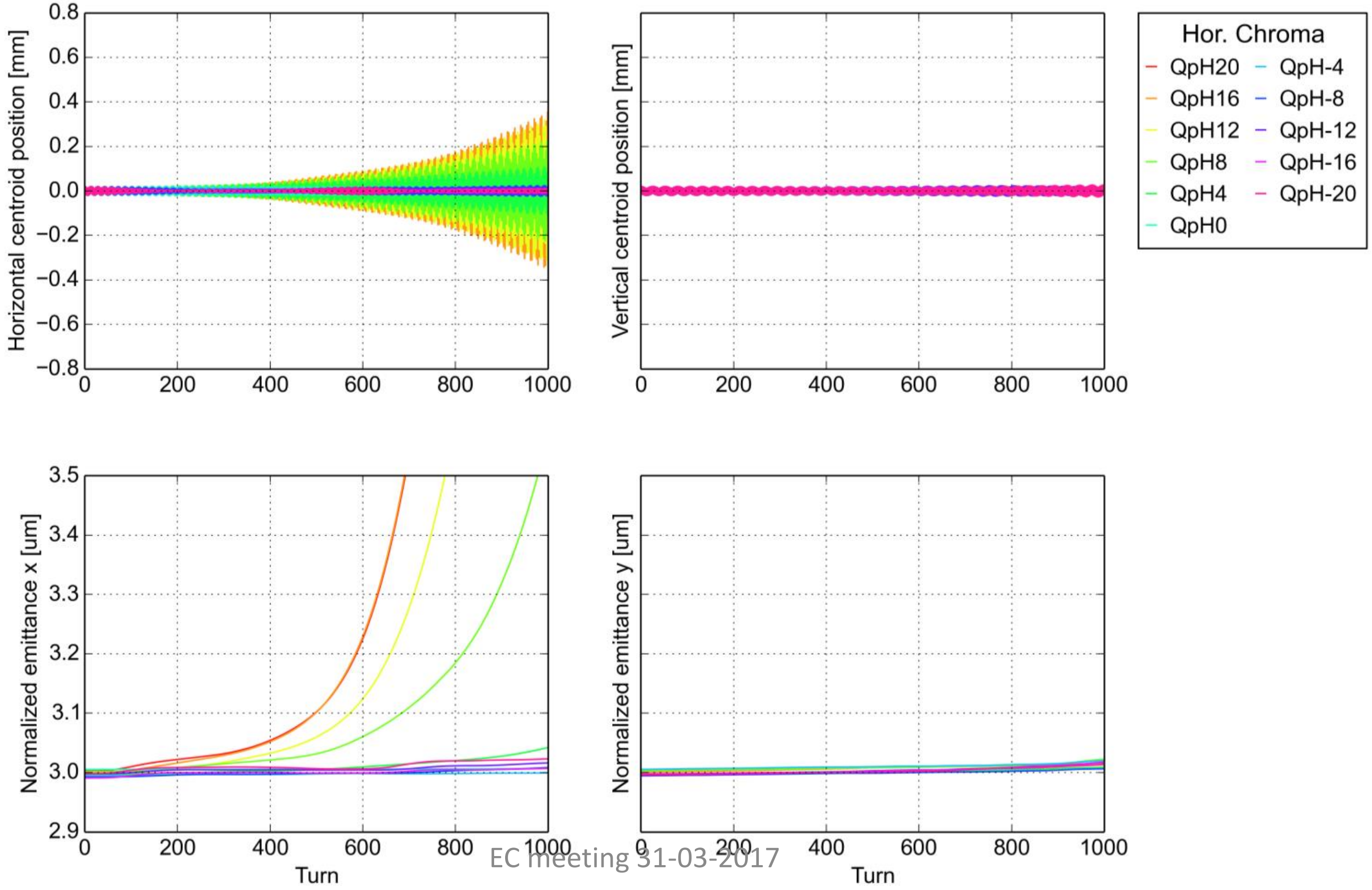






Horizontal instabilities @ 6.5TeV

- EC only in dipoles→ density fixed at **3.8e12**
- Horizontal chromaticity is scanned between -20 and 20
- Vertical chromaticity is kept at 0
- No emittance blown up observed in the vertical plane
- Strong horizontal emittance growth when increasing the horizontal chromaticity



Horizontal instabilities – Possible mechanism

Transverse wake function (dipolar)

$$W_x(z) = -\frac{E_0}{q_1 q_2}\frac{\Delta x_2'}{\Delta x_1}$$

Stability criterion for mode-0 assuming constant wake (see Chao, eq. 6.216)

$$\frac{(-W_x)z}{h} > 0$$

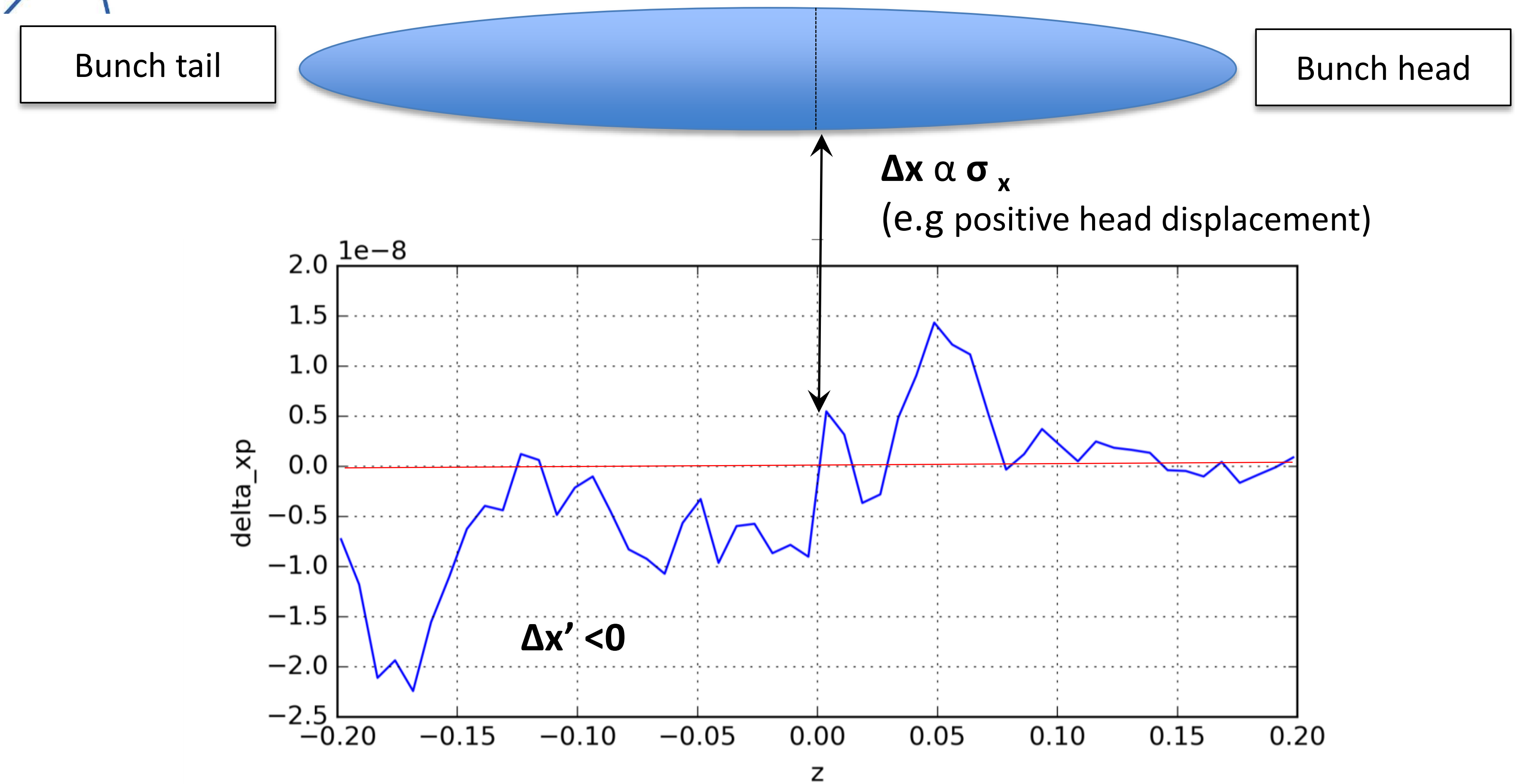
Sign of the wake

Stability condition (above transition)

W_x<0, i.e. tail gets kicked in phase w.r.t. the head displacement → **Positive chromaticity**

W_x >0, i.e. tail gets kicked in counter-phase w.r.t. the head displacement → **Negative chromaticity**

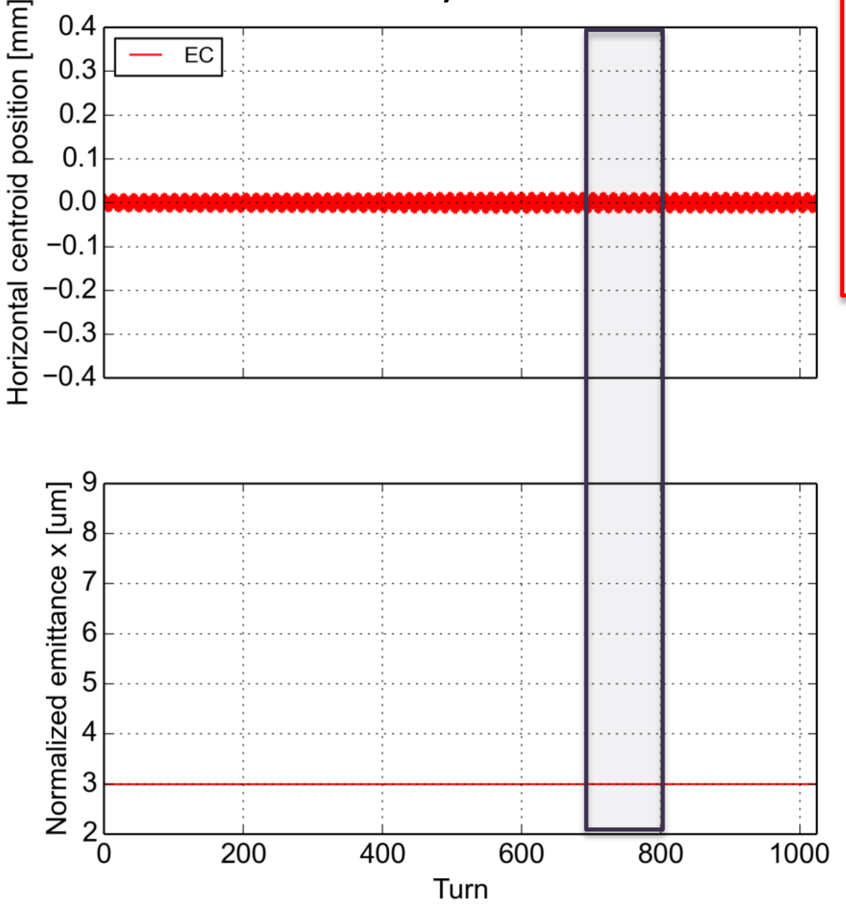
Horizontal instabilities – Possible mechanism



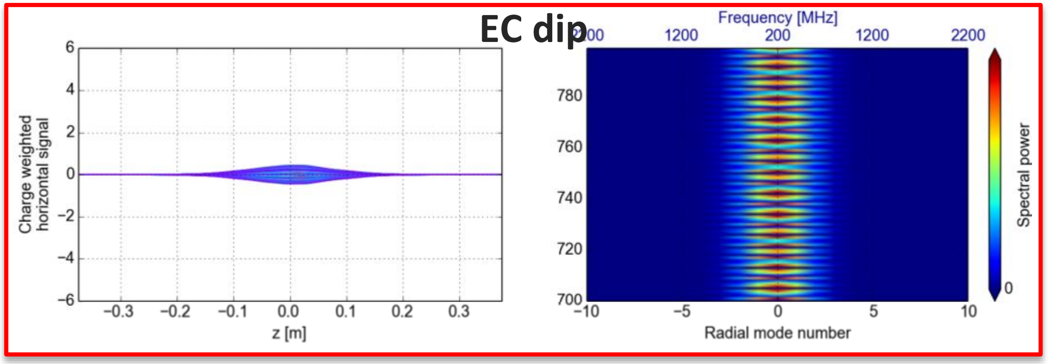
Tail gets kicked in **counter - phase** with the head displacement so we need negative chromaticity for stabilizing

Horizontal instabilities – effect of the damper

EC density **3.8e12**

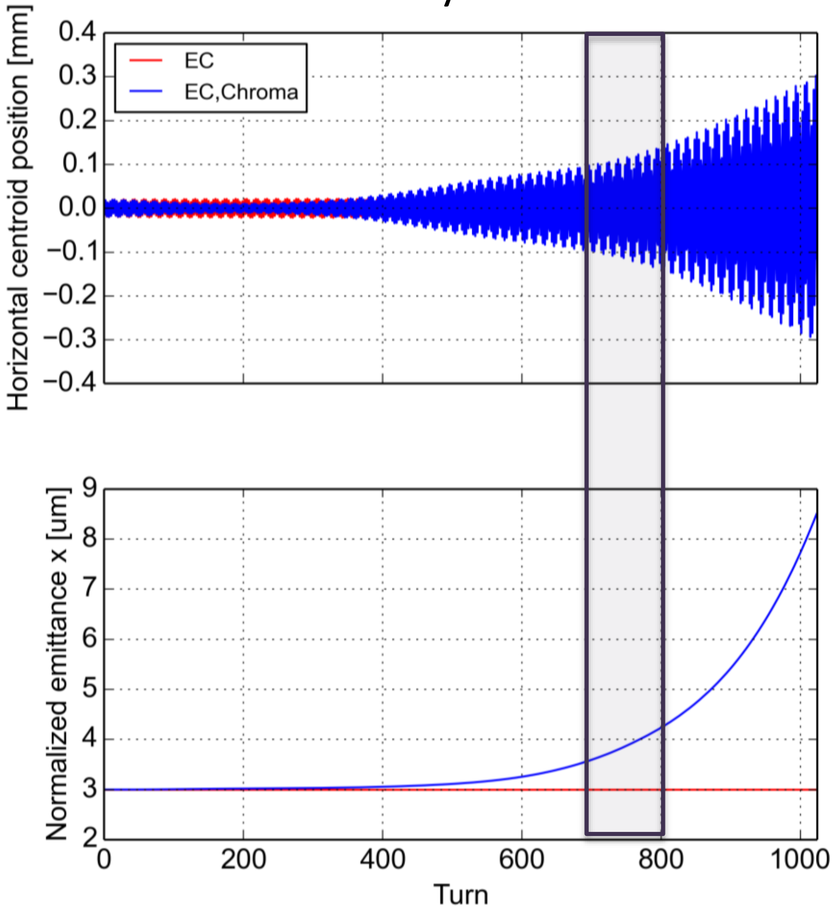


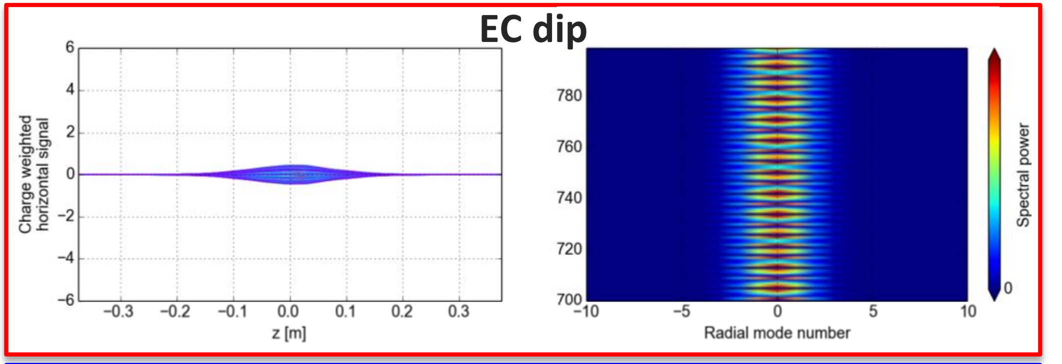
EC dip

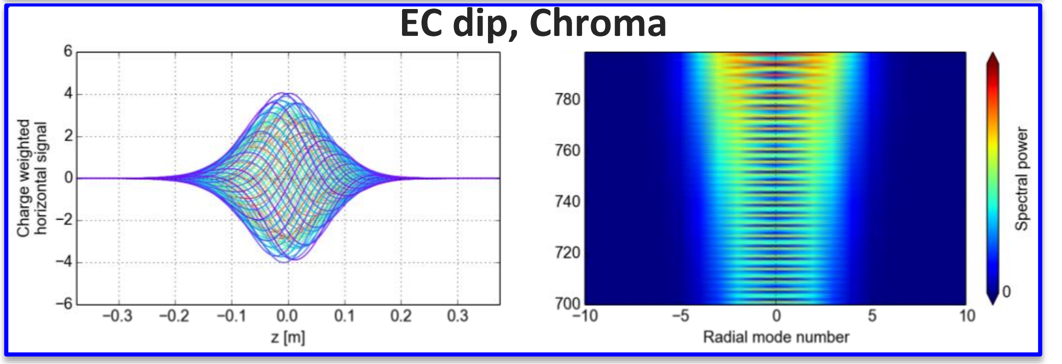


Horizontal instabilities – effect of the damper

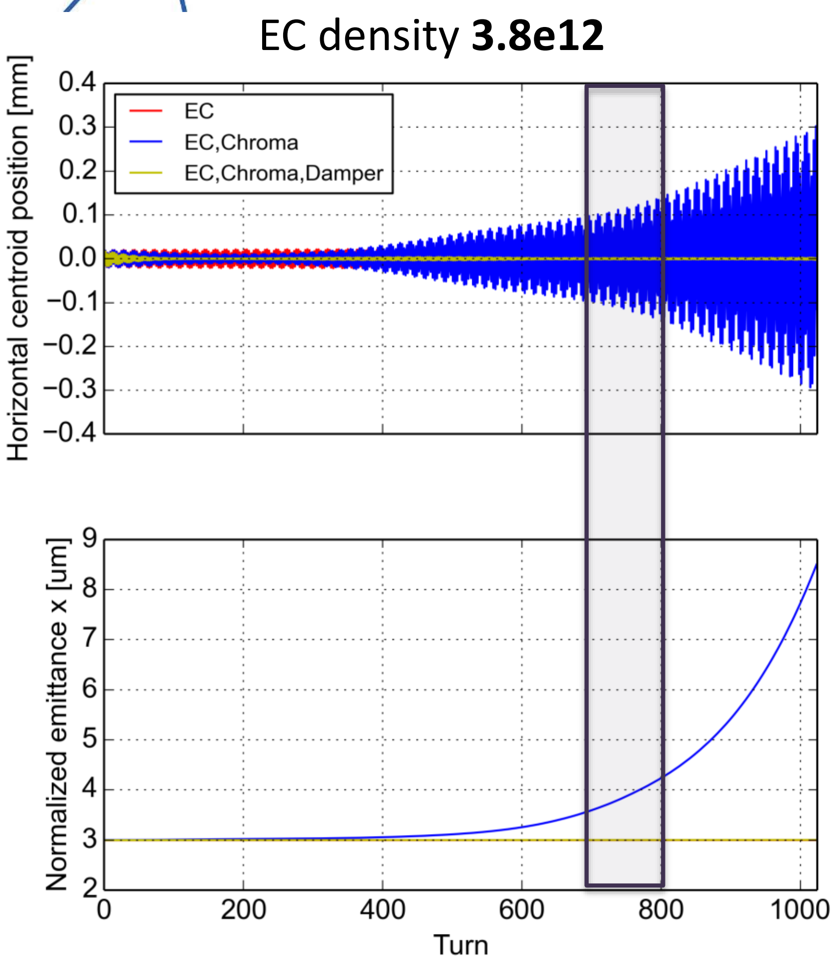
EC density **3.8e12**

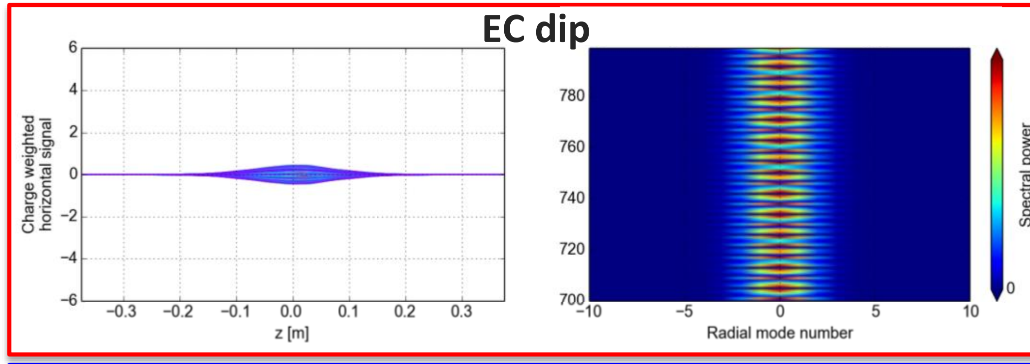


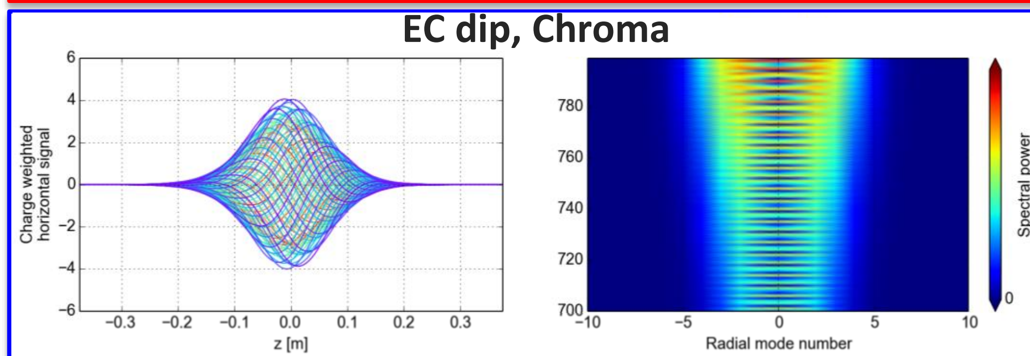


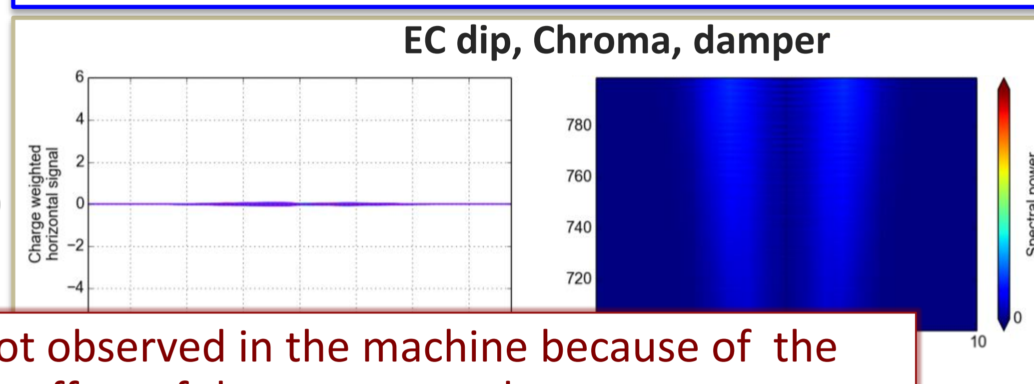


Horizontal instabilities – effect of the damper









This type of instability is not observed in the machine because of the strong stabilizing effect of the transverse damper