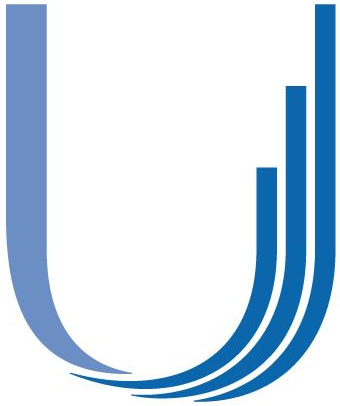

LHC Injectors Upgrade

PSB Experiments, 6D Tune evolution with SC

Space charge collaboration meeting – CERN – 20/05/2014

Layout

Tunes evolution in a space charge dominated beam

Measurements-simulations benchmark: the half-integer resonance (2Qy=9)

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Université Blaise Pascal – Clermont Ferrand - France

Thanks to:

E. Benedetto, M. McAteer, M. Migliorati, F. Schmidt

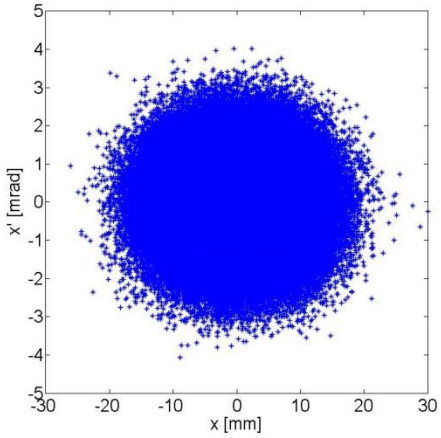
Tunes evolution in a space charge dominated beam

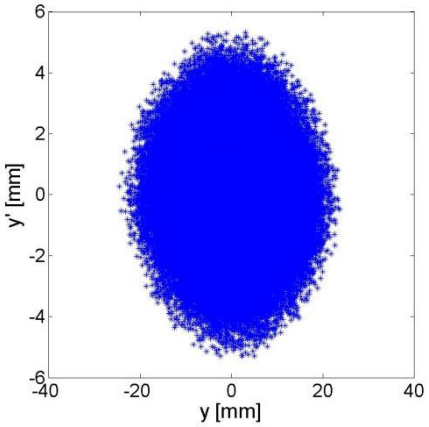
1. Relation between tunes and coord. phase space
2. Cuts
3. Single particle tunes modulation
4. Averaging

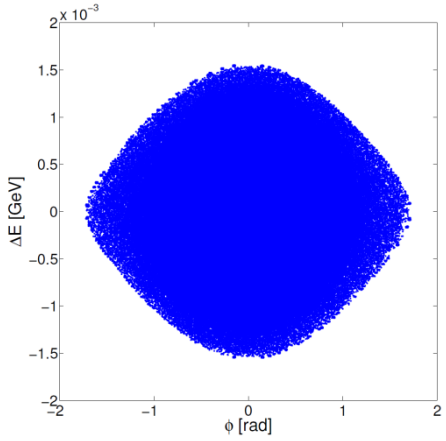
Tunes evolution in a space charge dominated beam

1. **Relation between tunes and coord. phase space**
2. **Cuts**
3. **Single particle tunes modulation**
4. **Averaging**

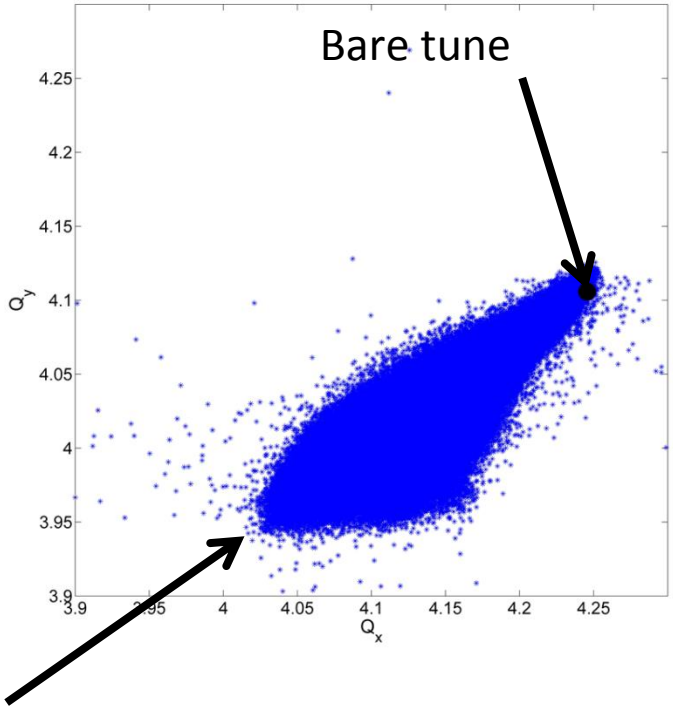
Relation between tunes and coord. phase space







?



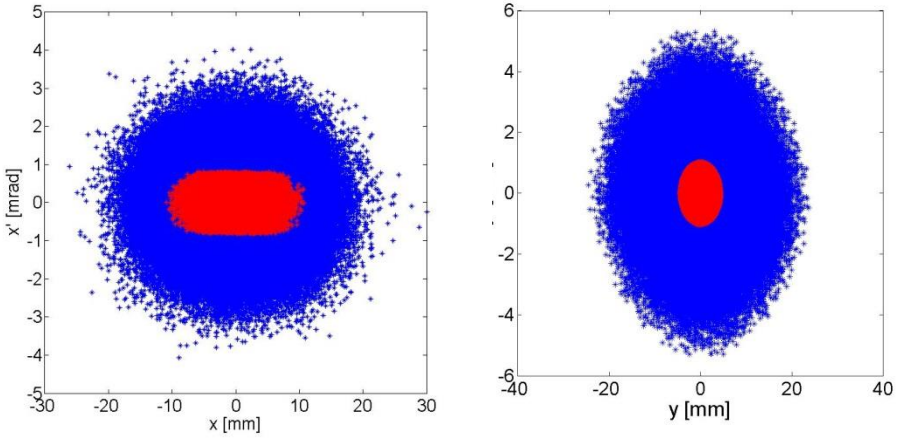
$$\Delta Q_{x,y} = -\frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)[\sigma_x(s)+\sigma_y(s)]} ds$$

The cuts

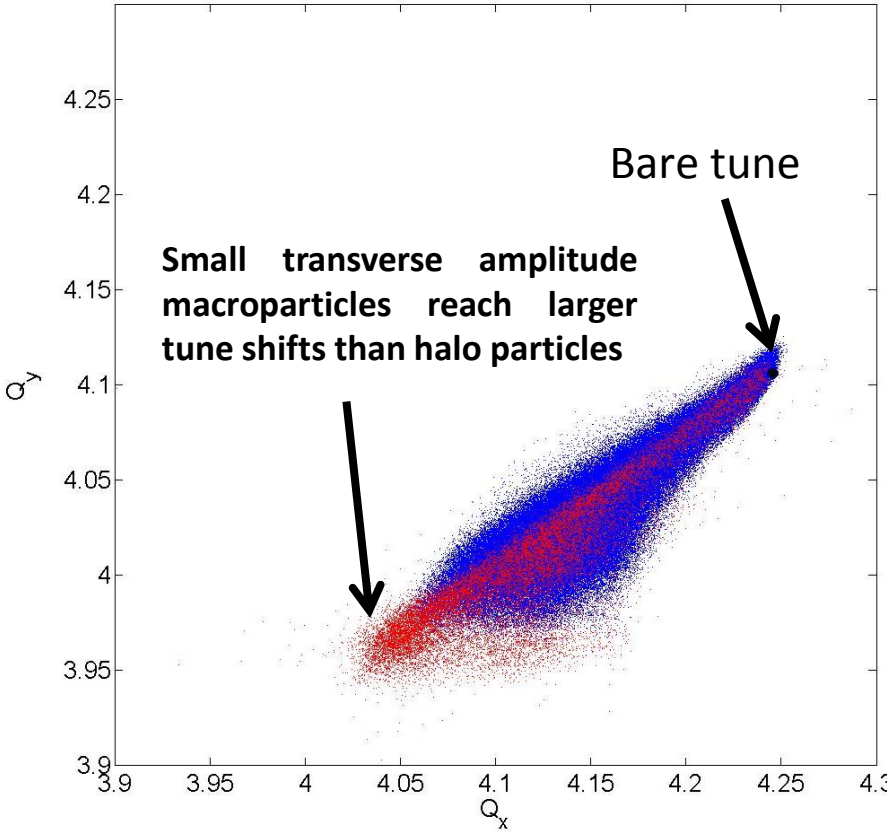
What happens to the particles in the necktie if one starts cutting the distribution in different sublets?

Subsets of macroparticles – transverse cut

In the next slides the analysis will be performed on a subset of macroparticles with small* transverse amplitude (red)

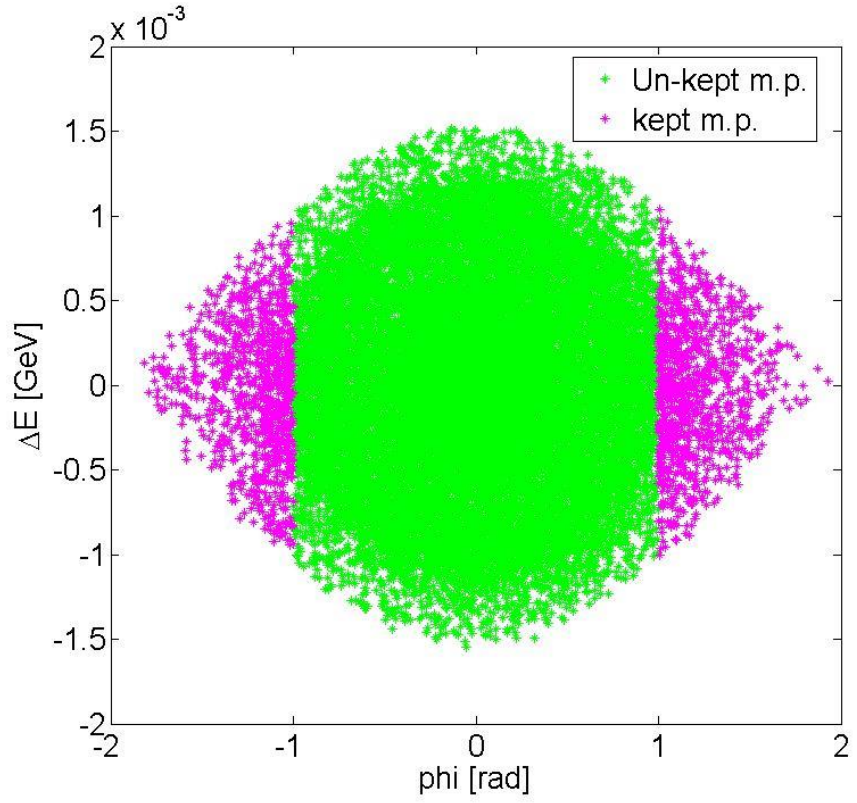


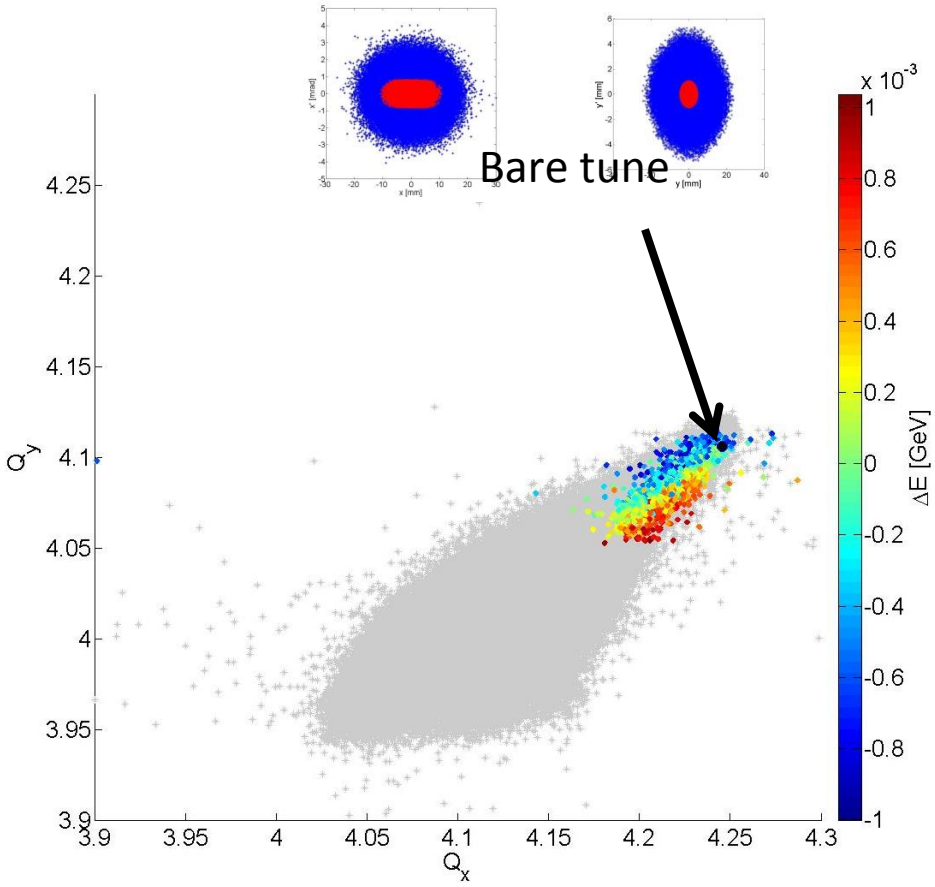
Transverse planes



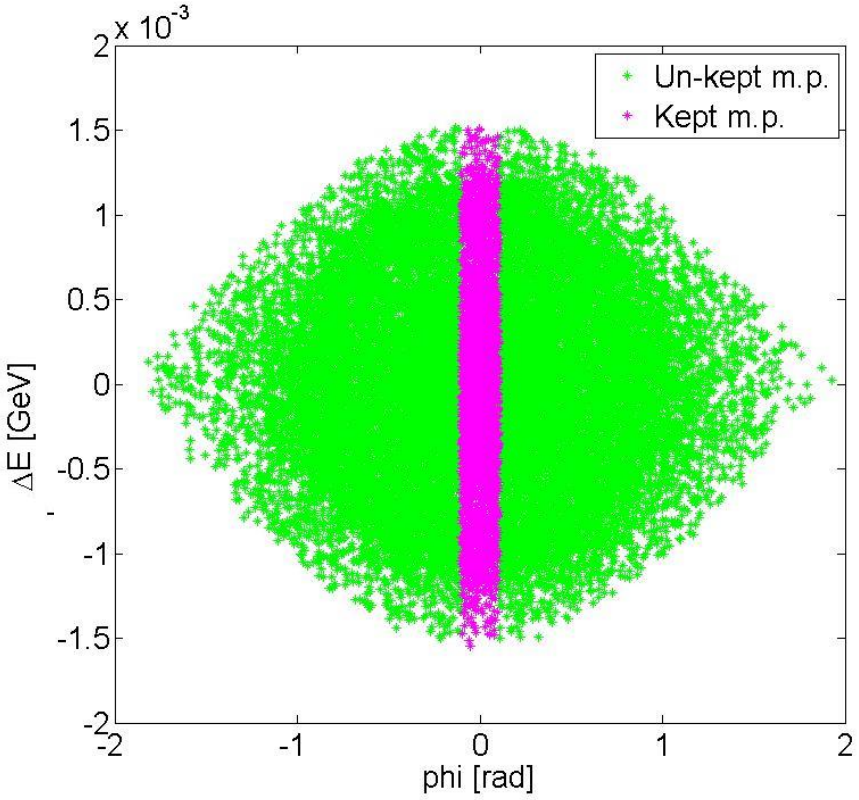
*4D Cut boundaries = 1/32 x max (Jx) & 1/32 x max(Jy)

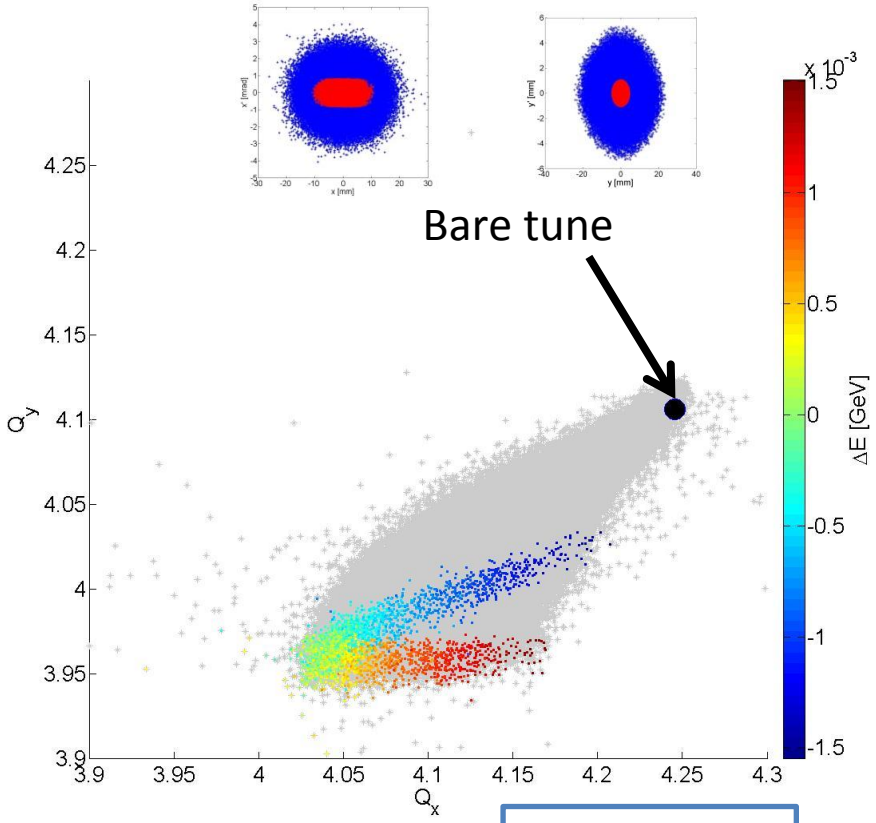
RED TRANSVERSE AREA + HEAD/TAIL CUT





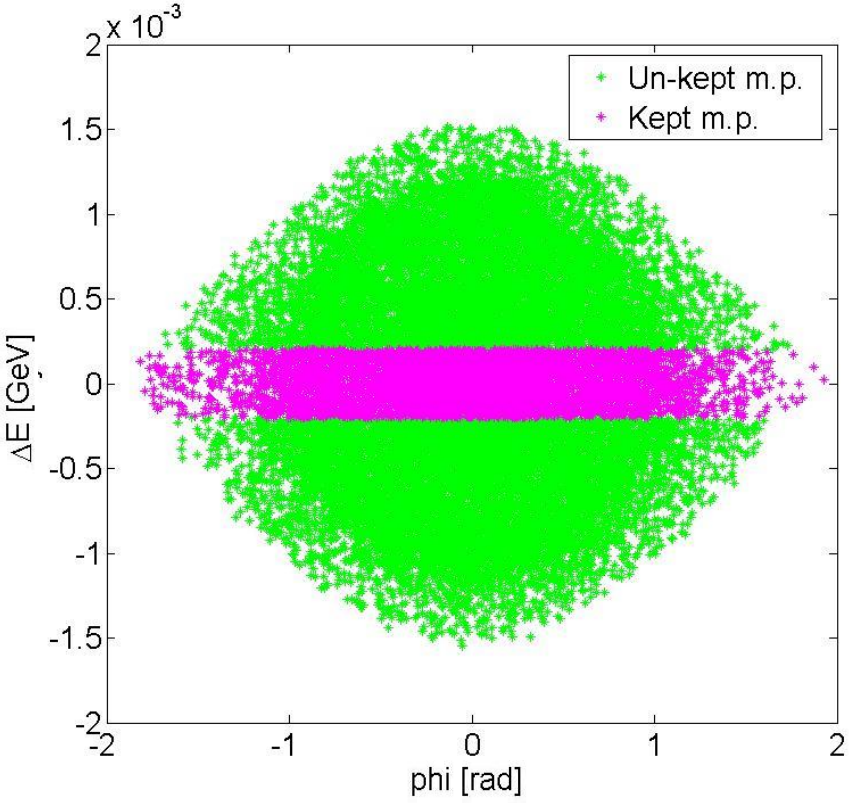
RED TRANSVERSE AREA + ZERO PHI CUT

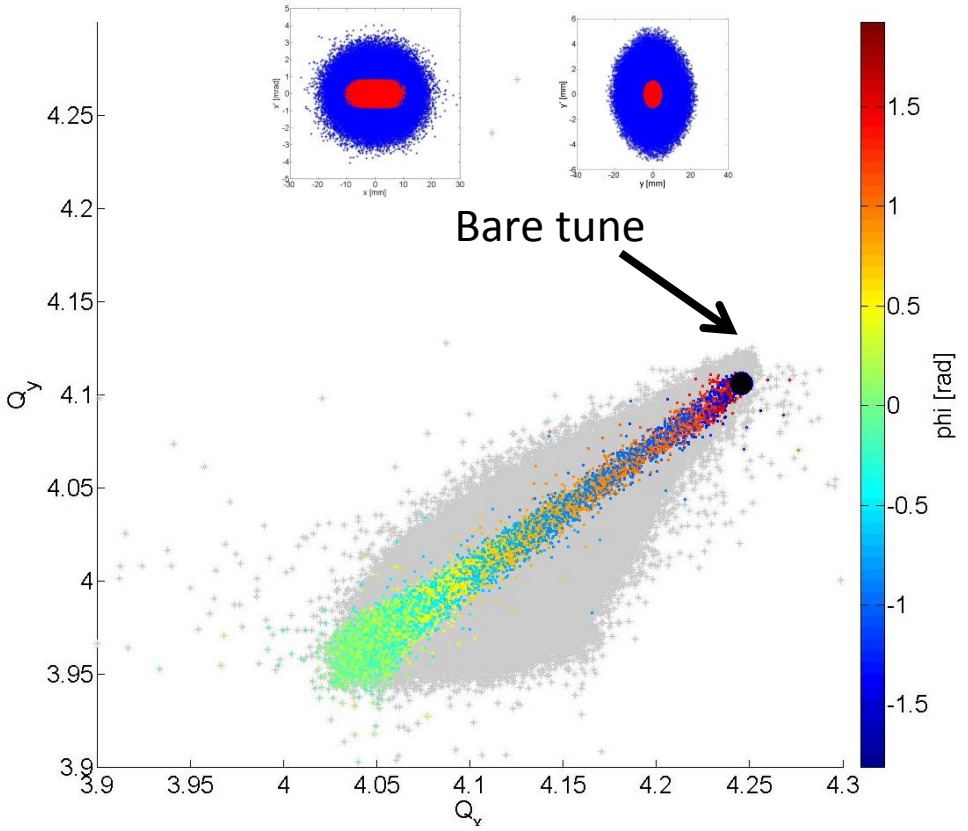




In the PSB:
Dx=1.4m;
DQx=-3.34;
DQy=-6.50;

RED TRANSVERSE AREA + ZERO ΔENERGY CUT





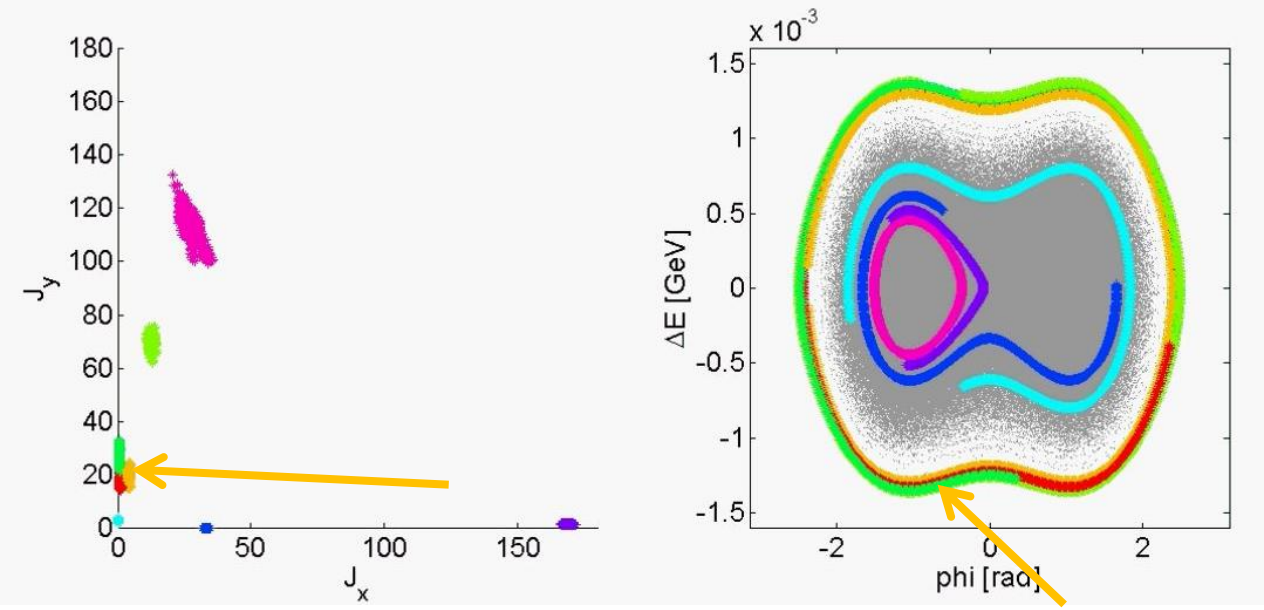
Tunes evolution in a space charge dominated beam

1. Relation between tunes and coord. phase space
2. Cuts
3. **Single particle tunes modulation**
4. Averaging

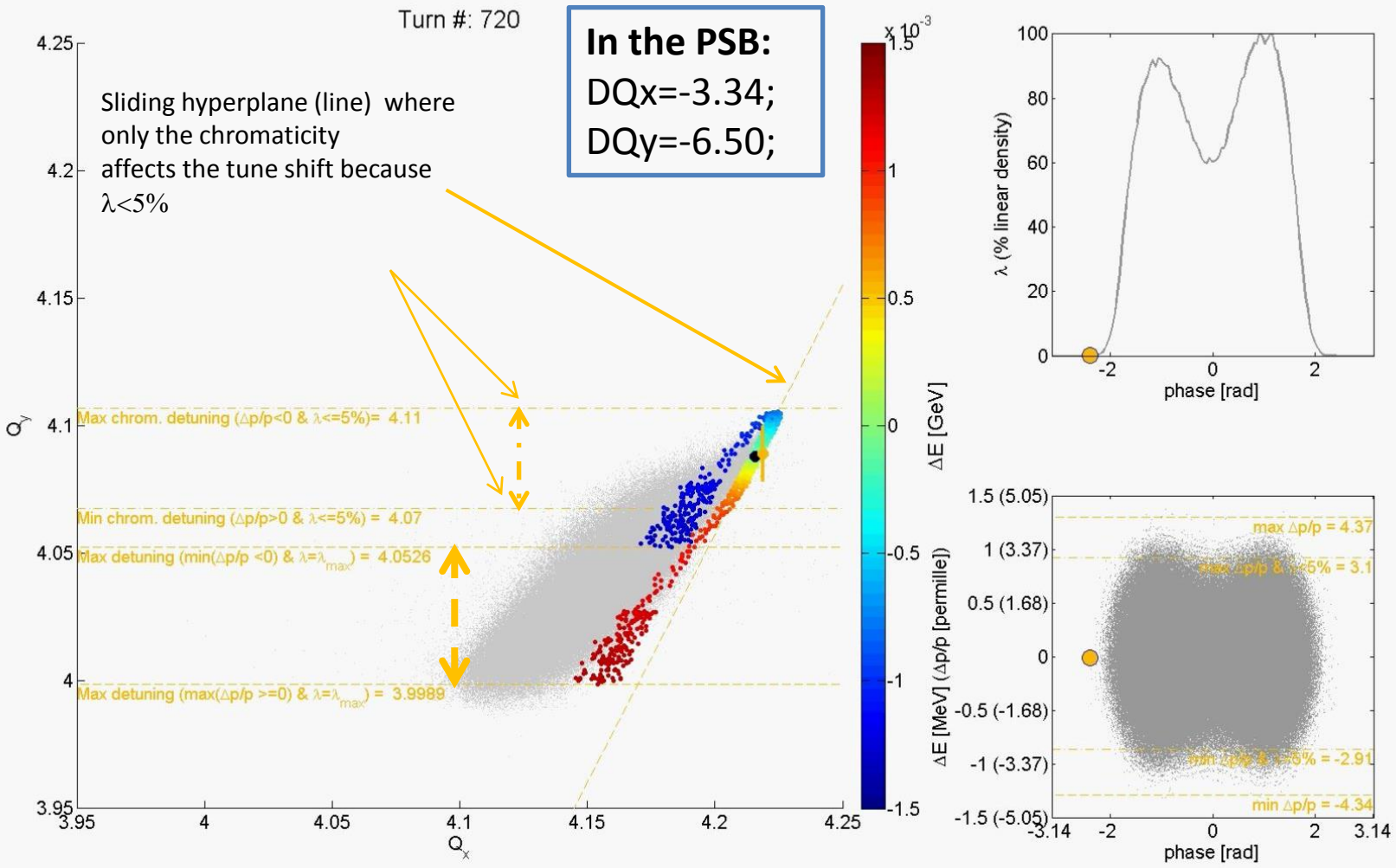
Single particle dynamic behavior (tunes modulation)

- A double RF bucket simulation (with h=1 and h=2 in antiphase) close to the vertical integer Qy=4 in the PSB has been taken as example for the analysis.

- The yellow particle (large synchrotron amplitude and relative small transverse actions) has been taken into account for an accurate turn-by-turn analysis.



Single particle dynamic behavior (tunes modulation)

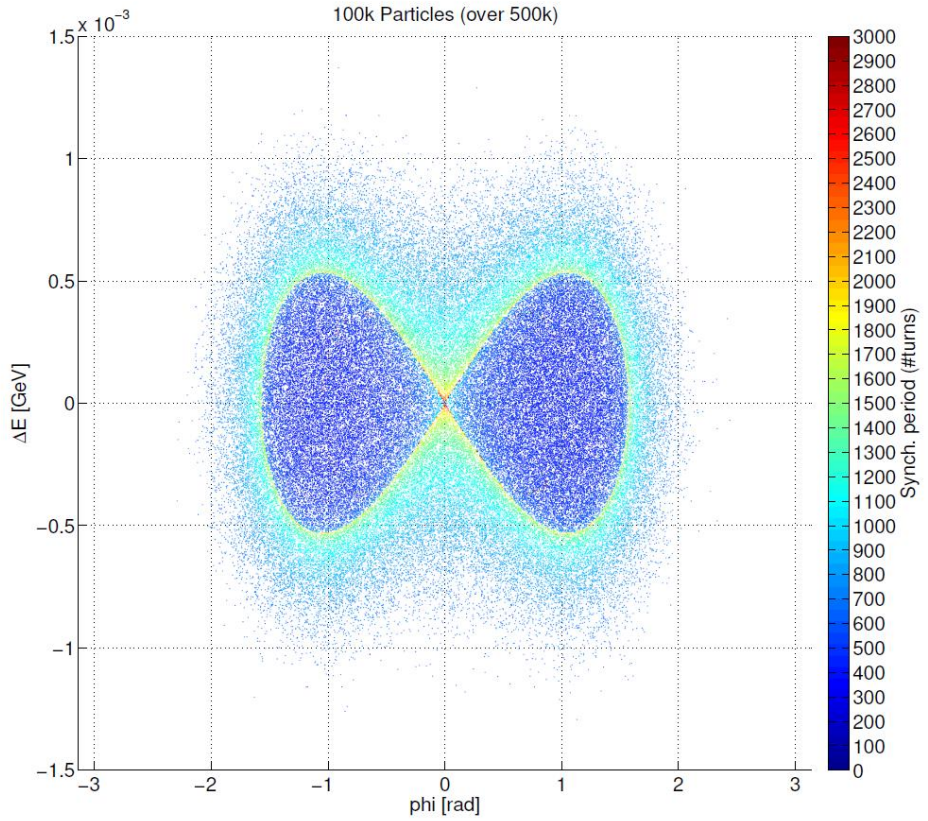


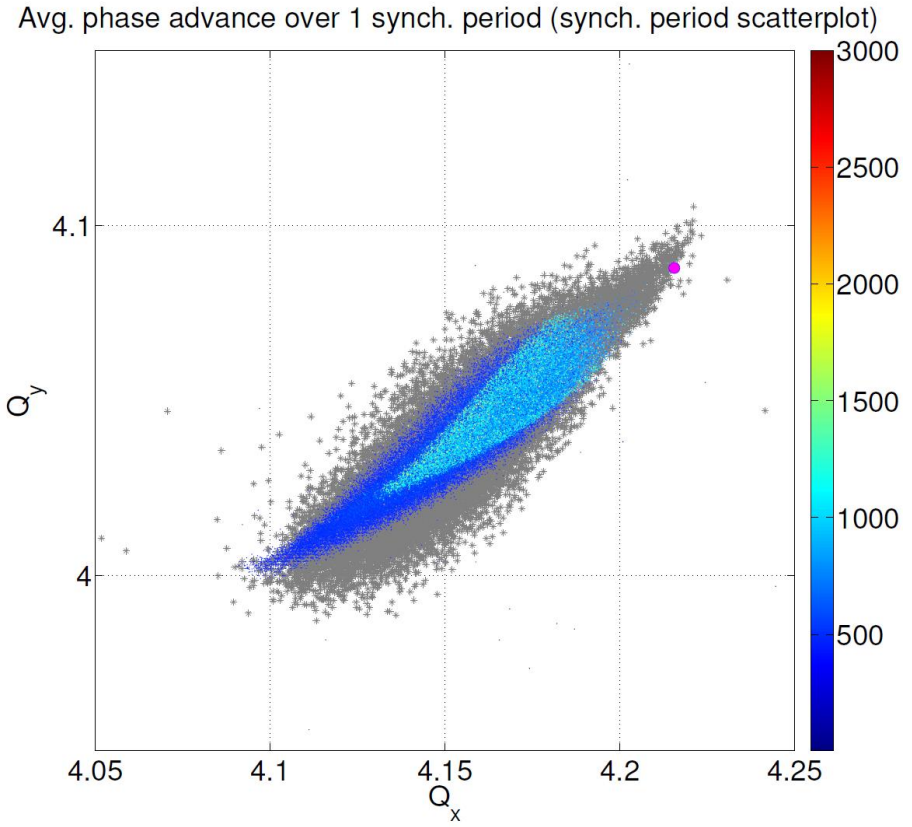
Tunes evolution in a space charge dominated beam

1. Relation between tunes and coord. phase space
2. Cuts
3. Single particle tunes modulation
4. **Averaging**

Averaging the phase advance over many turns…

- **The tunes of each particle, averaged over 1 synchrotron period, are shown on the right.**

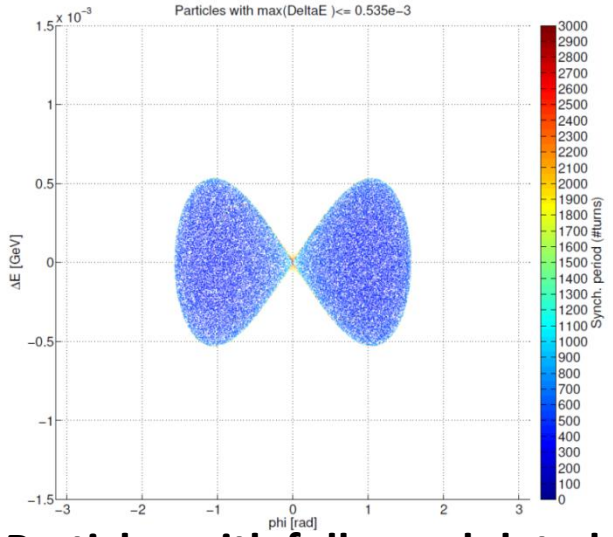


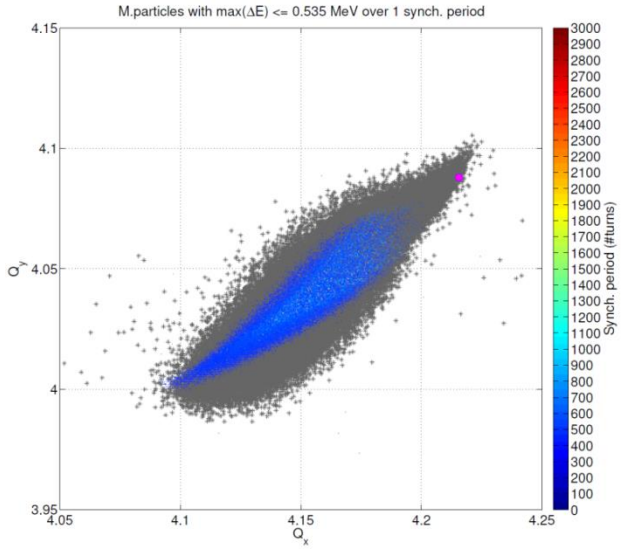


- **The averaging is extremely useful to underline some specific phenomena in the next part of the talk, in which the half-integer resonance has been studied to benchmark PTC-Orbit with the measurements.**

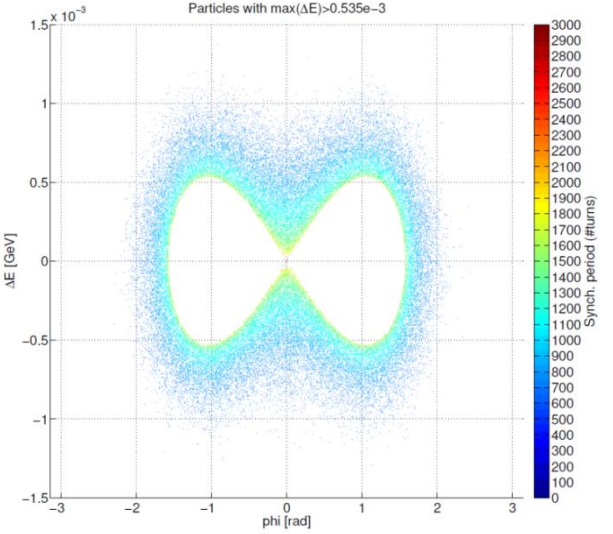
Averaging the phase advance over many turns…

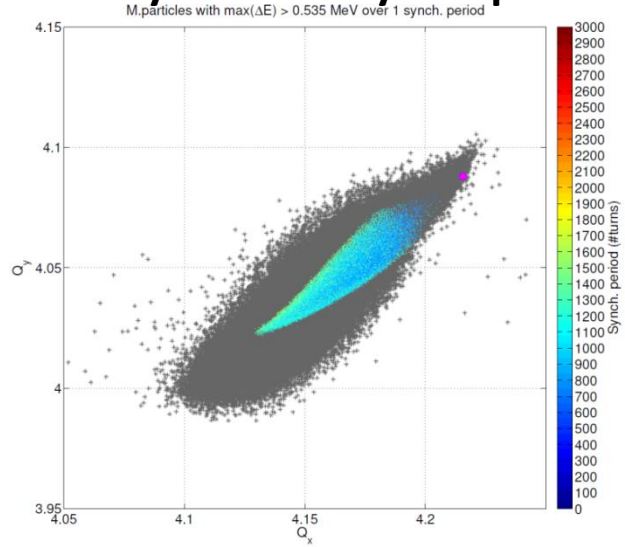
Particles with high (and less modulated) linear density over the synch. period





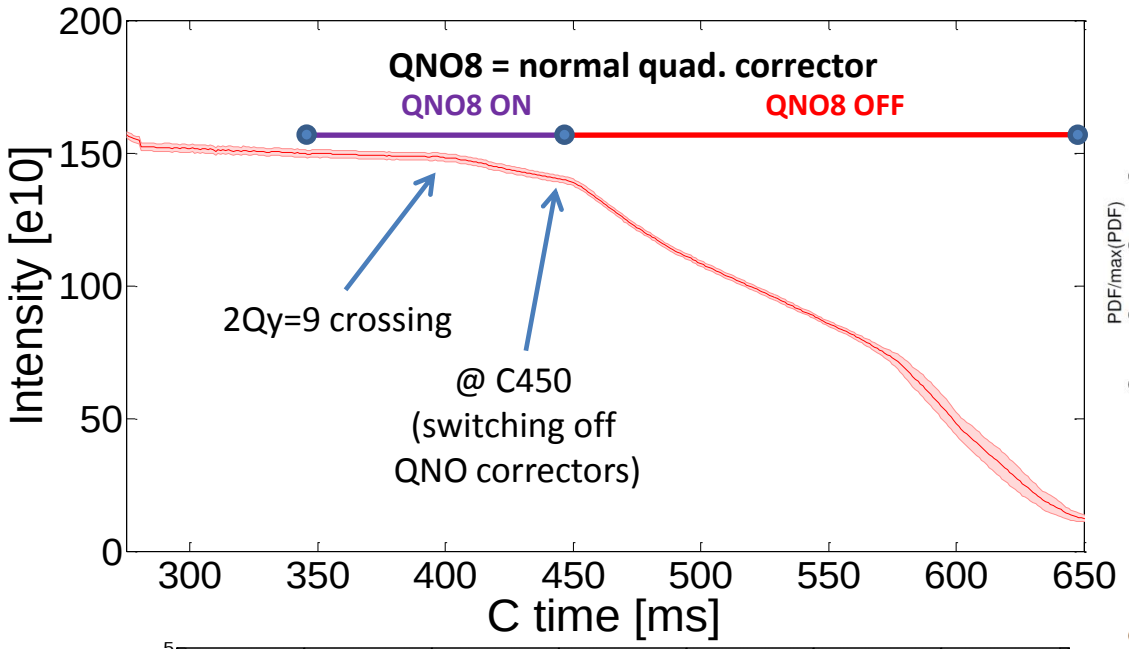
Particles with fully modulated linear density over the synch. period

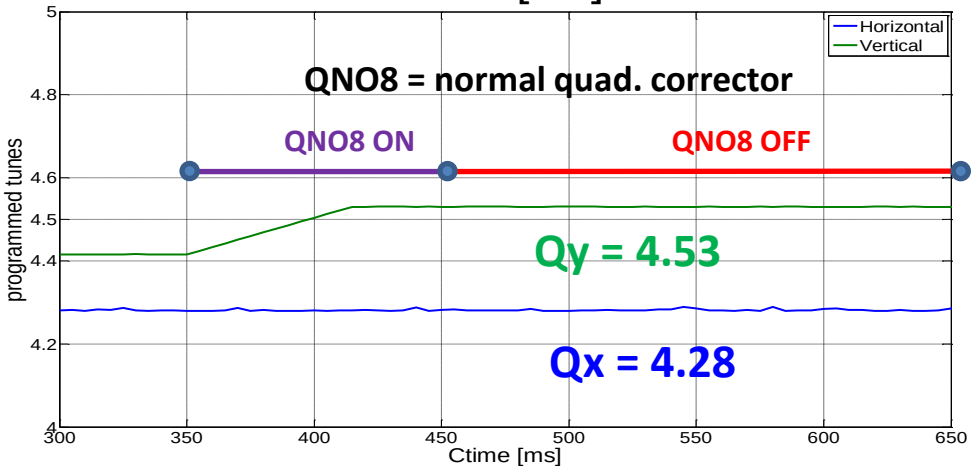




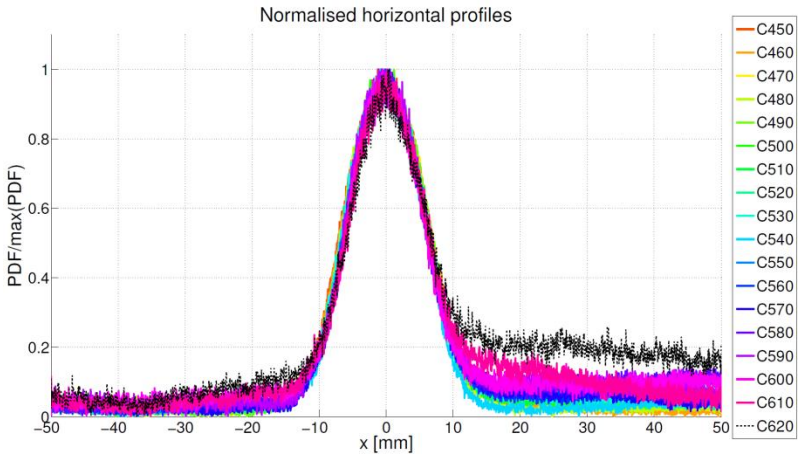
Measurements-simulations benchmark: the half-integer resonance (2Qy=9)

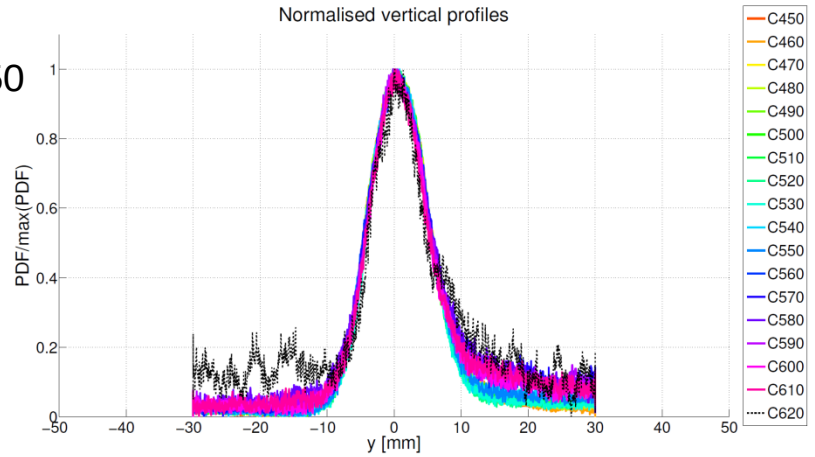
Measurements: intensity – programmed tunes – transverse profiles





@ 160MeV

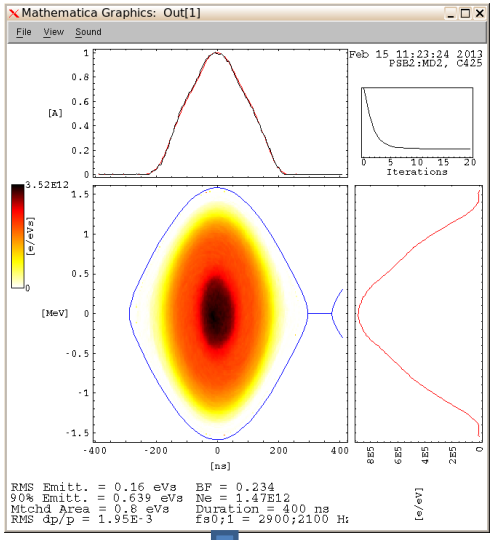


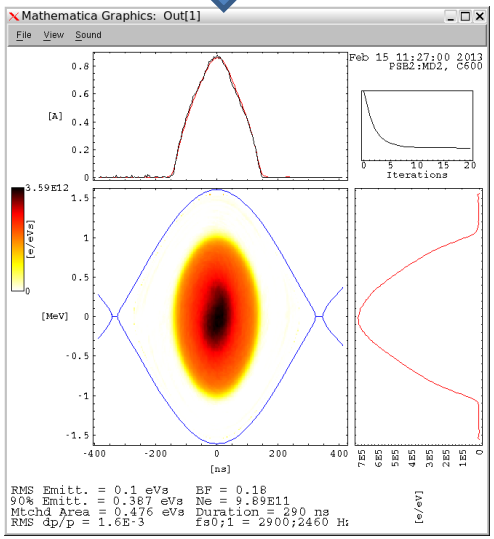


The core (1σ) of the beam is preserved during the losses!

Measurements: longitudinal profiles

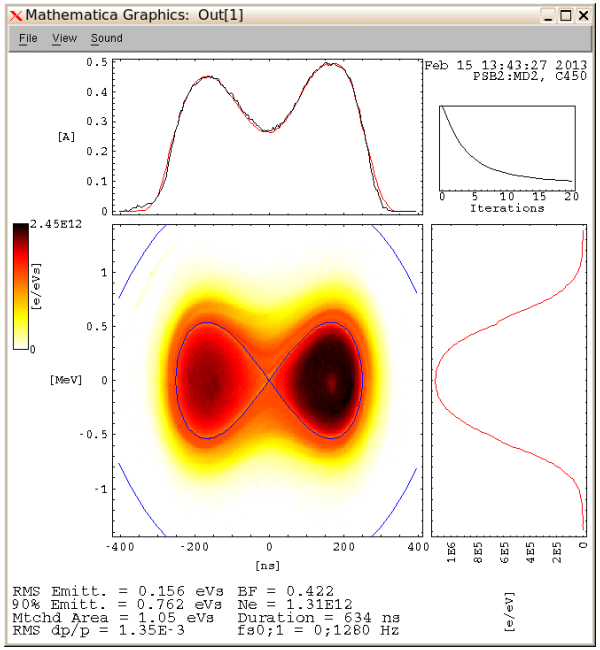
8kV/8kV in phase (short)





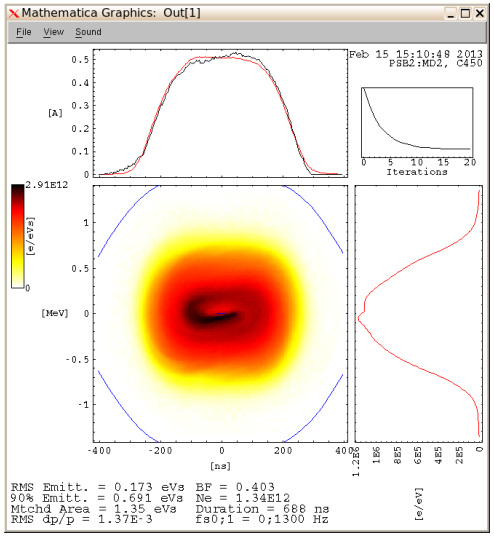
DOUBLE HARMONIC RF SYSTEM

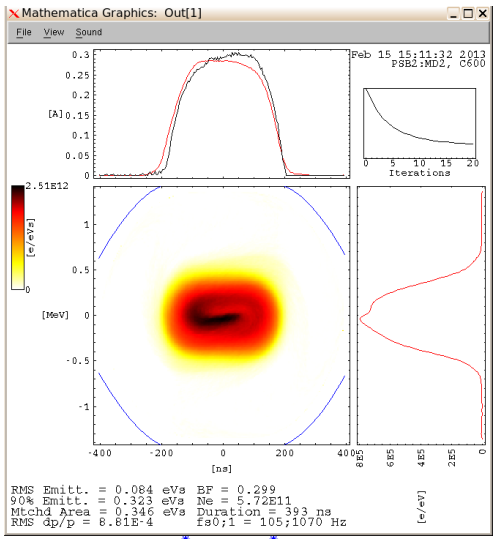
8kV/8kV in antiphase (long)



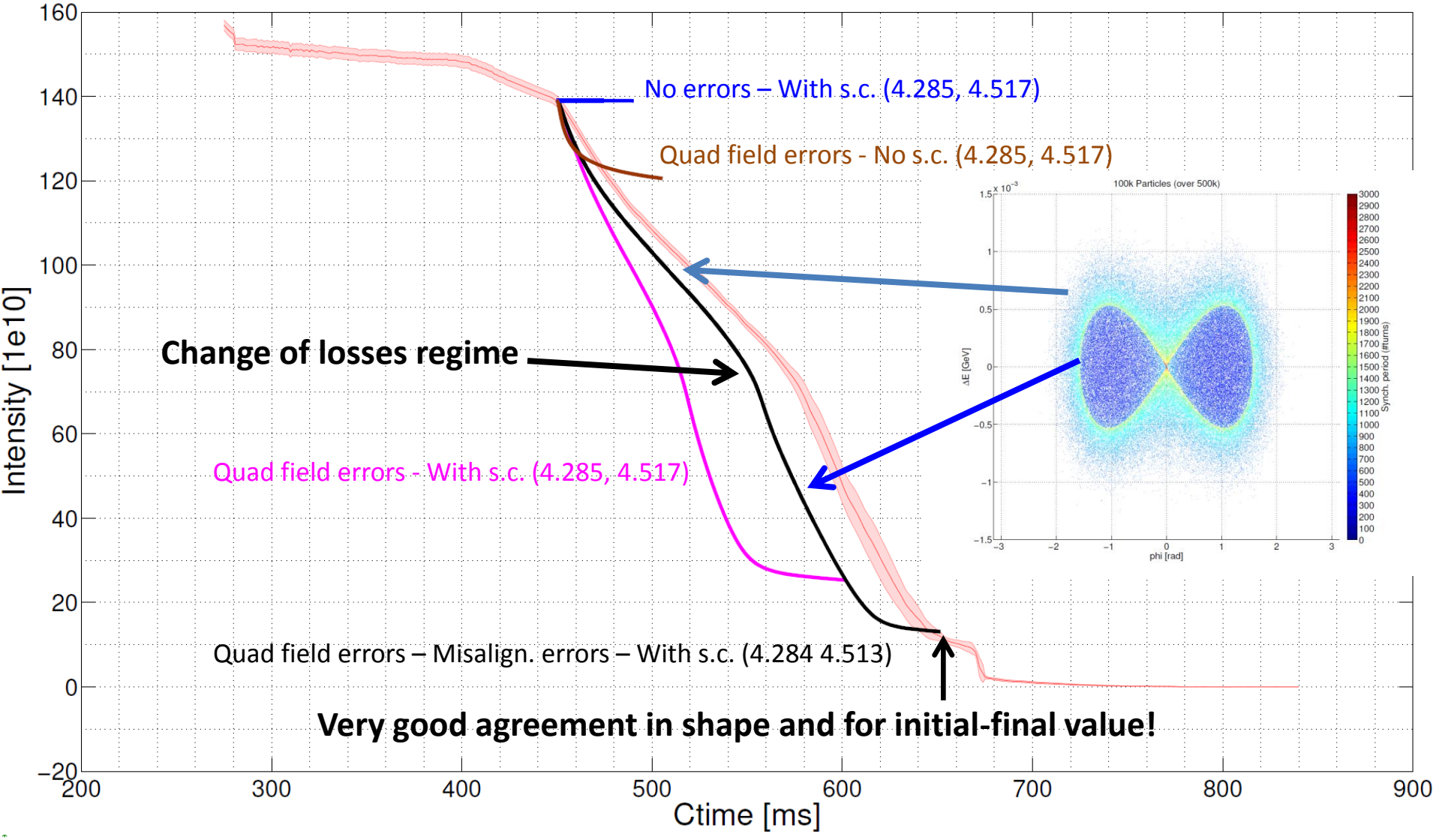
Cases in analysis

8kV/4kV in antiphase (long)



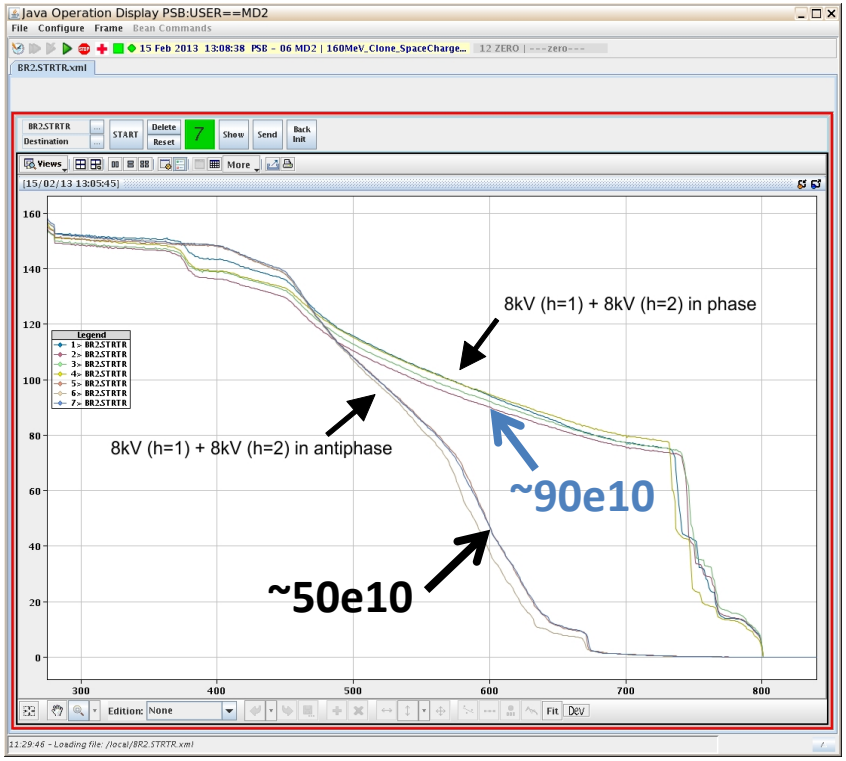


Simulations: losses behavior for long bunch

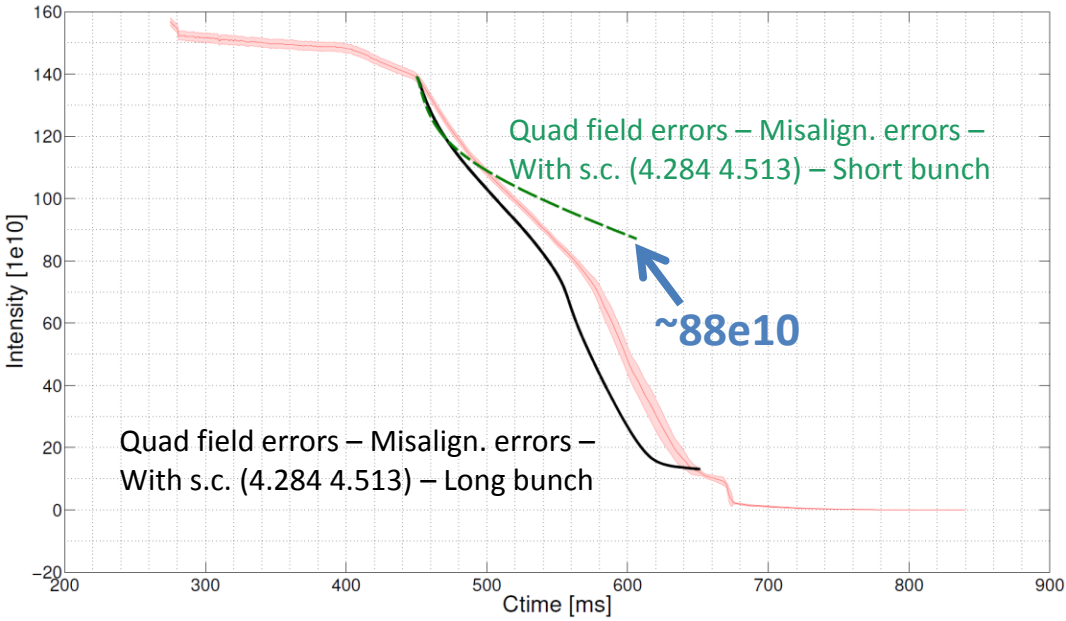


The complete model of the machine is FUNDAMENTAL !!

Simulations: losses behavior for long bunch and short bunch



Measurements

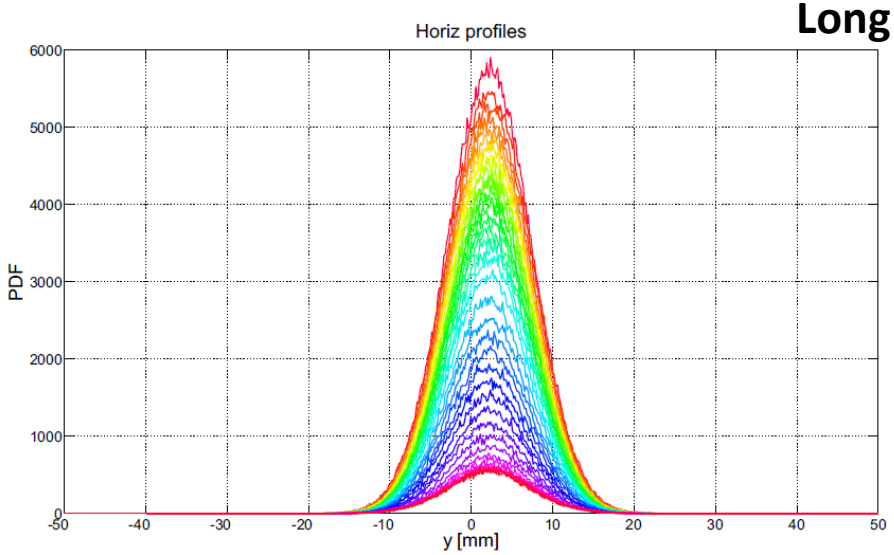


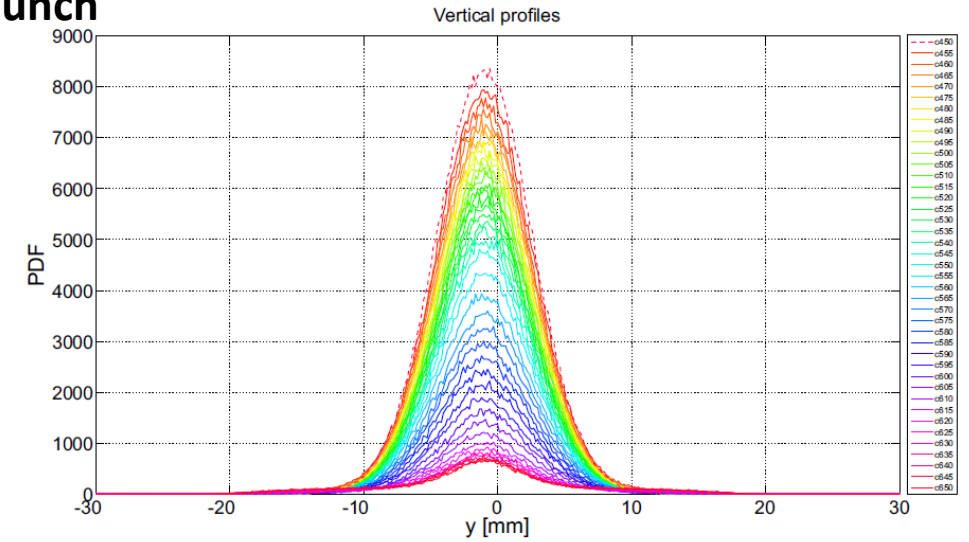
Simulations

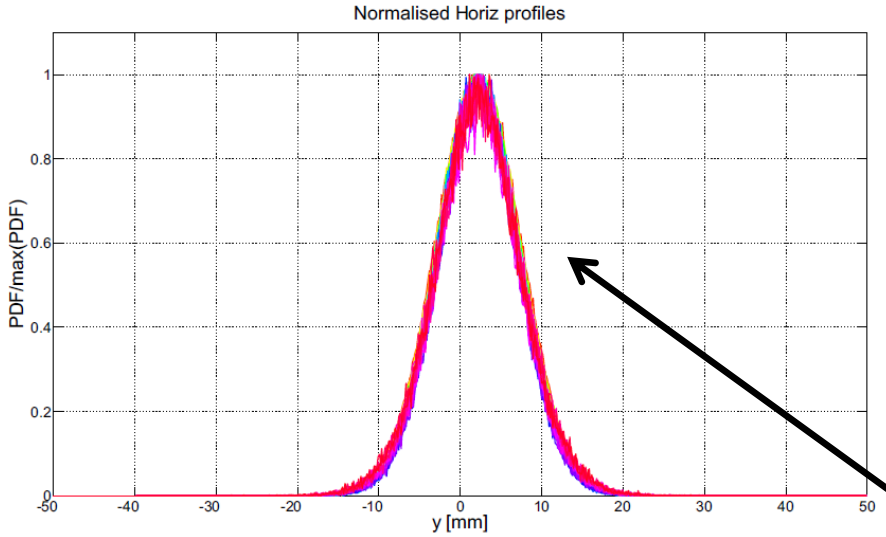
Short bunches lose more slowly and with different losses profiles.
At C600, the short bunch decreases the losses (w.r.t. the long one) by a factor ~1.8.

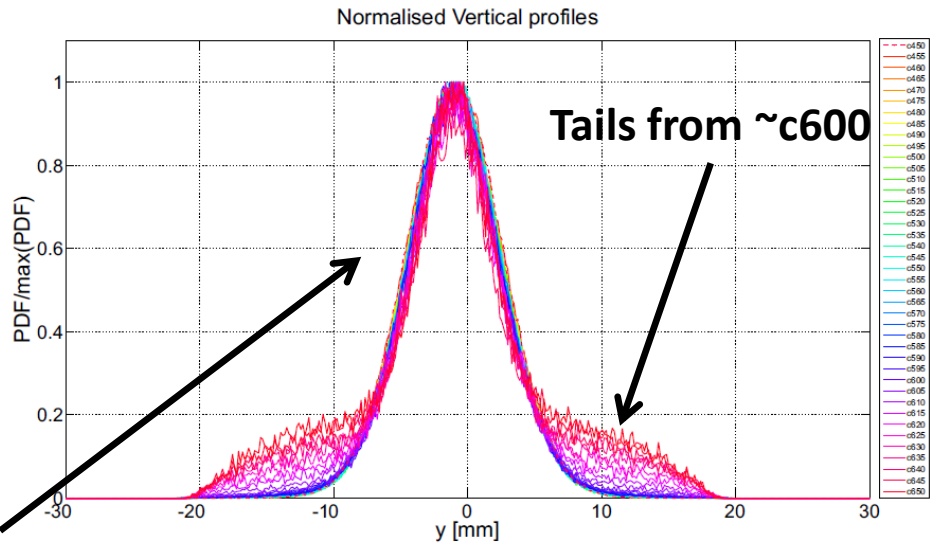
Simulations (with quad fields and misalign. errors): 200 ms transverse evolution

Long bunch

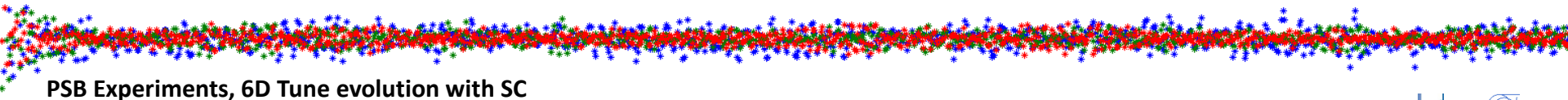






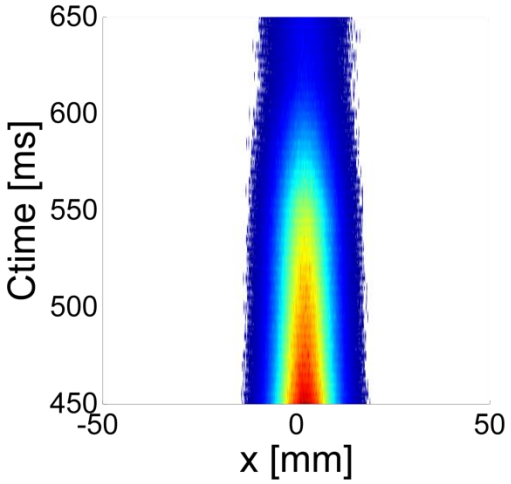


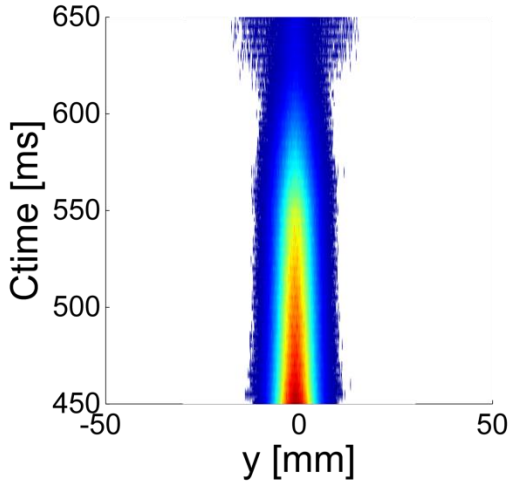
The beam size (1σ gaussian interpolation) is preserved along the cycle, as in the measurements

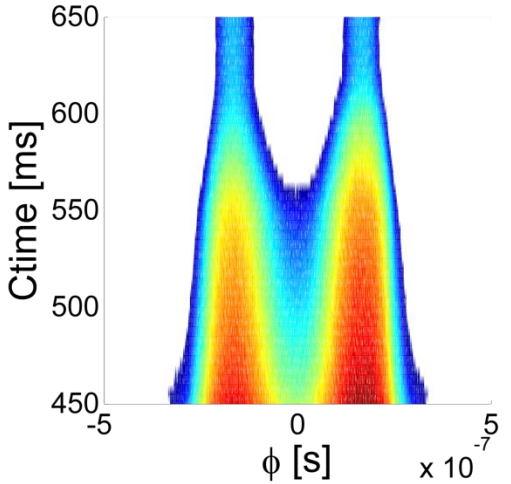


Simulations (with quad fields and misalign. errors): 200 ms waterfall evolution

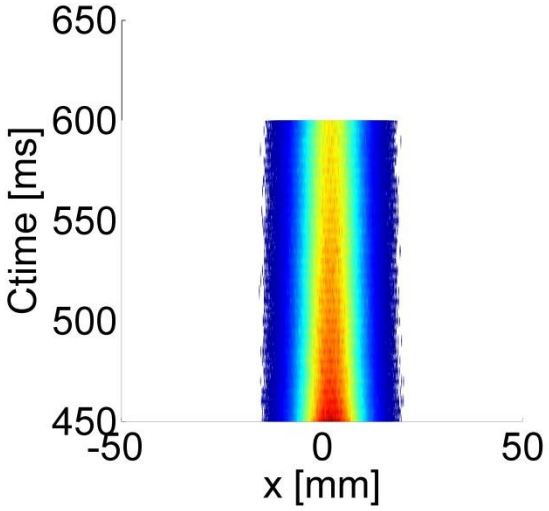
Long bunch

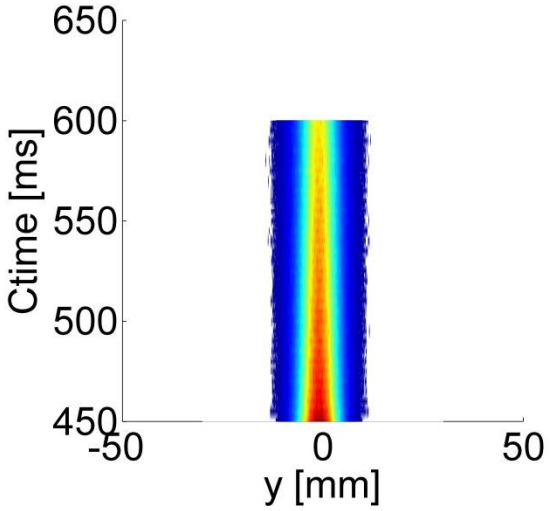


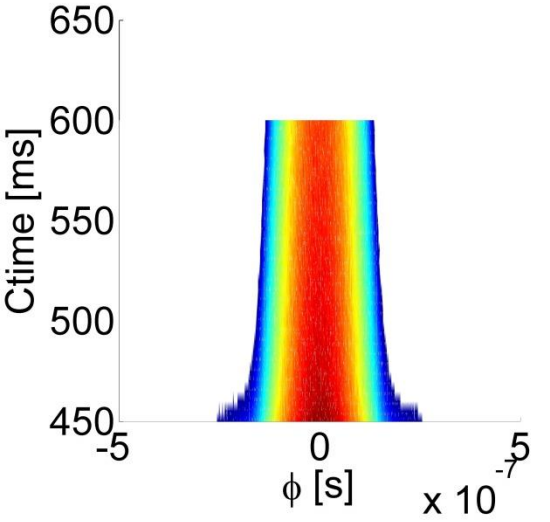


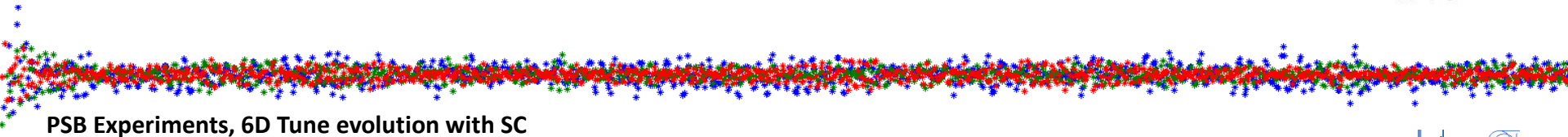


Short bunch

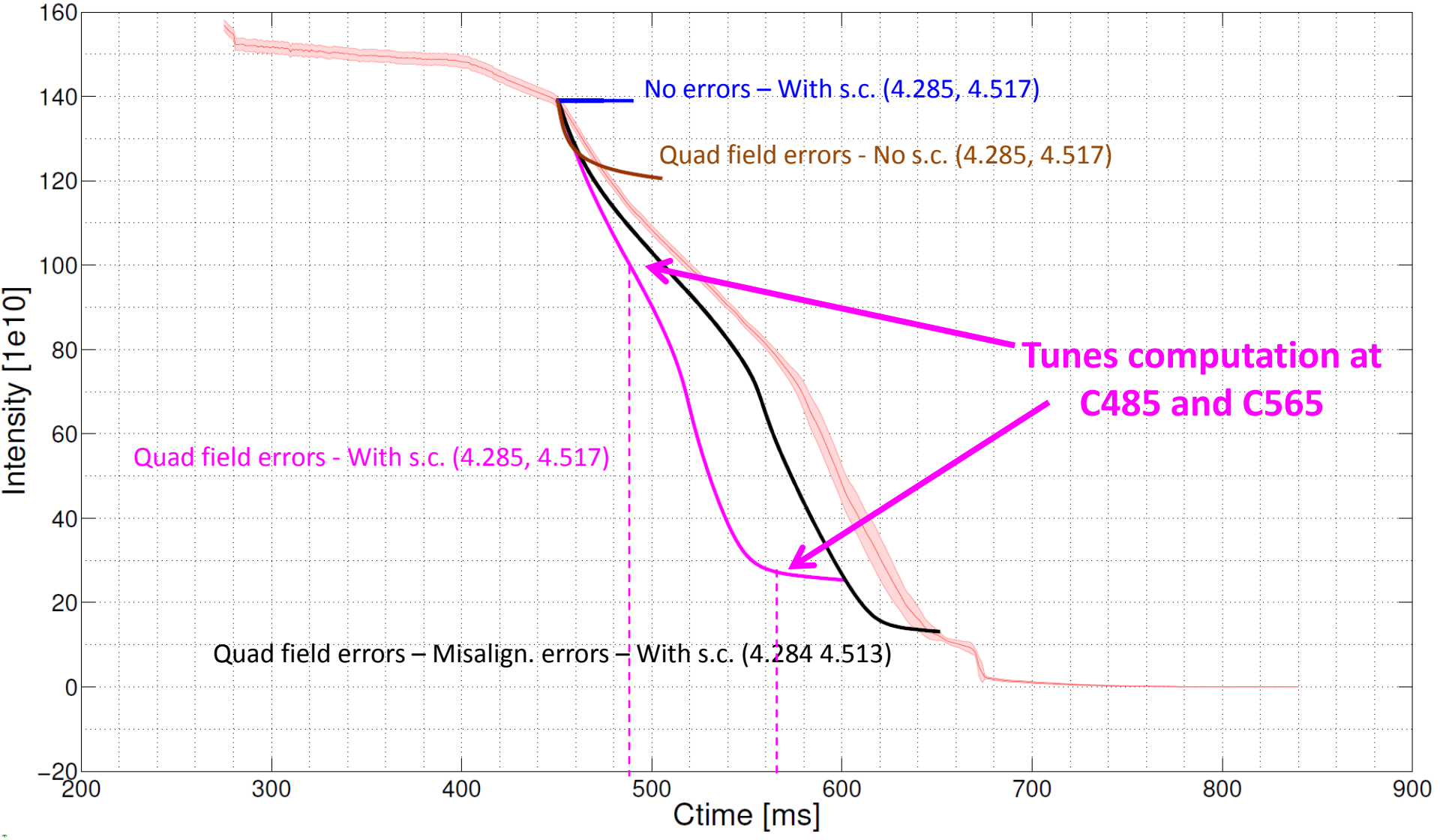


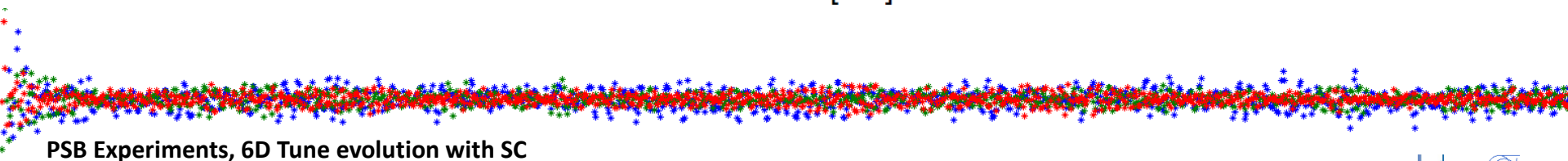






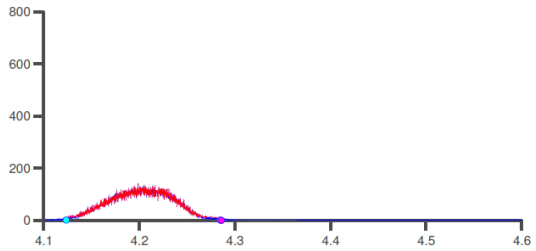
Simulations: tunes behavior for long bunch





Tunes Simulations (with quad field errors): after ~35ms and ~115ms

C485 on the magenta curve



Turn #:35000

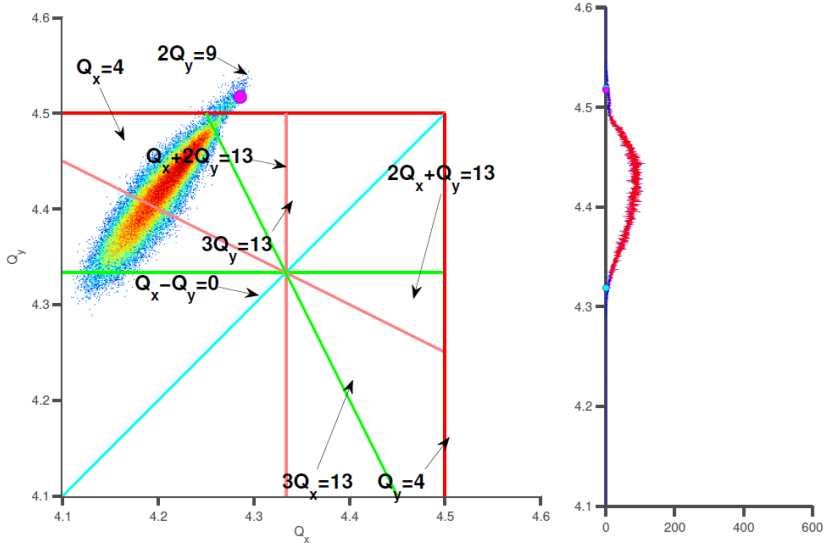
ΔQ_x:–0.1622 (–0.1613)

ΔQ_y:–0.1982 (–0.2001)

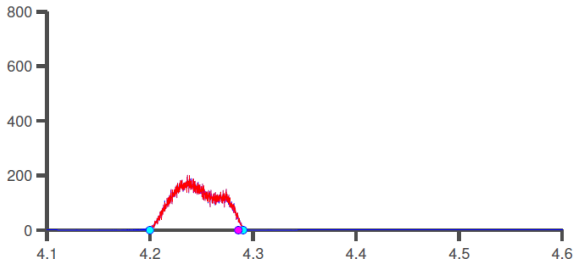
Lower threshold: 0.01% of # mp.

% mp excluded (Q_x): 2.236% of total mp.s

% mp excluded (Q_y): 3.394% of total mp.s



C565 on the magenta curve



Turn #:115000

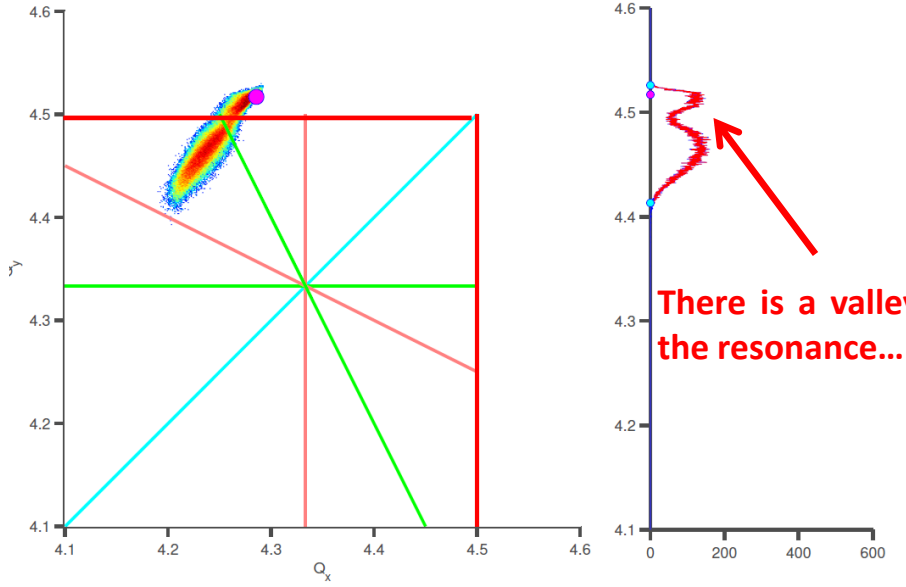
ΔQ_x:–0.086 (–0.0906)

ΔQ_y:–0.1038 (–0.1128)

Lower threshold: 0.01% of # mp.

% mp excluded (Q_x): 0.49171% of total mp.s

% mp excluded (Q_y): 0.71662% of total mp.s

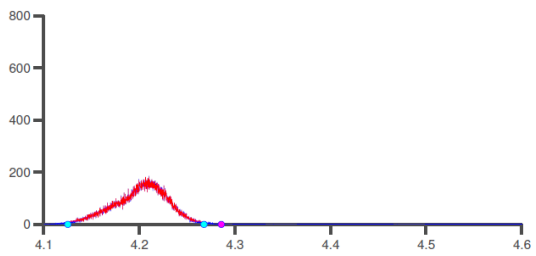


There is a valley on the resonance…

Tunes computation (phase advance per turn)

Tunes Simulations (with quad fields): after ~35ms and ~115ms

C485 on the magenta curve



Turn #:35000

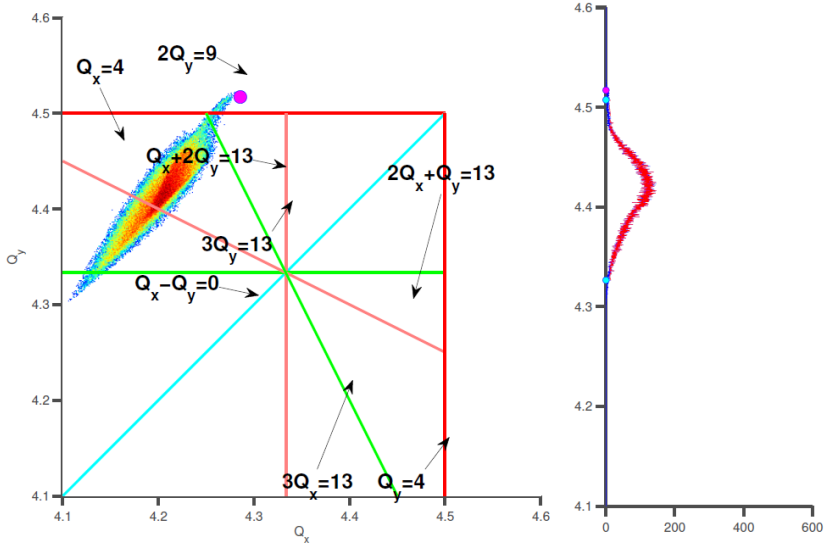
ΔQ_x:–0.1605 (–0.1425)

ΔQ_y:–0.1905 (–0.1808)

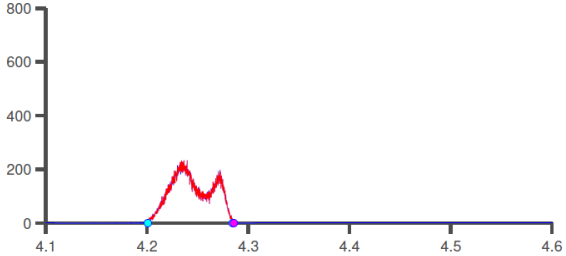
Lower threshold: 0.01% of # mp.

% mp excluded (Q_x): 1.958% of total mp.s

% mp excluded (Q_y): 3.286% of total mp.s



C565 on the magenta curve



Turn #:115000

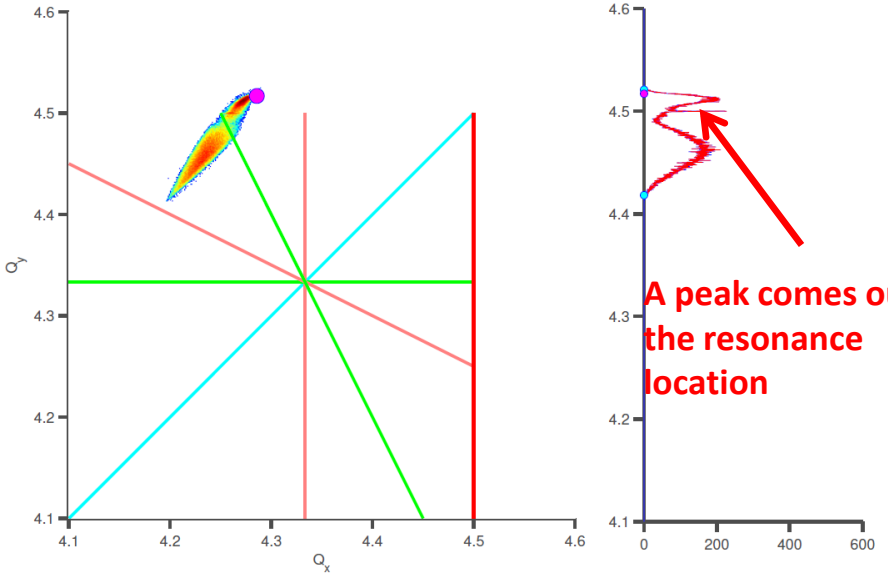
ΔQ_x:–0.085 (–0.0838)

ΔQ_y:–0.0989 (–0.1028)

Lower threshold: 0.01% of # mp.

% mp excluded (Q_x): 0.42731% of total mp.s

% mp excluded (Q_y): 0.45696% of total mp.s

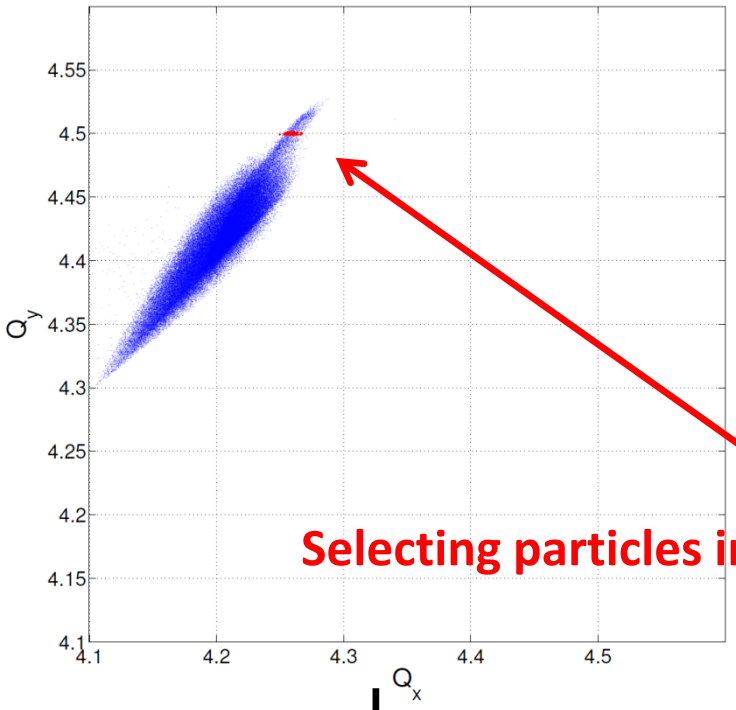


A peak comes out at the resonance location

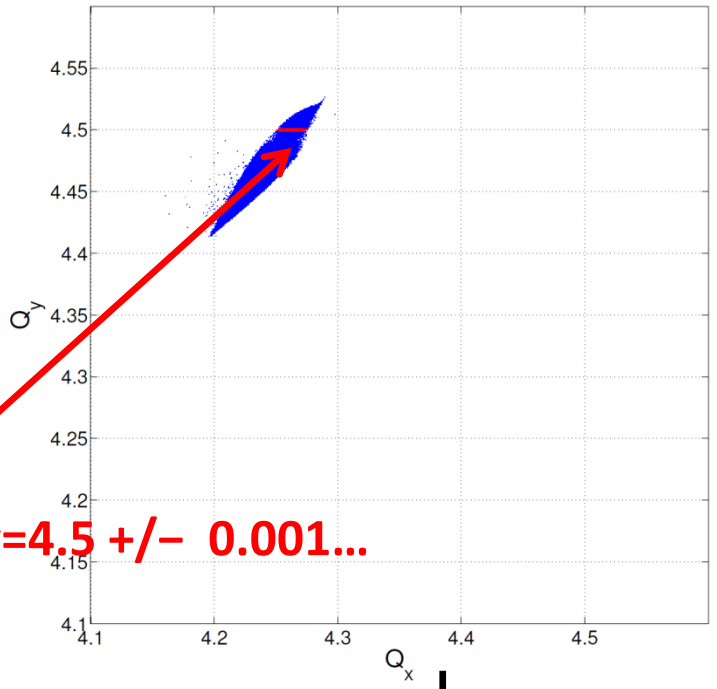
Tunes (avg. over 1500 turns)

Tunes Simulations (with quad field errors)

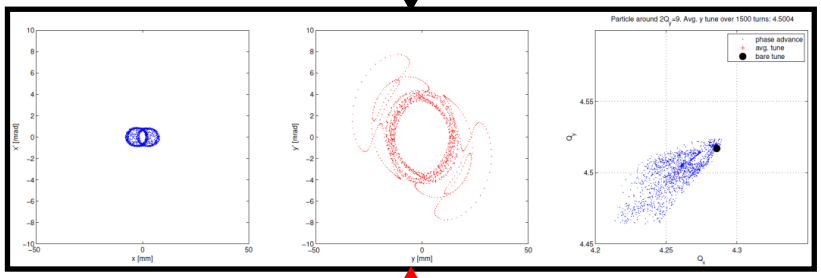
C485 on the magenta curve

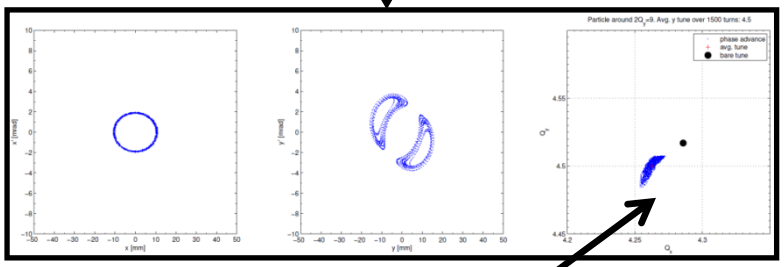


C565 on the magenta curve



Selecting particles inside Qy=4.5 +/− 0.001…



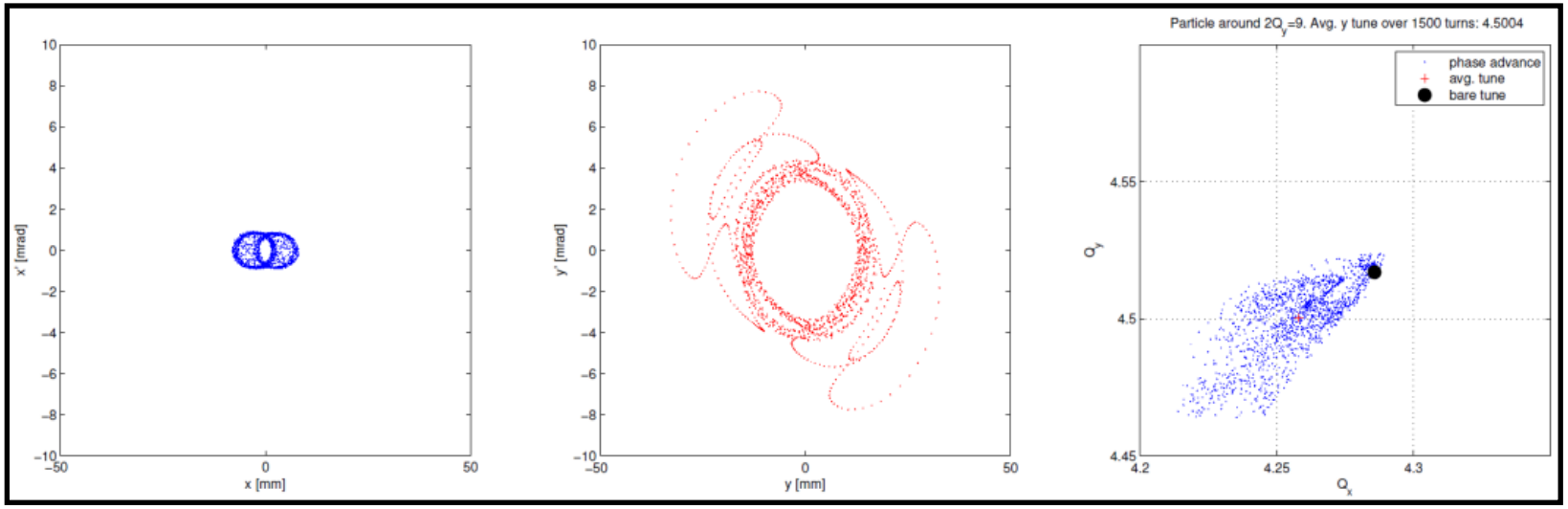


Red because it gets lost

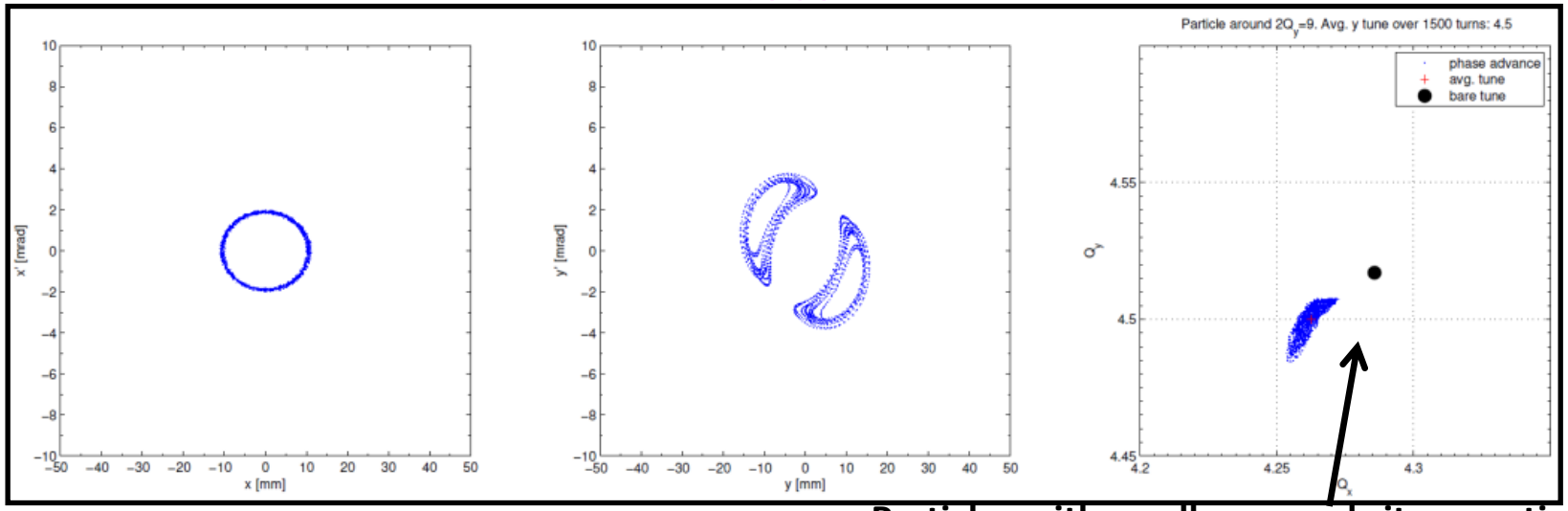
Particles with smaller spread sit on vertical transverse islands!

Particles which interact with the resonance…

C485



C565

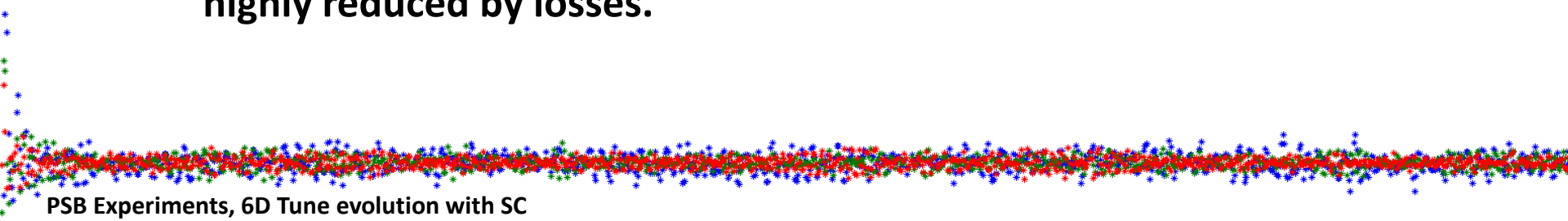


Particles with smaller spread sit on vertical transverse islands!

Summary and conclusions

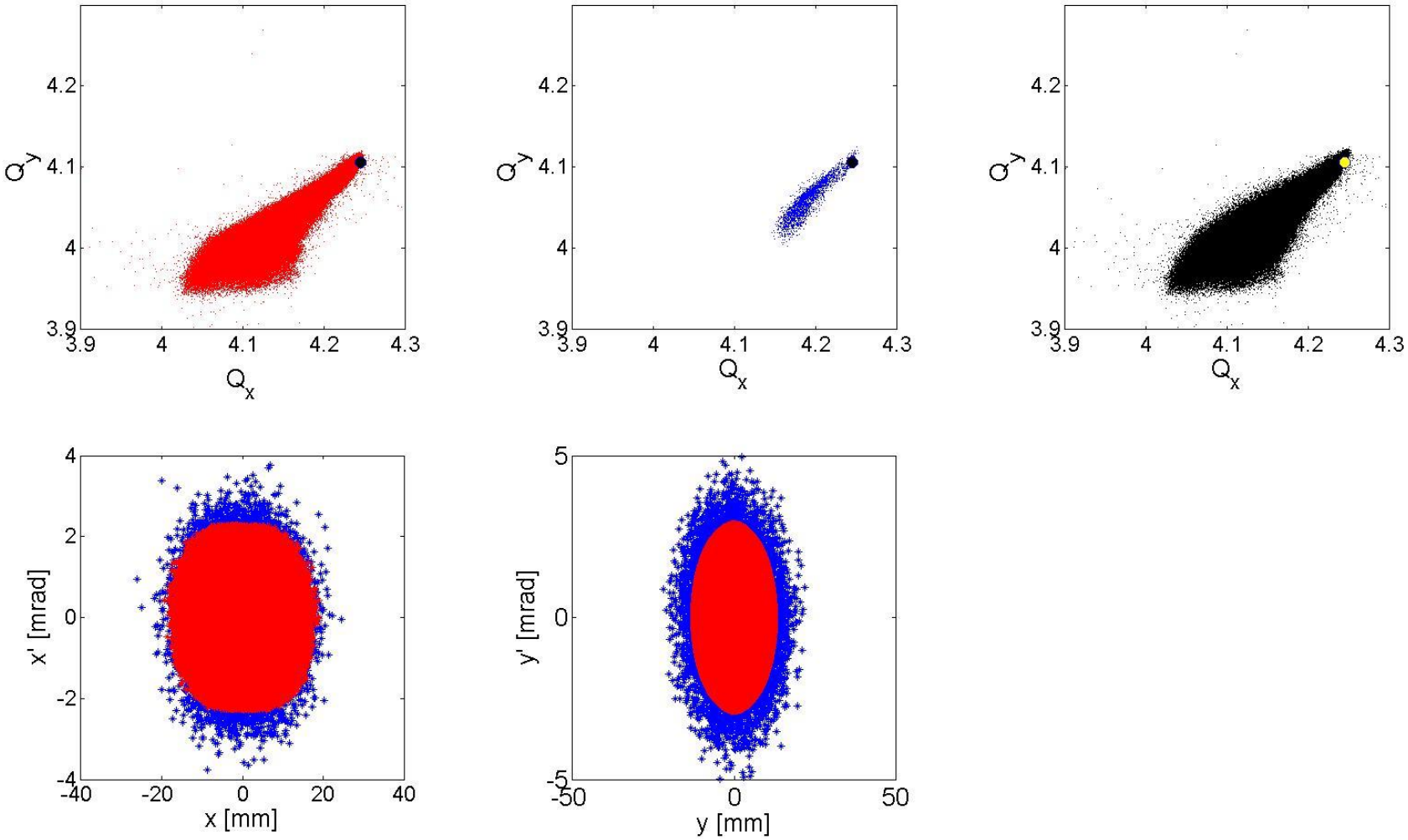
- **Tunes evolution in a space charge dominated beam.**
  - **Different positions in 6D phase space cause different location in the necktie.**
  - **The modulation due to the bunched motion is relevant for particles performing large synchrotron oscillations.**
  - **The single turn tunes computation differs from the averaged one.**

- **Measurements-simulations benchmark: the half-integer resonance (2Qy=9)**
  - **Very good agreement between measurements and simulations.**
  - **The quadrupolar fields and misalignment errors play an important role in the simulations.**
  - **Different longitudinal bunch shapes correspond to different losses profiles.**
  - **Tails (islands creation) arise from the simulations when the space charge is highly reduced by losses.**

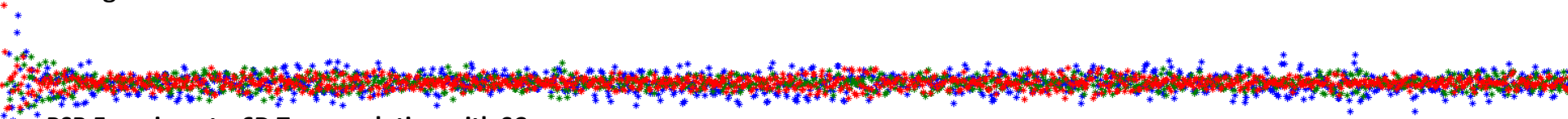


Appendix

The particles as an ensemble



Cutting the macroparticles in both planes, the blue (external) are the ones closer to the bare tune, having the large amplitude. The red ones (that are mainly in the core of the bunch) can circulate all around the necktie, spreading because the longitudinal effect.



Tunes evolution in a space charge dominated beam

$$\Delta Q_{x,y} = -\frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)[\sigma_x(s)+\sigma_y(s)]} ds$$

- The time-varying quantities (at constant energy and optics) are:
  - λ, as the longitudinal linear density (protons/m), that is modulated in time for bunched beams
  - σ, as the transverse beam sizes (mm);
- The term inside the integral is, in a certain way, the inverse of the beam emittances along the ring.

The direct space charge tune shift is directly proportional to λ, and inversely proportional to the emittances

- **PTC-Orbit** has been used for the analysis, from which is possible to extract the tunes necktie and the raw data useful for the post-processing analysis. The simulations here presented refer to the **CERN PS Booster, Ring 2.**

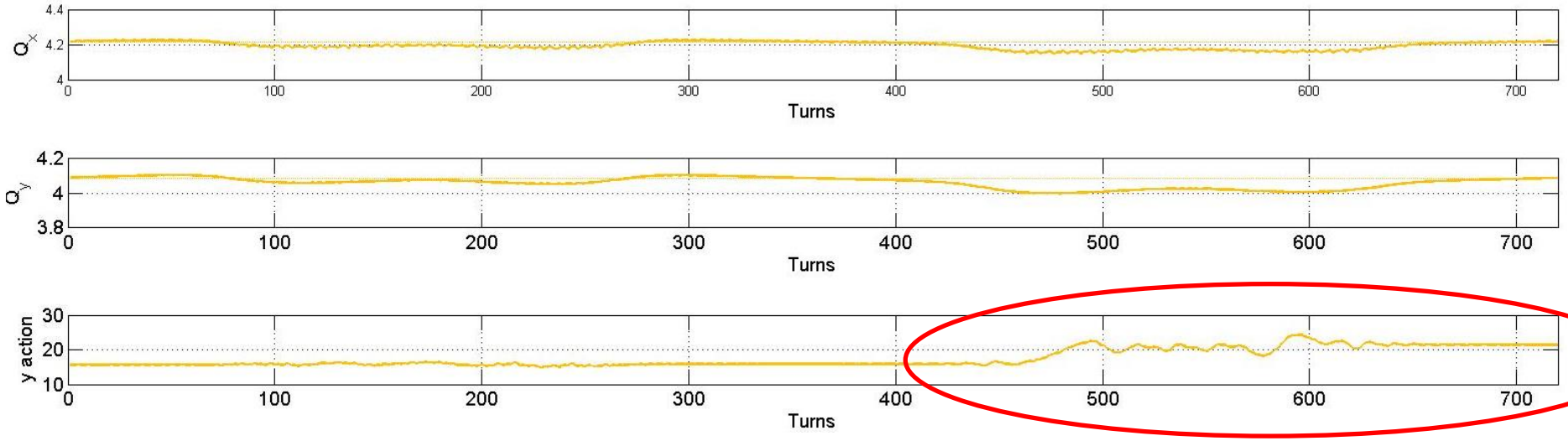
- **Chromatic effects** are a **not negligible** additive component to the space charge tune shift. This must be evaluated because affects the motion of a single particle inside a necktie.

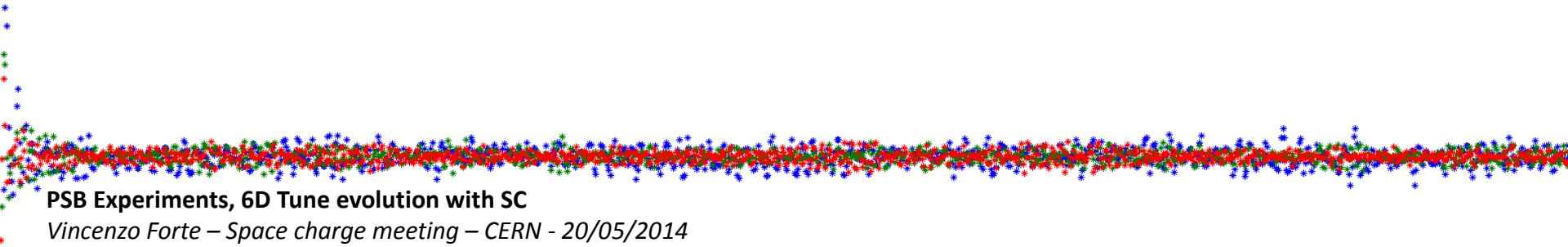
- The 4D formalism of the space charge can be seen as a constant linear density $\lambda(s)$ case.

Single macroparticles behaviors

- An increase in Jy (vertical action) has place when the particles approaches the integer resonance Qy=4.

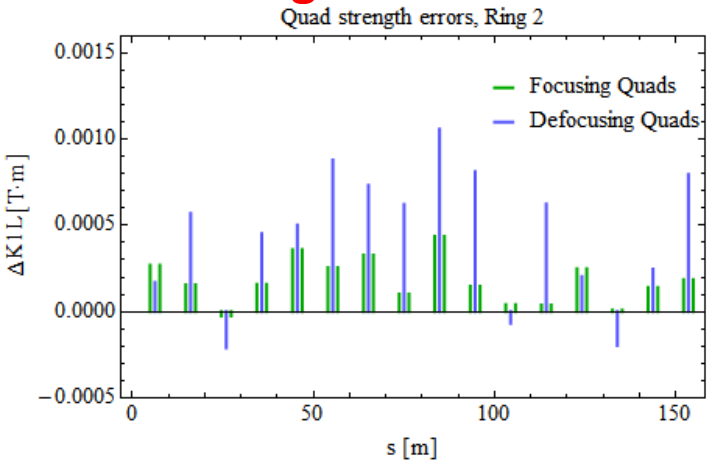
1 synch. period

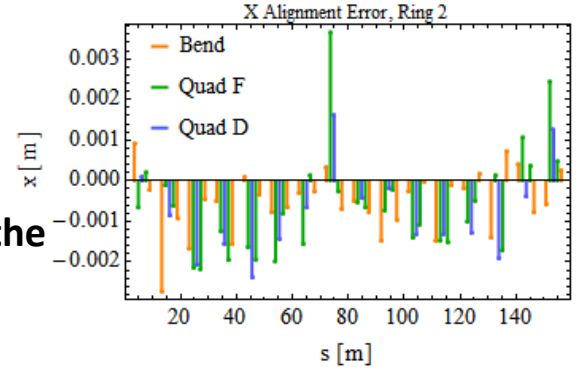


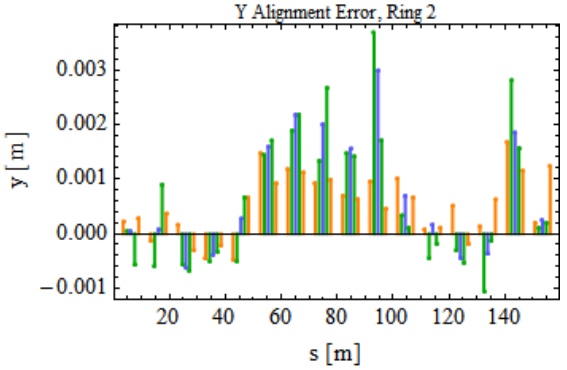


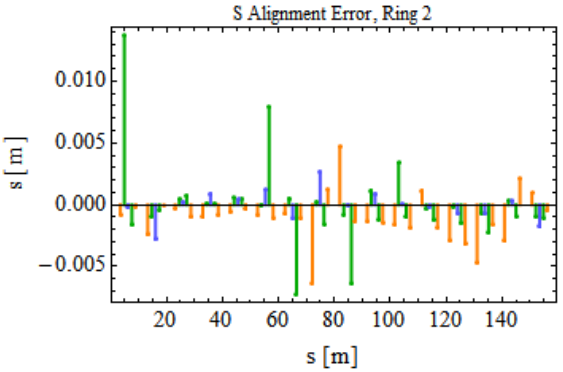
Measurements: quadrupolar field and misalignment errors

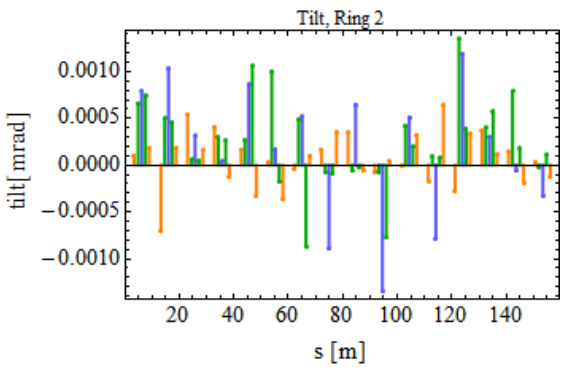
- **To drive the 2Qy=9 resonance a set of quadrupolar errors is necessary. Without these, it would be impossible to appreciate the effect of the resonance on the beam.**
- **The misalignment errors are also provided.**
- **A realistic errors model is used for the simulations.**





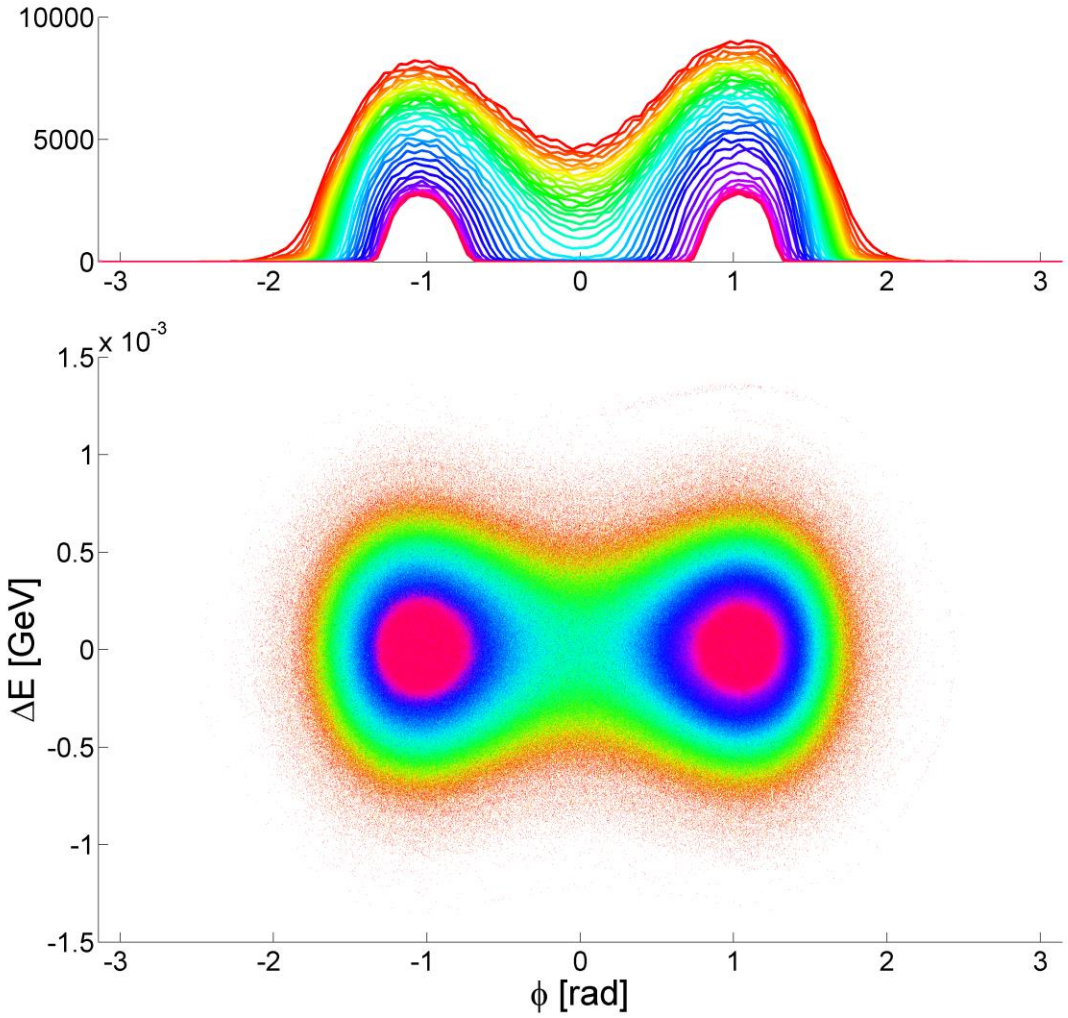




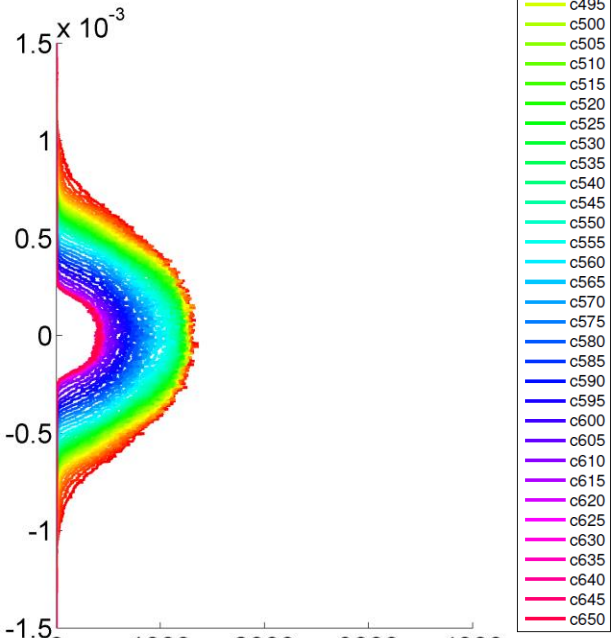


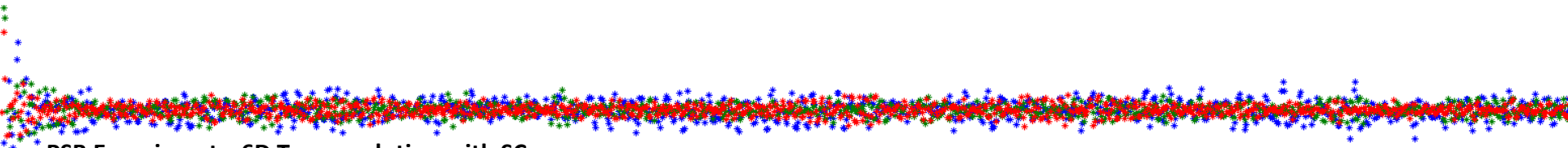
Courtesy M. McAteer

Simulations (with quad fields and misalign. Errors): 5-200 ms long. profiles



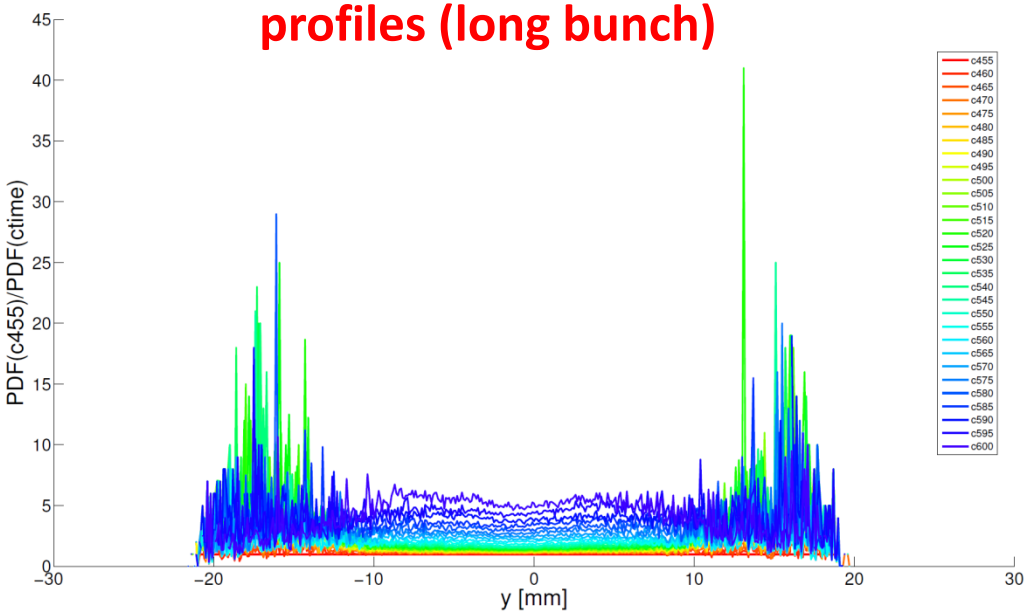
remained particles





Simulations (with quad fields and misalign. errors): 200 ms losses vs y position profiles (long bunch)

Initially the losses are mainly for bigger transverse vertical particles…



…then the spread reduces and also particles in the core start getting lost.