First results on the LHC beam dynamics simulations

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Many thanks to: E. Belli, L. Mether, E.Metral

Goal & Outline

- The aim of this work is to simulate the effect of the EC on the LHC beam dynamics for the nominal beam and evaluate under different operational scenarios the impact on the incoherent tune spread as well as on the coherent tune shift and instability threshold

- Investigations of coherent effects pose new challenges, especially at high energy because simulations were strongly limited by the computational burden → need to resolve very small beam within a much bigger chamber

- In order to improve the efficiency of the simulations
  - A new multi-grid solver has been implemented in PyPIC → finer grid resolution only in the vicinity of the beam
  - A new code for running in parallel computation has been developed (PyPARIS)

OUTLINE:

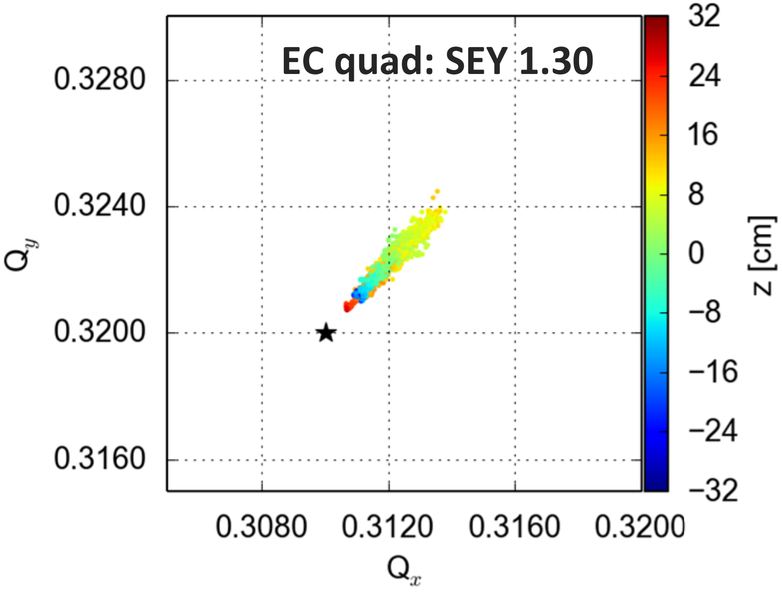
- Tune footprint at 6.5 TeV
- Coherent tune shift
- Coherent instability thresholds
- Preliminary results on the long simulation runs
- Brief status of the EC studies at injection

EC at 6.5 TeV – incoherent tune footprint

Simulating incoherent effects on the LHC at high energy:

- Intensity: 1.1e11 ppb
- Emittance: 3 um
- Bunch lenght: 1ns

- First step has been to check the contribution given by the different mechanisms on the tune footprint
  - EC in quadrupoles: self consistent simulation from the buildup → significant impact on the tune footprint*



*G. Iadarola, presentation at Joint HiLumi-LARP Meeting, Fermilab, 2015

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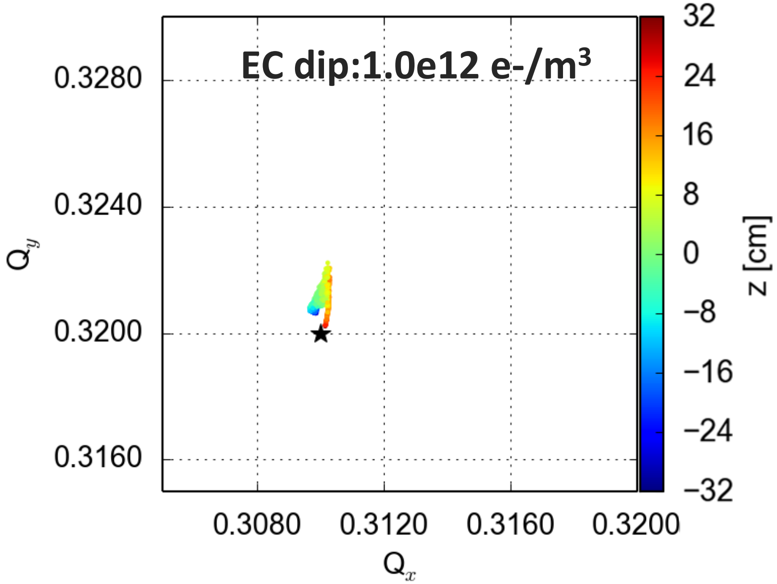

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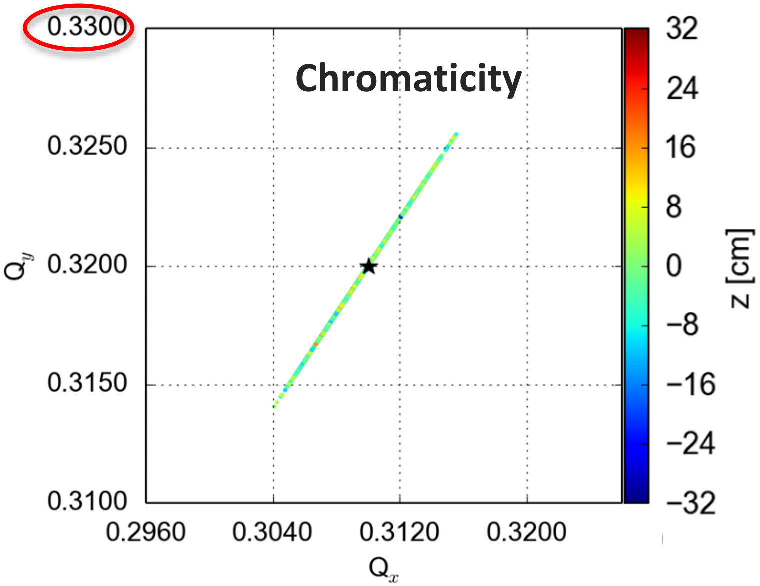
  - ✧ Chromaticity 20/20



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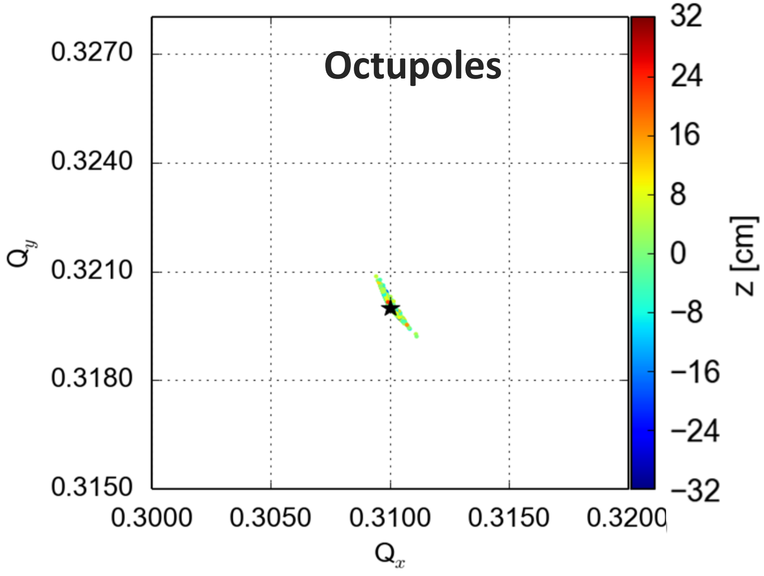
  - Chromaticity 20/20
  - Octupoles -2.5



In order to obtain a "complete" characterization we start combining all these effects

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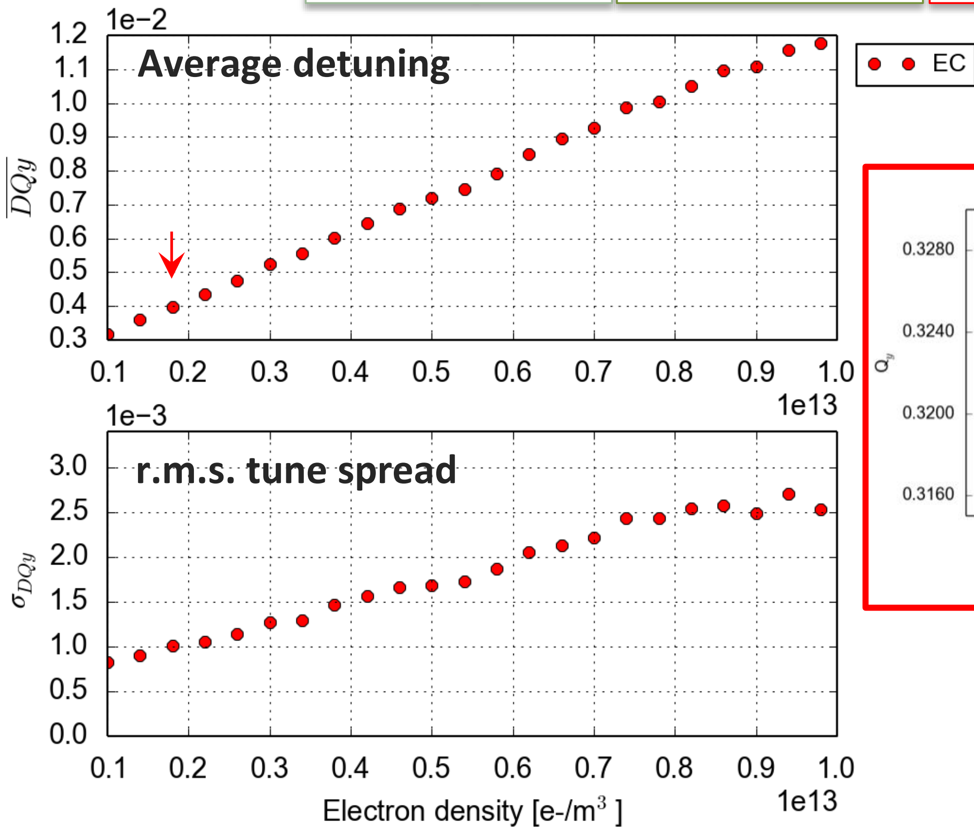
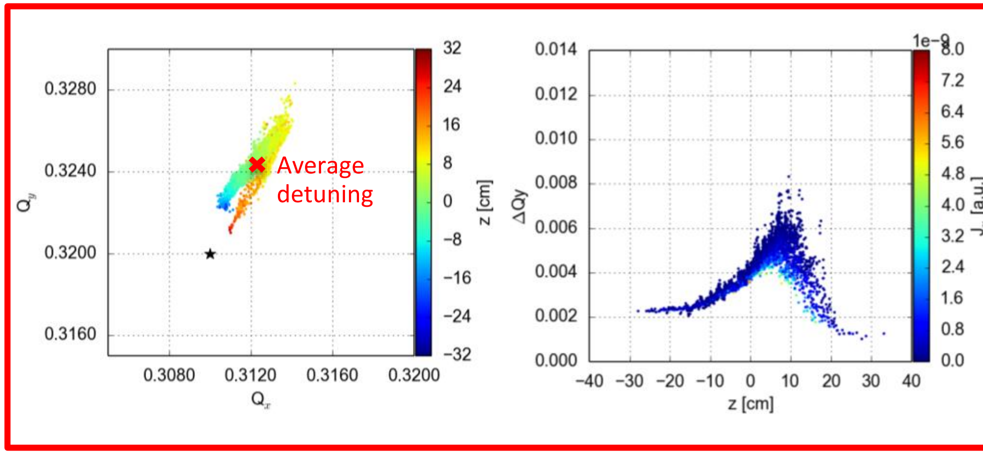
EC at 6.5 TeV – incoherent tune footprint

EC dipoles	EC quadruoles	Chromaticity	Oct
Density scan	SEY 1.30	✗	✗

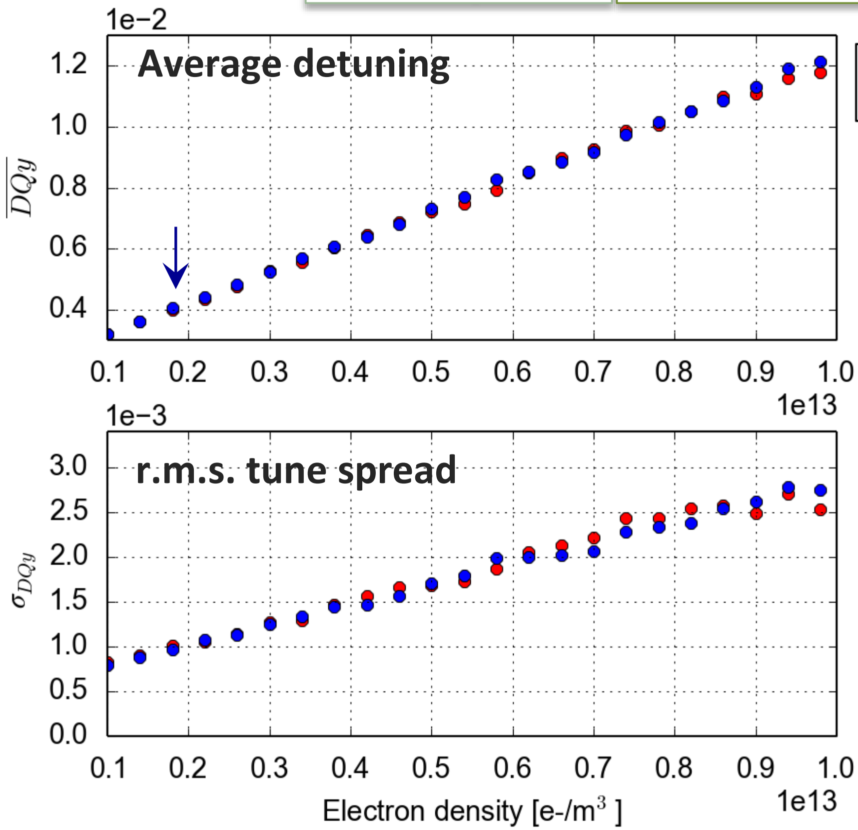


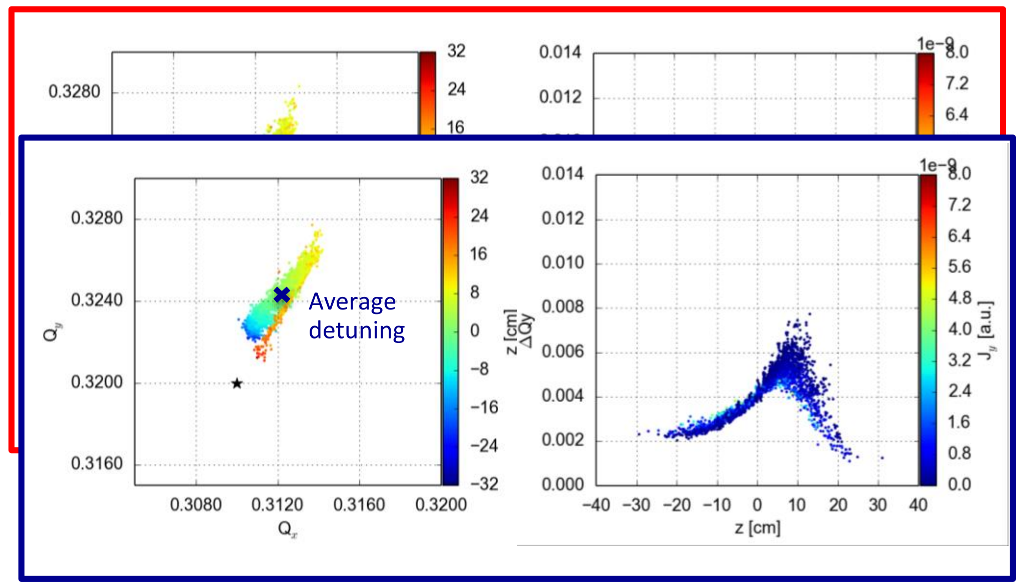


- Average incoherent detuning and r.m.s. tune spread are evaluated on the vertical plane
- Assuming an EC density of 1.8e12 e/m^3 :
  - Visible effect of the EC in dipoles in the tune footprint
  - Stronger detuning at ecloud pinch position

EC at 6.5 TeV – incoherent tune footprint

EC dipoles	EC quadruoles	Chromaticity	Oct
Density scan	SEY 1.30	✗	-2.5

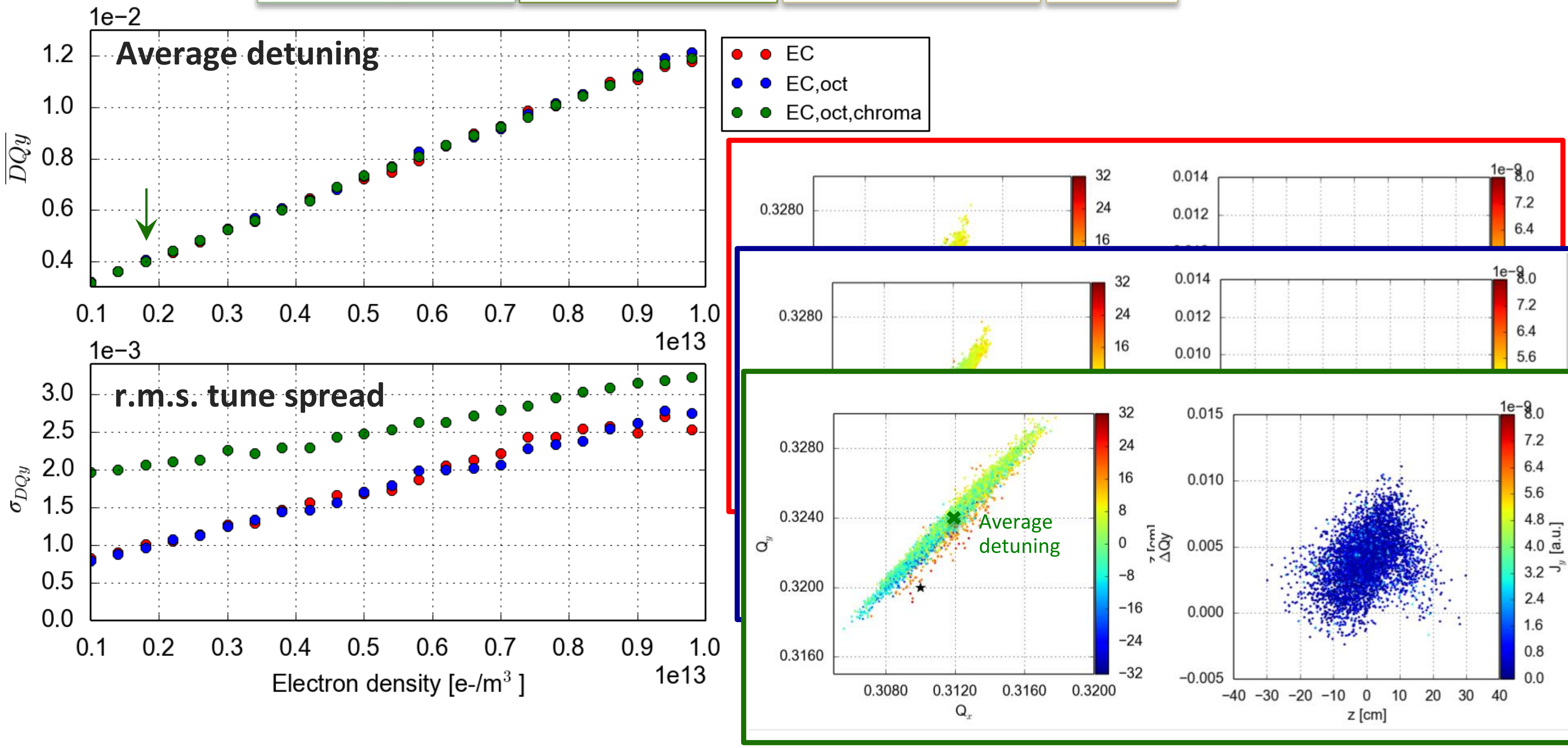




- Average incoherent detuning and r.m.s. tune spread are evaluated on the vertical plane
- Introducing the octupoles the tune footpirnt does not change significantly
  → Weak impact of the octupoles

EC at 6.5 TeV – incoherent tune footprint

EC dipoles	EC quadruoles	Chromaticity	Oct
Density scan	SEY 1.30	20/20	-2.5



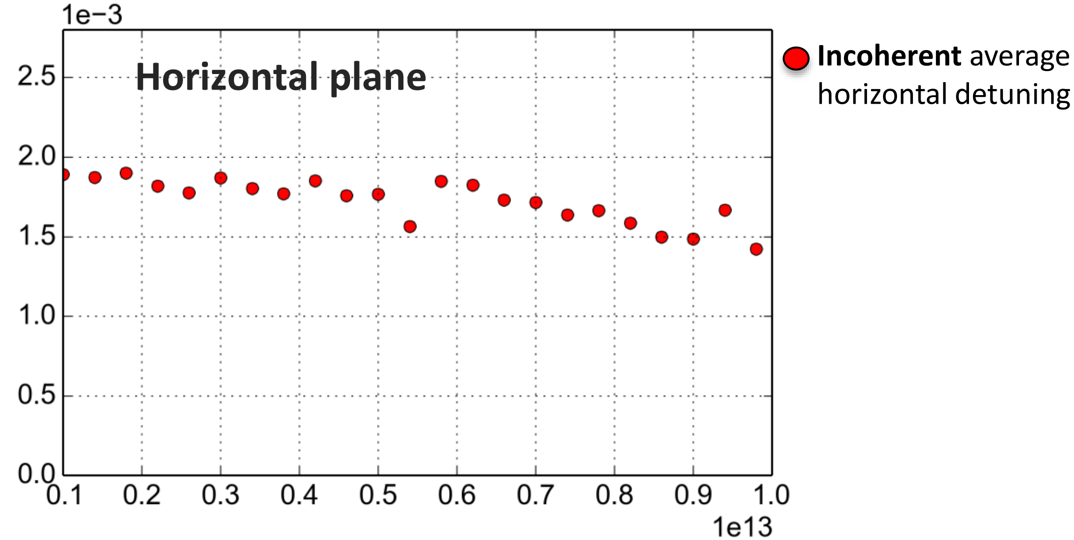
- Average incoherent detuning and r.m.s. tune spread are evaluated on the vertical plane
- Increasing the chromaticity:
  - The average detuning does not change
  - Stronger distortion to the tune spread (the Ecloud pinch is not visible anymore)

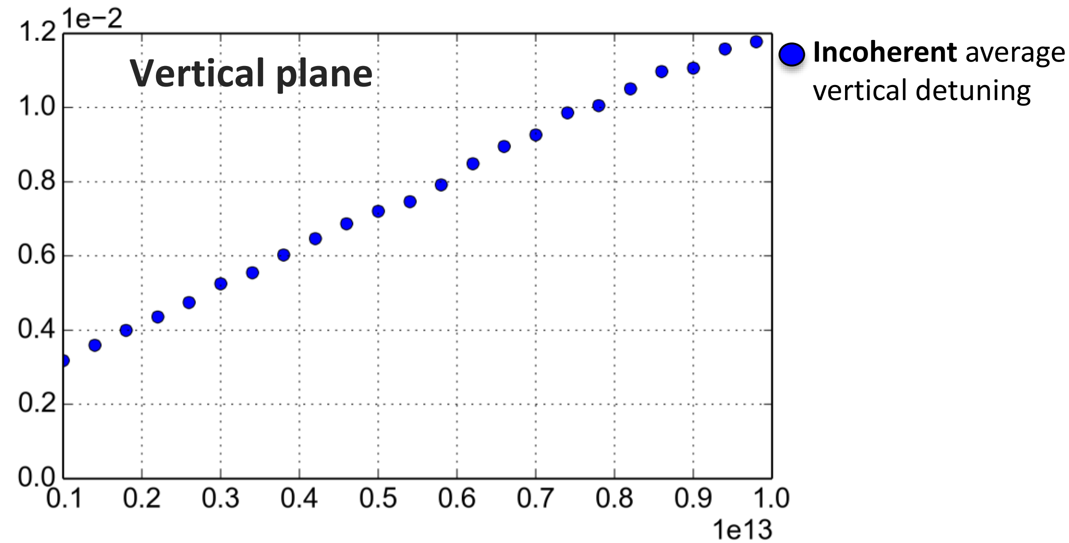
EC at 6.5 TeV – coherent tune shift

EC dipoles	EC quadruoles	Chromaticity	Oct
Density scan	SEY 1.30	✗	✗

Incoherent tune average detuning

- Horizontal: detuning does not change significantly over the EC density in dipoles → it depens from the EC in the quadrupoles which is fixed
- Vertical: it grows linearly with the EC density in dipoles → asymmetric footprint





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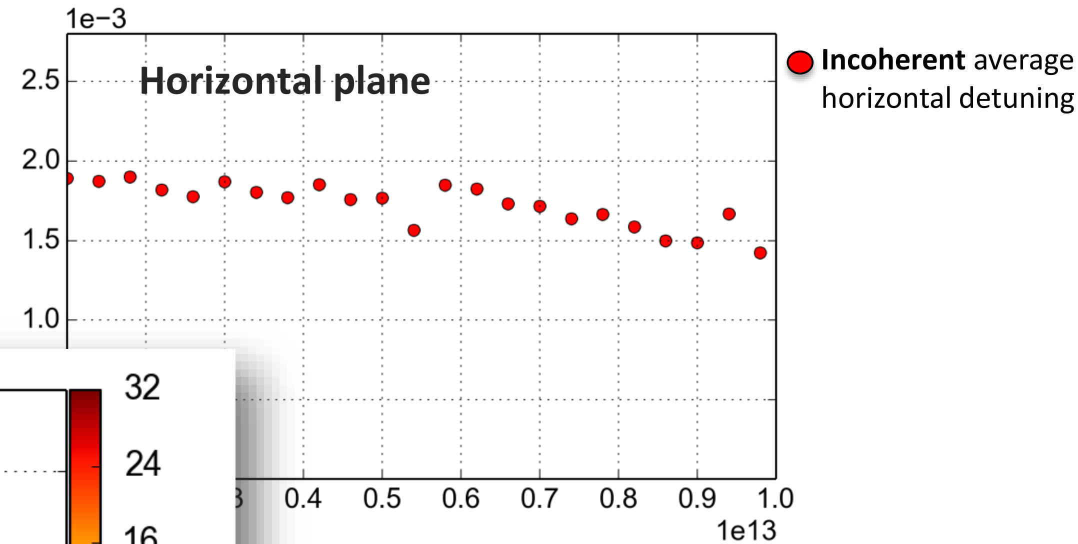
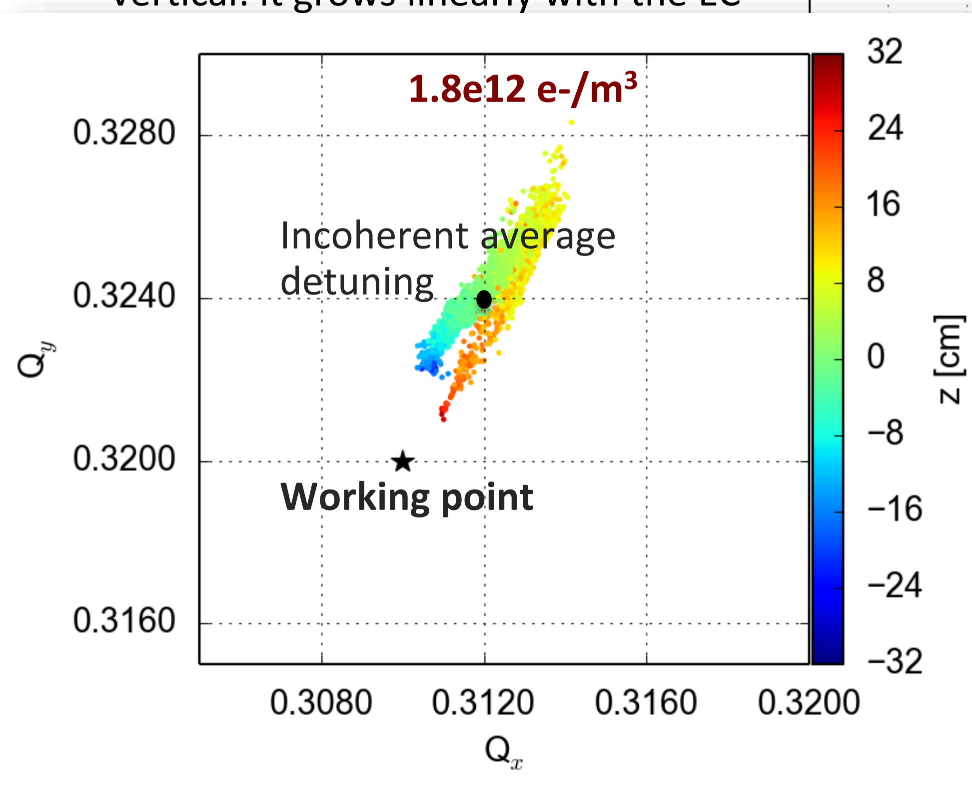
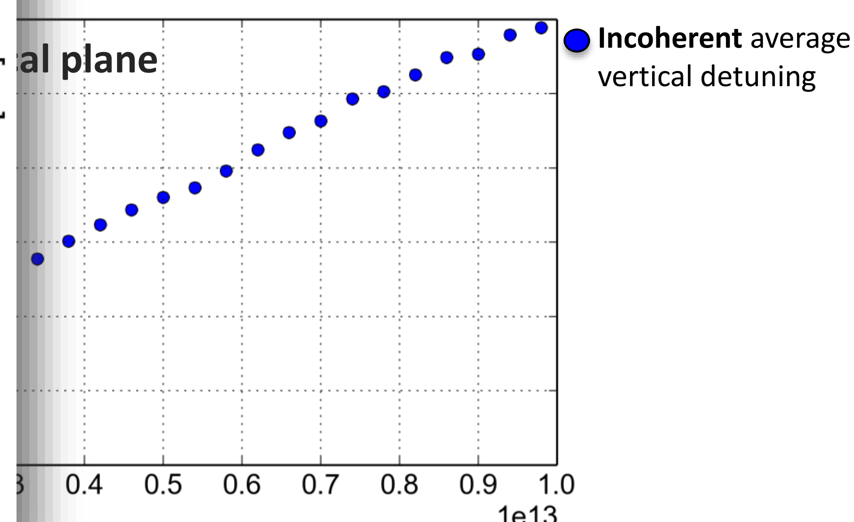
- Vertical: it grows linearly with the EC







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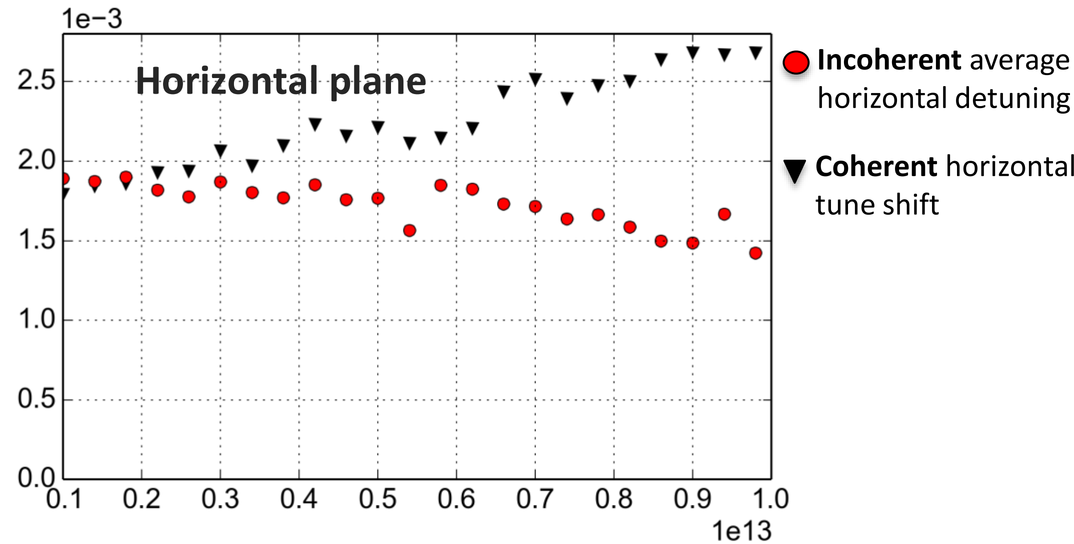
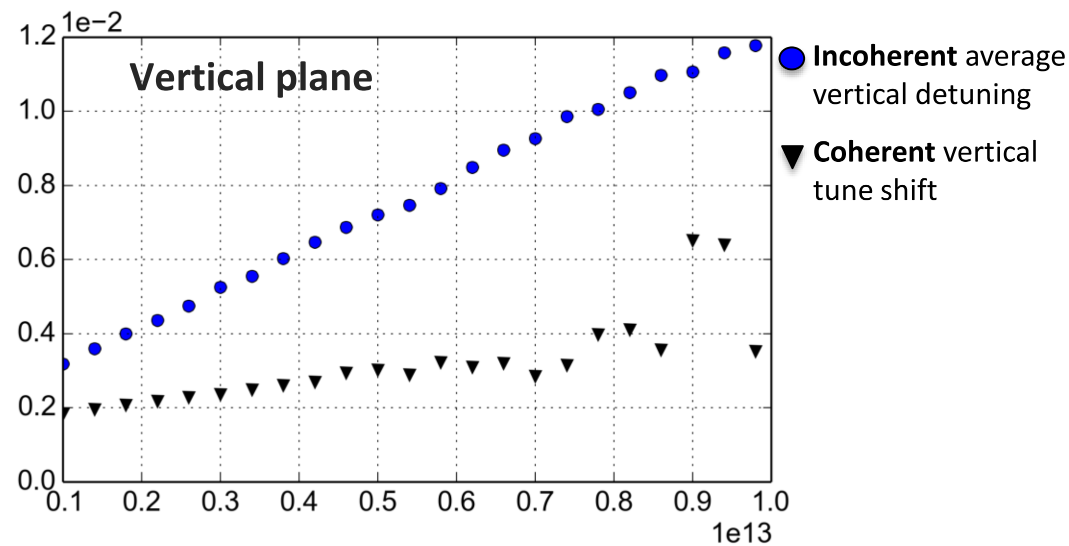


Coherent tune shift computed using PySUSSIX → Full instability-like simulations

- Comparing with the incoherent detuning
  - ✧ Horizontal: opposite sign
  - ✧ Vertical: ~2 times smaller



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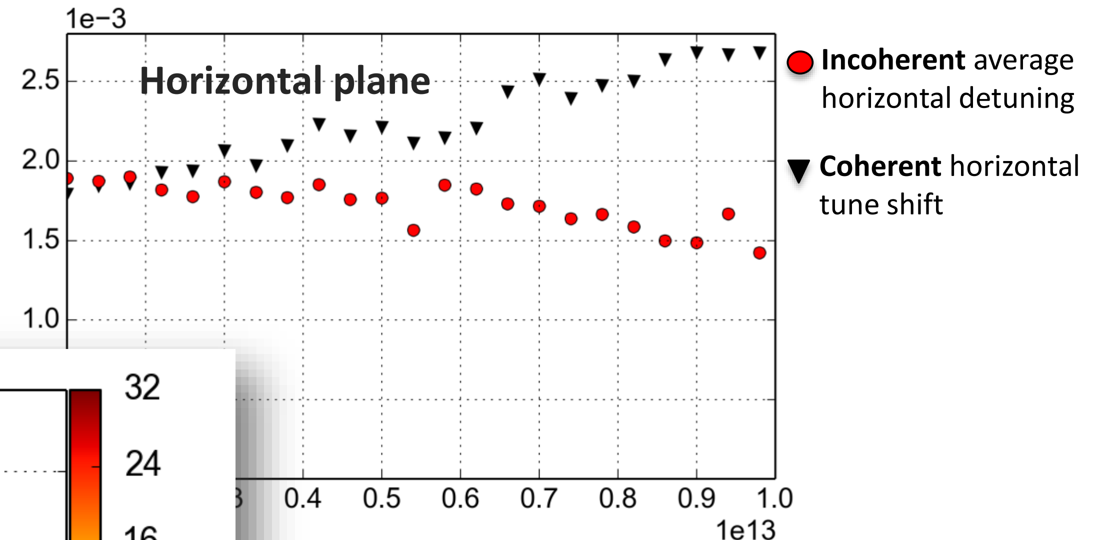
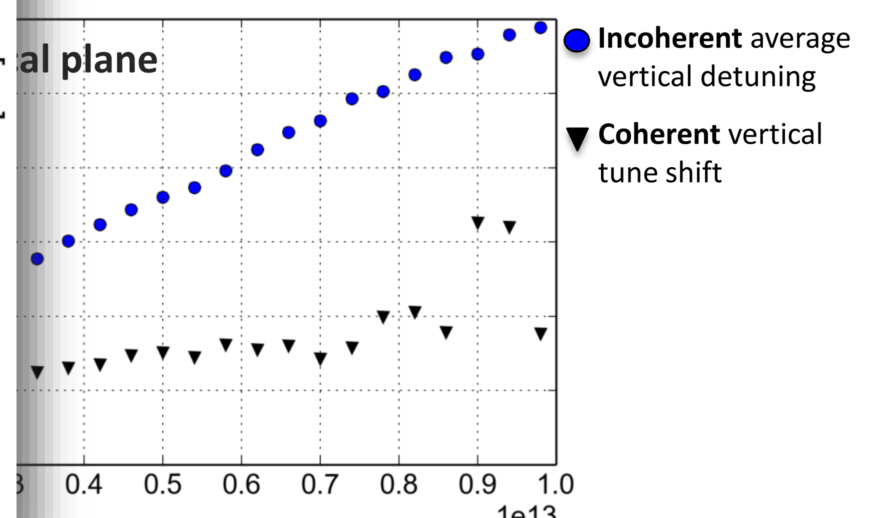
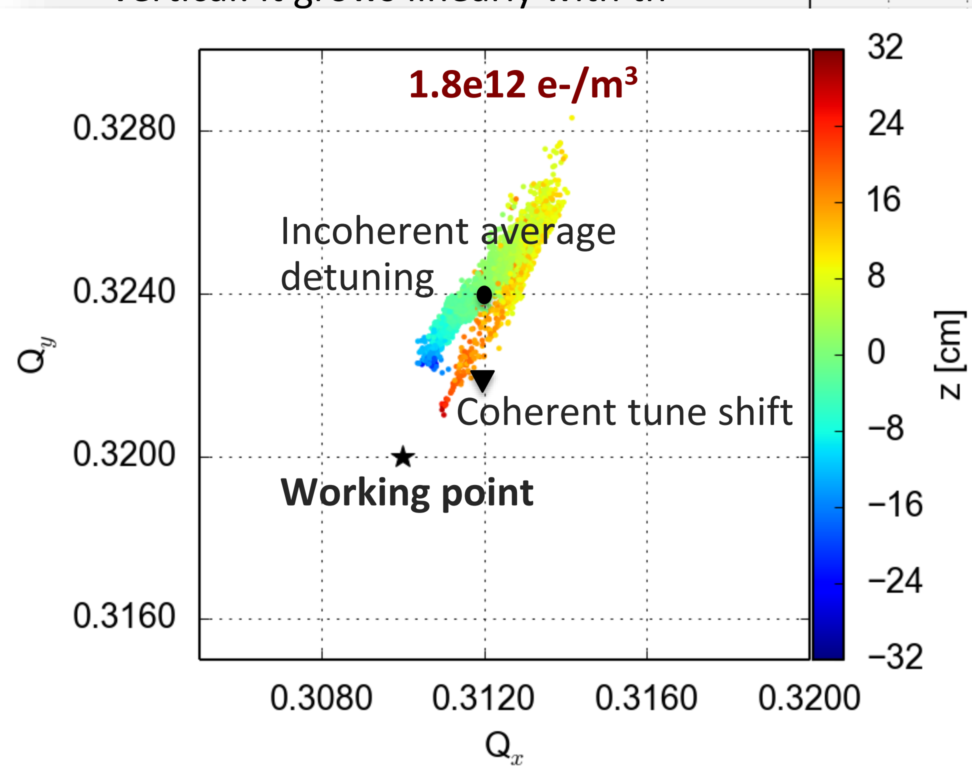






EC at 6.5 TeV – instability threshold

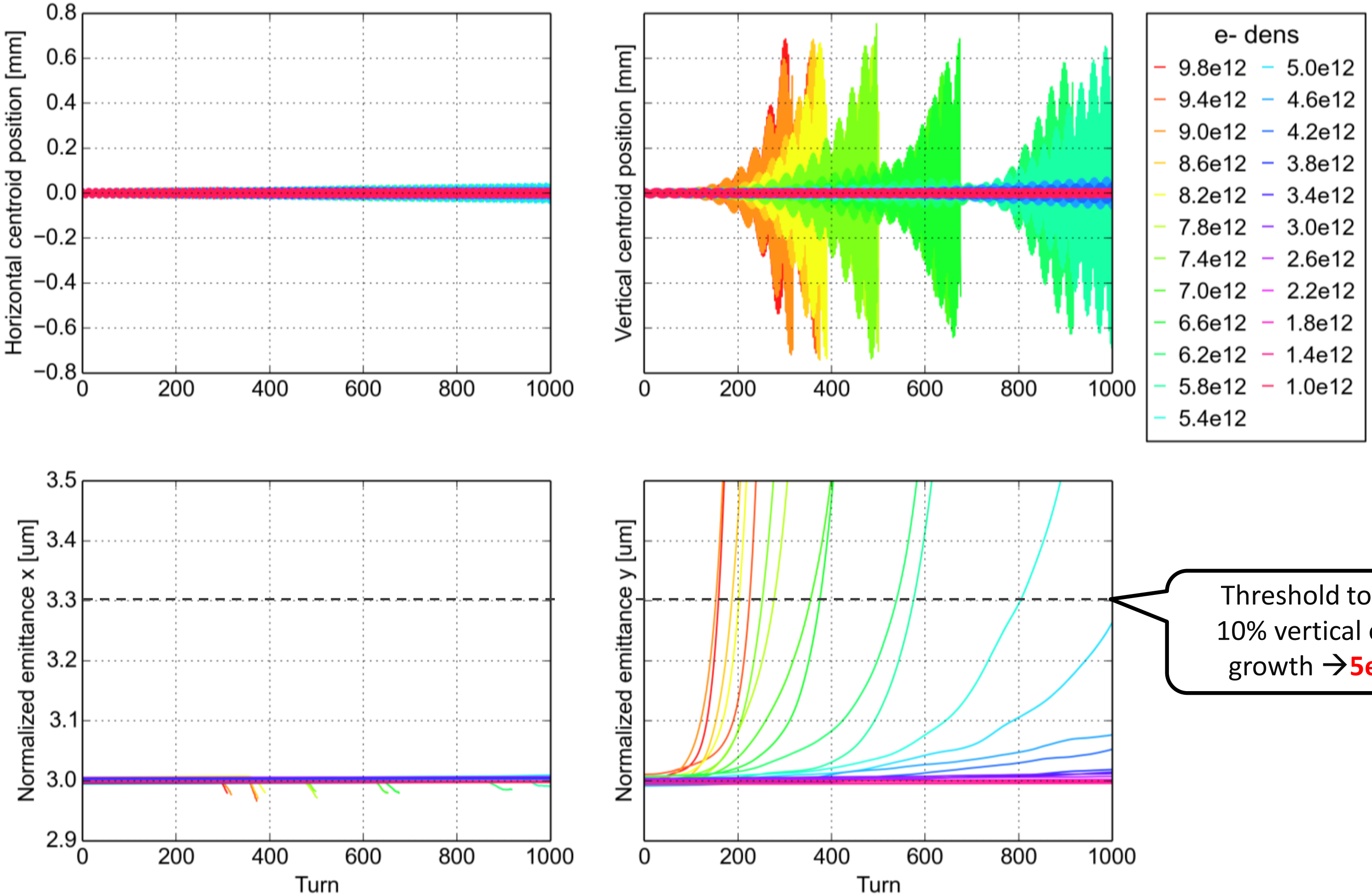
Simulating coherent effects on the LHC at high energy:

- Intensity: 1.1e11 ppb
- Emittance: 3 um
- bunch lenght: 1ns

- Fast simulations have been carried out → preliminary approch before going to more realistic simulations
  - Short time scale (1024 turns)
  - Machine settings (chroma, octupoles, damping time) bit exaggerated w.r.t. the real ones → we want to see the role played by the different mechanisms

EC at 6.5 TeV – instability threshold

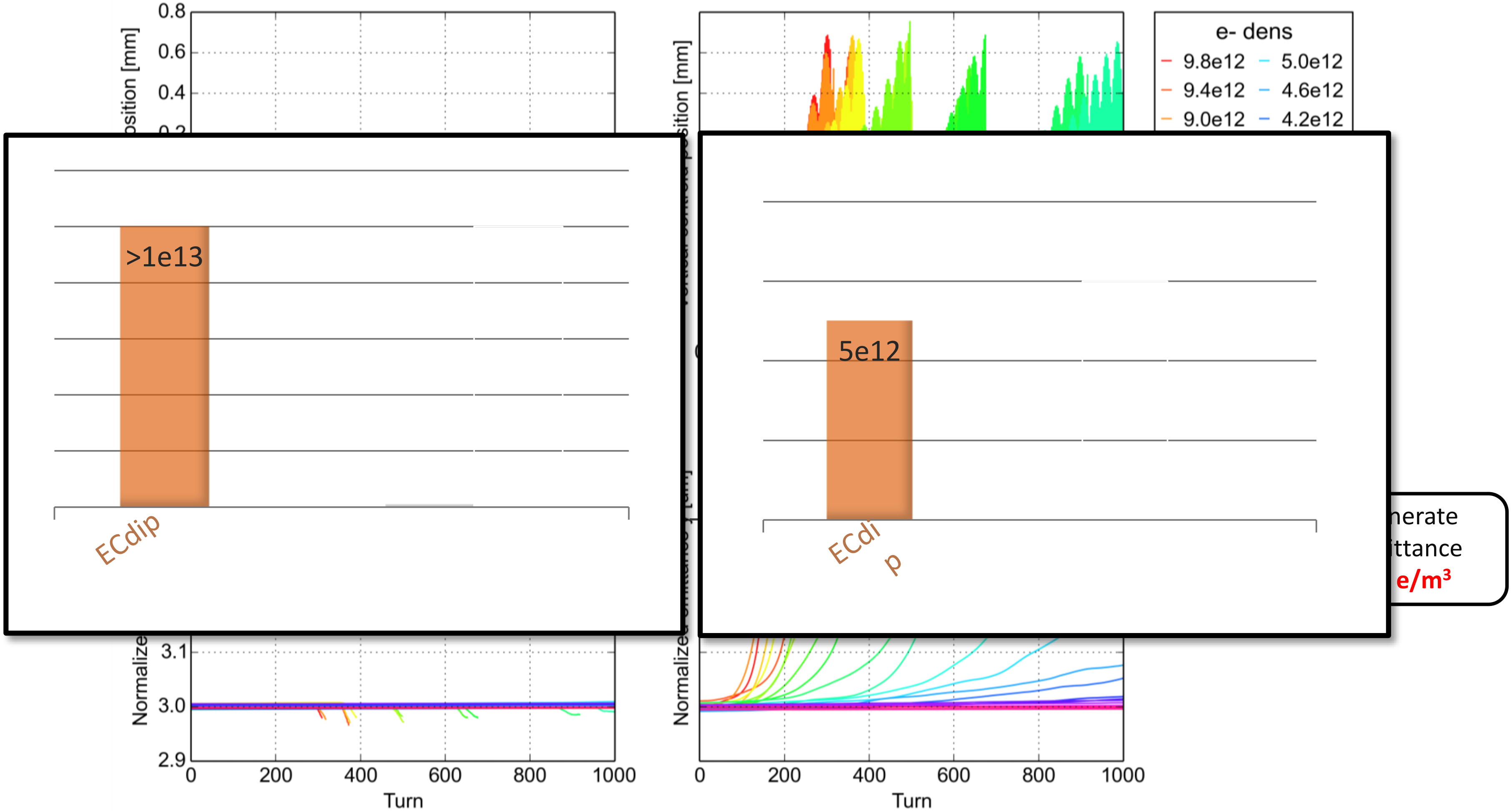
EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	✗	✗	✗



Threshold to generate 10% vertical emittance growth → **5e12 e/m³**

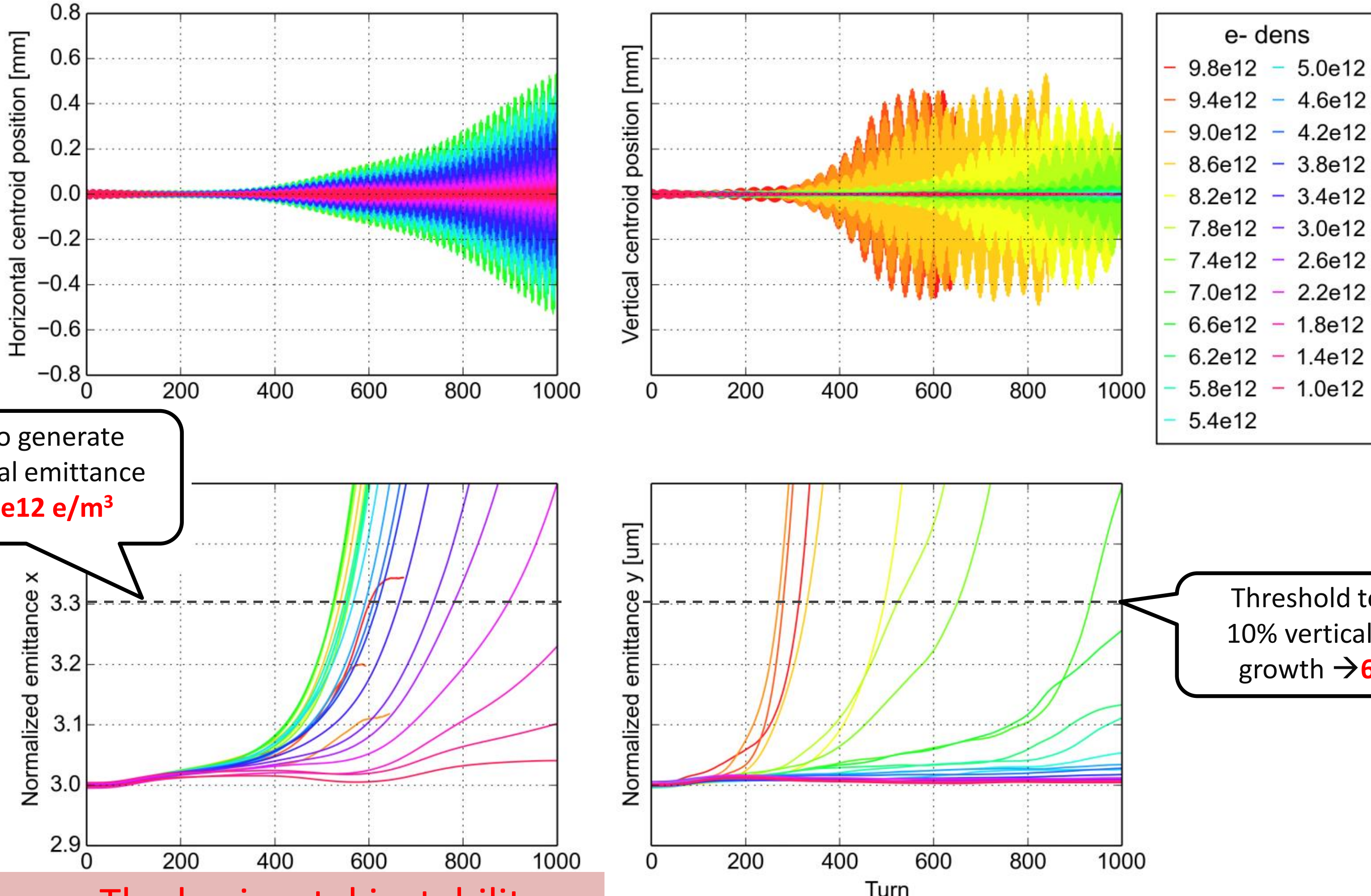
EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	✗	✗	✗



EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	20/20	✗	✗



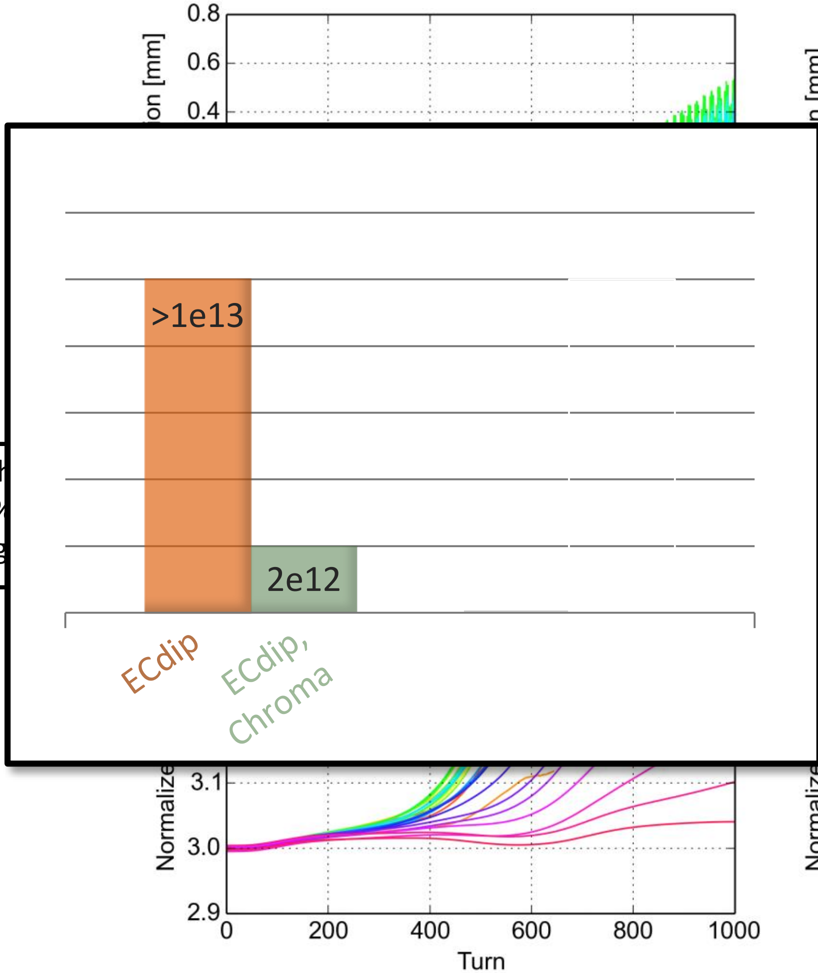
Threshold to generate 10% horizontal emittance growth→**2e12 e/m³**

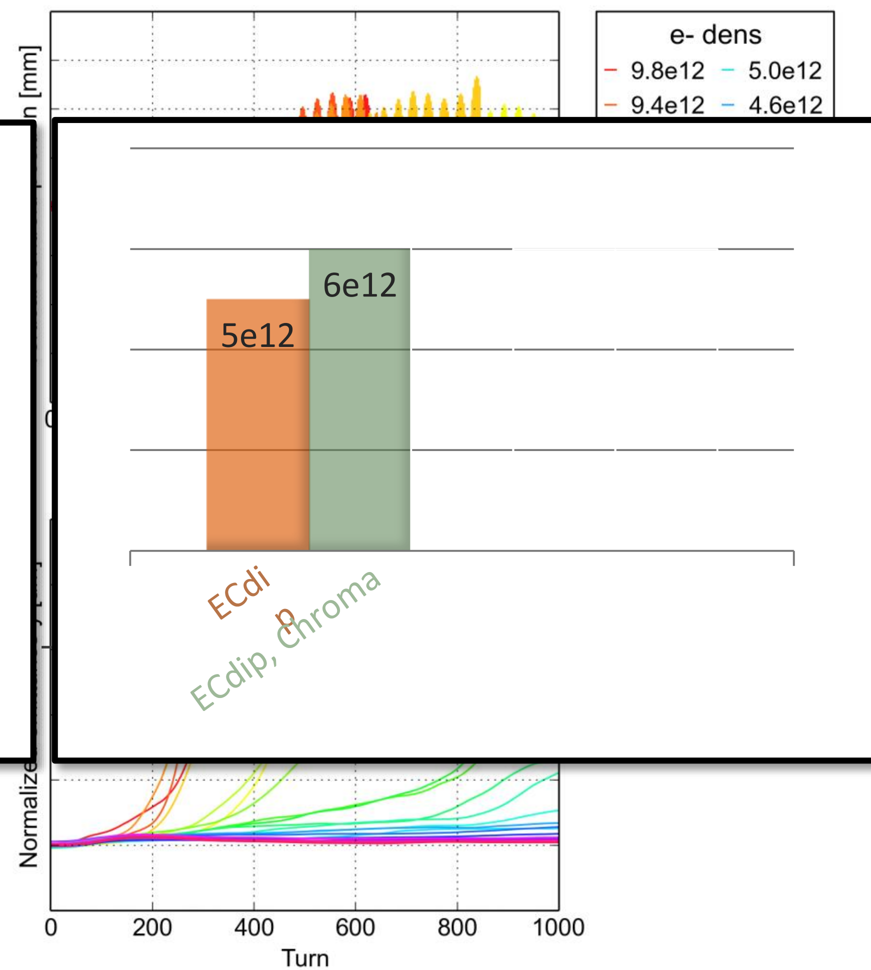
Threshold to generate 10% vertical emittance growth →**6e12 e/m³**

The horizontal instability will be treated further into the presentation

EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	20/20	✗	✗





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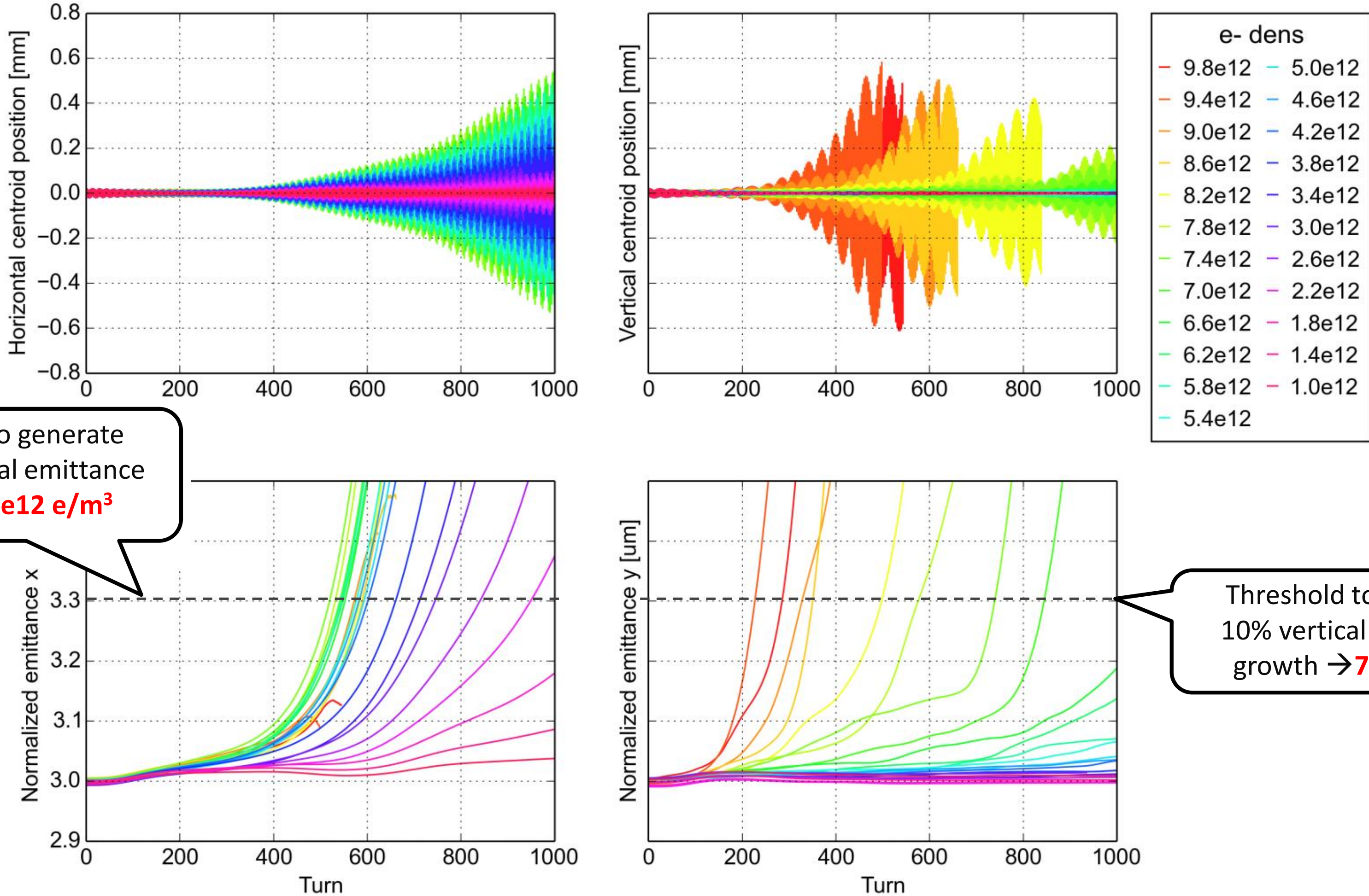
e/m³

EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	20/20	-2.5	✗

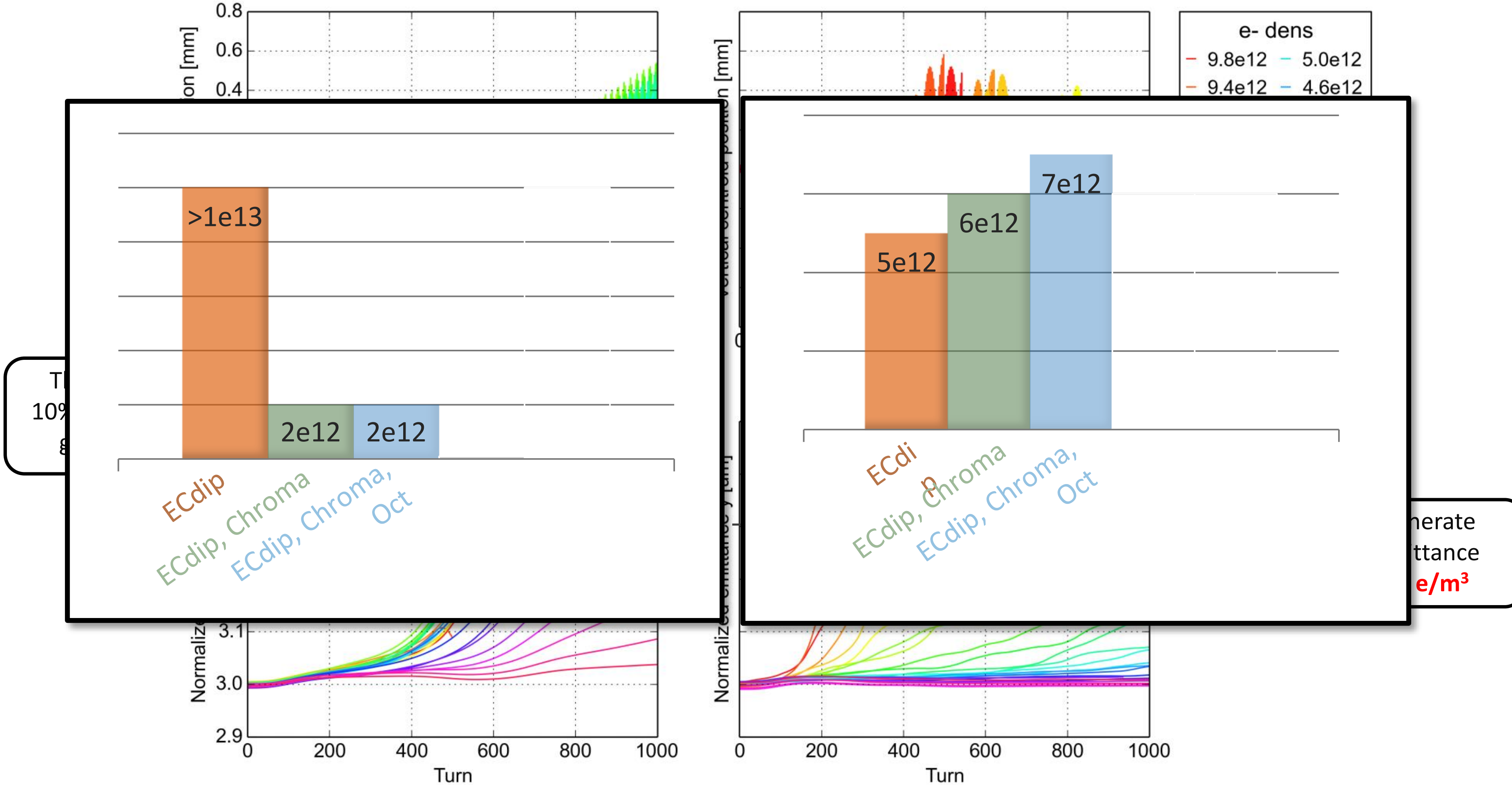


Threshold to generate 10% horizontal emittance growth→**2e12 e/m^3**

Threshold to generate 10% vertical emittance growth →**7e12 e/m^3**

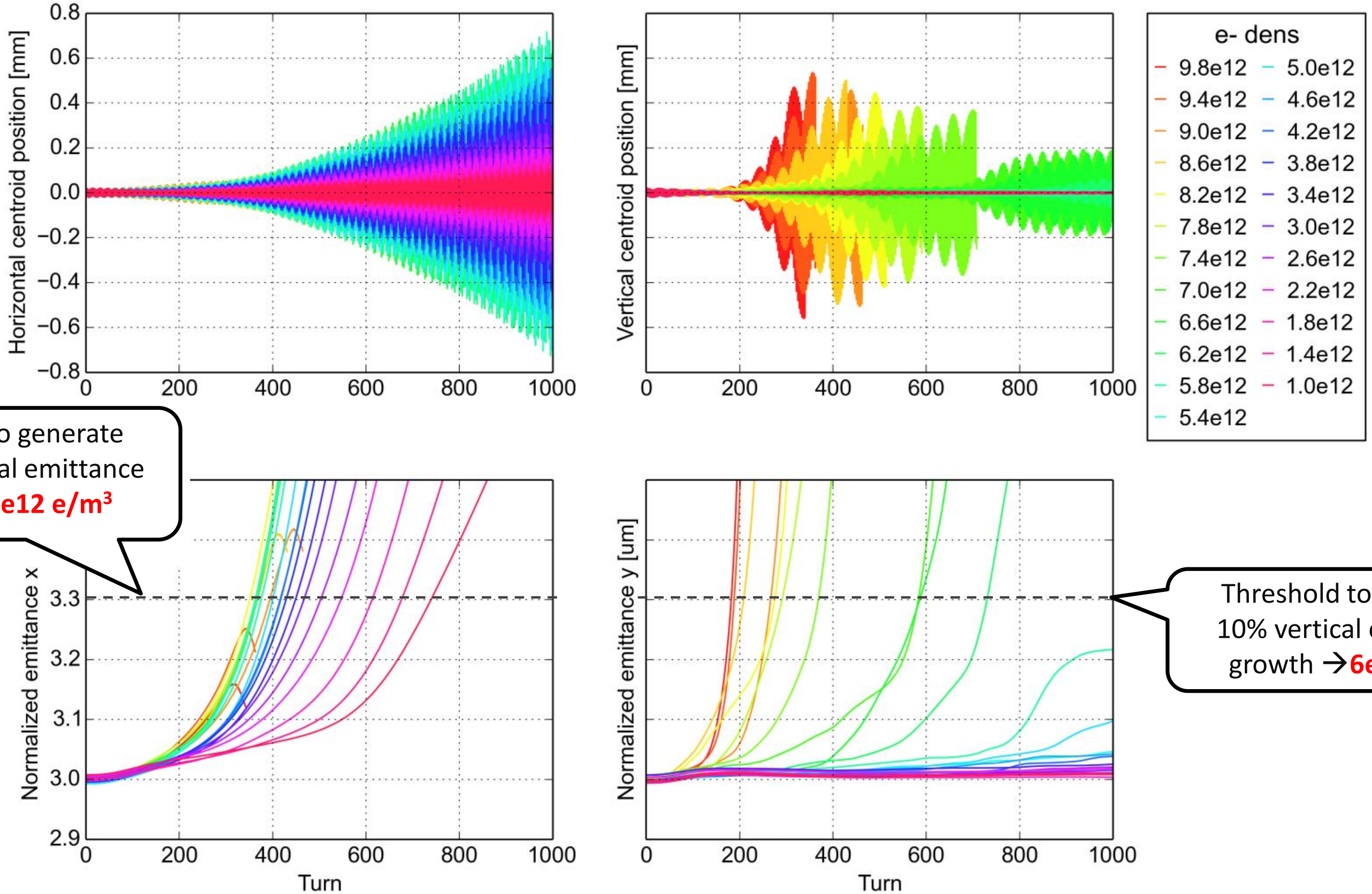
EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	20/20	-2.5	✗



EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	SEY 1.30	20/20	-2.5	✗



Threshold to generate 10% horizontal emittance growth→**1e12 e/m³**

Threshold to generate 10% vertical emittance growth →**6e12 e/m³**

EC at 6.5 TeV – instability threshold

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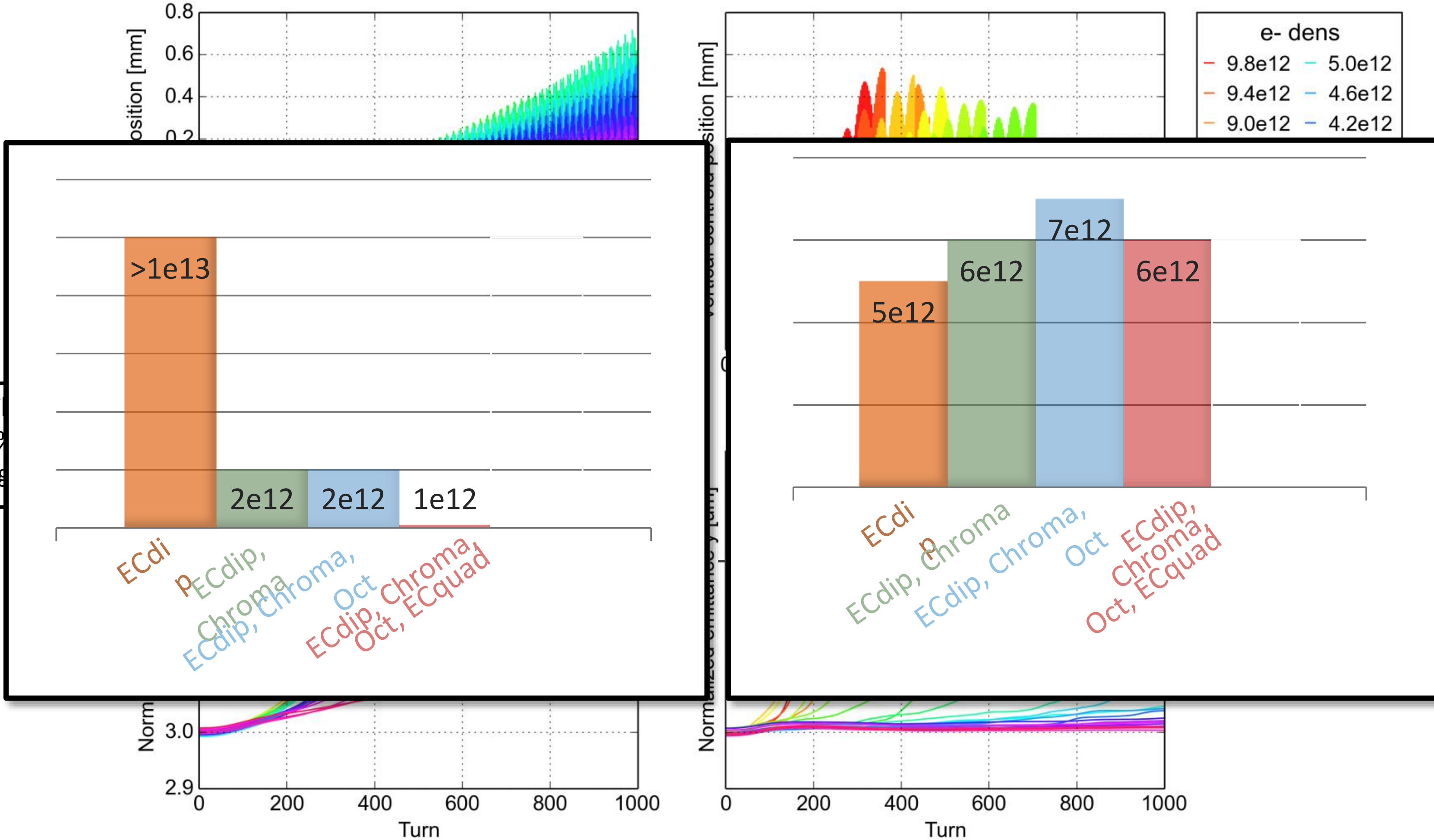
Density scan	SEY 1.30	20/20	-2.5	✗

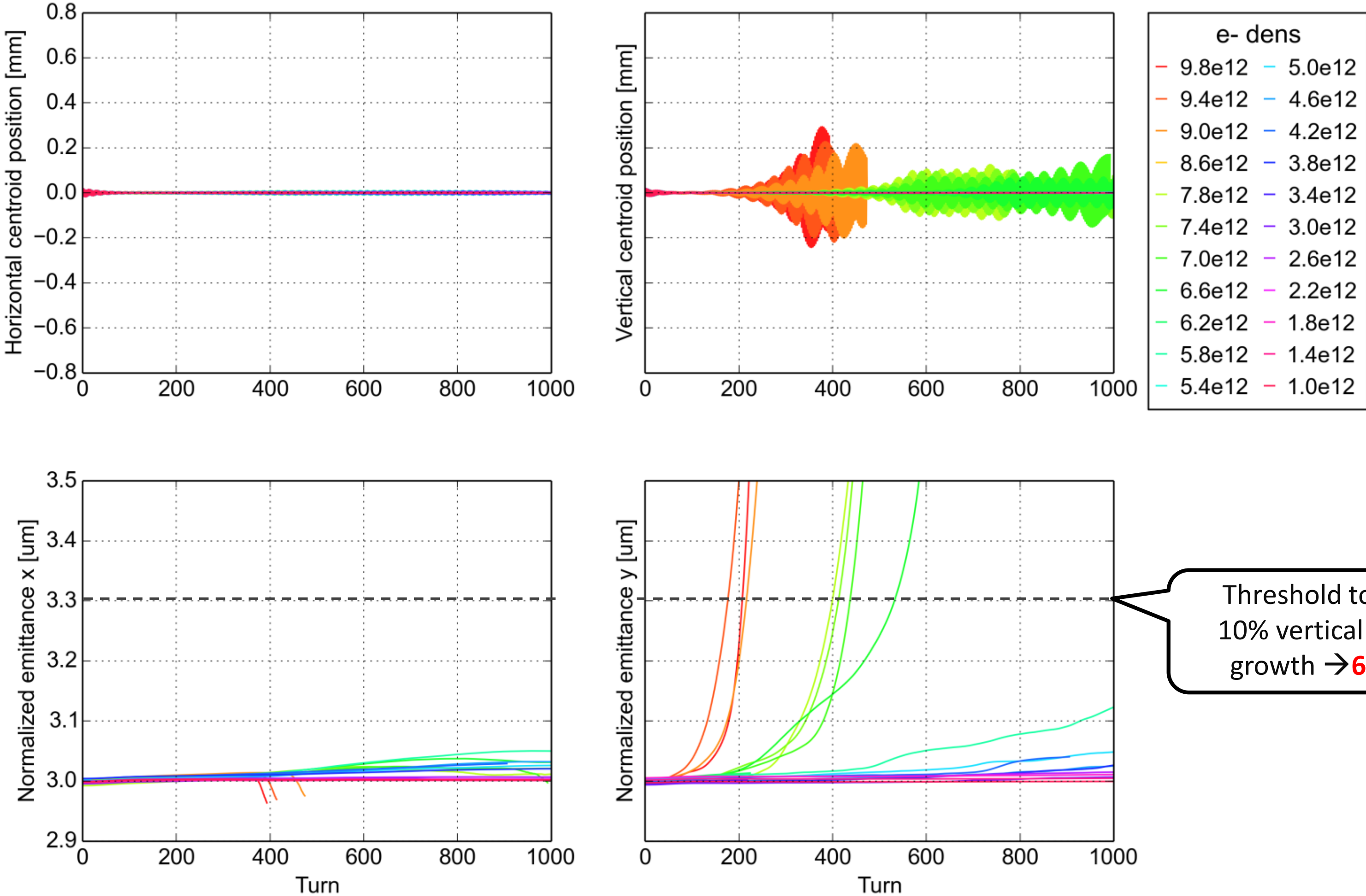


Th… 10% …

…nerate …ittance … e/m³

EC at 6.5 TeV – instability threshold

EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	SEY 1.30	20/20	-2.5	50 turns

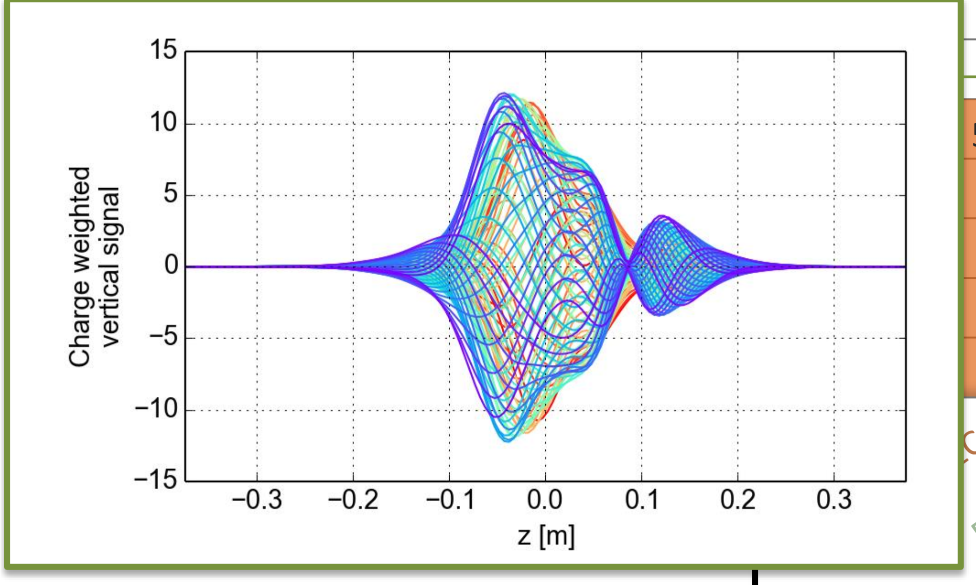


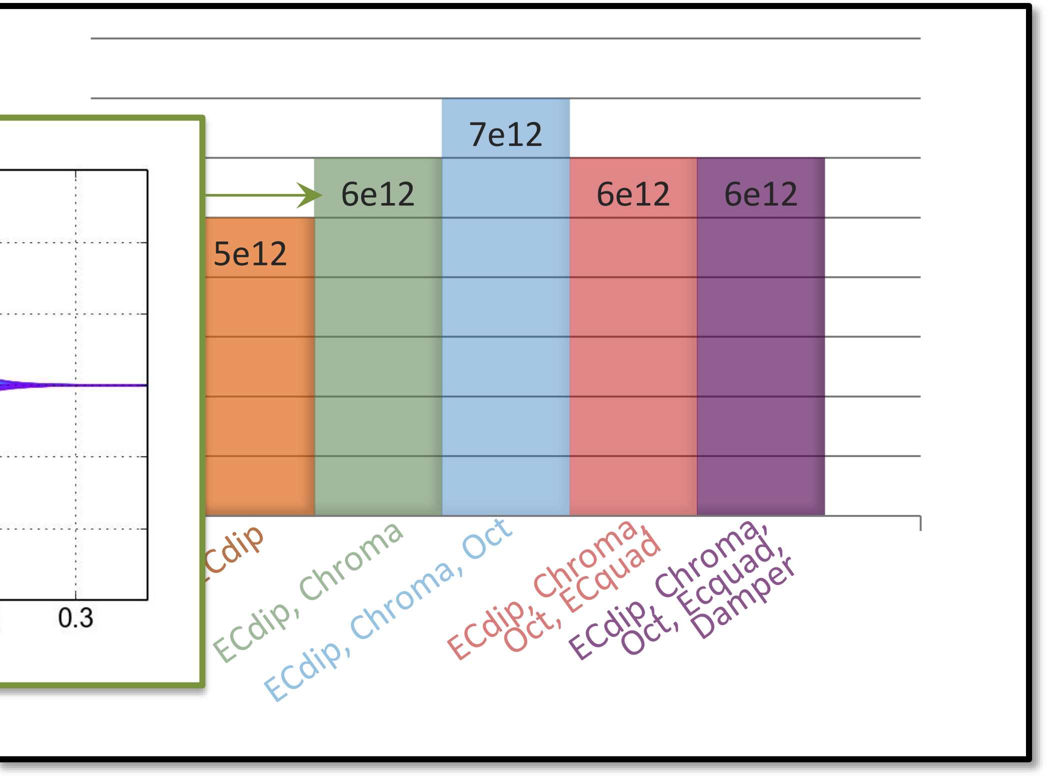
Threshold to generate 10% vertical emittance growth → **6e12 e/m^3**

EC instability thresholds: vertical plane

EC instability threshold defined as density needed to generate 10% emittance growth over 1024 turns

- Mild stabilizing effect of chromaticity (20/20)
- Mild stabilizing effect of octupoles (-2.5)
- Destabilizing effect of the Ecloud in quadropules (but not dominant effect)
- No effect of the damper (50 turns damping time)

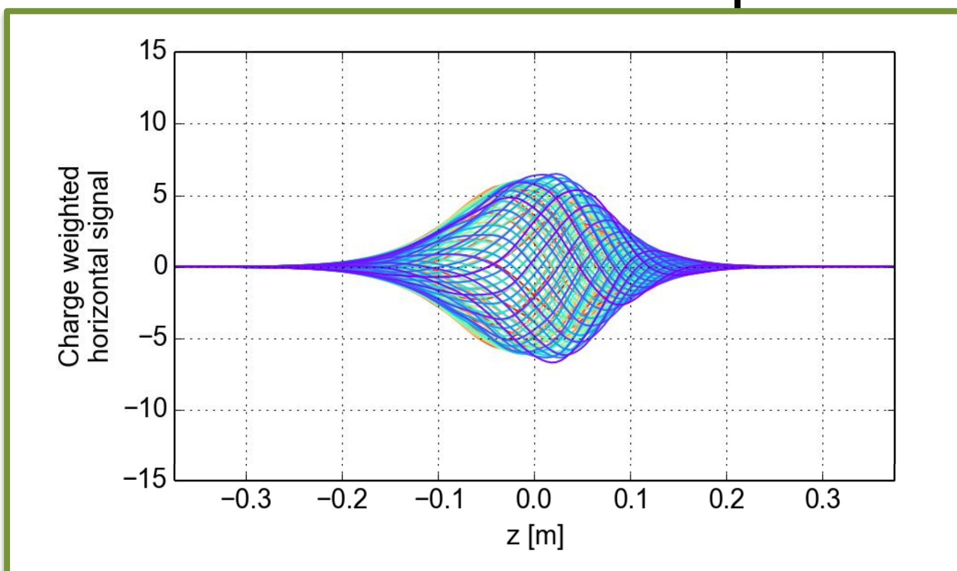


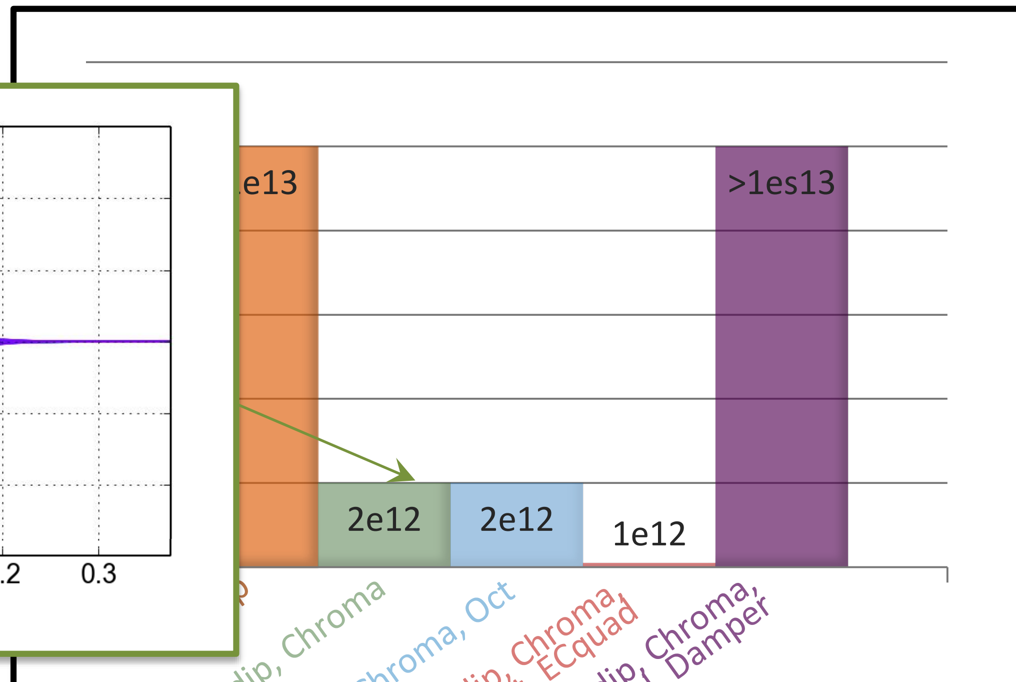


EC instability thresholds: horizontal plane

EC instability threshold defined as density needed to generate 10% emittance growth over 1024 turns

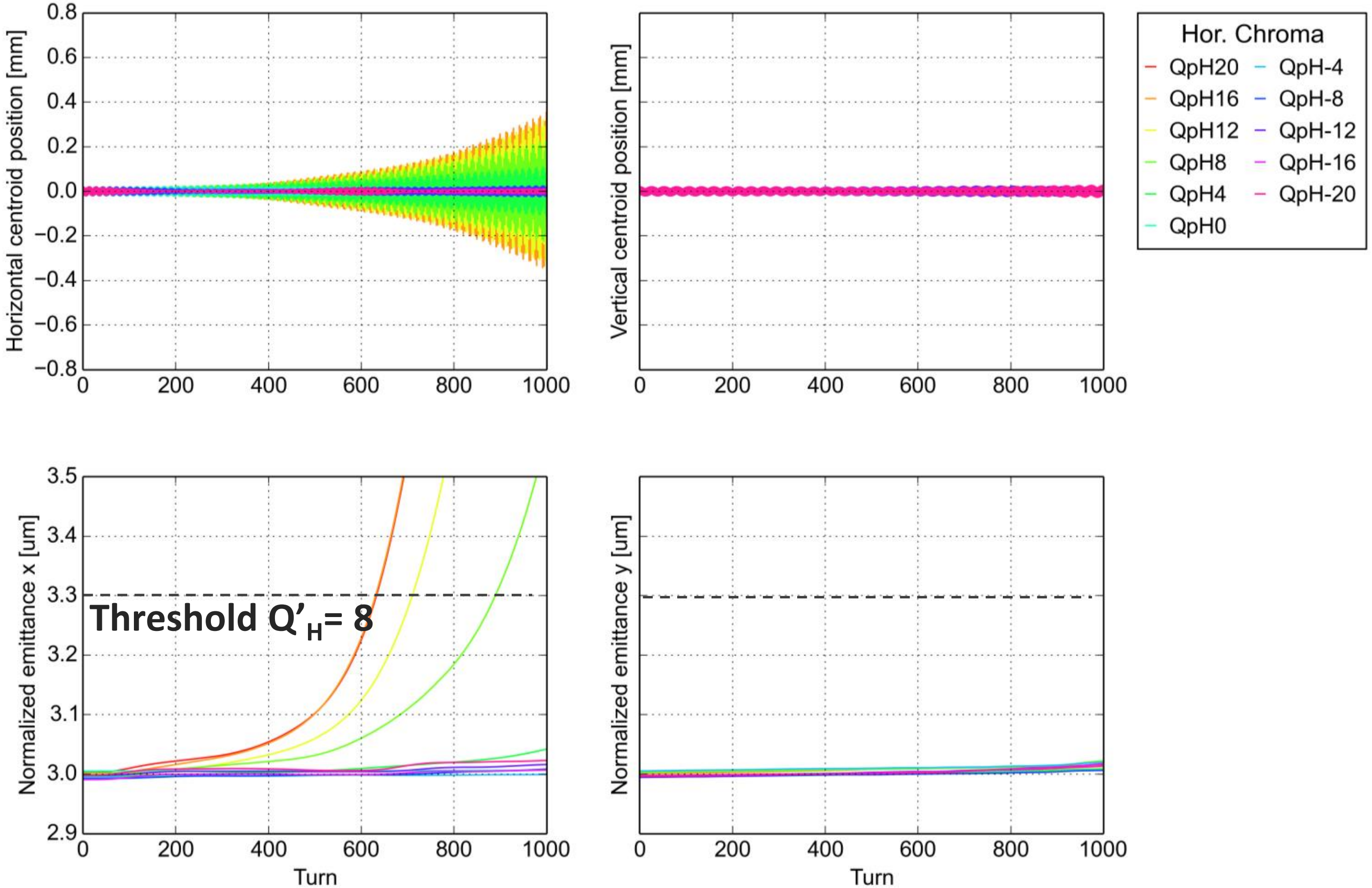
- Strong destabilizing effect of chromaticity (20/20)
- No effect of octupoles (-2.5)
- Mild destabilizing effect of the Ecloud in quadropules (but not dominant effect)
- Strong stabilizing effect of the damper (50 turns damping time)





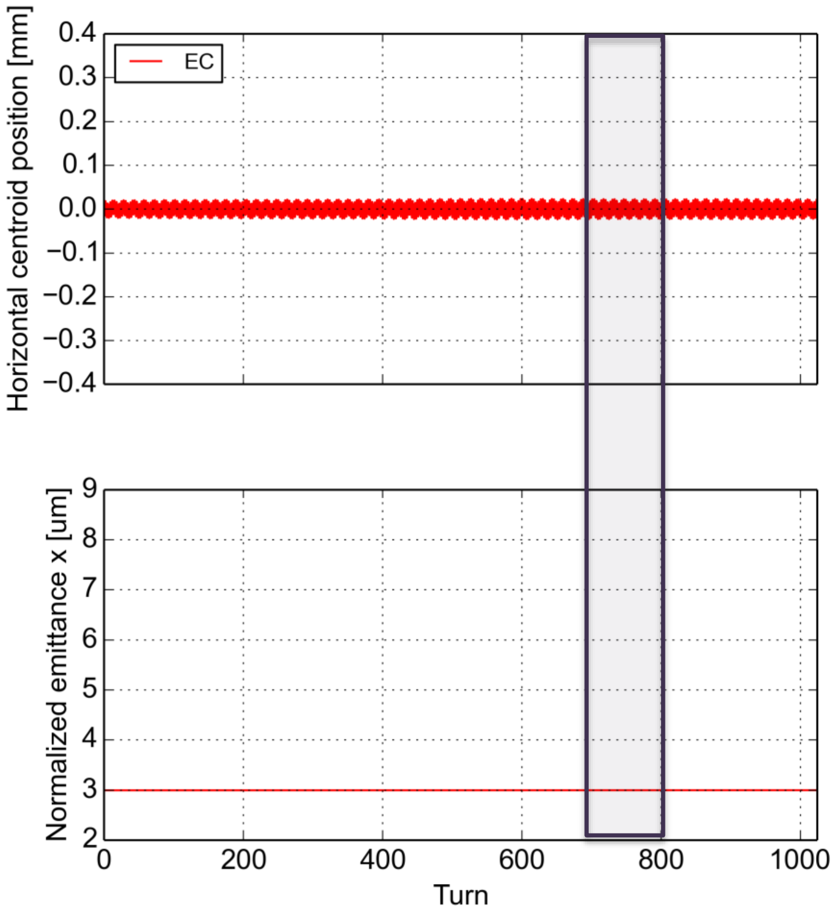
We want to check the impact of the chromacity as well as the damper on the instability mechanism

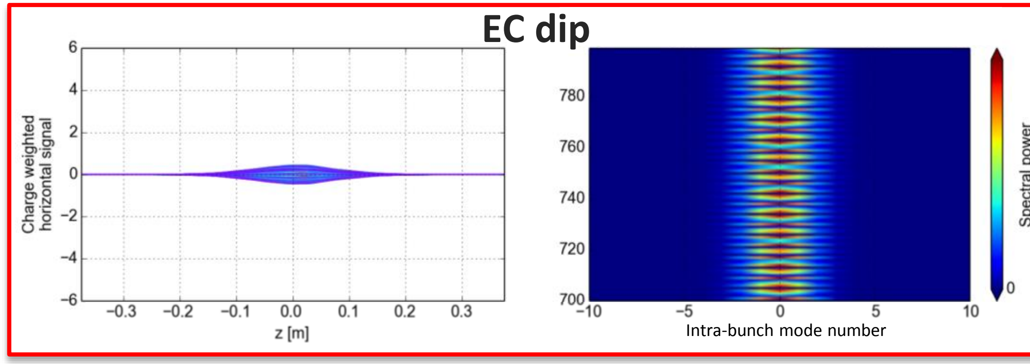
Horizontal instabilities – effect of the chromaticity



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

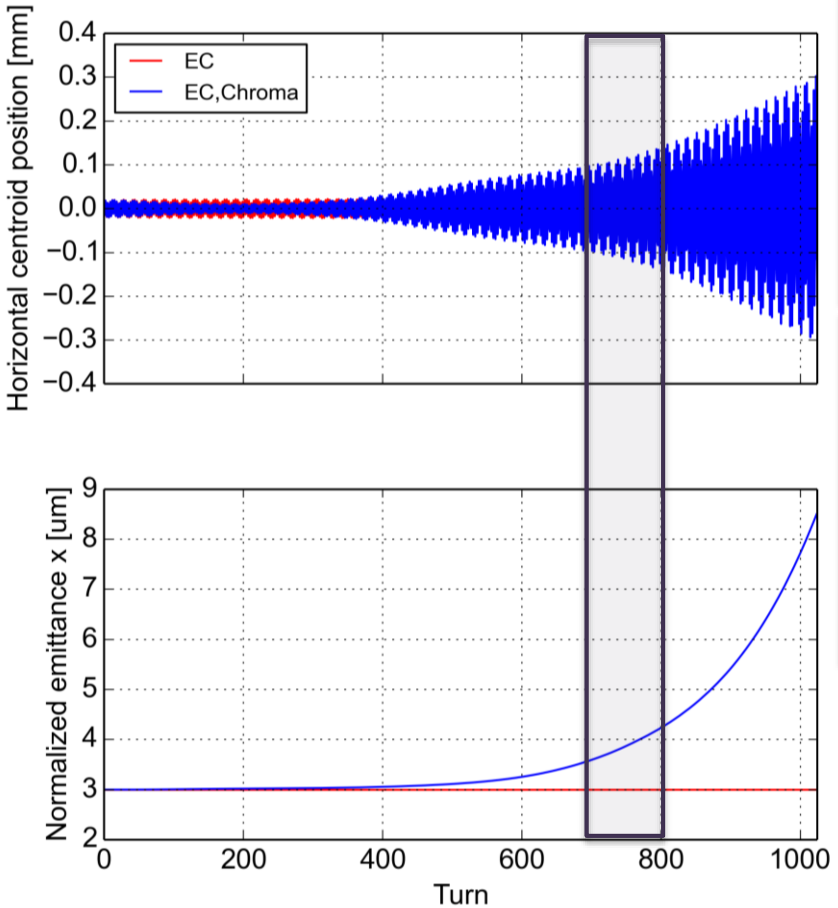
Horizontal instabilities – effect of the damper

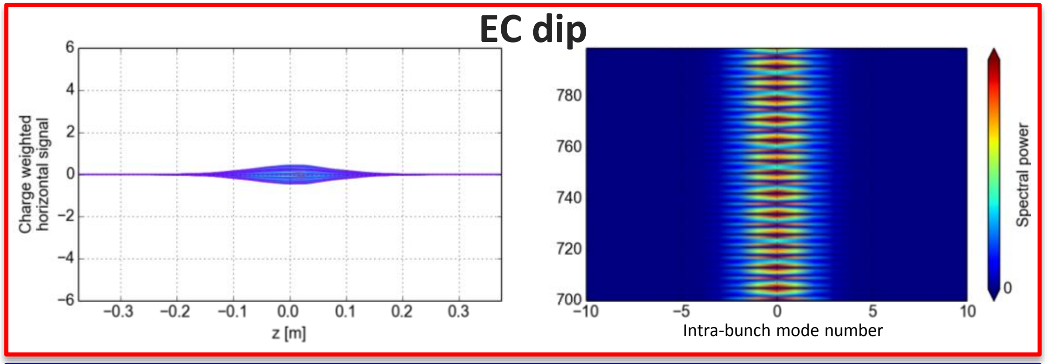


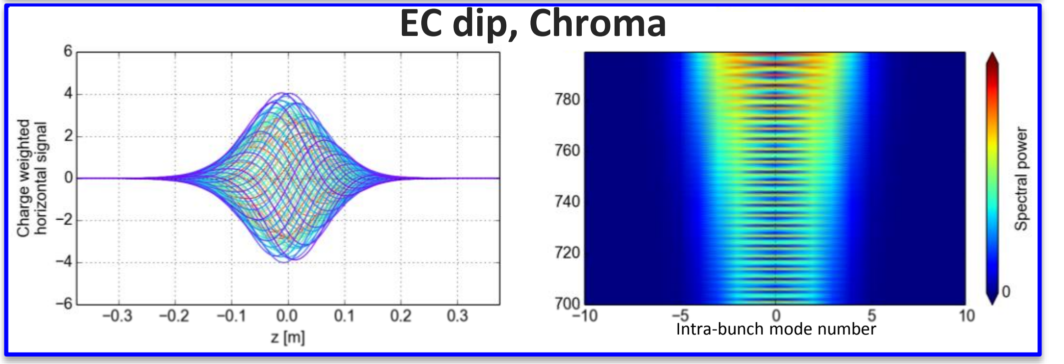


- EC only in dipoles, density fixed at **3.8e12**
- No horizontal emittance blown-up → beam is stable
- Intra-bunch modes have been excited → spectrogram reveals strong centered motion

Horizontal instabilities – effect of the damper

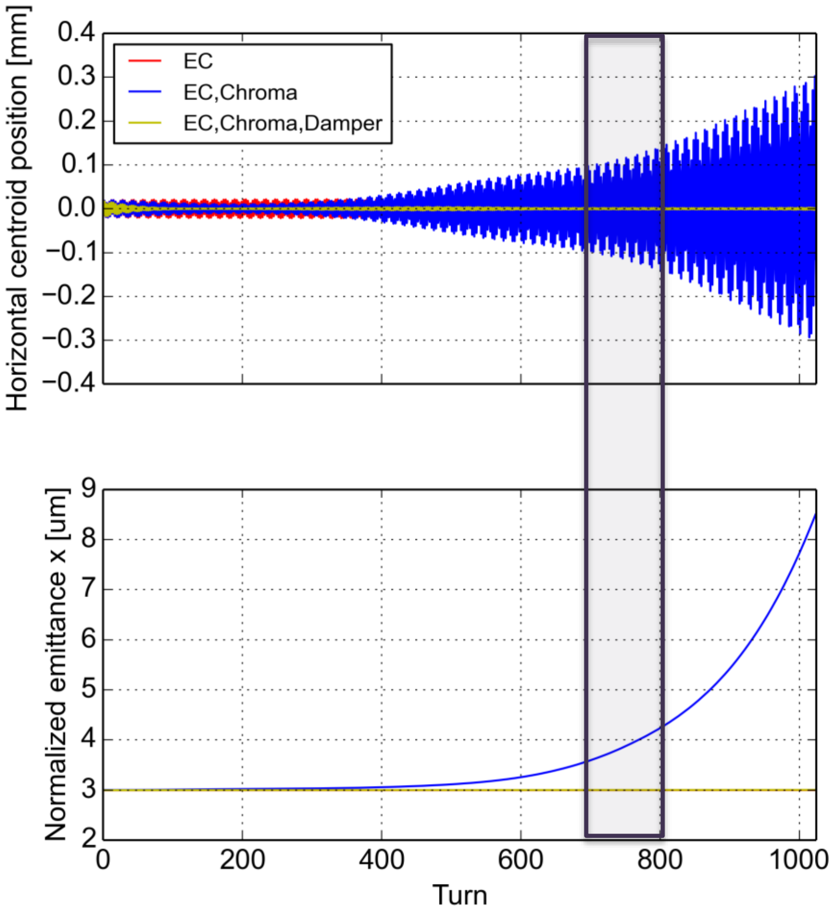


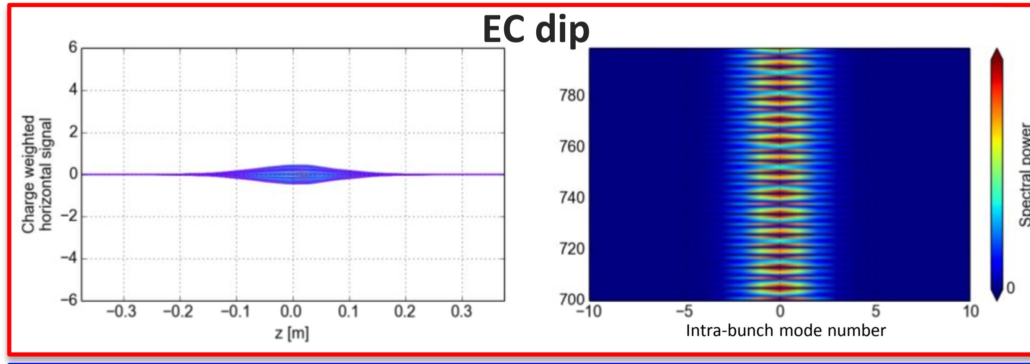


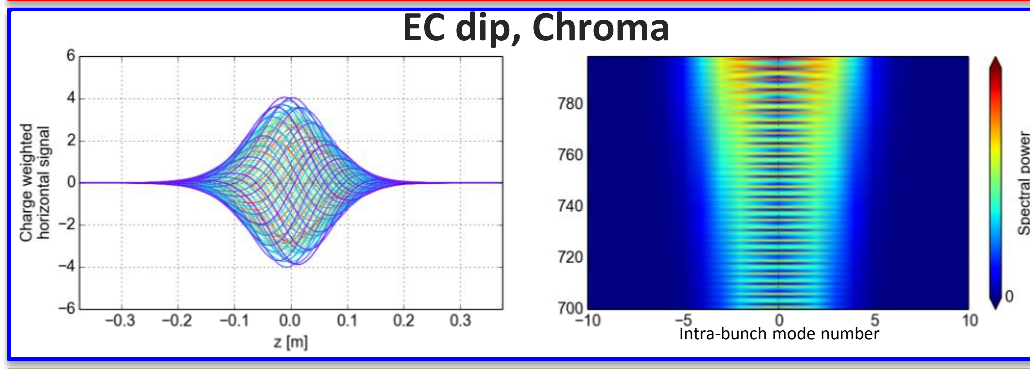


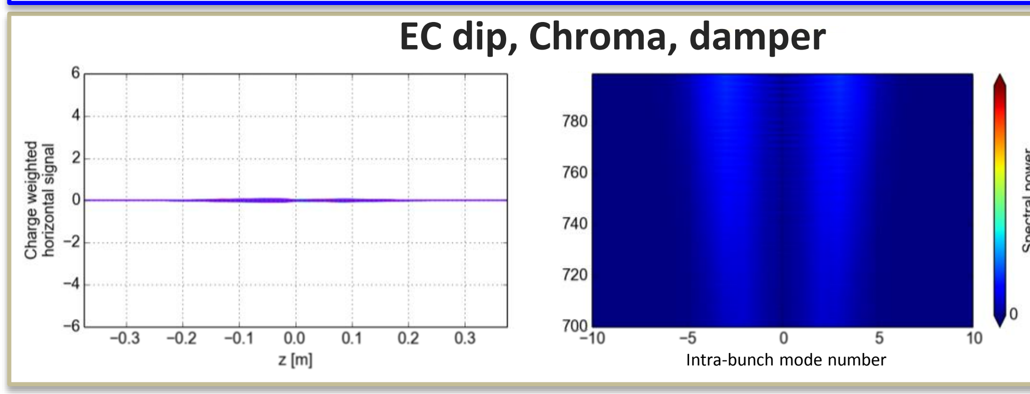
- EC only in dipoles, density fixed at **3.8e12**
- Horizontal chromaticity has been introduced (Q'_H=20) → beam becomes unstable
- Mode 0 –like instability
- High order intra-bunch modes

Horizontal instabilities – effect of the damper









- EC only in dipoles (**3.8e12 e/m³)**
- Horizontal chromaticity (Q'_H=20)
- Transverse damper is introduced (50 turns damping time) → beam is stable
  - Mitigation of the intra-bunch mode-0

Horizontal instabilities – Possible mechanism

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

$$\frac{W_0 \xi}{\eta} > 0$$

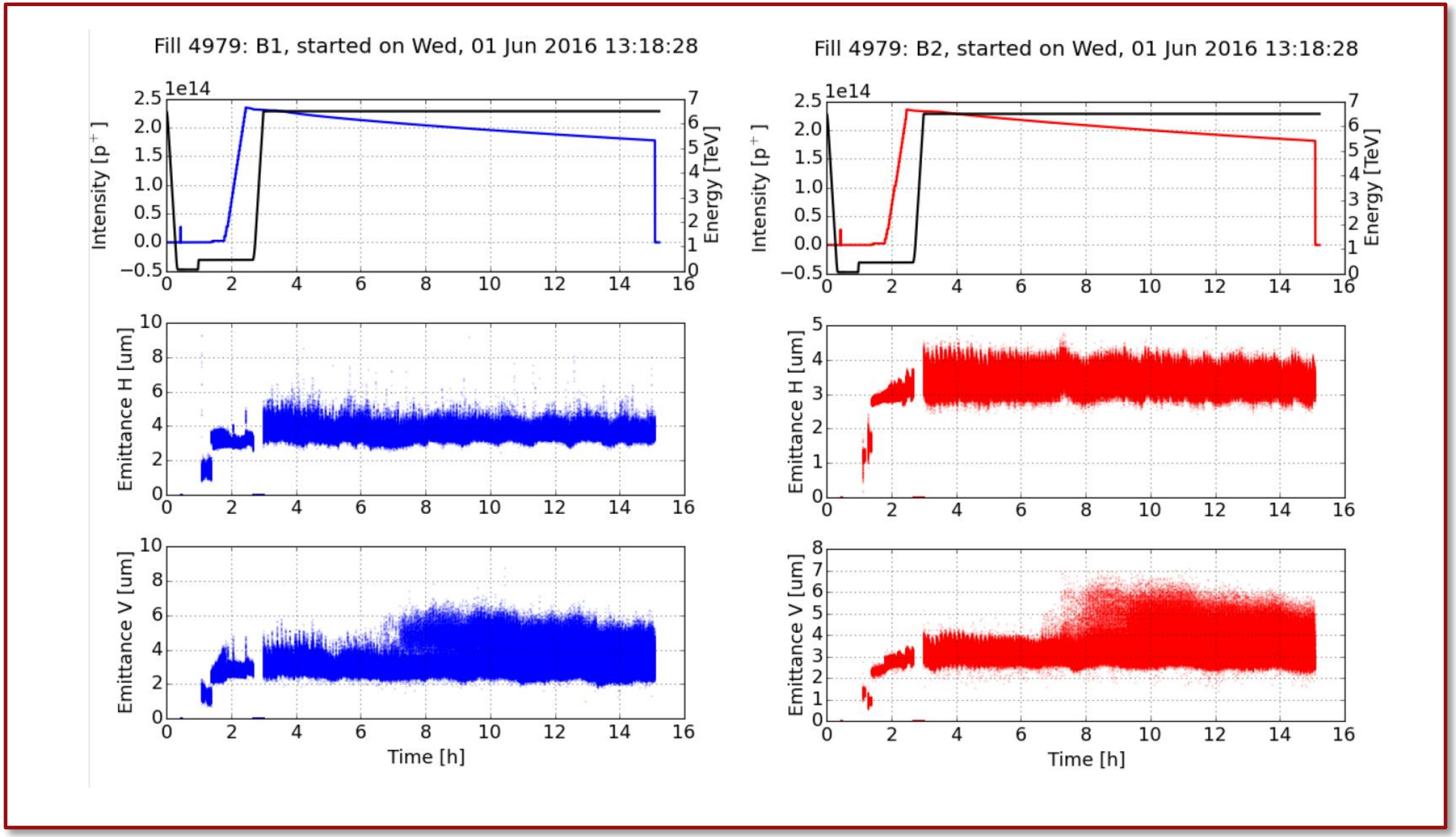
<u>**Sign of the wake**</u>		<u>**Stability condition**</u>
W_0>0, i.e. tail gets kicked in phase w.r.t. the head displacement	→	**Positive chromaticity**
W_0<0, i.e. tail gets kicked in counter-phase w.r.t. the head displacement	→	**Negative chromaticity**

Possible that for the e-cloud in the dipoles, horizontal forces on the tail tend to be opposite to the head displacement…

Next step of this study: verify this hypothesis by extracting and analyzing transverse forces from the PyEC-PyHT simulation (requires some implementation work).

Long simulation runs – first look

- “Pop-corn instabilities” were observed in the LHC after few hours in stable beam

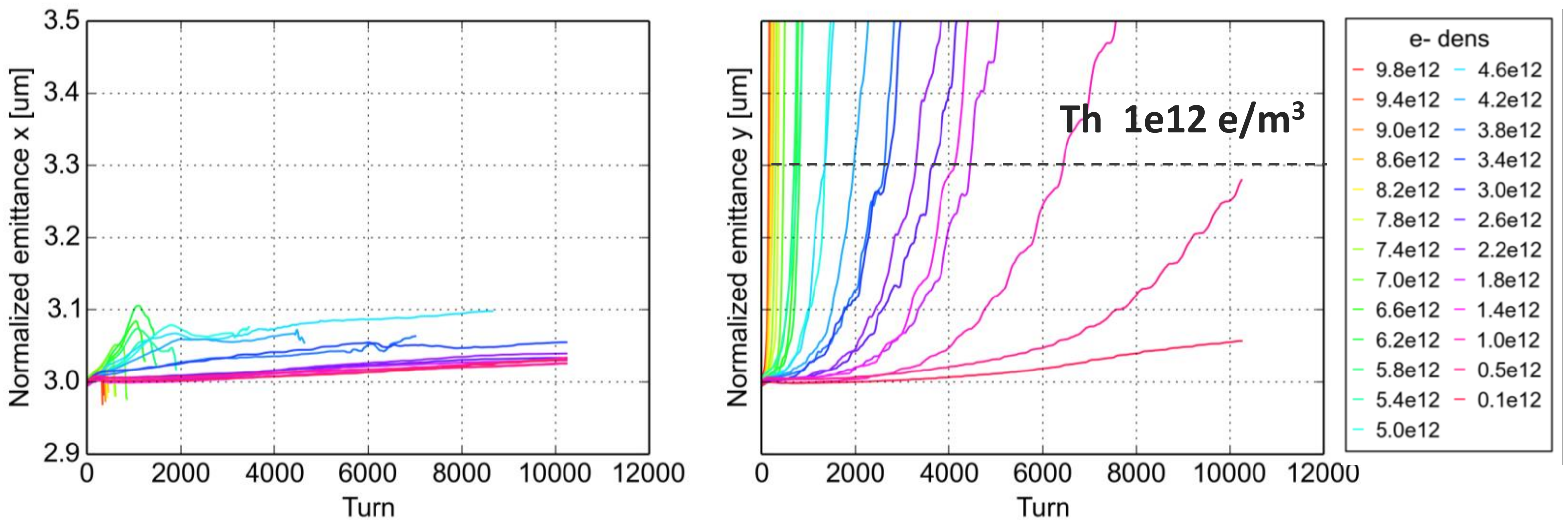


Long simulation runs – first look

- "Pop-corn instabilities" were observed in the LHC after few hours in stable beam
- To check the potential role played by the EC, more realistic conditions were simulated→ more simulated turns are needed
- First study: finding the instability threshold at high energy
  - beam intensity of 1.1e11 ppb
  - 1ns bunch length
  - 3um transverse emittance
  - Ecloud in dipoles (uniform density scan)
  - Ecloud in quadruopoles (SEY 1.30)
  - Octupoles set to -2.5
  - Chromaticity 15/15
  - Transverse damper (100 turns damping time)
  - 10000 turns simulated

Long simulation runs – first look

- "Pop-corn instabilities" were observed in the LHC after few hours in stable beam
- To check the potential role played by the Ecloud, more realistic simulations have been carried out → more simulated turns are needed
- First study: finding the instability threshold at high energy
  - beam intensity of 1.1e11 ppb



- Strong emittance blown up only in the vertical plane
- Vertical instability threshold below 1e12 e/m^3

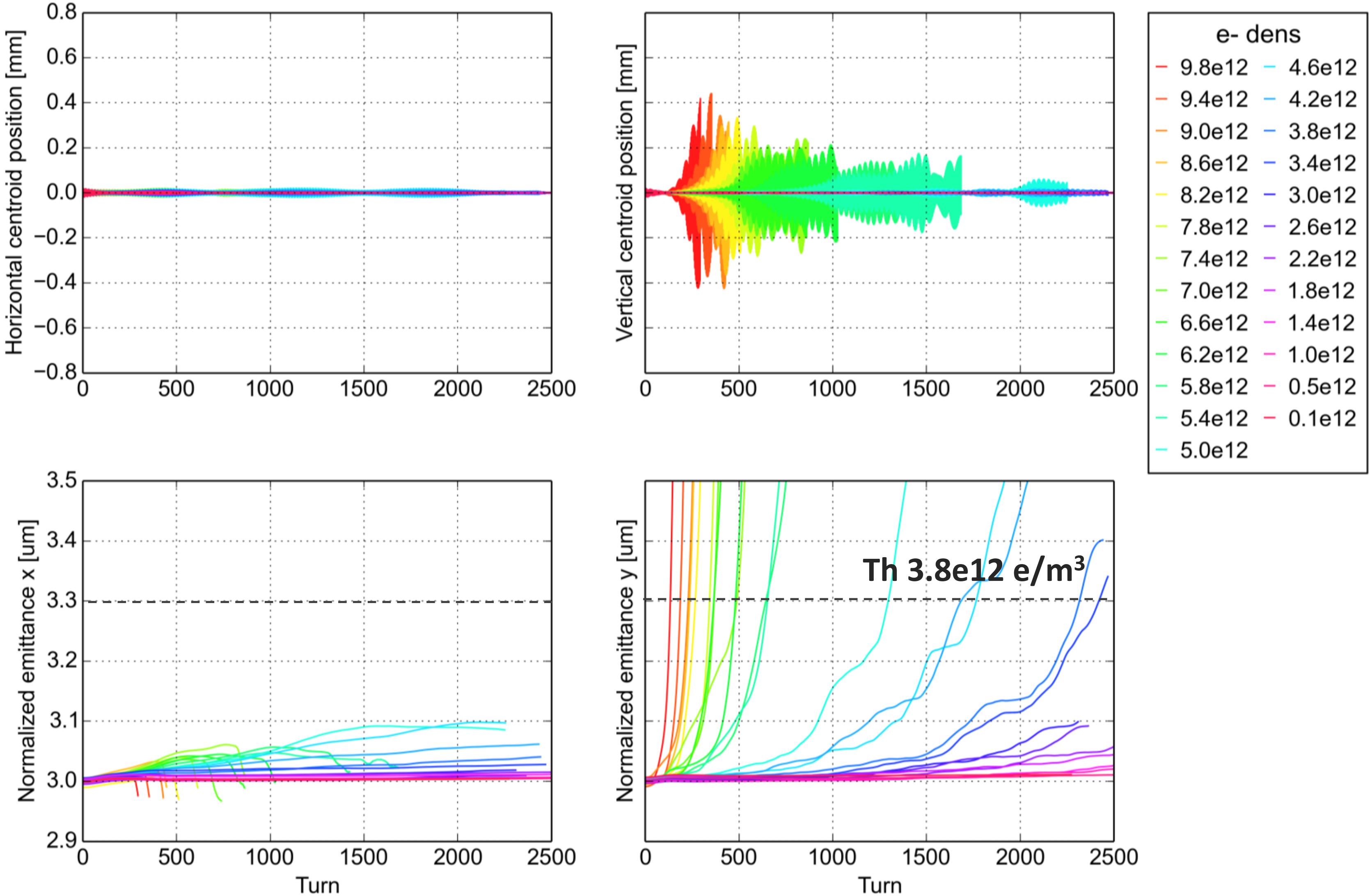
Long simulation runs – first look

- The same exercise has been repeated by changing only the beam intensity → 0.7e11 ppb (intesity reached after few hours in stable beam)
  - ✧ we want to check the impact of the beam intensity on the instability threshold and compare the results with the estimation from the buildup simulations

- These simulations will run for 3-4 weeks **→ Unfortunately they are not finished yet, but we can try to have a look on the preliminary results**

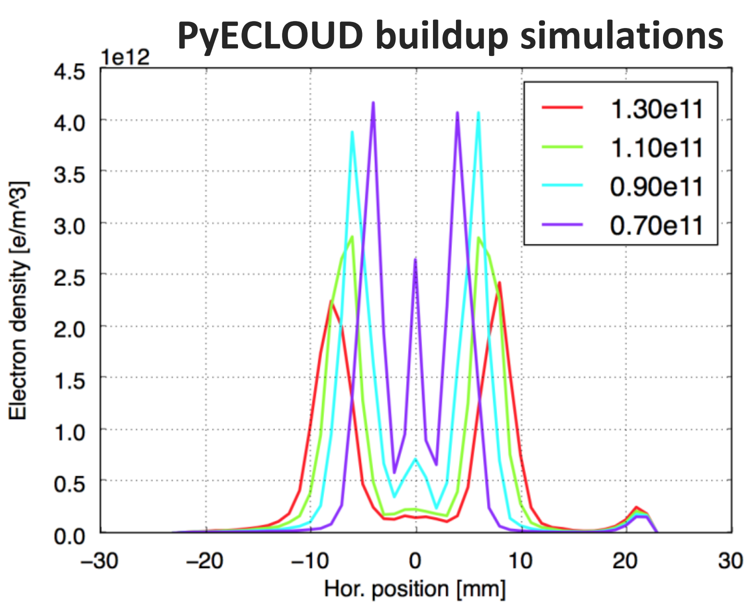
Long simulation runs – first look

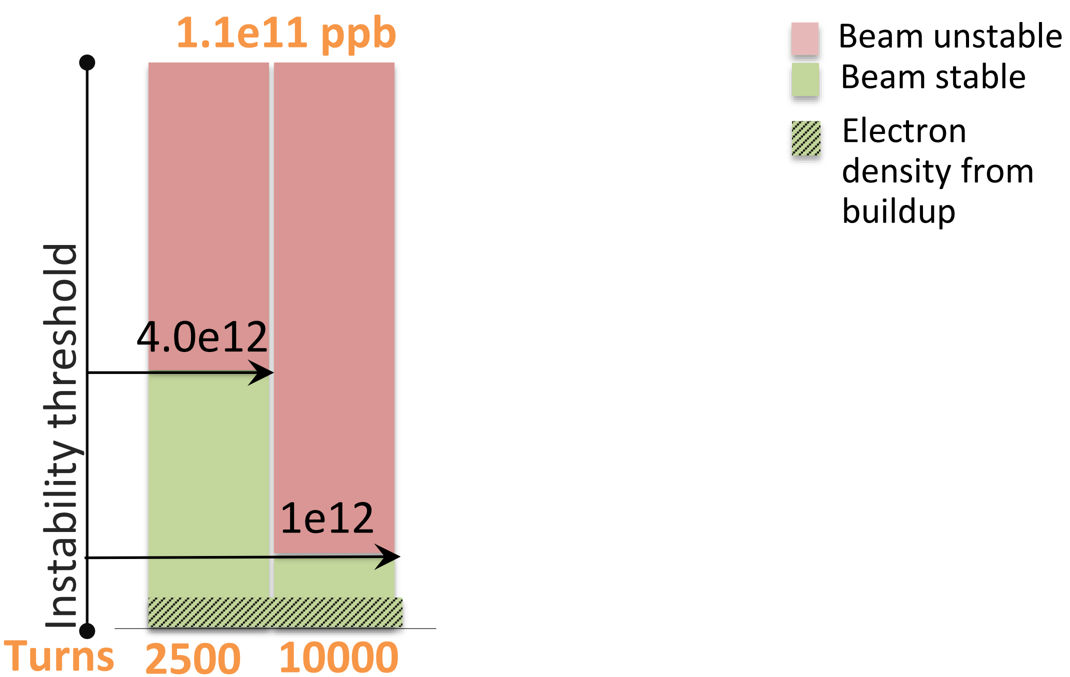
Beam intensity 0.7e11 ppb



Long simulation runs – first look

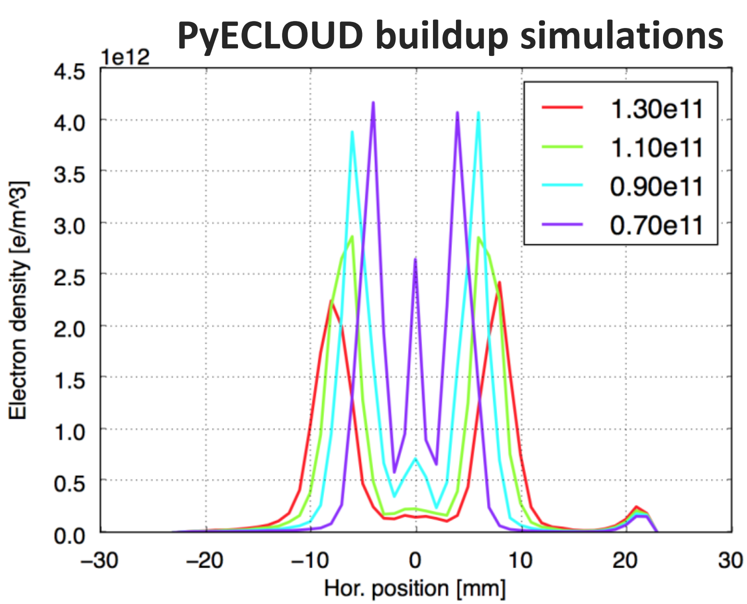
- Preliminary considerations
  - From the buildup simulations: when the beam intesity decreases the e- central density increases
  - Beam intensity of 1.1e11 ppb
    - the ecloud density estimated from the buildup is lower than the instability threshold both over 2500 and 10000 turns → **the beam is stable**

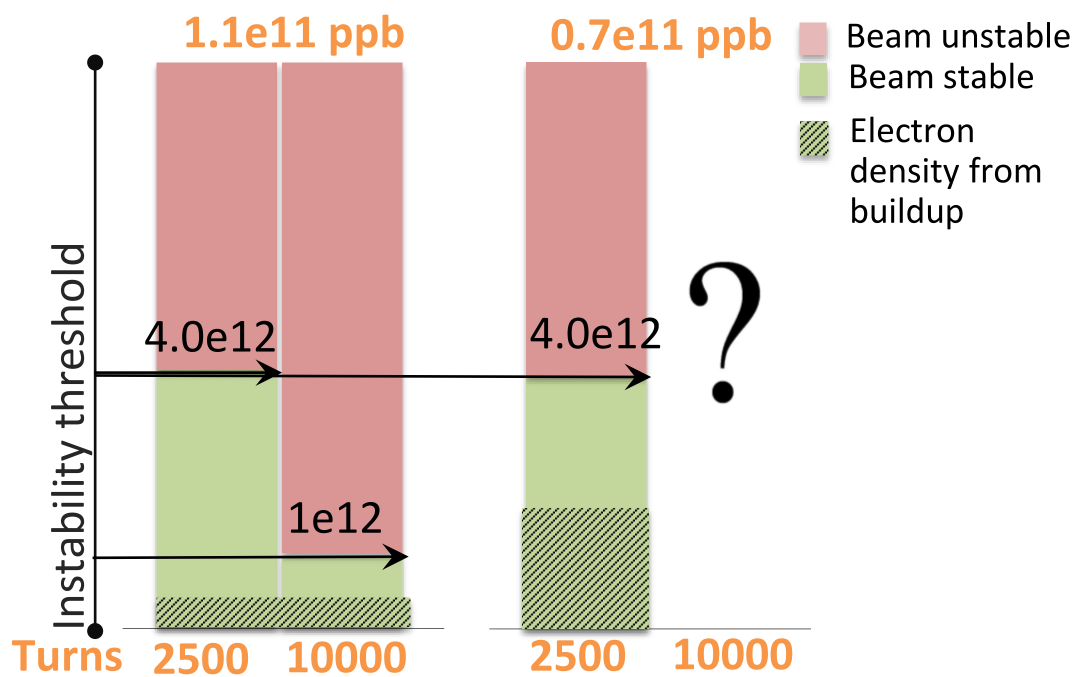




Long simulation runs – first look

- Preliminary considerations
  - ✧ From the buildup simulations: when the beam intesity decreases the e- central density increases
  - ✧ Beam intensity of 1.1e11 ppb
    - the ecloud density estimated from the buildup is lower than the instability threshold both over 2500 and 10000 turns → **the beam is stable**
  - ✧ Beam intensity of 0.7e11 ppb
    - the instability threshold has been found only over 2500 turns
    - the ecloud density from the buildup is below the threshold → **apparently the beam is still stable**
    - next step: check the instability threshold after 10000 turns → **can the beam get unstable?**





Summary and Conclusions

- A preliminary “complete” characterization of the EC effects on the beam dynamics at high energy is being performed → exaggerated settings have been choosen and short simulations (1024 turns) have been carried out in order to understand the contribution from the different mechanism (EC, chromaticity, octupoles, damper)

  - Incoherent tune footprint: average detuning and tune spread have been studied → results have shown that the chromacitity introduced a strong distortion to tune spread even in present of high electron density in dipoles

  - Coherent tune shift: full instability-like simulations have been carried out and the results compared with the incoherent detuning

  - Coherent instability threshold:
    -finding the instability thresholds under different scenarios
    -preliminary studies on the horizontal instability driven by the chromaticity have been performed

- Next steps:
  - Understanding the mechanisms of the horizontal instability → we want to study the transverse forces induced by the EC on the bunch
  - More realistic conditions are being simulated (real machine settings, long simulation time)

Brief status on the EC studies at injection

Simulating coherent effects on the LHC at injection:

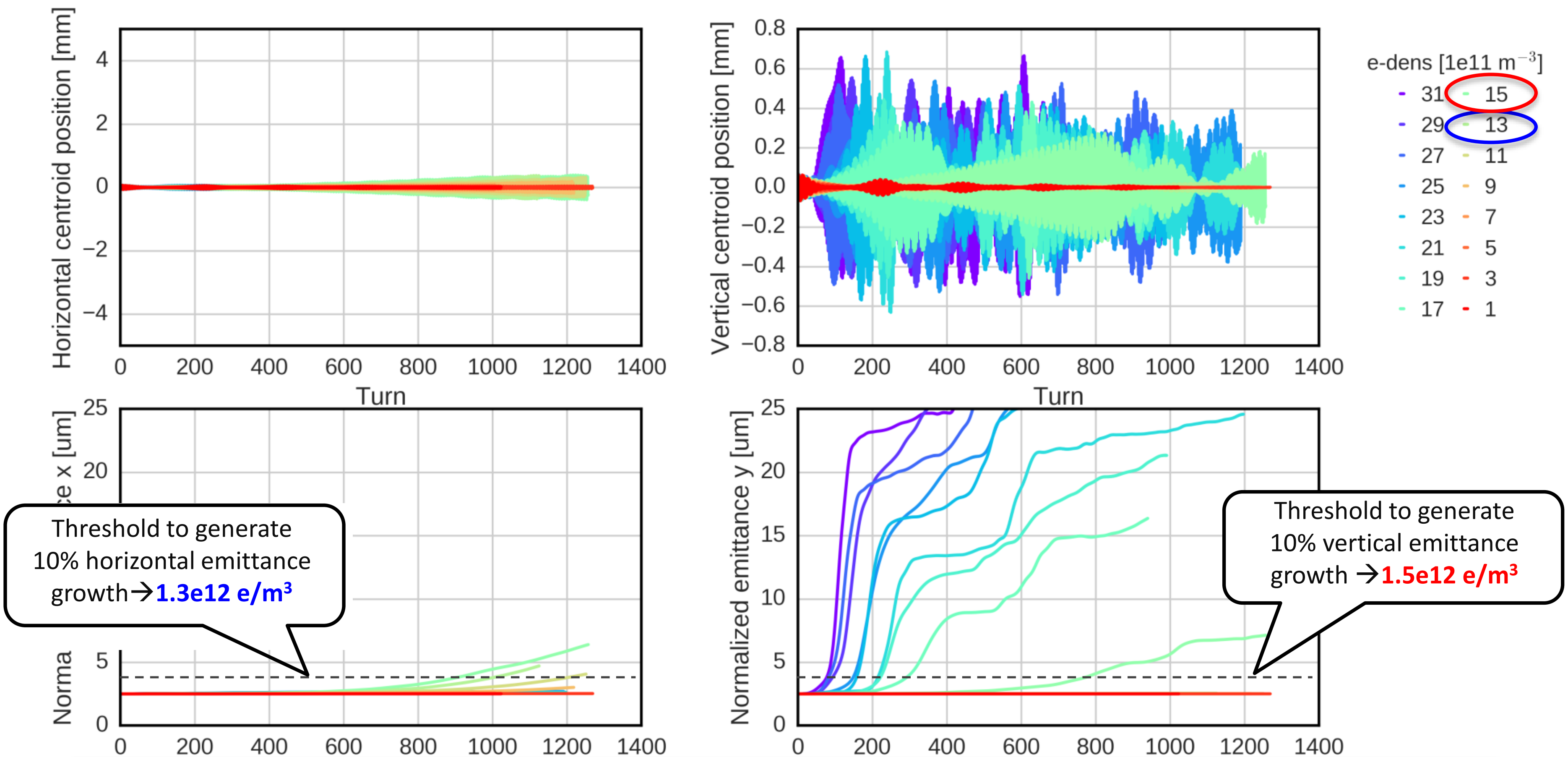
- Intensity: 1.1e11 ppb
- Emittance: 2.5 um
- Bunch lenght: 1.25ns

- First step has been scanning the chromaticity vs the EC density in dipoles in order to find the instability thresholds
  - EC in dipoles → uniform density scan
  - Chromaticity scanned between -10 and 30

Brief status on the EC studies at injection

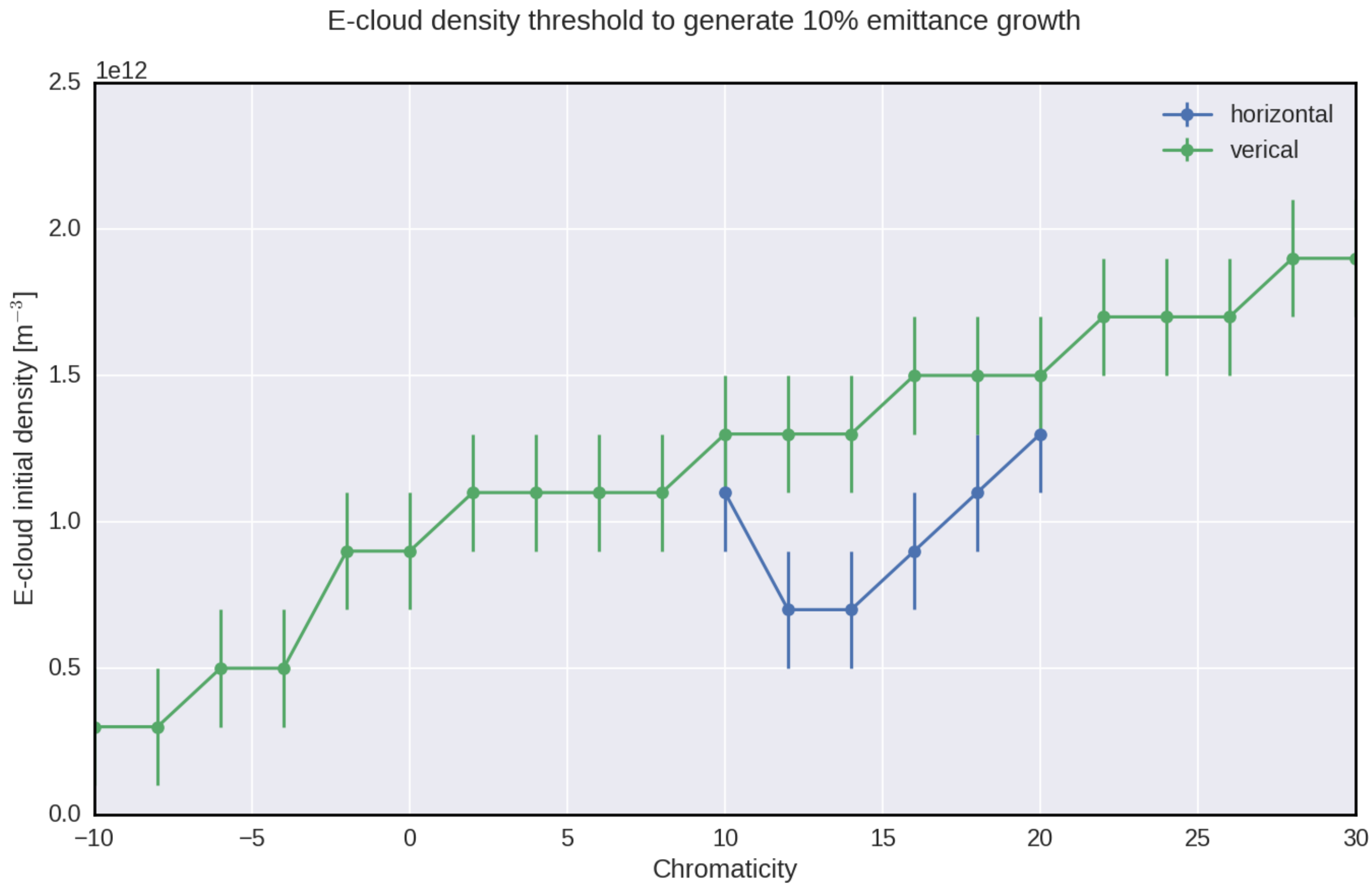
EC dipoles	EC quadruoles	Chromaticity	Oct	Damper
Density scan	✗	20/20	✗	✗

LHC e-coud density scan for chromaticity 18



The instability thresholds have been found for all other chromaticities

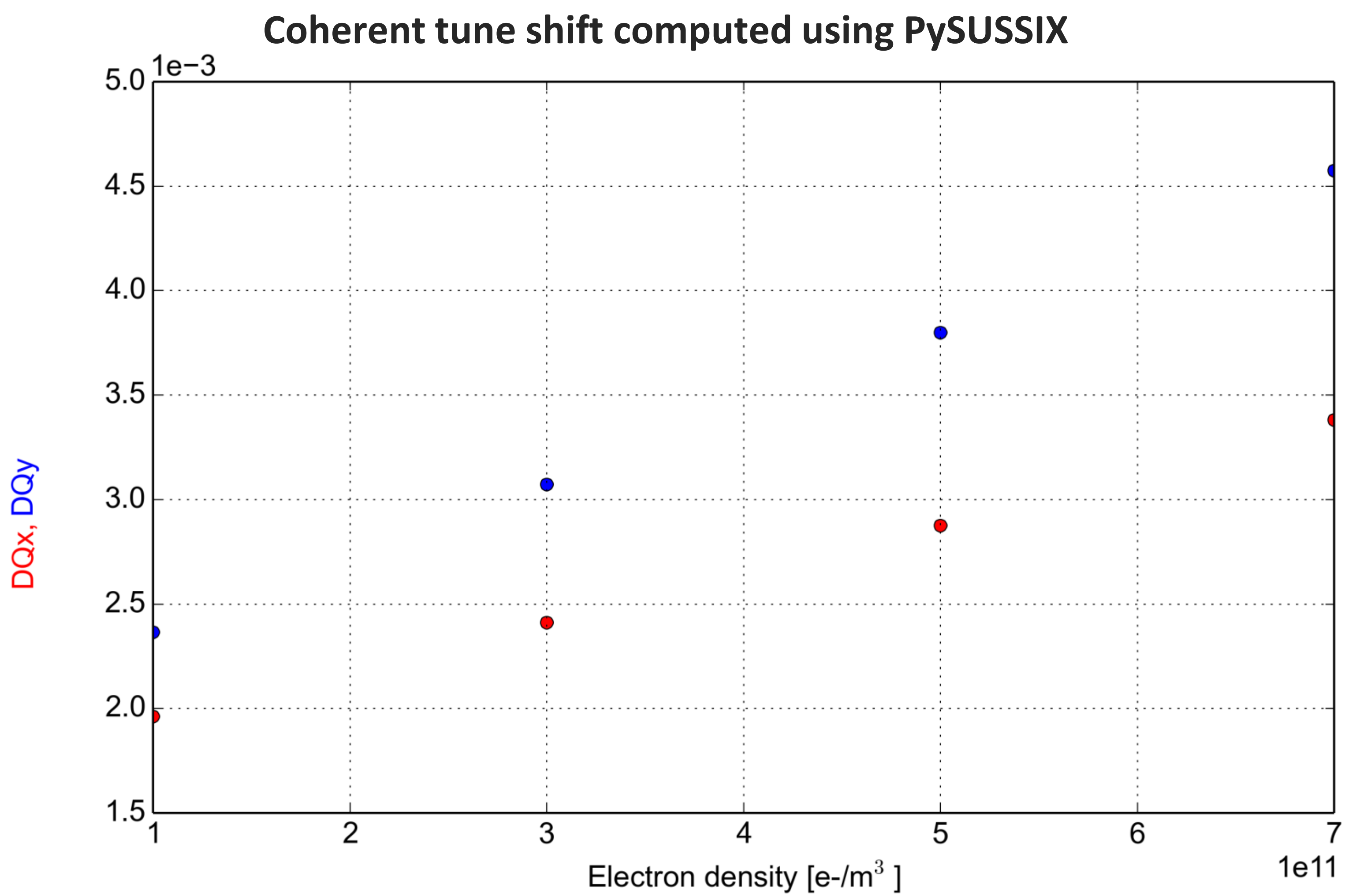
Brief status on the EC studies at injection



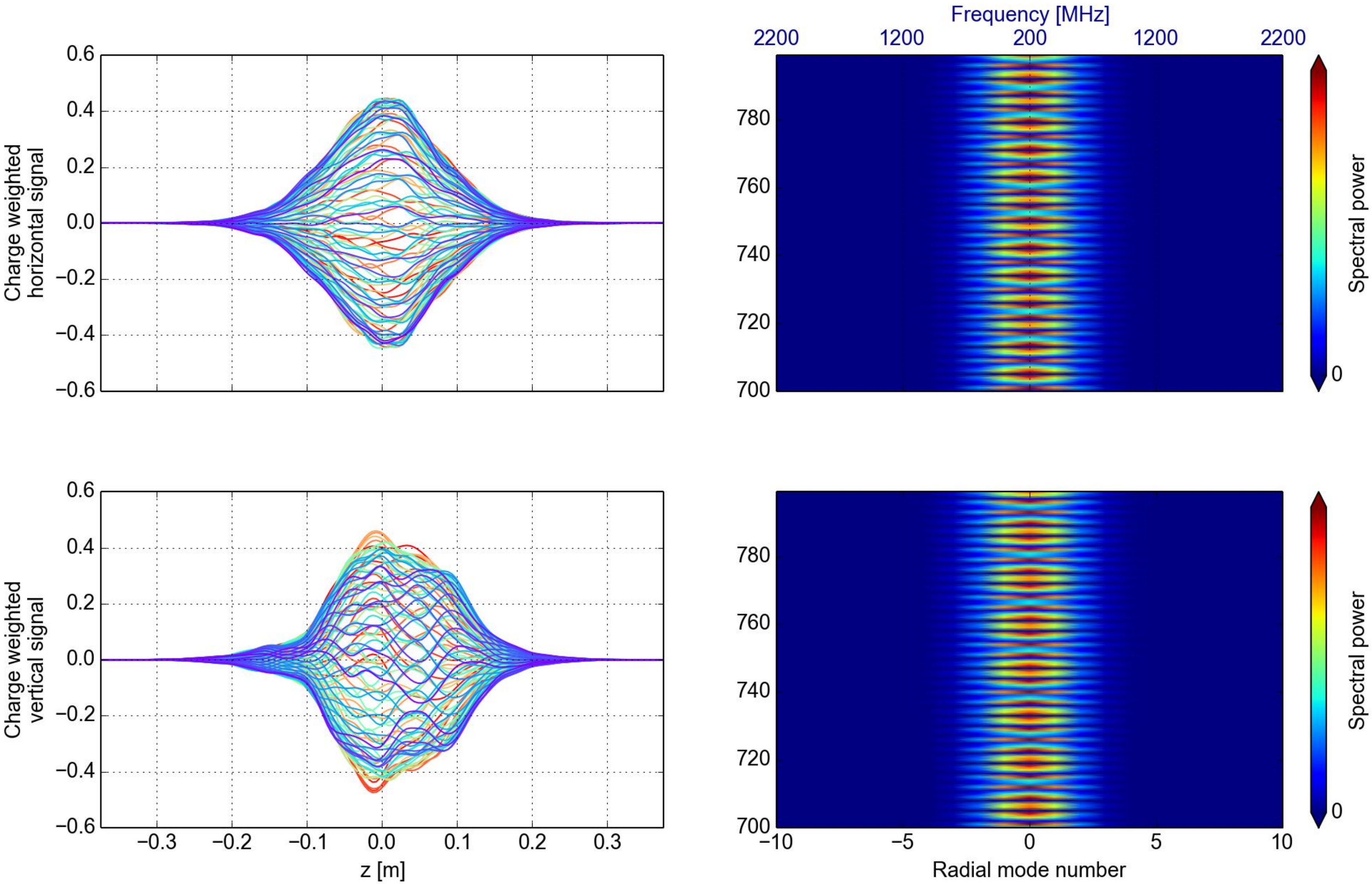
- Next on the list:
  - ✧ EC in quadrupoles is being included in simulations at injection → studies ongoing
  - ✧ Studying the horizontal and the vertical instabilities independently → we want to stabilized the beam in vertical and check what happens in horizontal

Coherent tune shift at injection

EC dipoles	EC quadruoles	Chromaticity	Oct
Density scan	SEY 1.30	✗	✗



Thanks for your attention!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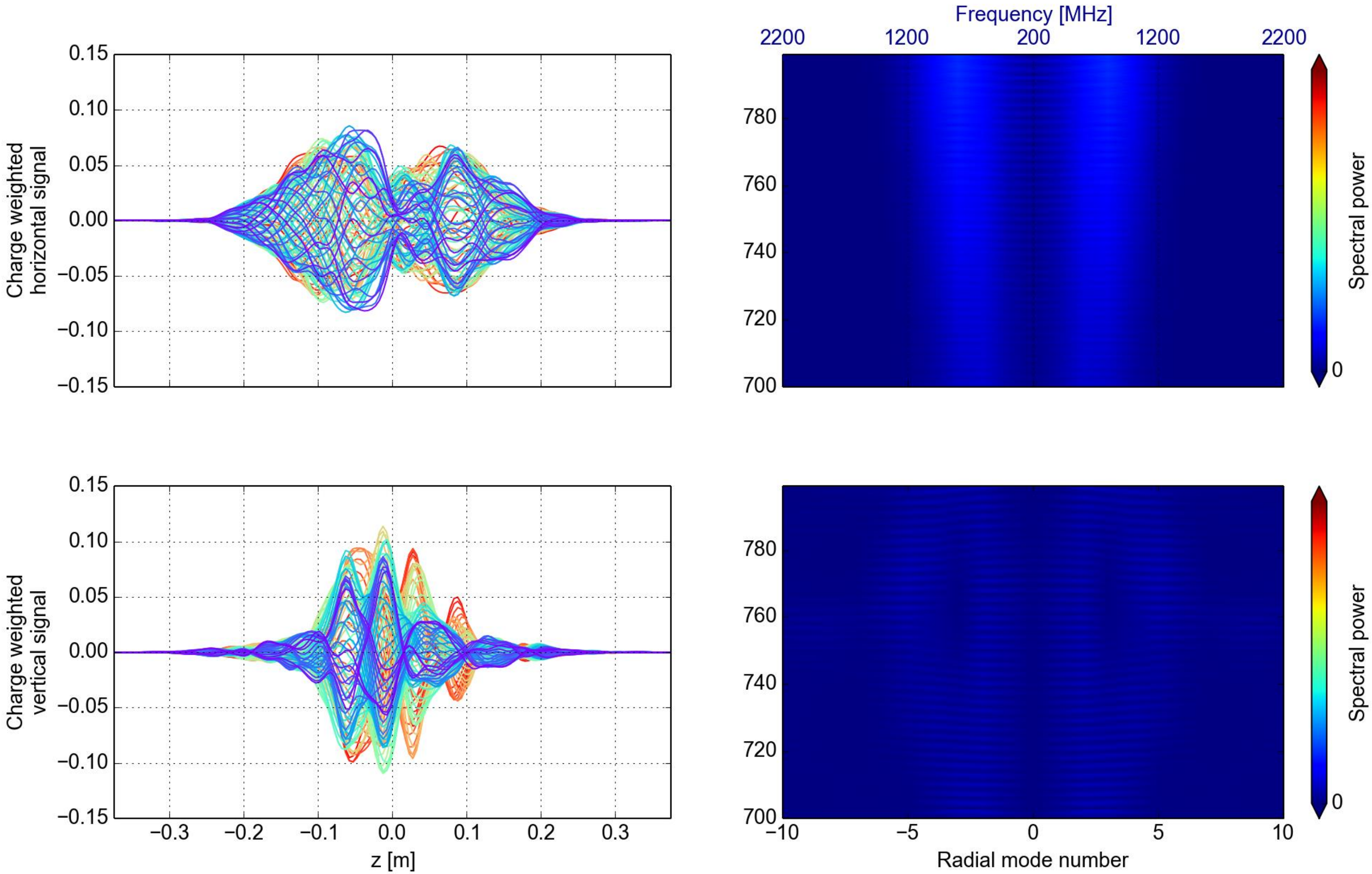
Charge weighted vertical signal
z [m]
Frequency [MHz]
2200
1200
200
1200
2200
Spectral power
0
Radial mode number


Charge weighted horizontal signal
Frequency [MHz]
2200
1200
200
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2200
Spectral power
0
Charge weighted vertical signal
z [m]
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