LHC Injectors Upgrade

Chromaticity Effects for Space Charge Dominated Beams in the CERN PS Booster

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Acknowledgements:

The CERN Space Charge Working Group, The PSB OP team

The CERN PS Booster (PSB)

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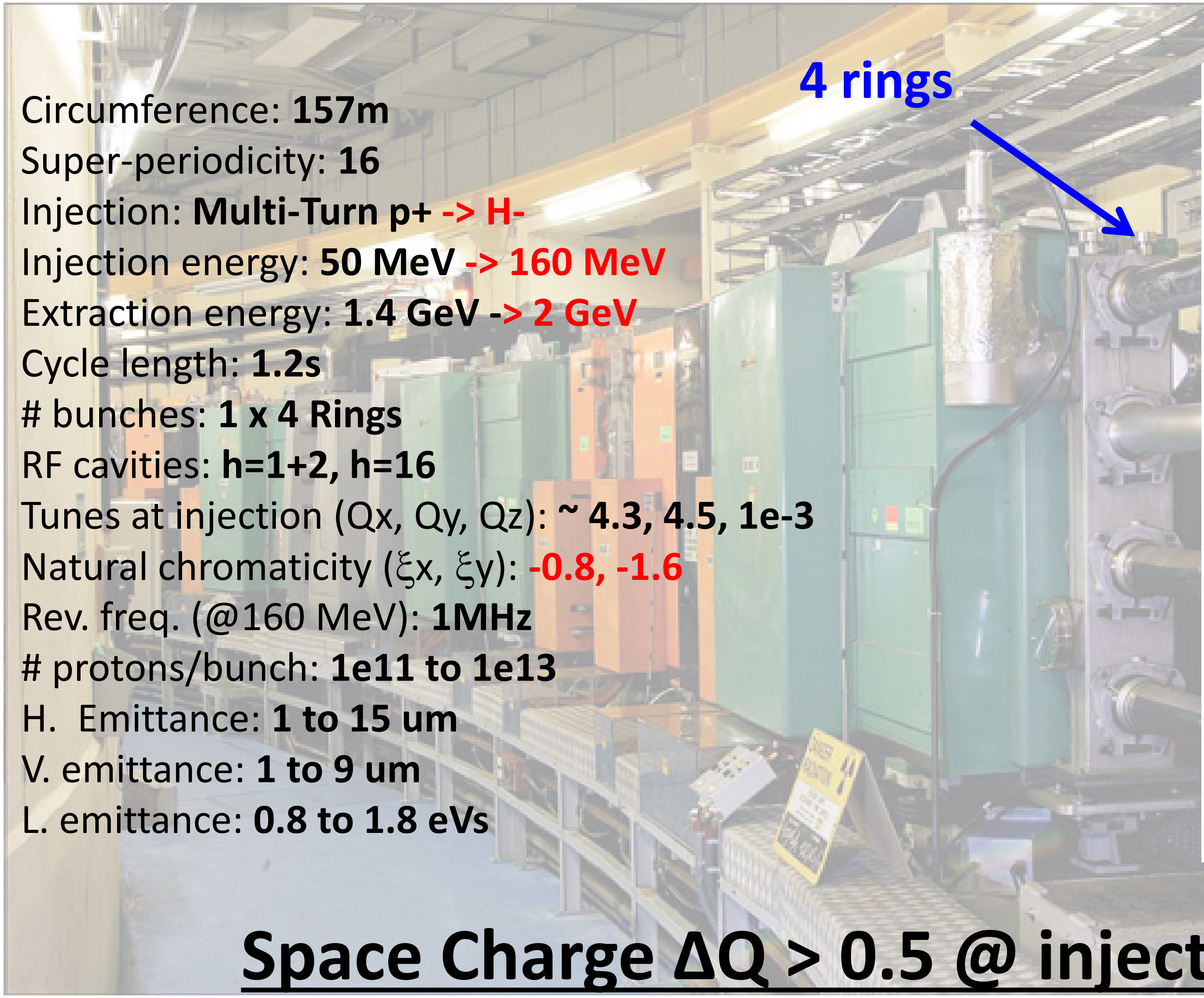


Circumference: **157m**
Super-periodicity: **16**
Injection: **Multi-Turn p+ -> H-**
Injection energy: **50 MeV -> 160 MeV**
Extraction energy: **1.4 GeV -> 2 GeV**
Cycle length: **1.2s**
bunches: **1 x 4 Rings**
RF cavities: **h=1+2, h=16**
Tunes at injection (Qx, Qy, Qz): **~ 4.3, 4.5, 1e-3**
Natural chromaticity (ξx, ξy): **-0.8, -1.6**
Rev. freq. (@160 MeV): **1MHz**
protons/bunch: **1e11 to 1e13**
H. Emittance: **1 to 15 um**
V. emittance: **1 to 9 um**
L. emittance: **0.8 to 1.8 eVs**

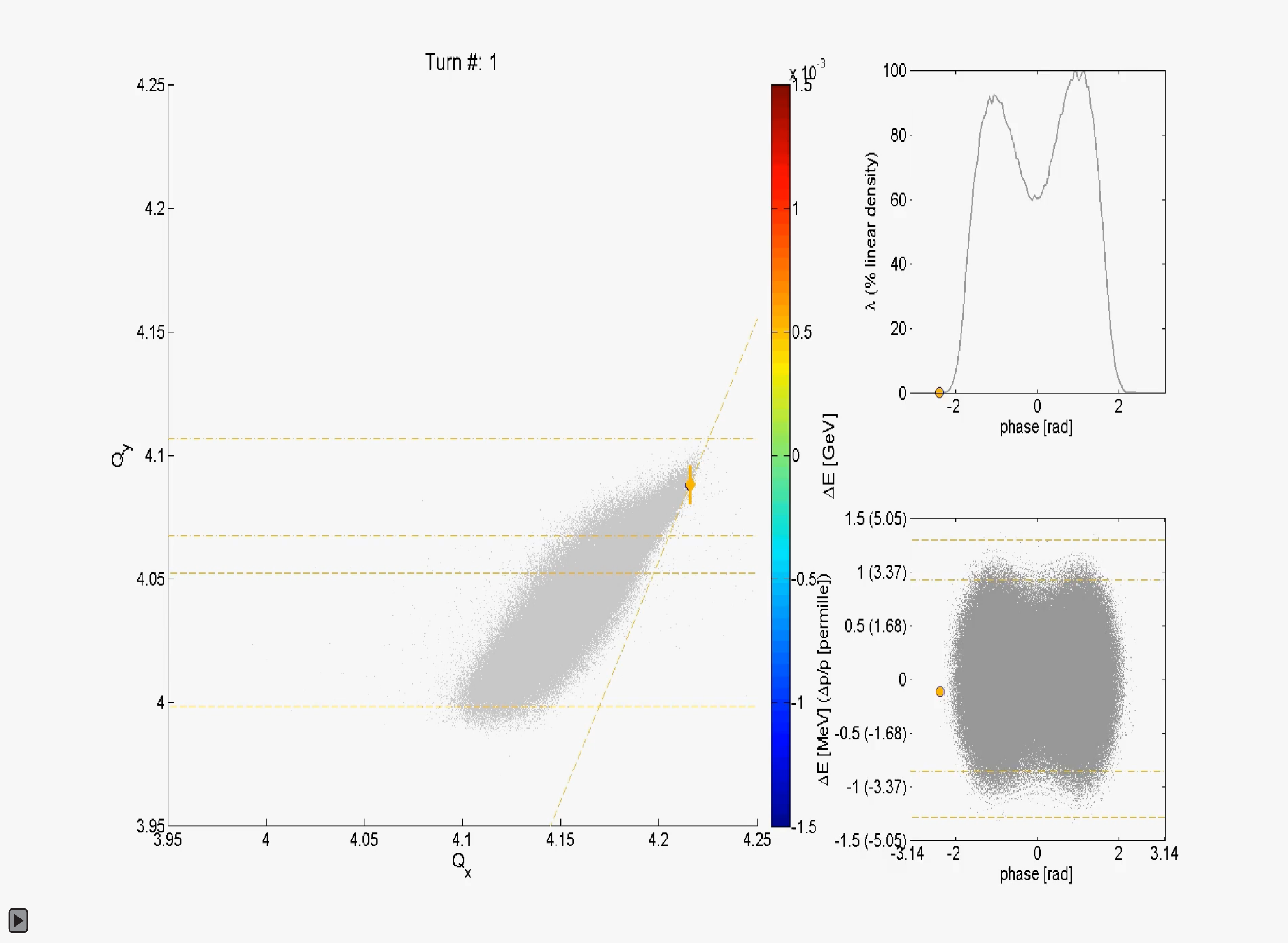
PSB
AD
CNGS
EASTA
EASTB
EASTC
LHCINDIV
LHCPROBE
LHC 100ns SB
LHC 25ns DB A
LHC 25ns DB B
LHC 25ns H9 A & B
LHC 50ns DB A & B
LHC 50ns SB
LHC 75ns SB
MTE
NORMGPS-HRS
SFTPRO
STAGISO 1.4Gev
STAGISO 1Gev
TOF

Space Charge ΔQ > 0.5 @ injection

Reasons for the study

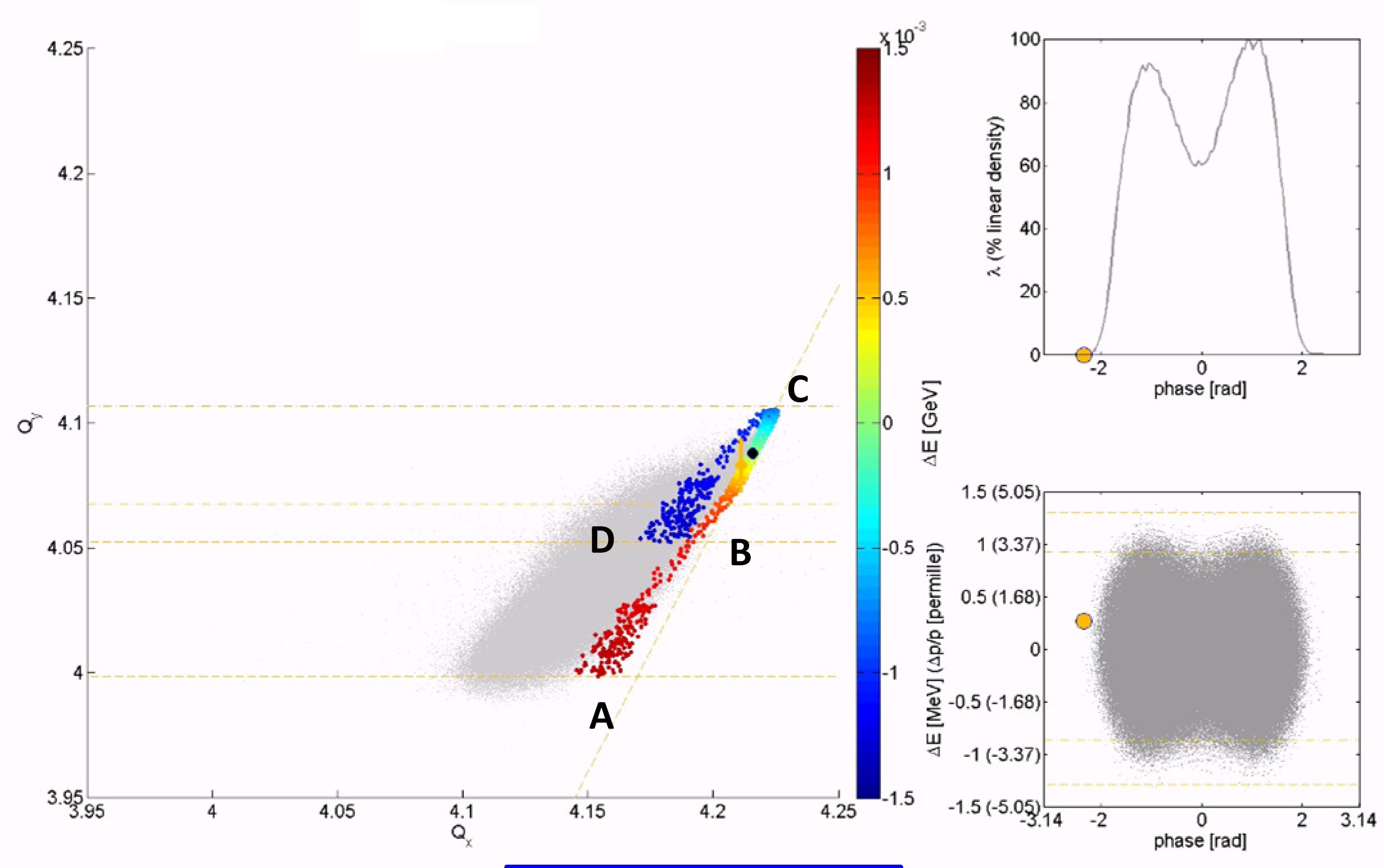
- The CERN PSB works without chromaticity correction.
- Space charge is a concern in the PSB now and in the future upgrade scenario to not exceed the present 0.5 tune spread.
- Simulations (through PTC-Orbit) and ad-hoc measurements studies show that the chromaticity has an impact in the tune spread for space charge dominated beams.
- The correction of the chromaticity, avoiding coherent instabilities, could be helpful to improve brightness for the LHC upgrade scenario.
- We will discuss:
  - ***Tune spread and chromaticity***
  - ***Two experiments for code/measurements benchmark***
  - ***LHC High Brightness prediction***

Tune spread and chromaticity*



*reference: V. Forte et al., ***6D Tunes Computation For Space Charge Dominated Beams***, **Nuclear Instruments and Methods (to be published)**

Tune spread and chromaticity*

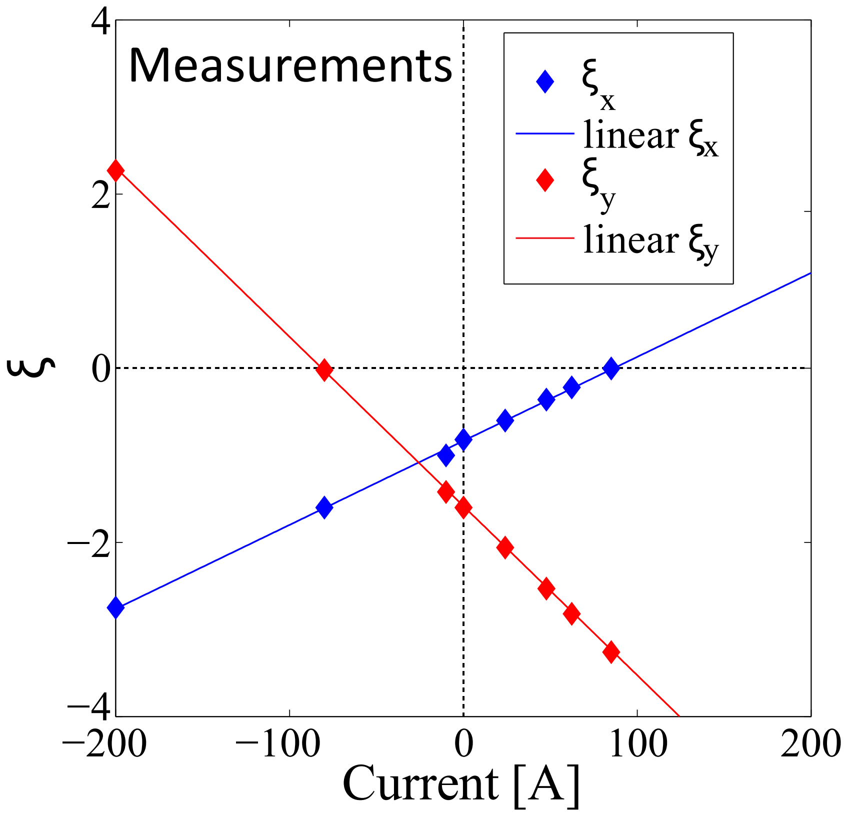


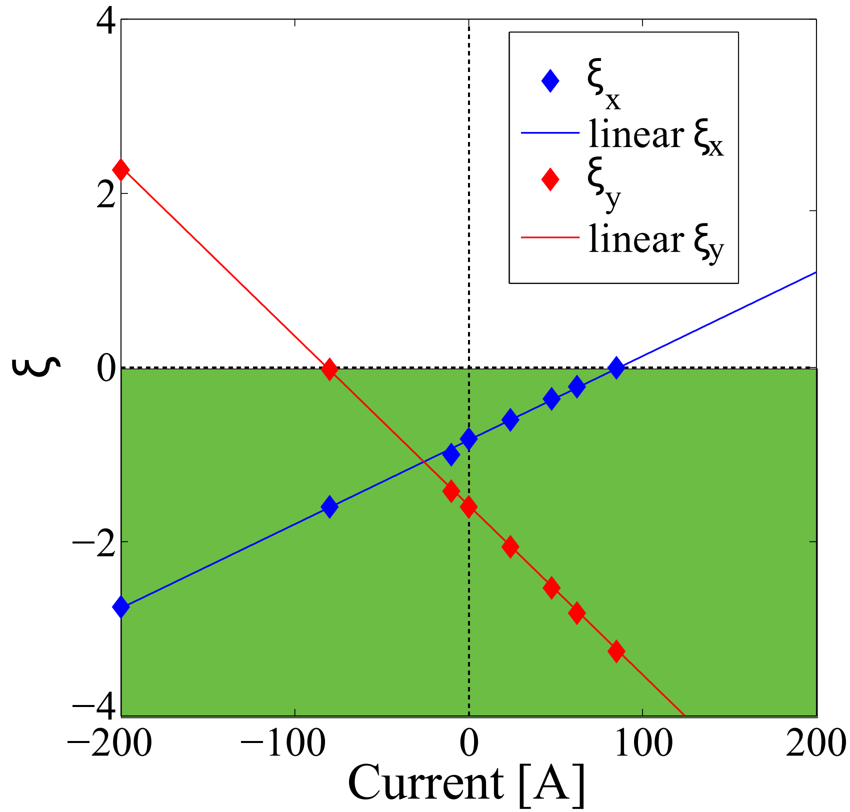
"C" shape

*reference: V. Forte et al., *6D Tunes Computation For Space Charge Dominated Beams*, Nuclear Instruments and Methods (to be published)

Chromaticity change in the PSB

- **Through normal chromatic sextupoles, one per period.**
- **Only one family available -> Coupled control**

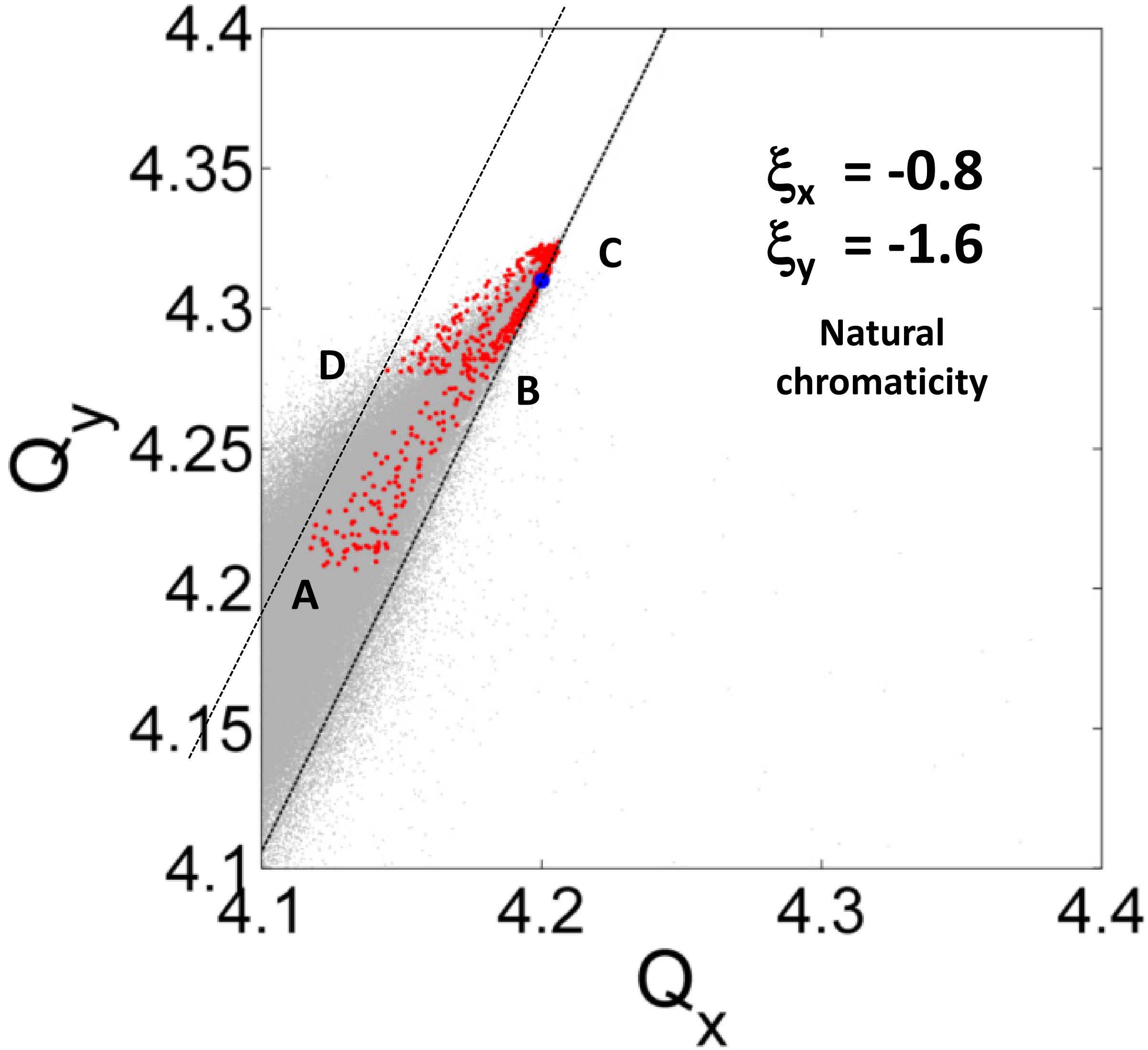




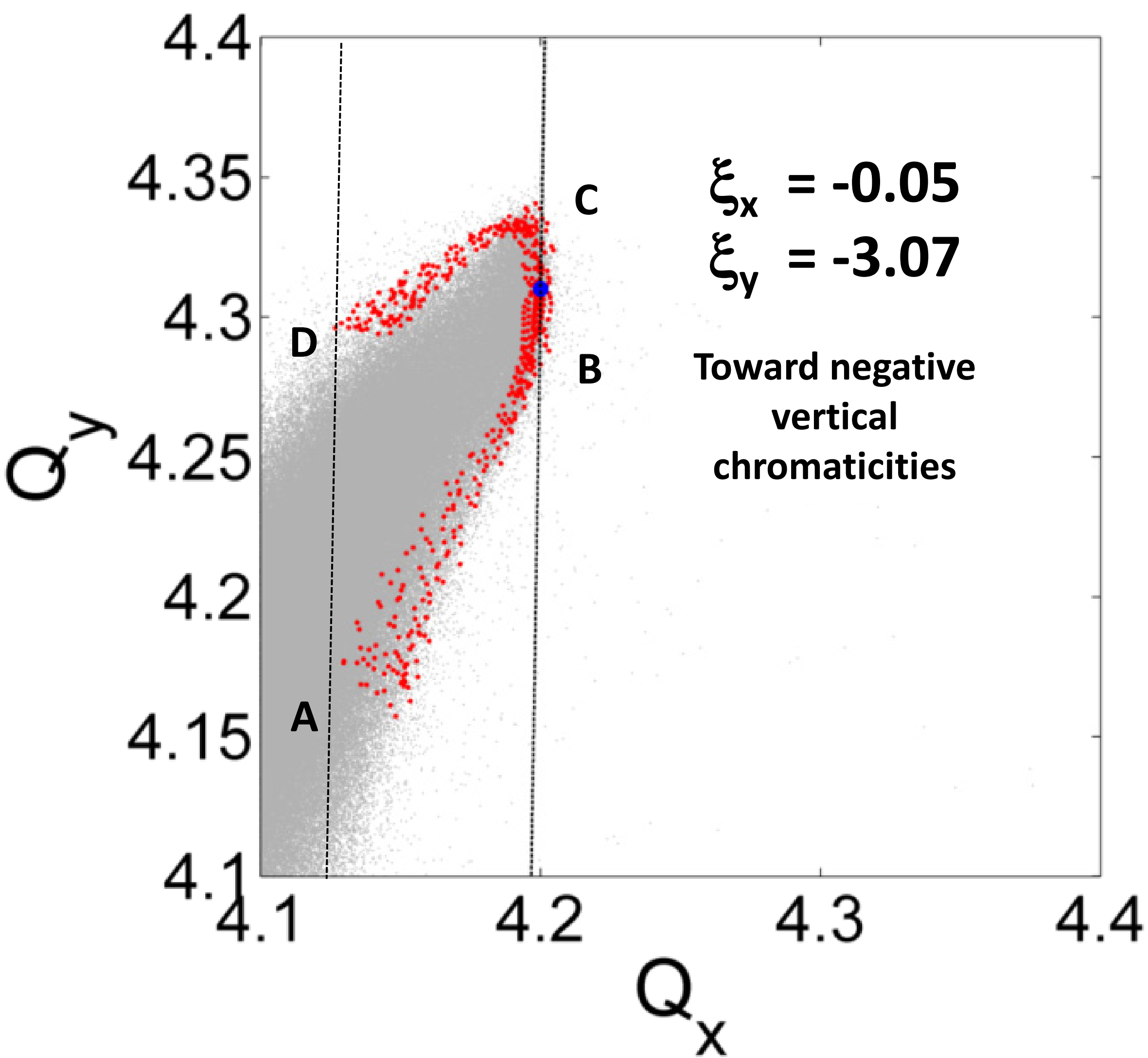
We consider only negative chroma to avoid instabilities (below transition)

Current [A]	ξx	ξy	ΔQx max (chromatic)	ΔQy max (chromatic)
85.05	-0.0026	-3.26	0.000	+/-0.071
0	**-0.82**	**-1.6**	**+/-0.017**	**+/-0.035**
-80	-1.6	-0.02	+/-0.034	+/-0.000

Motion of particles with very large synchrotron oscillation



Motion of particles with very large synchrotron oscillation



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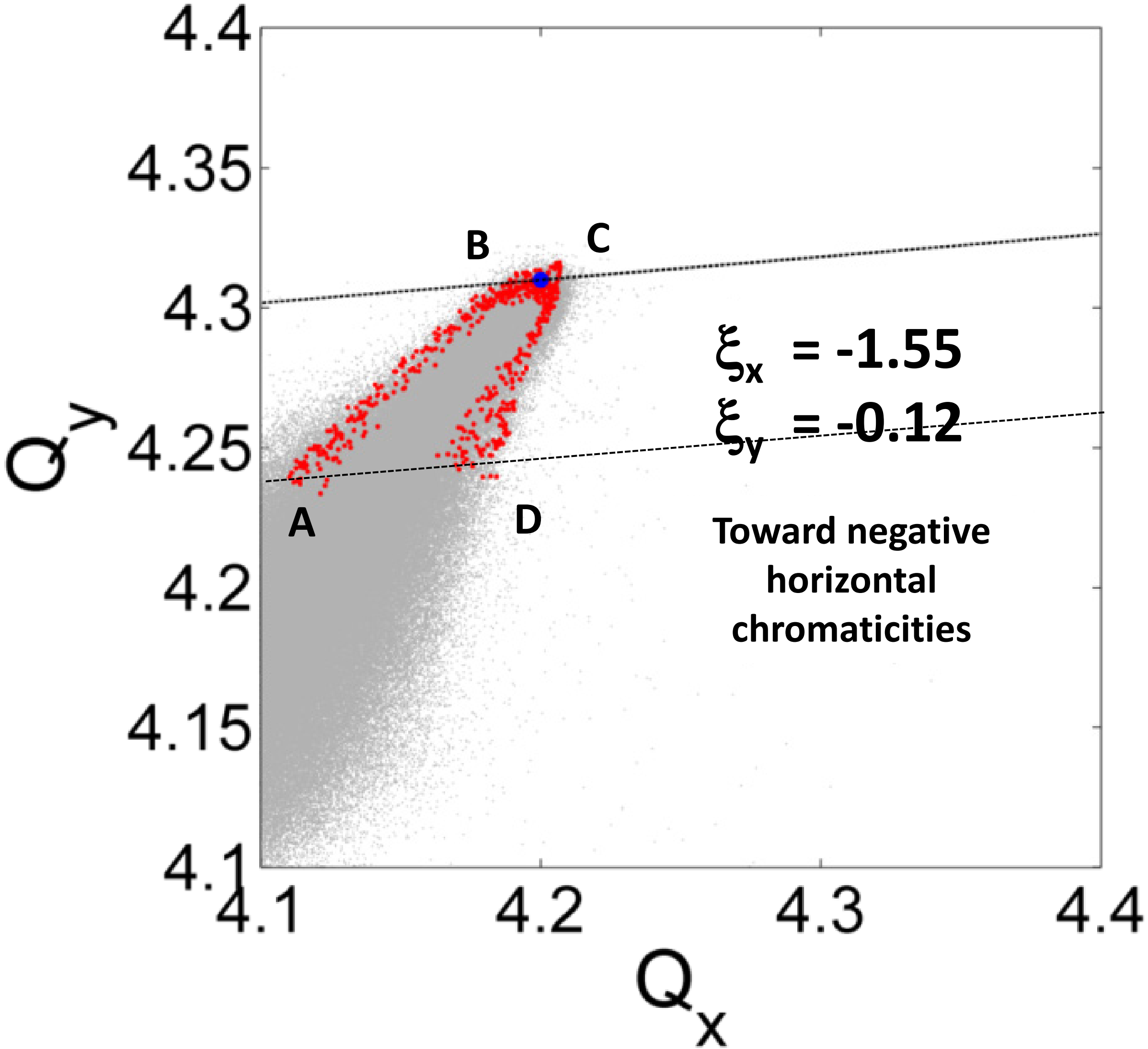
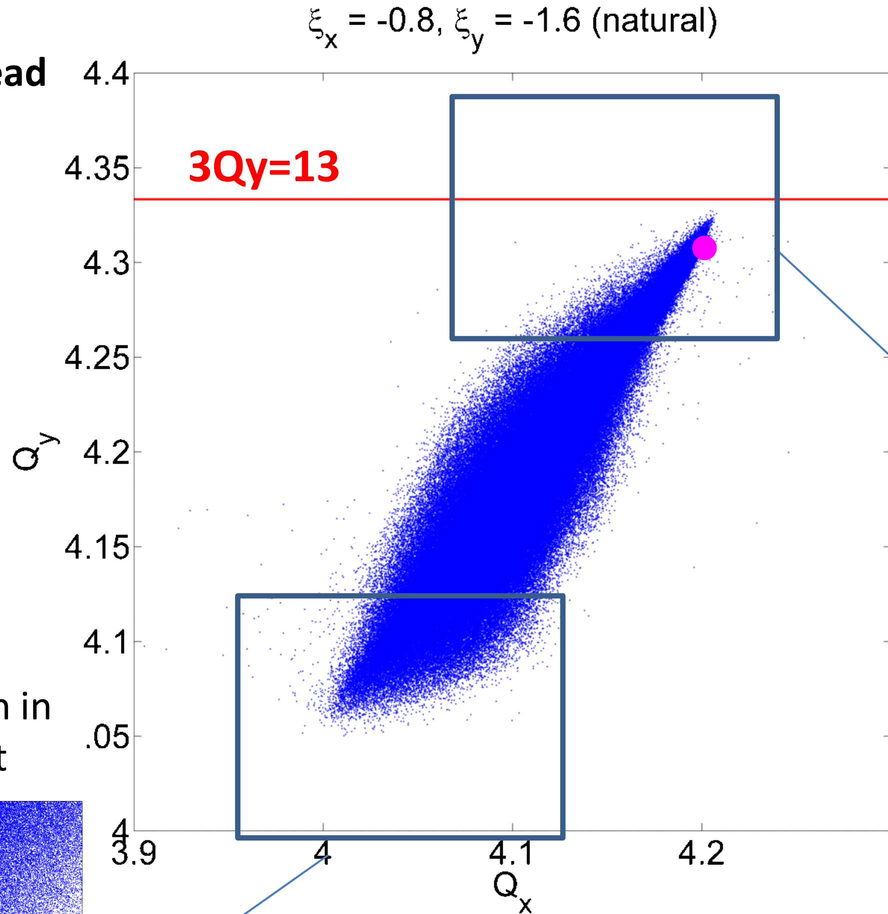


Two experiments for negative chromaticity quadrants

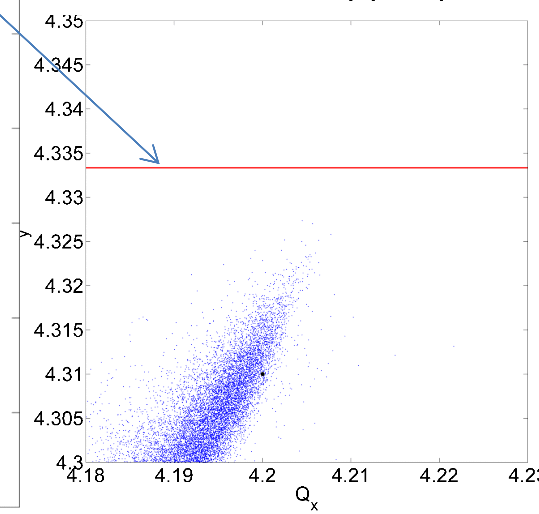
1. **Touching the 3Qy=13 line with upper part of the footprint**
2. **Touching the horizontal integer resonance**

Touching with upper part of the footprint the 3Qy=13 line

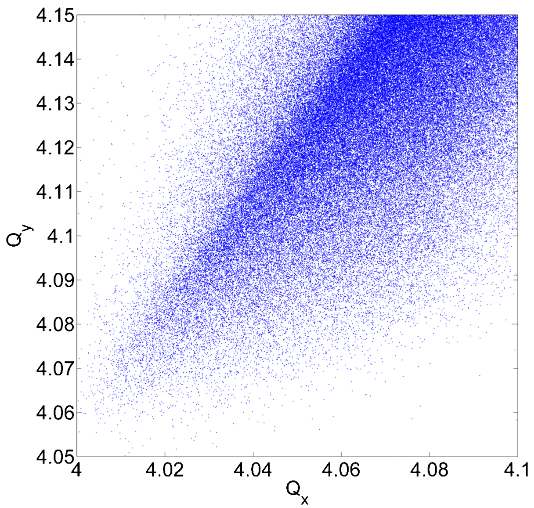
Single turn tune spread



Bigger overshoot in the upper part



Bigger diffusion in the lower part

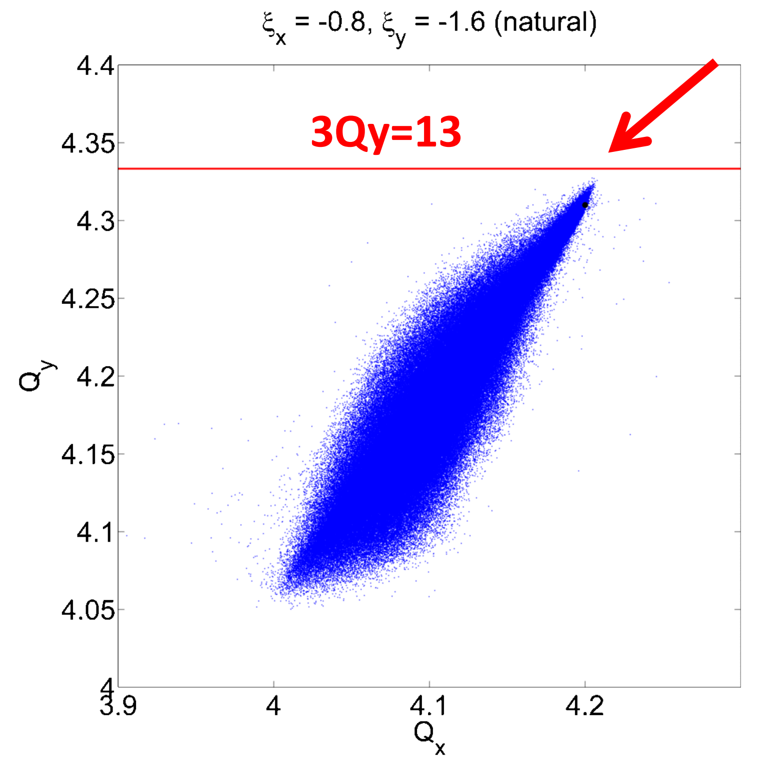


Negative vertical chromaticity direction

Changes of chromaticity induce deformation in the tune spread.

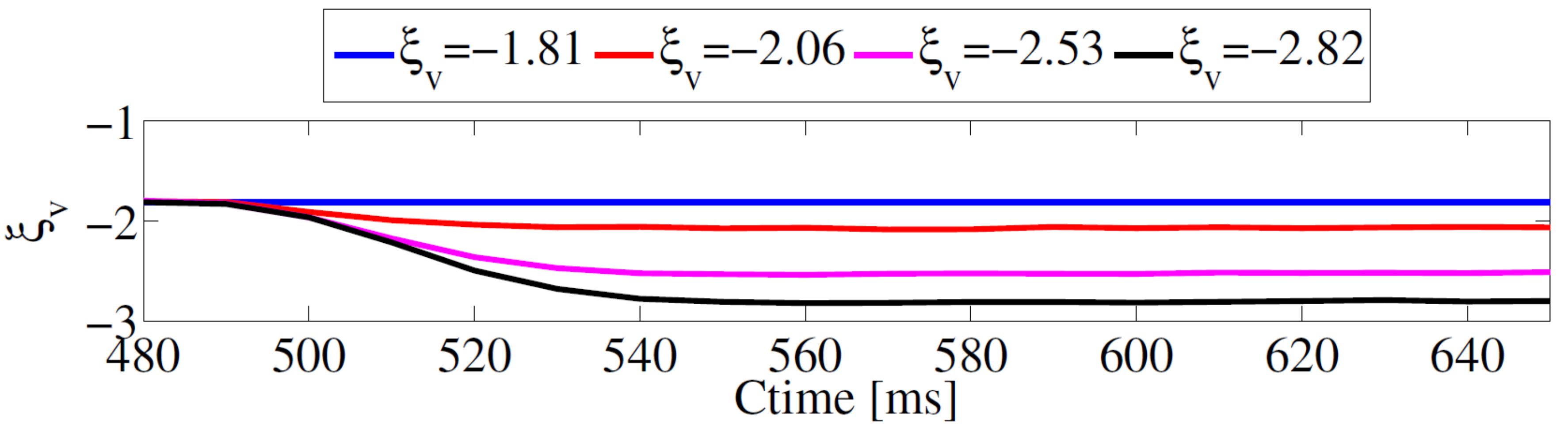
Touching with upper part of the footprint the 3Qy=13 line

- 163 MeV flat top



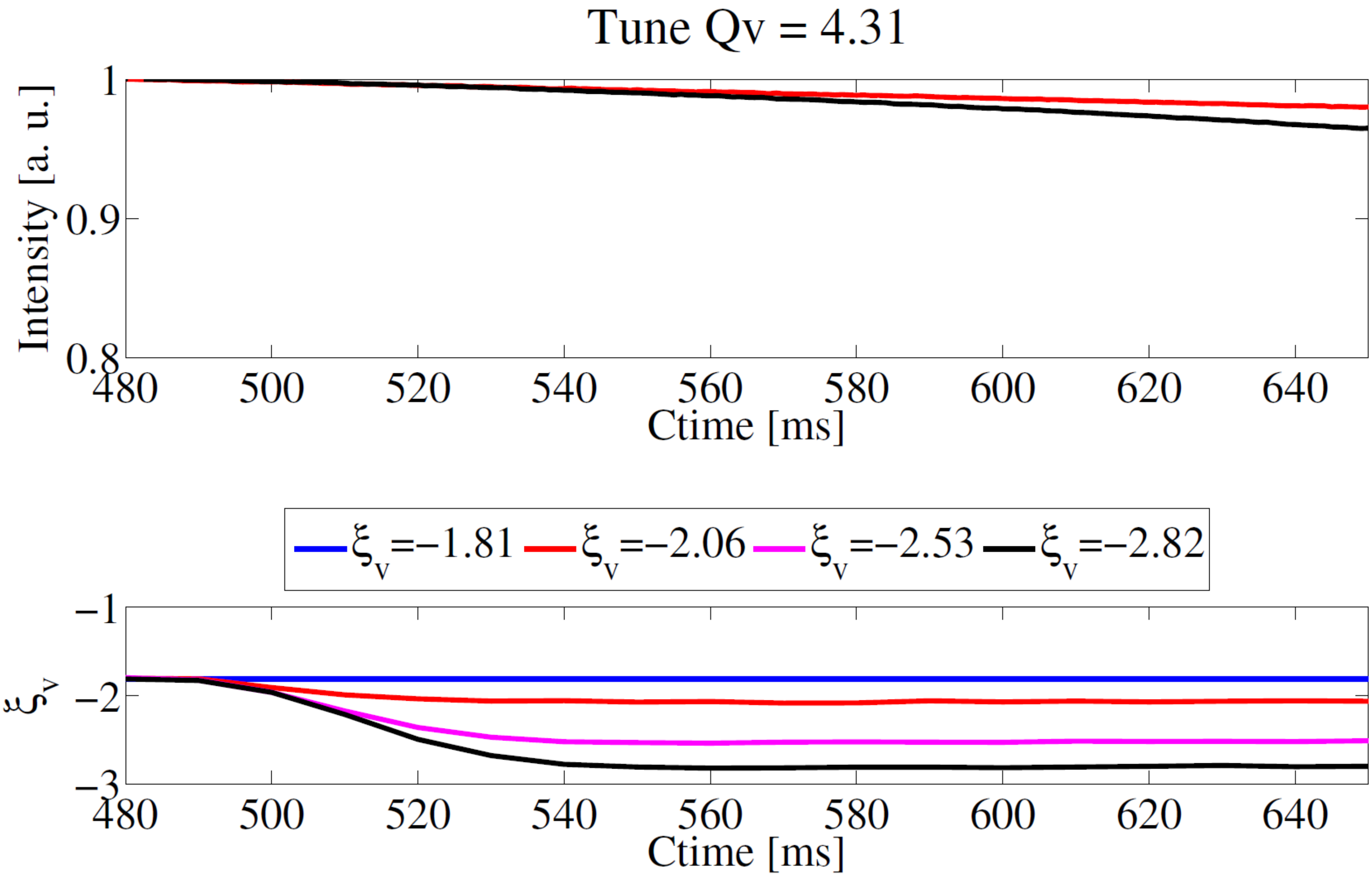
- 3Qy=13 excited through skew sextupole
- Tune scan at Qx=4.2, Qy=4.31…4.34

- Chromaticity ramps (measurements)



Touching with upper part of the footprint the 3Qy=13 line

- **Measurements @320e10 p.**



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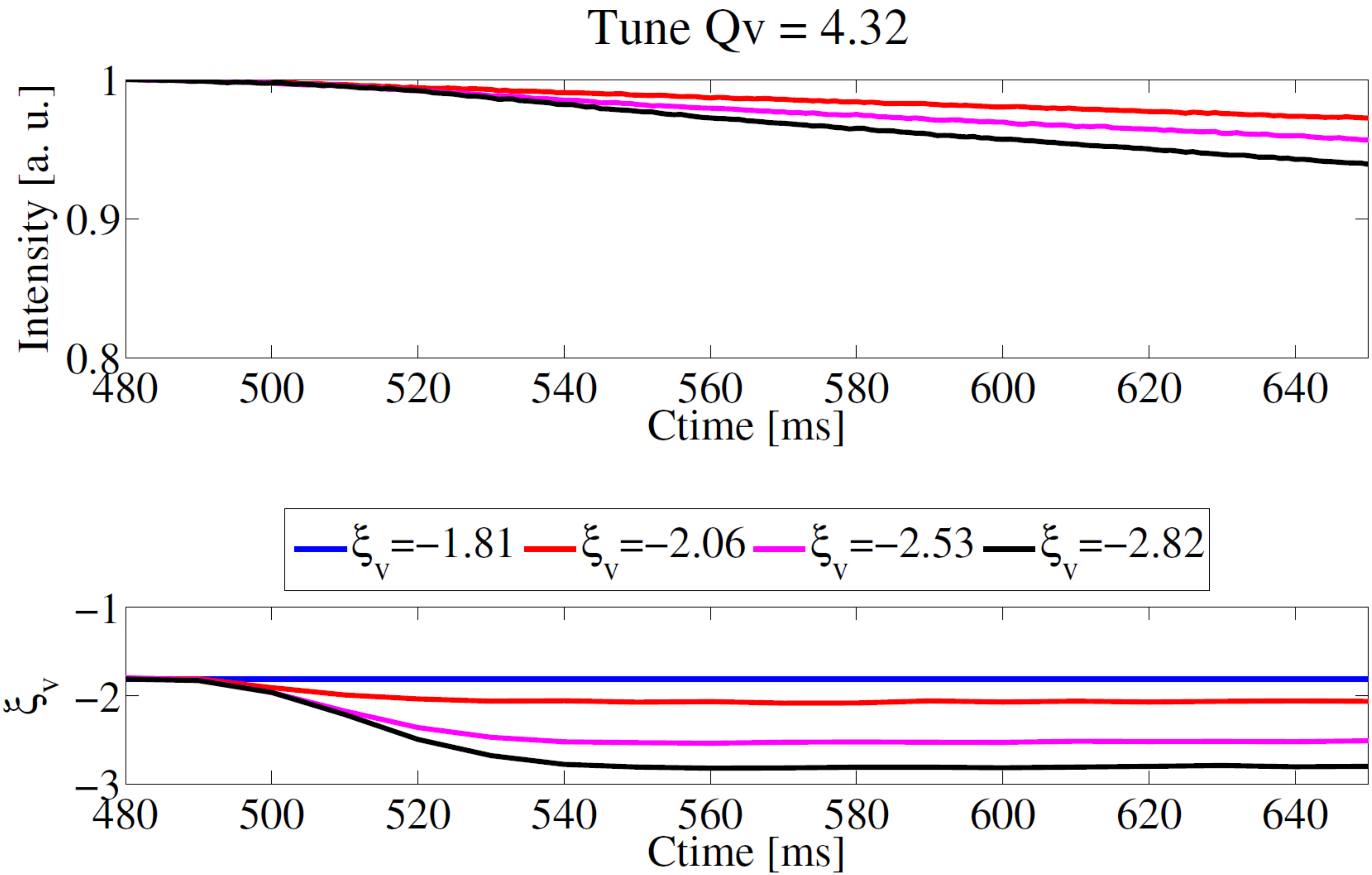

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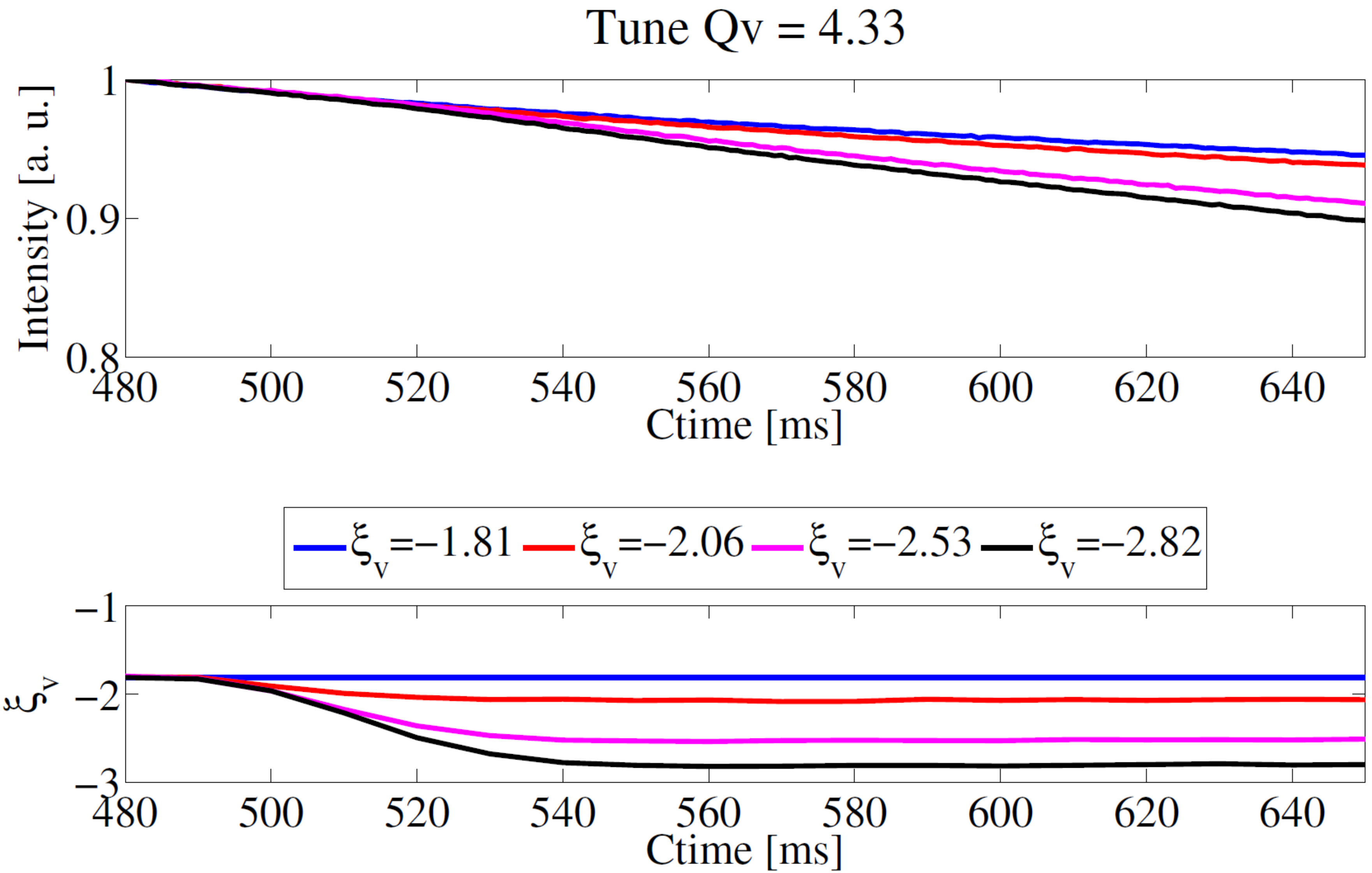

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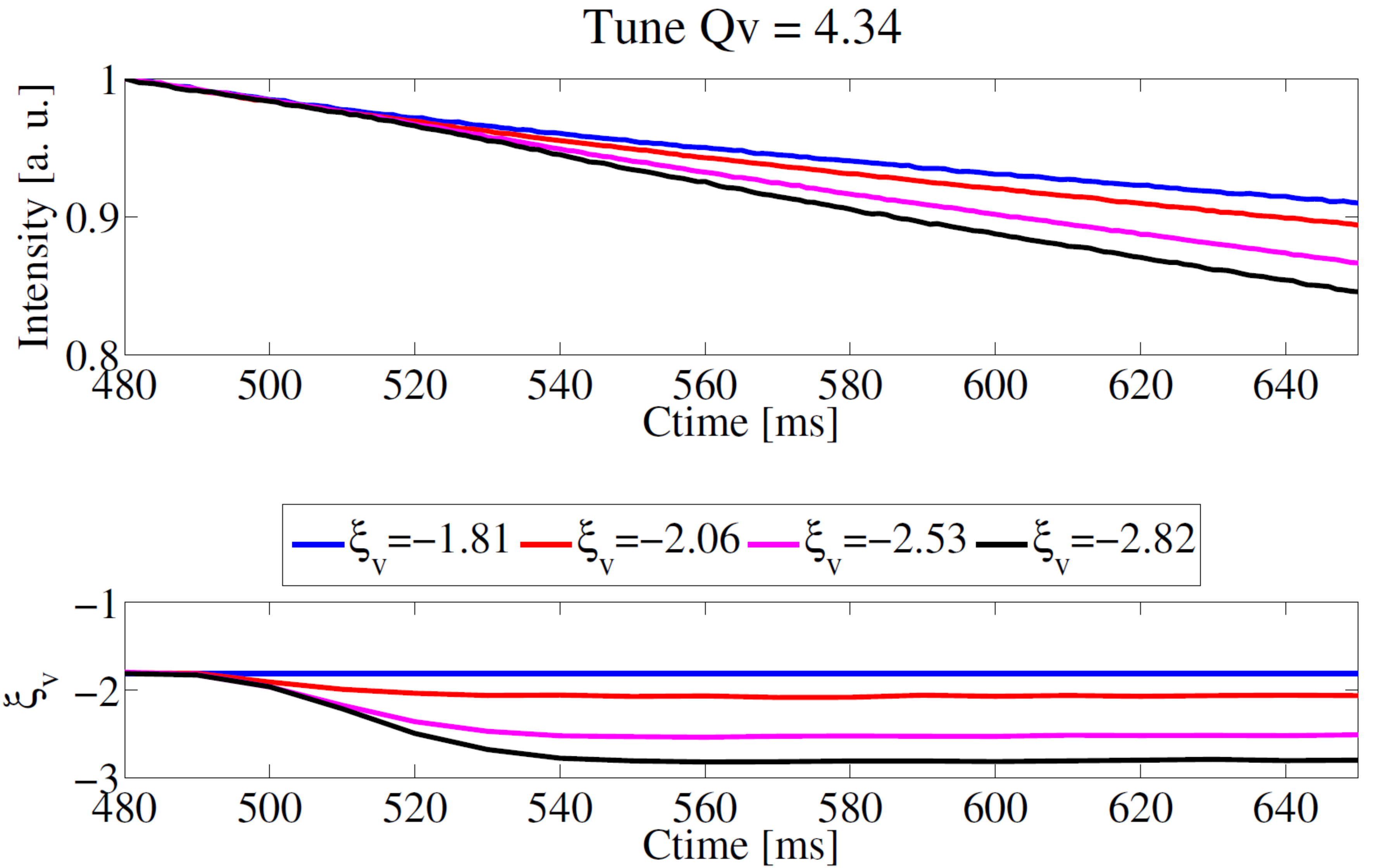
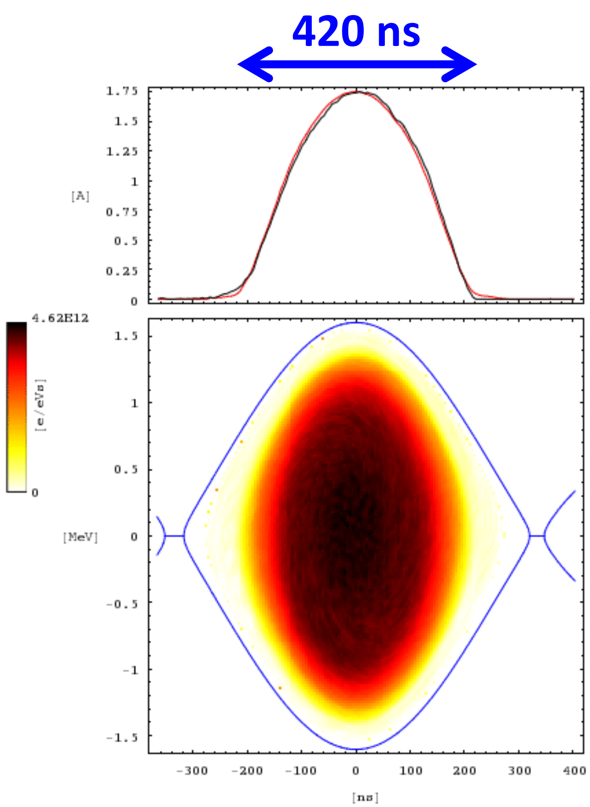


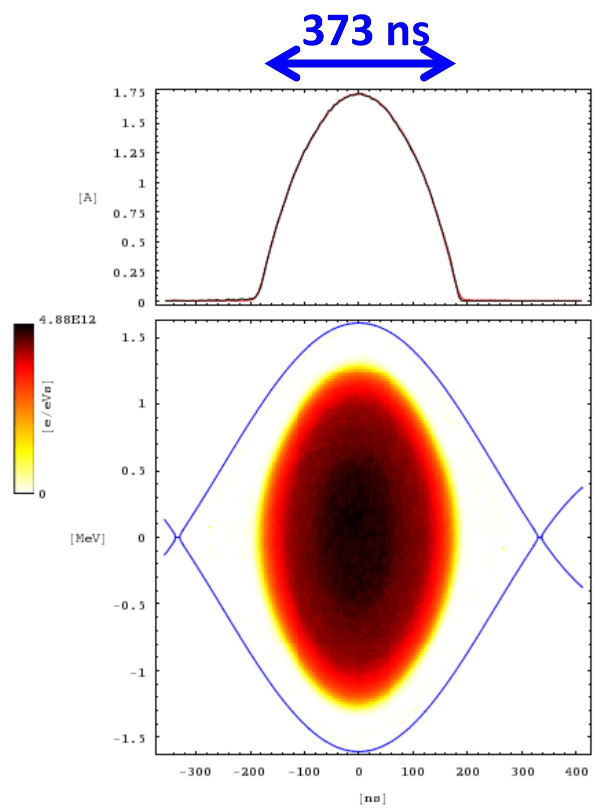
Benchmark with simulations is on-going

Touching with upper part of the footprint the 3Qy=13 line

$Q_y = 4.34$ / $\xi_y = -2.82$



t= 450 ms



t= 650 ms

Bunch shortening

Two experiments for negative chromaticity quadrants

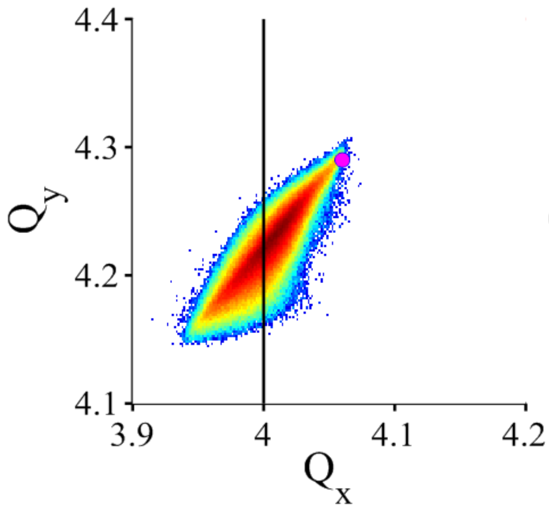
1. Touching the 3Qy=13 line with upper part of the footprint
2. **Touching the horizontal integer resonance**

The horizontal integer resonance Qx=4

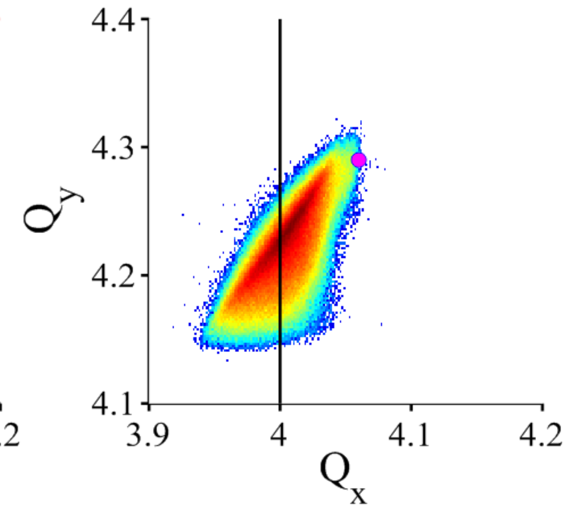
Initial beam parameters	(ξ_x, ξ_y)=(-0.73, -1.7)	(ξ_x, ξ_y)=(-0.15, -2.8)
Bunch populations [10^{11} p]	6.95	
ε^*_x, ε^*_y [mm mrad]	1.66, 1.6	1.68, 1.59

Tune spreads for different chromaticities

(ξ_x, ξ_y)=(-0.73, -1.7)

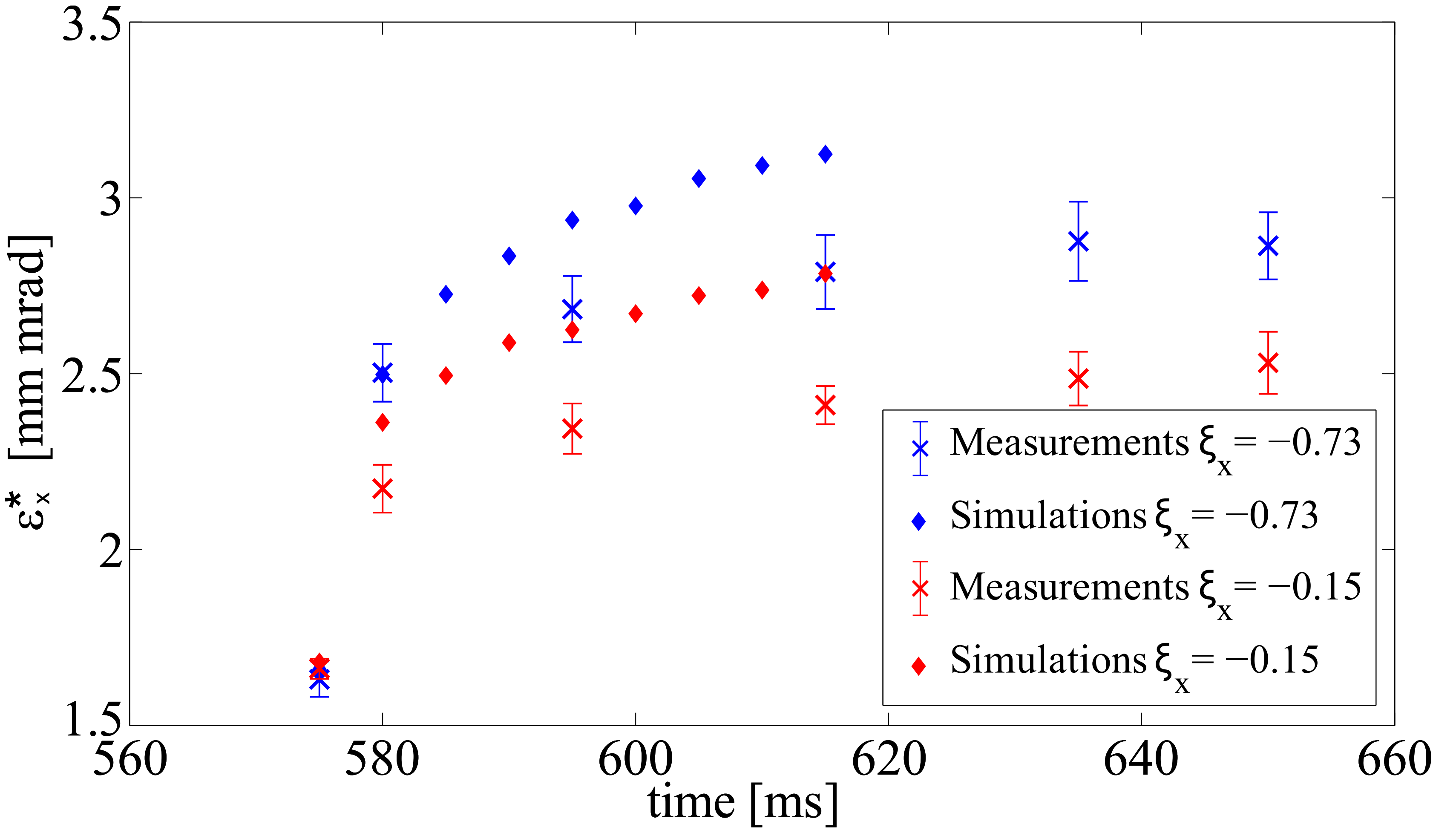


(ξ_x, ξ_y)=(-0.15, -2.8)



PTC-ORBIT SIMULATIONS

The horizontal integer resonance Qx=4



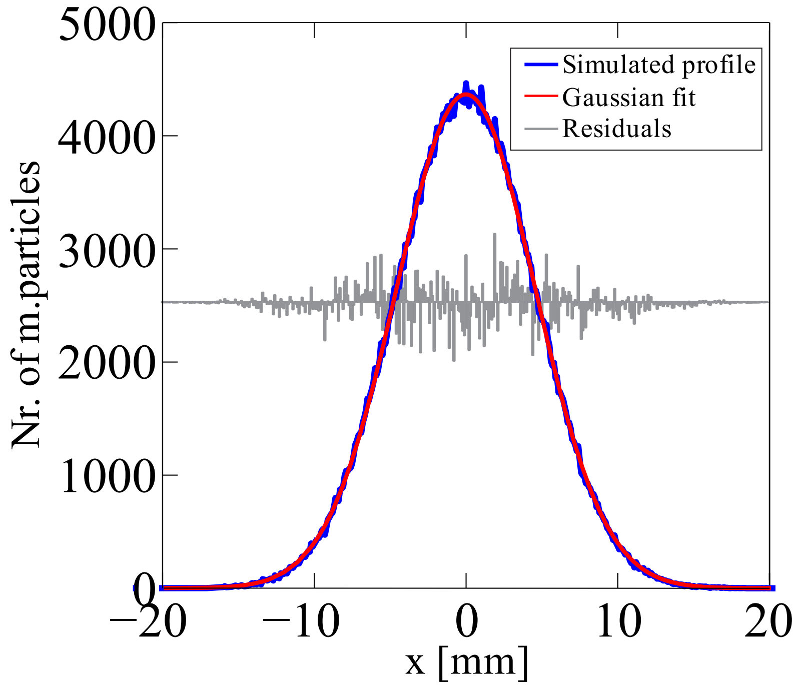
- The normalized emittance blow-up is present in both cases, but **always higher with bigger horizontal chromaticity**.
- PTC-ORBIT simulations and measurements show the same trend.

The horizontal integer resonance Qx=4

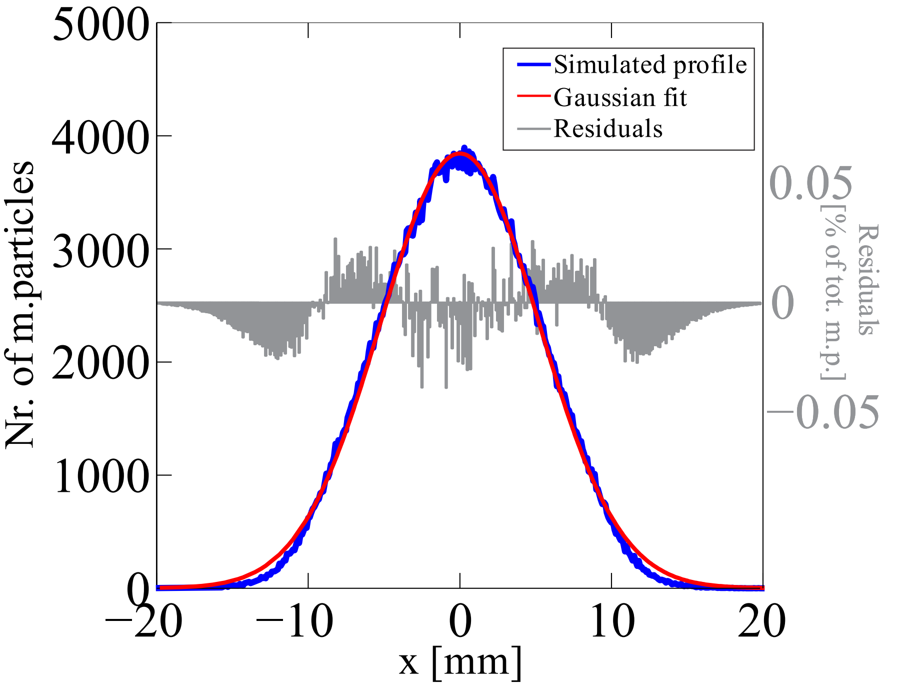
- In both cases the beam loses the initial Gaussian shape in the first 5 ms.

Simulations with (ξ_x, ξ_y)=(-0.73, -1.7)

575 ms



580 ms

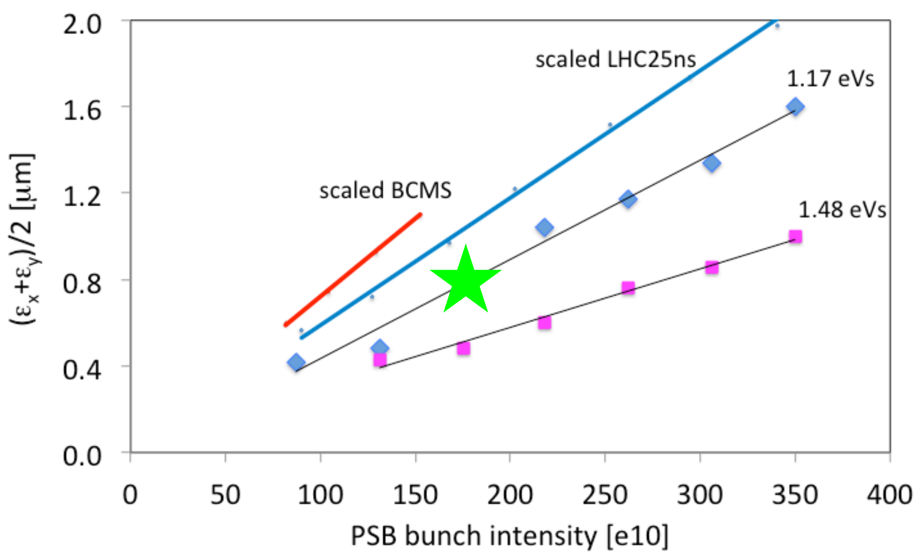


Measurements show the same trend

LHC High Brightness prediction

The brightness for the LHC beams is defined in the PSB!

Purpose: reduce the slope of the brightness (Intensity vs. Emittance) curve

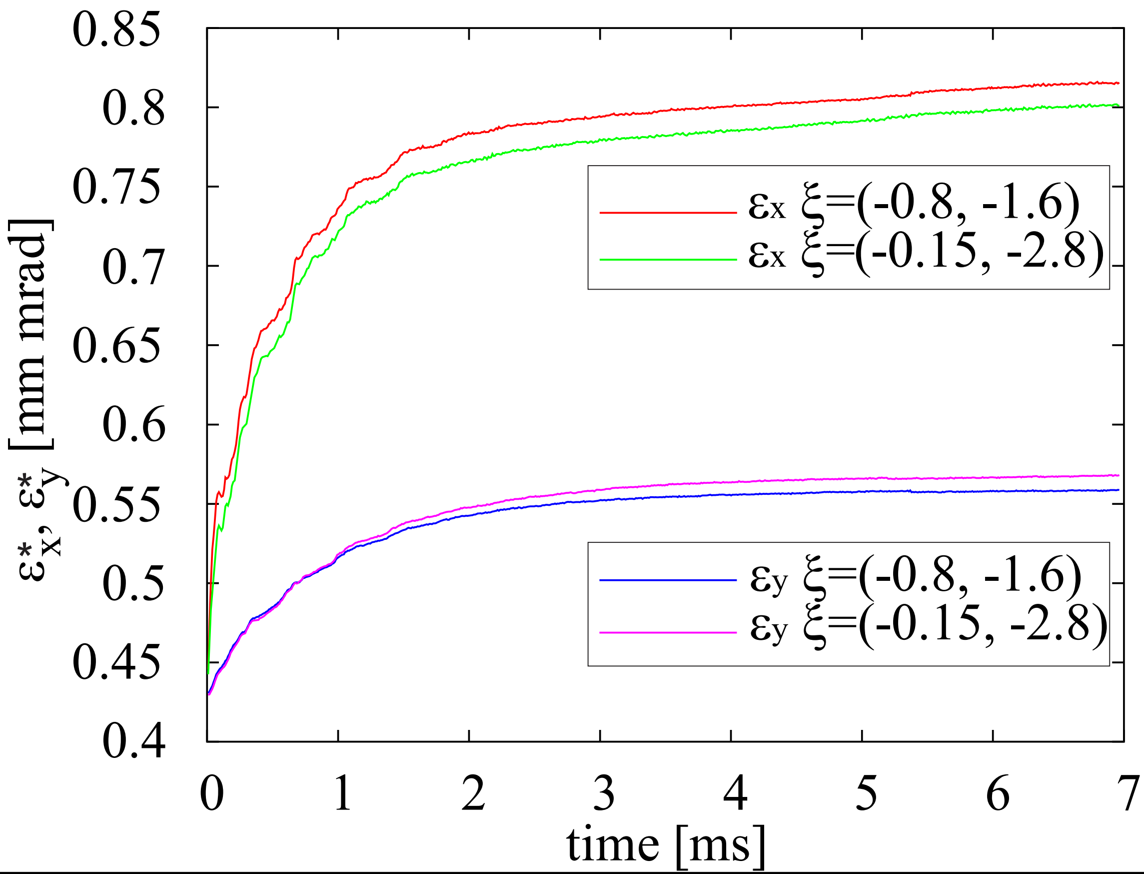


Ref. E. Benedetto et al., THPF088, IPAC'15 proceedings

Simulation parameters for 1 point

- Injection in a chicane bump
- Acceleration in a double RF bucket
- $(Q_x, Q_y)=(4.28,4.55)$
- $\Delta Q_{x,y}$ ~ 0.5
- Bunch population=1.755 $x10^{12}$ p
- $\varepsilon^*_{x,y,0}$= 0.4µm
- ε_z= 1.17 eVs

LHC High Brightness prediction



Results

- Few % blow-up reduction in the horizontal plane.
- Same relative blow-up increase in the vertical plane.
- Coupled control of ξ_x, ξ_y
  - An intermediate chromatic working point could give better results.
  - Study effect to correct both ξ_x, ξ_y, i.e. by adding 1 family of sextupoles.

Highlights

- The **relation between chromaticity and incoherent tune spread with space charge** has been shown in simulation for the PSB.
    - Chromatic particles follow **different tune patterns** depending on the chromaticity values.
- Since the PSB works with natural chromaticity, this effect is **significant**.
- V&H **chromaticitiy control is coupled** in the PSB through the unique normal sextupoles family.

- A benchmark between measurements and simulations is on-going for the following case:
    - Excitation of the upper part of the spread through the **3Qy=13 resonance.**
    - Preliminary measurements for the **3Qy = 13 case** show an **increase of losses for increased vertical chromaticities**.

- A complete comparison measurements vs. simulations has been proposed for the following case:
    - The **Qx=4 resonance**.
    - Simulations and measurements show **dependence of the emittance blow-up with the chromaticity**.

- An attempt of prediction for the upgrade scenario has been presented.
    - **Coupled control of chromaticity limits the gain** in term of beam brightness.
    - Intermediate chromatic points may improve the results.
    - **Studies should be done** correcting both the chromaticities and including coherent effects.

Thanks for your attention

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