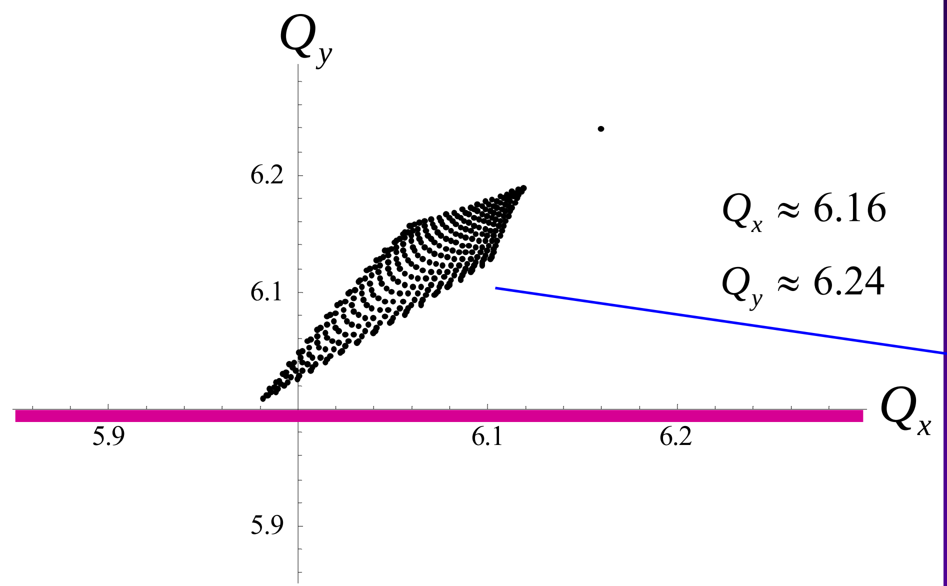
SPACE CHARGE EXPERIMENTS AND BENCHMARKING IN THE PS

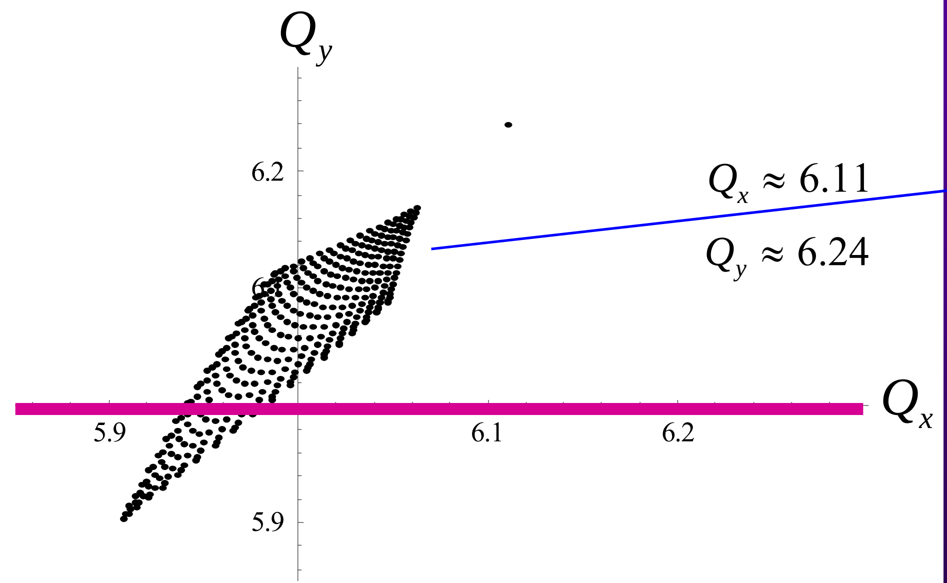
E. Métral

- Crossing the integer or half-integer resonance
- Montague resonance
  - Static & Dynamic
  - Benchmarking of the simulation codes
- Space charge driven resonance phenomena
- Transverse Landau damping with space charge
  ⟹ Comparison theory and PATRIC simulations
- Decoherence without and with space charge at PS injection
- Possible experiments in the PSB-PS to benchmark the space charge codes?
- Appendix: Some space charge codes characteristics (Oxford03)

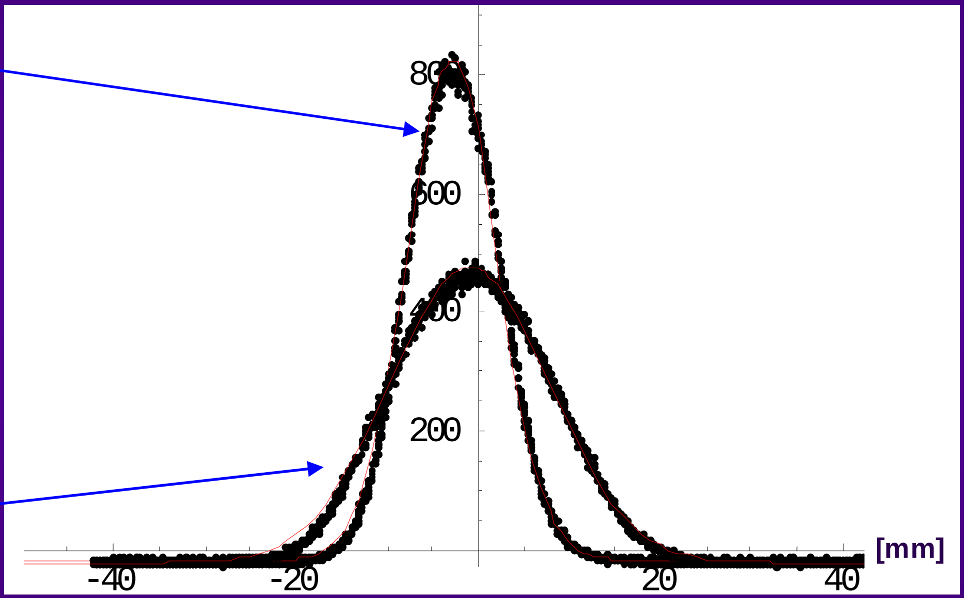
Crossing the integer or half-integer resonance (1/2)

M. Giovannozzi *et al.*, PAC2003



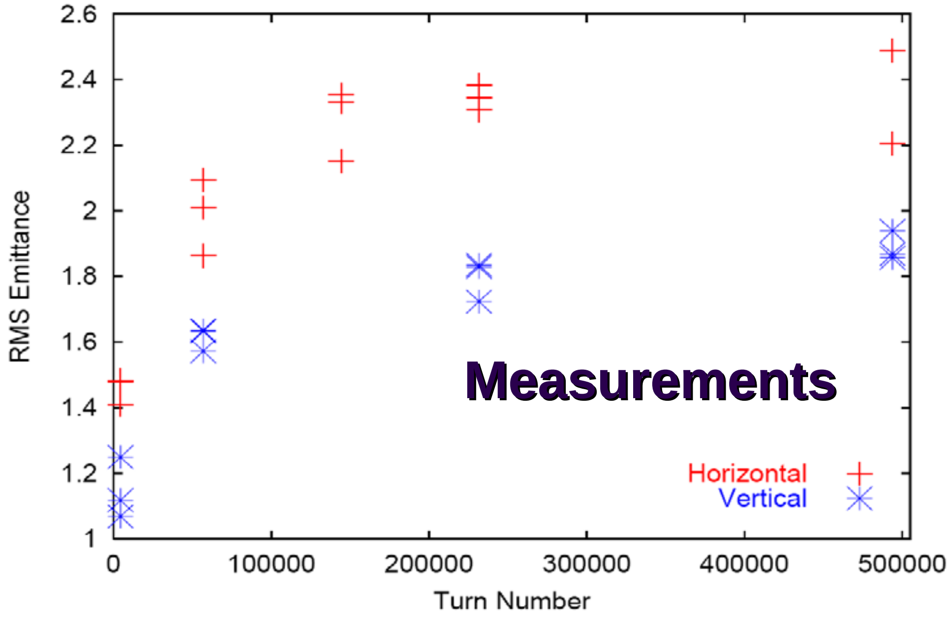


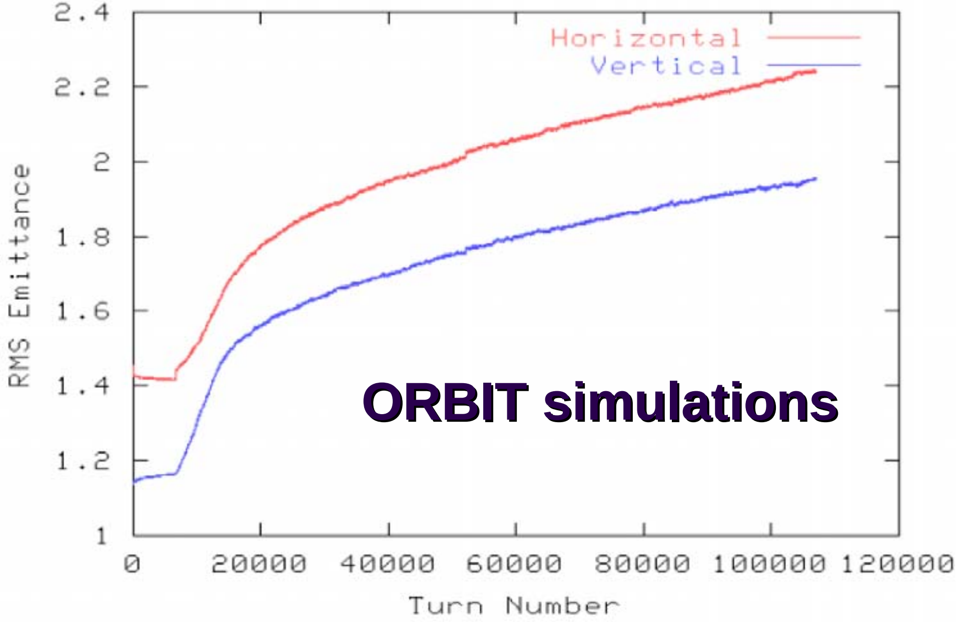
Horizontal bunch profile + Gaussian fit



Regime of loss-free core-emittance blow-up

Crossing the integer or half-integer resonance (2/2)





S. Cousineau *et al.*, EPAC2004

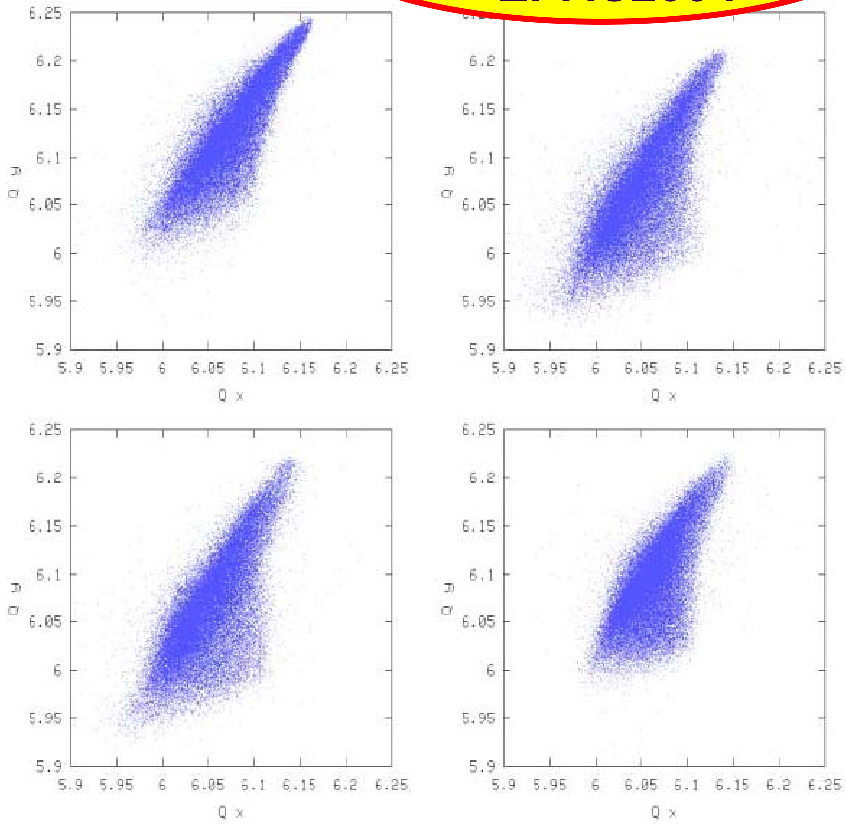


Figure 4: a) The tune footprint before the RF ramp-up and tune change. b) The tune footprint at the middle of the RF ramp-up. c) The tune footprint at the end of the RF ramp-up. d) The tune footprint 90,000 turns after the end of the RF ramp-up.

Montague resonance (1/8)

- Montague showed in 1968 that the space-charge potential could excite a 4th order coupling resonance

$$\boxed{2Q_x - 2Q_y = 0}$$

  - $\Longrightarrow$ Beating in amplitude between *x* and *y* for the single-particle motion, resulting in an apparent increase in emittance in the plane of smaller emittance $\Longrightarrow$ Growth in few (~ 1-5) turns for synchrotron at the space-charge limit
  - Montague said that this effect should be taken into account in the choice of parameters for future high-intensity synchrotrons
  - Baconnier knew in 1987 that “The Montague stop band was certainly one of the most effective in losing particles at injection in the CERN PS”

Montague resonance (2/8)

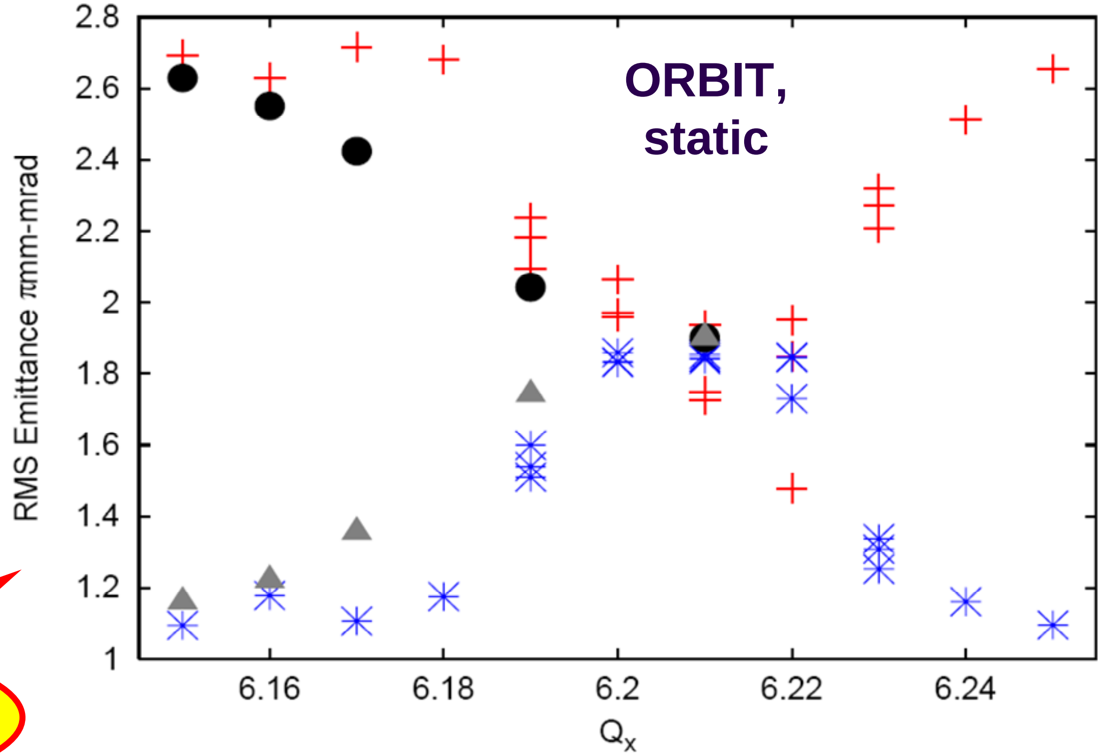
STATIC CASE in 2002

(constant tunes from injection to the measurement point)

$$Q_y = 6.21$$

$$\Delta Q_{inc,x0} = -0.06$$

$$\Delta Q_{inc,y0} = -0.107$$



ORBIT, static

S. Cousineau *et al.*, EPAC2004

Figure 5: The simulated rms horizontal (solid black circles) and vertical (solid gray triangles) emittances, along with the horizontal (red crosses) and vertical (blue stars) experimental data.

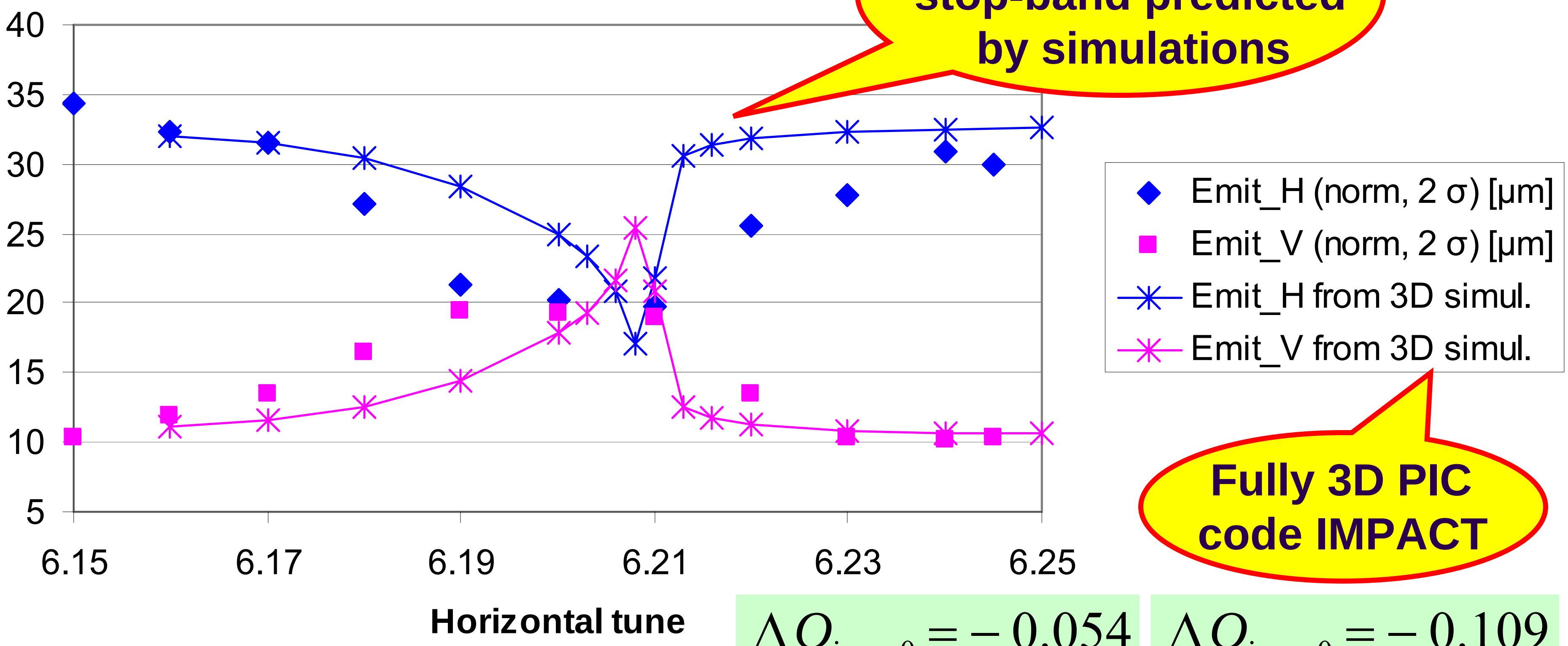
Montague resonance (3/8)

E. Métral *et al.*, HB2004, Bensheim

STATIC CASE in 2003
(constant tunes from injection to the measurement point)

$$Q_y = 6.21$$

Asymmetrical stop-band predicted by simulations



Fully 3D PIC code IMPACT

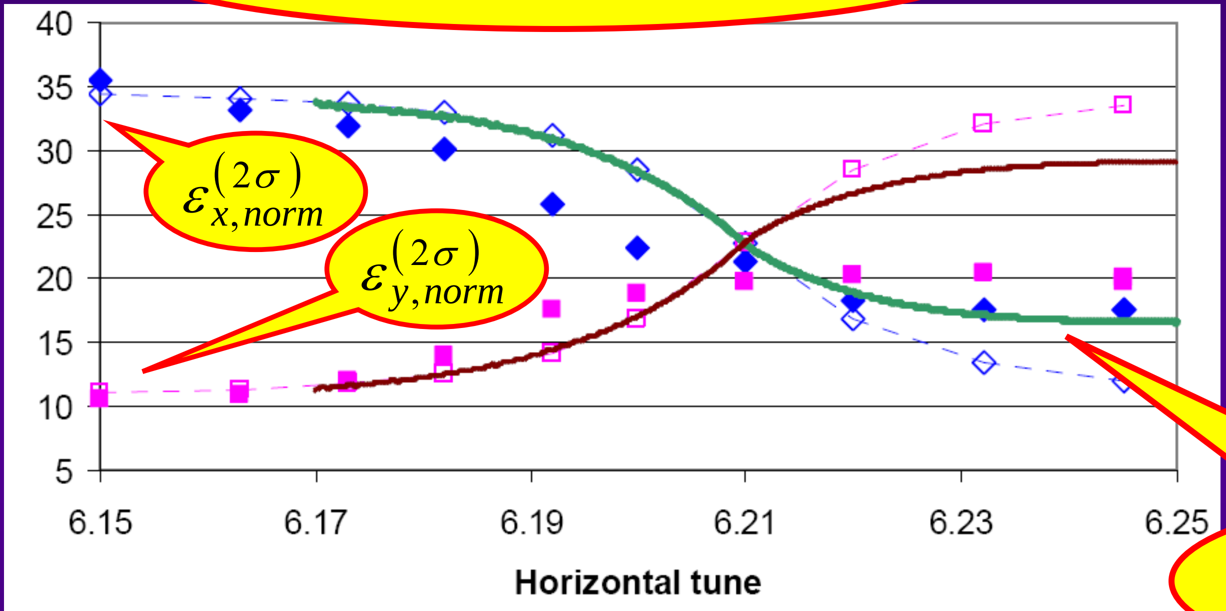
$$\Delta Q_{inc,x0} = -0.054 \quad \Delta Q_{inc,y0} = -0.109$$

Montague resonance (4/8)

DYNAMIC CASE in 2003

(the horizontal tune was changed linearly from 6.15 to 6.25 in 100 ms)

$T_{rev} = 2.3\ \mu\text{s} \Longrightarrow$ ~ 44 000 turns



Mixing due to longitudinal motion

FIGURE 5. Measurements (dots, see Fig. 2), 3D simulation results (IMPACT code) in the real measured case where the synchrotron period is not much larger than the crossing time (full line), and fit of the 3D simulation results in the case where the synchrotron period is much larger than the crossing time (dotted line).

Montague resonance (5/8)

I. Hofmann *et al.*, EPAC04

Simulations of the DYNAMIC CASE

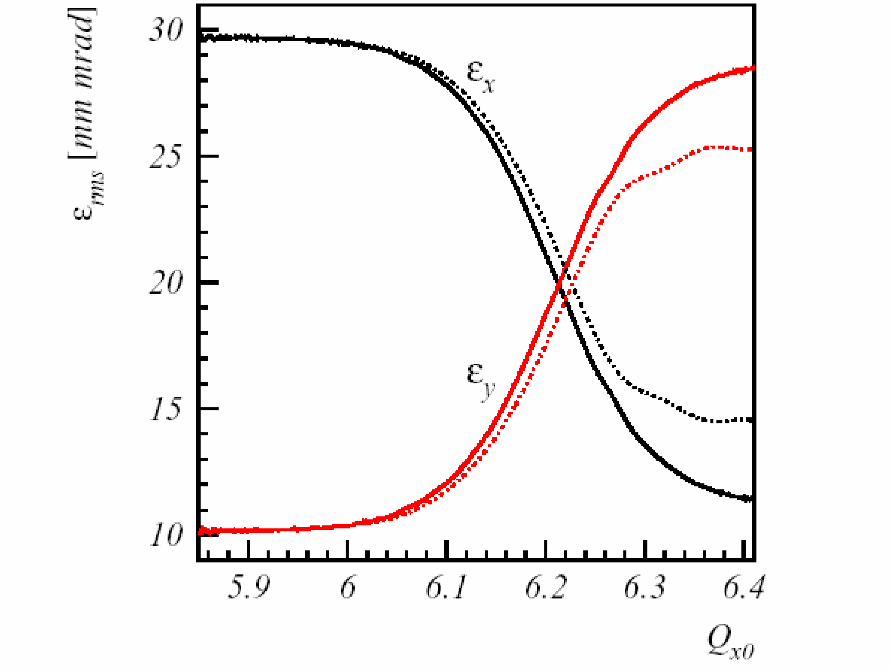


Figure 2: Rms emittance evolution in 2D for a tune ramp $Q_x = 5.85 \rightarrow 6.45$ over 30 and 100 turns.

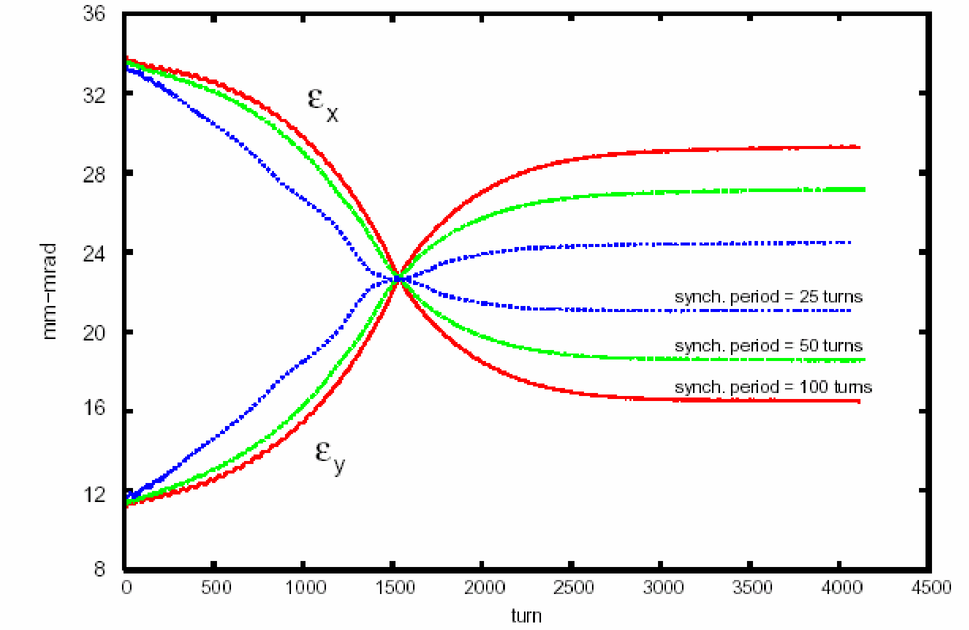


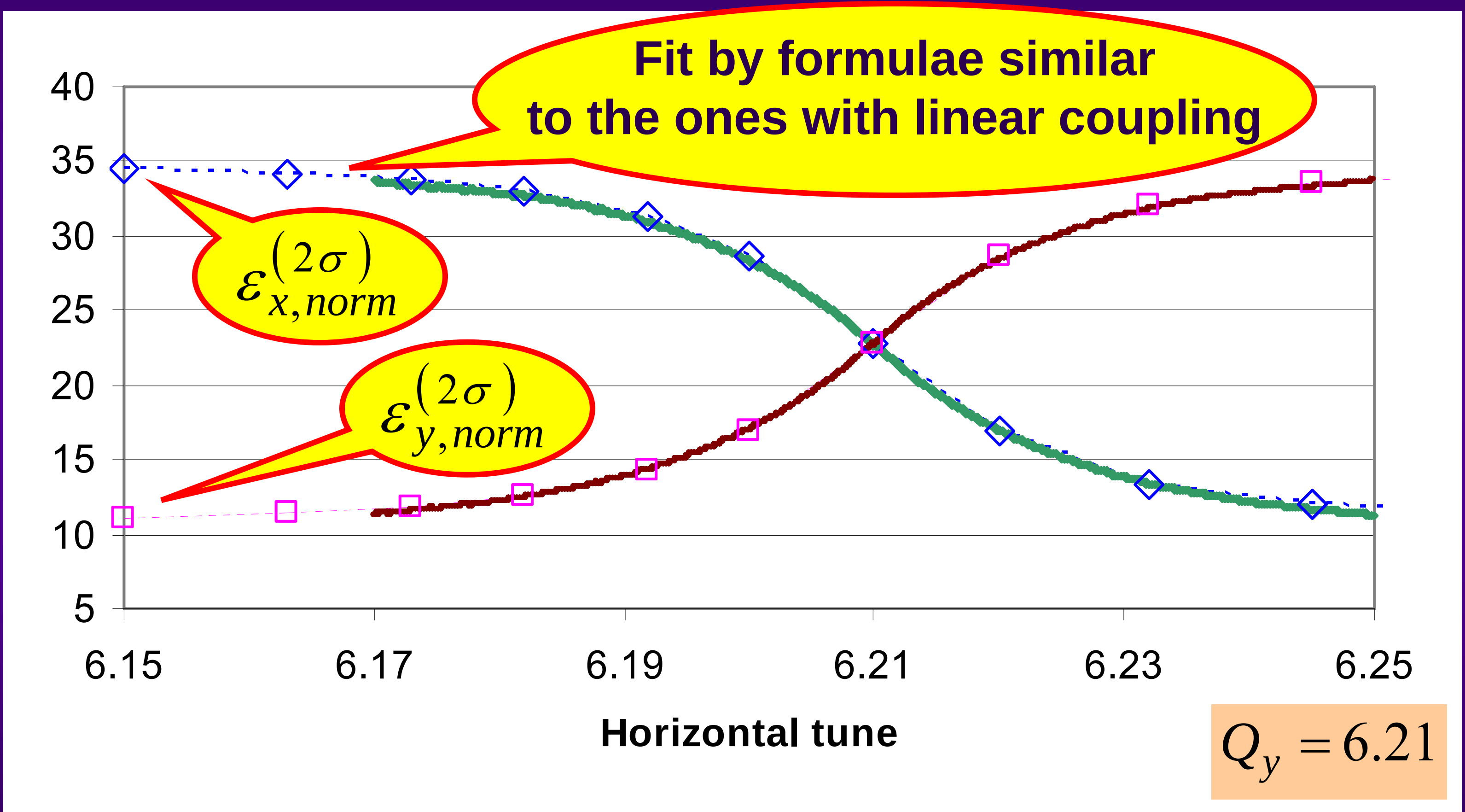
Figure 6: Rms emittances in 3D bunched beam for given tune ramp, but doubled and quadrupled synchrotron frequency.

$\Longrightarrow$ **The crossing speed has to be slow compared to the time scale during which the coupling occurs**

$\Longrightarrow$ **The crossing speed has to be fast compared to the synchrotron motion**

Montague resonance (6/8)

Simulations of the DYNAMIC CASE



Fit by formulae similar to the ones with linear coupling

$\varepsilon_{x,norm}^{(2\sigma)}$

$\varepsilon_{y,norm}^{(2\sigma)}$

$Q_y = 6.21$

3D simulation results (IMPACT code from R.D. Ryne) for the PS in the case where the synchrotron period is much larger than the crossing time

Montague resonance (7/8)

BENCHMARKING OF SIMULATION CODES BASED ON THE MONTAGUE RESONANCE IN THE CERN PROTON SYNCHROTRON

(I. Hofmann et al. PAC2005)

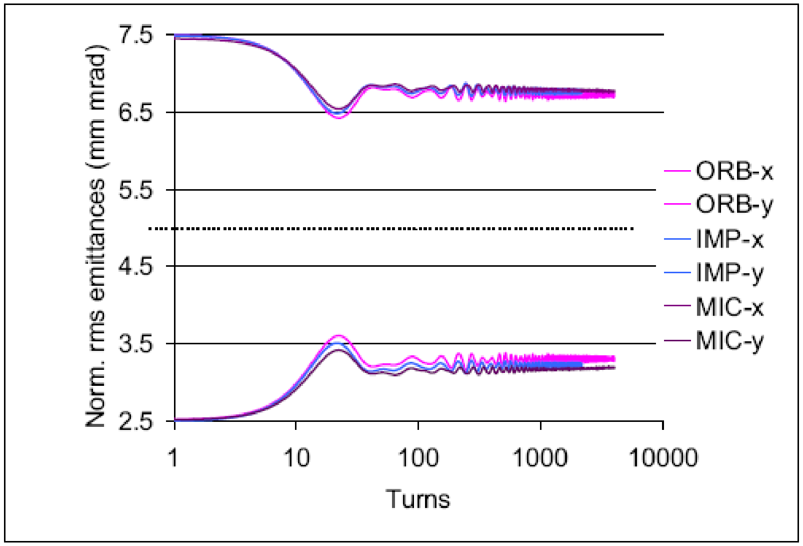


Figure 2: $\epsilon_{x,y}$ for constant focusing lattice, $Q_{0,x} = 6.19$.

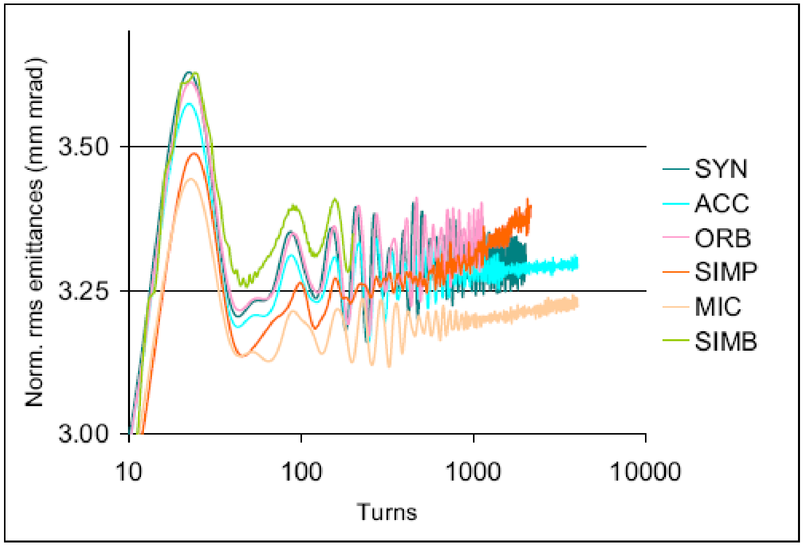


Figure 3: ϵ_y for linearized AG lattice, $Q_{0,x} = 6.19$.

Montague resonance (8/8)

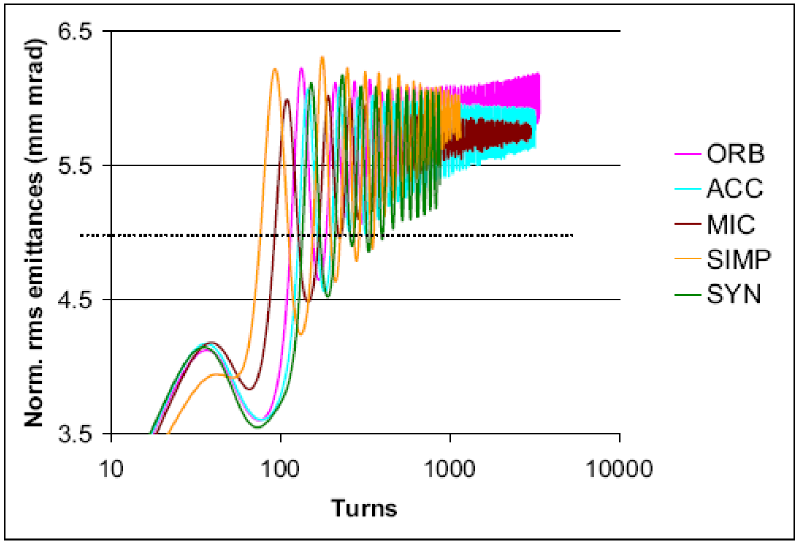


Figure 4: ϵ_y for linearized AG lattice, $Q_{0,x} = 6.207$.

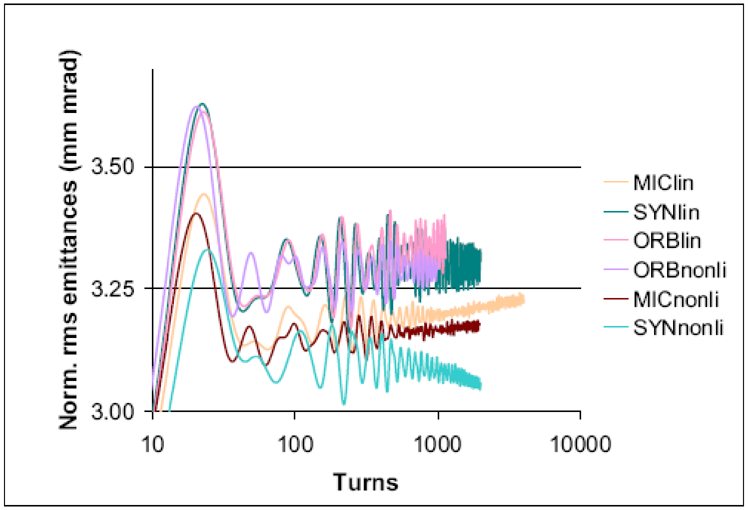
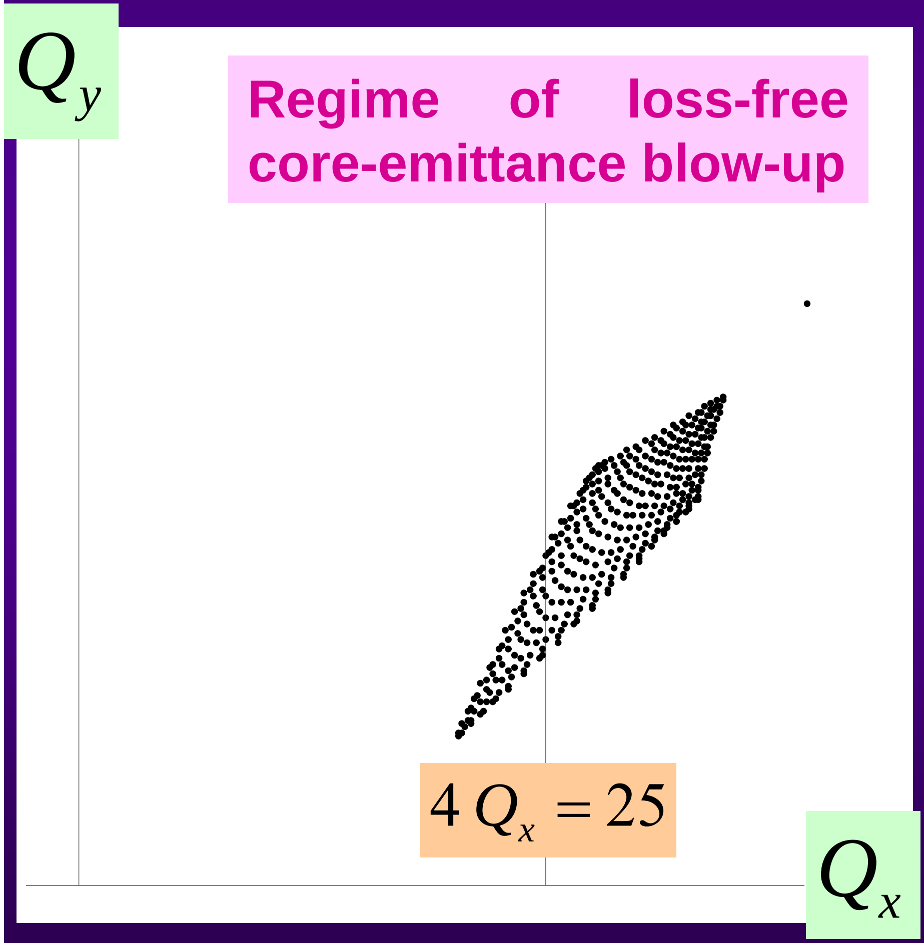
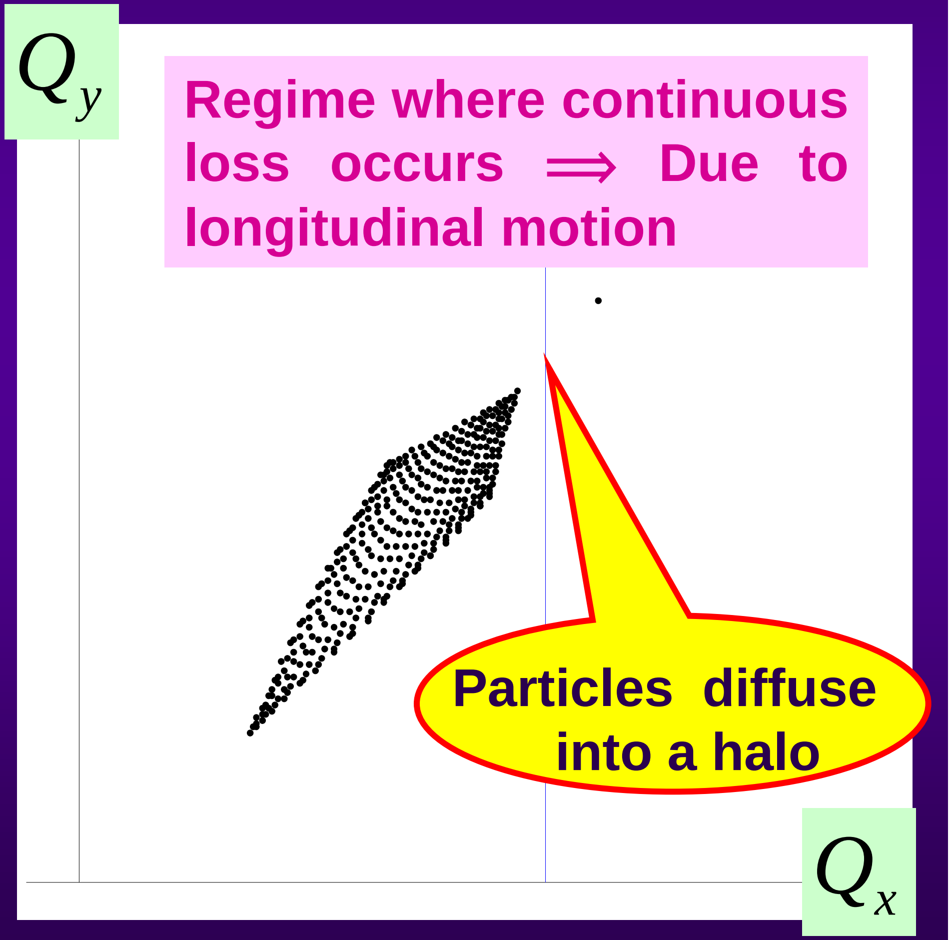


Figure 5: ϵ_y for fully nonlinear lattice, $Q_{0,x} = 6.19$ (compared with linearized AG).

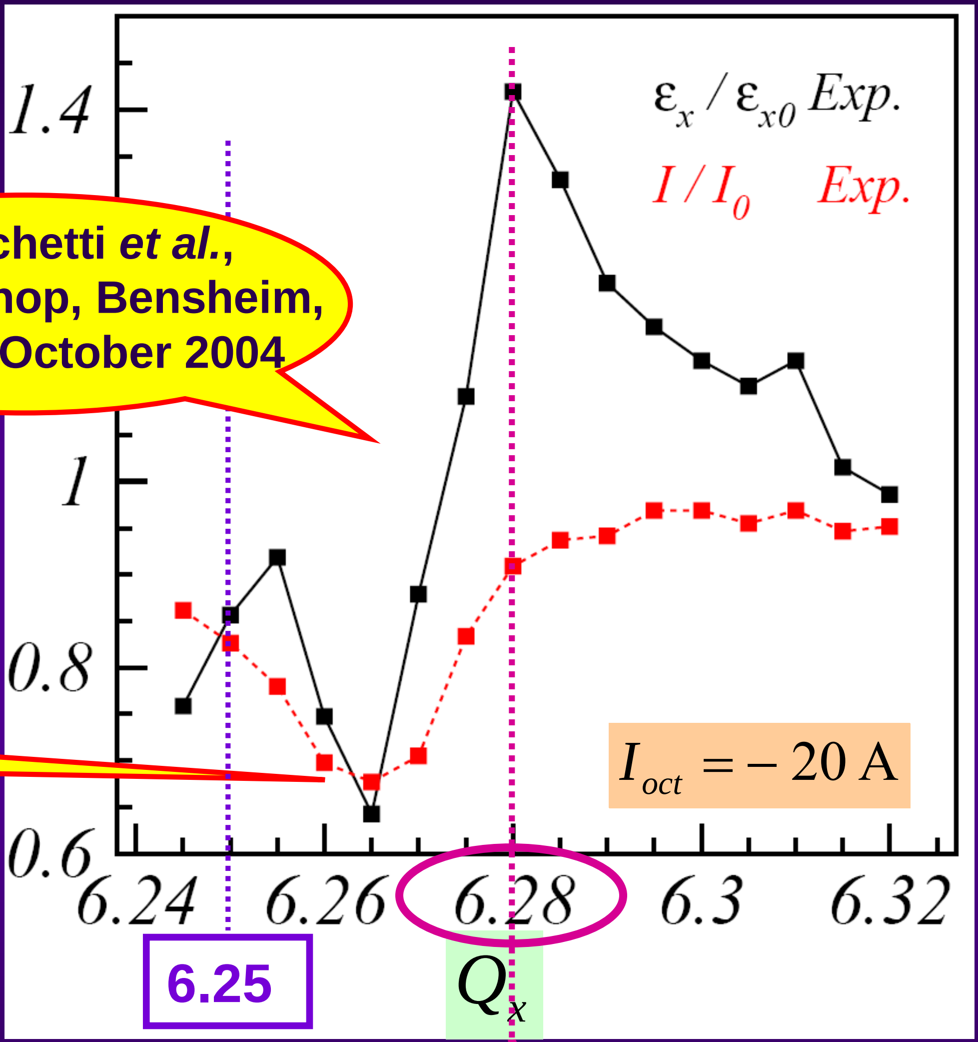
Space charge driven resonance phenomena (1/6)

- **Mechanism anticipated by G. Franchetti & I. Hofmann, which involves**
  - Space charge tune spread
  - Nonlinear (octupole) resonance
  - Synchrotron motion





Space charge driven resonance phenomena (2/6)



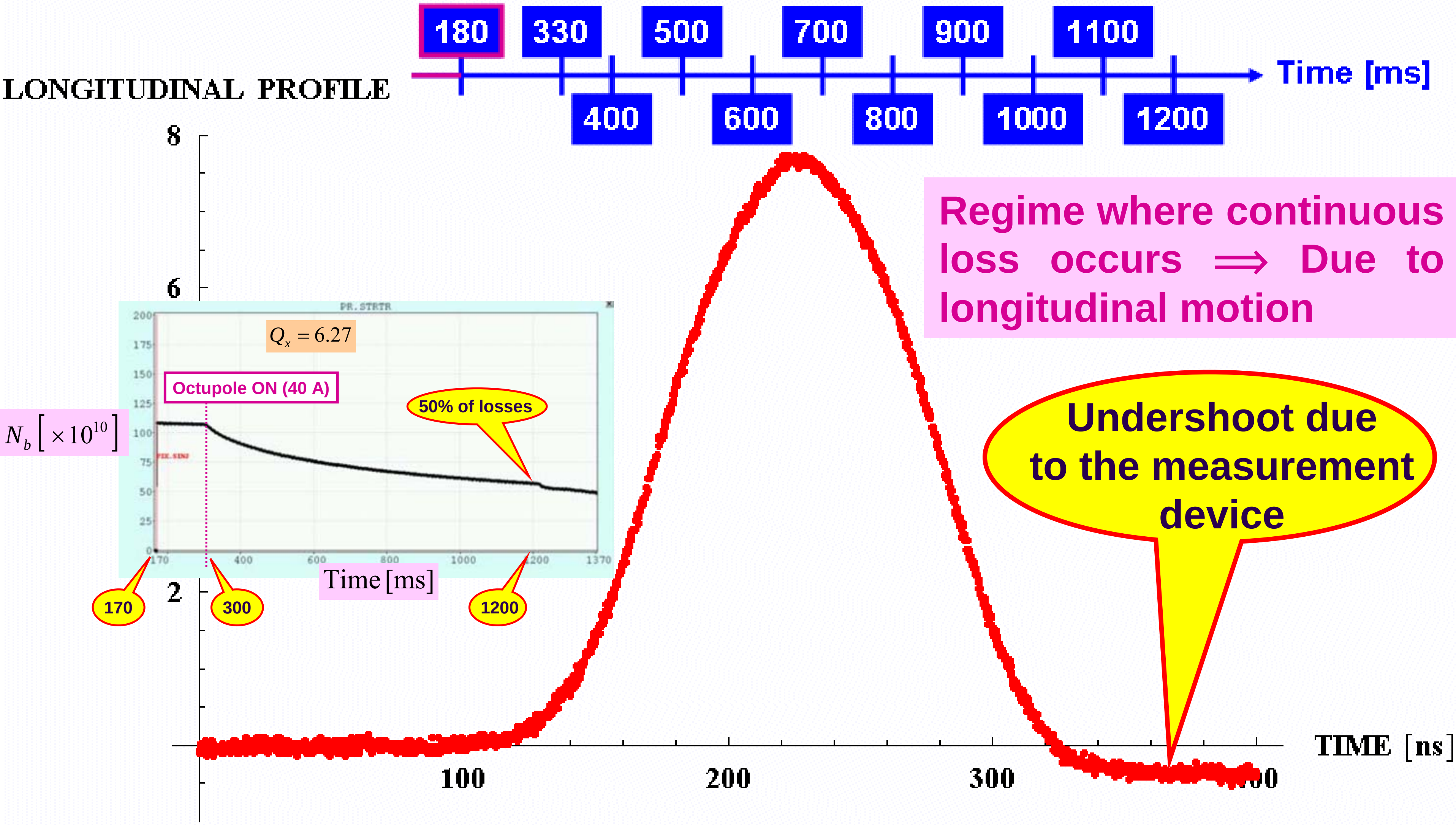
G. Franchetti *et al.*, ICFA workshop, Bensheim, Germany, October 2004

6.265

Loss dominated regime

Emittance growth dominated regime

Space charge driven resonance phenomena (3/6)



Regime where continuous loss occurs $\Longrightarrow$ Due to longitudinal motion

Undershoot due to the measurement device

Space charge driven resonance phenomena (4/6)

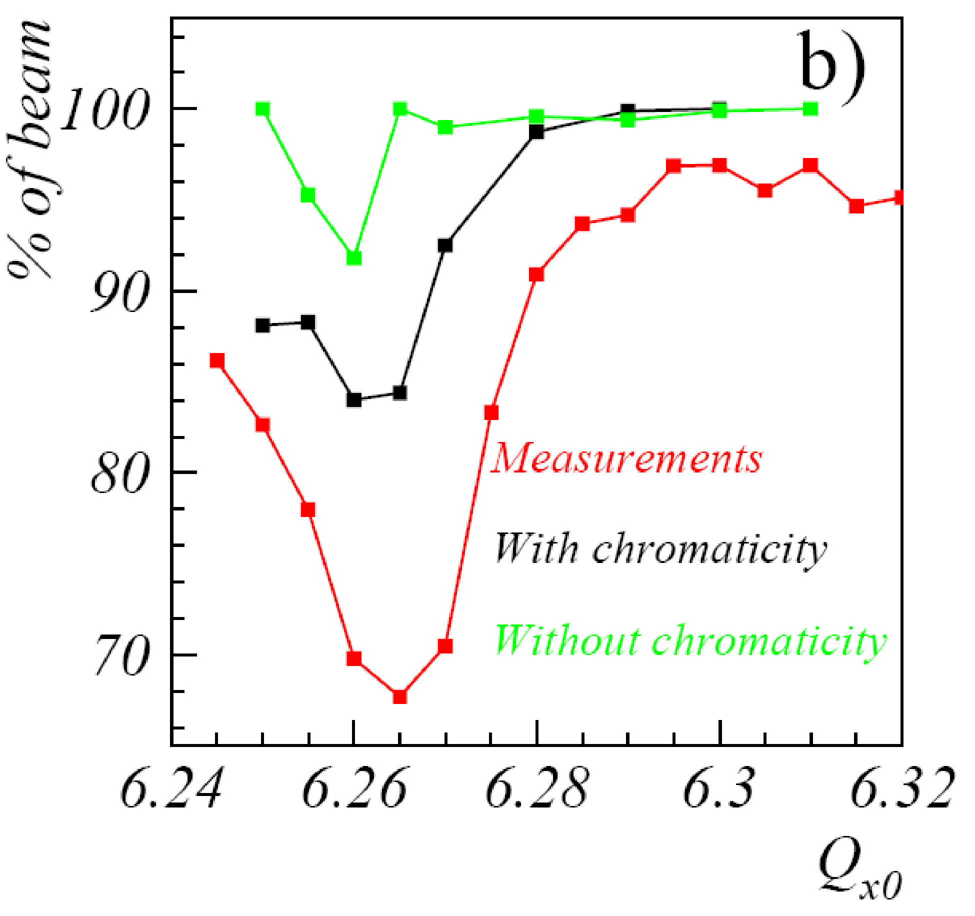
- By lowering the working point towards the resonance 4 Qx = 25, a gradual transition from a regime of loss-free core emittance blow-up to a regime dominated by continuous beam loss has been observed, as expected by Ingo&Giuliano

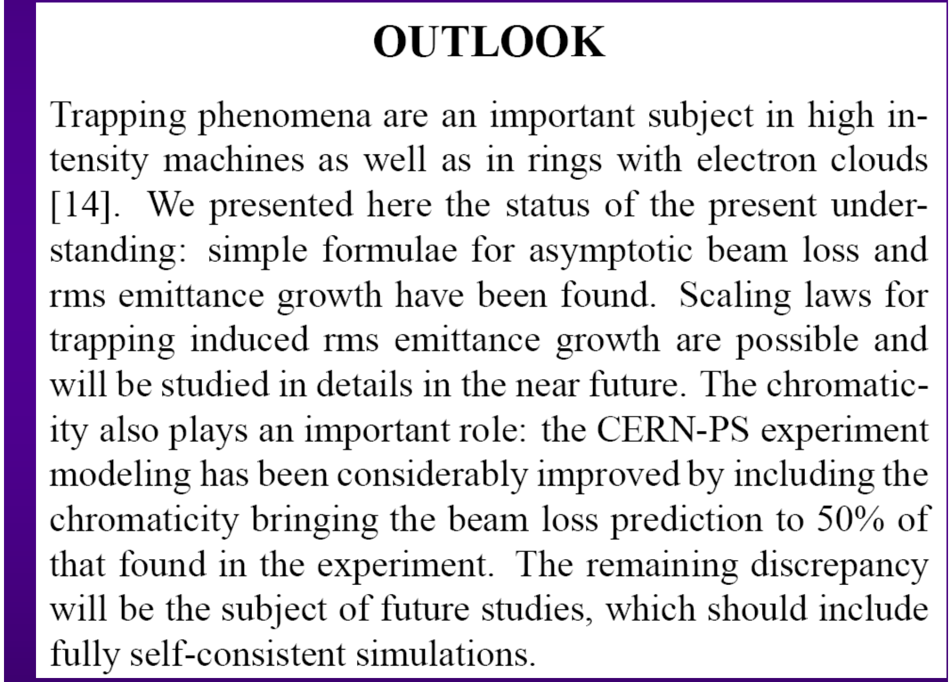
- Emittance growth in good agreement with predictions

- The observed maximum losses (~30%) are still larger than predicted (~8%) ⟸ At COULOMB05, Senigallia

Space charge driven resonance phenomena (5/6)

- **Latest results presented by Giuliano&Ingo (HB2006, Japan)**



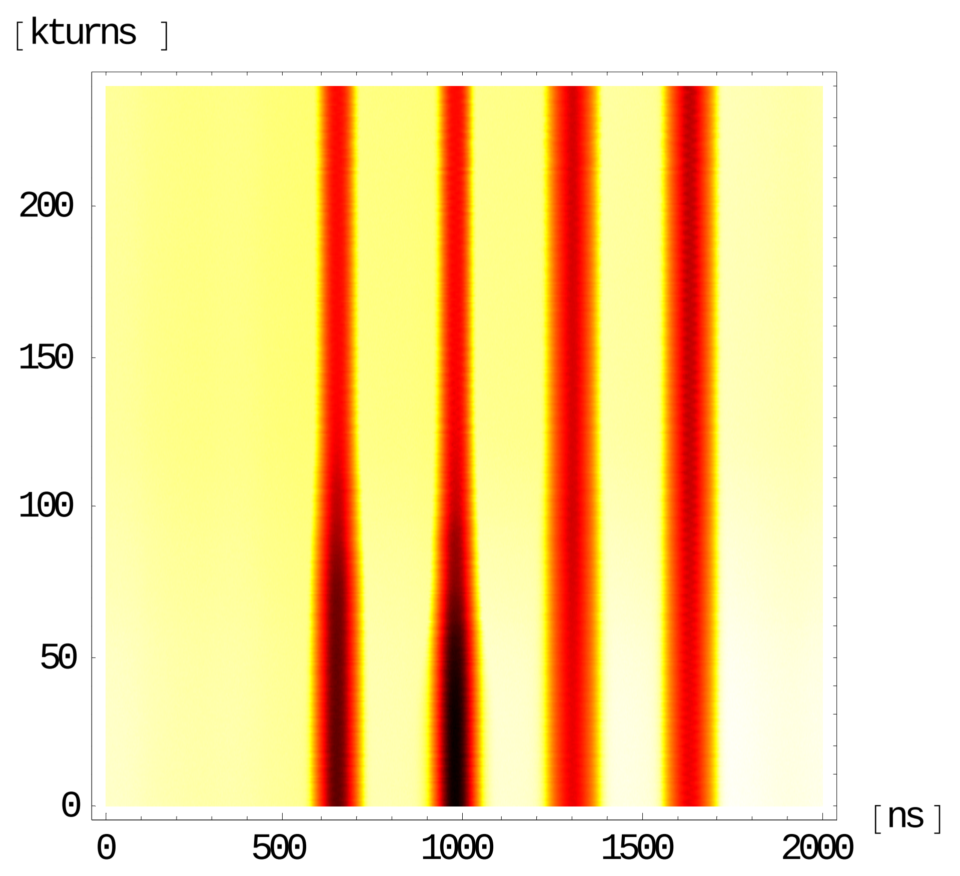


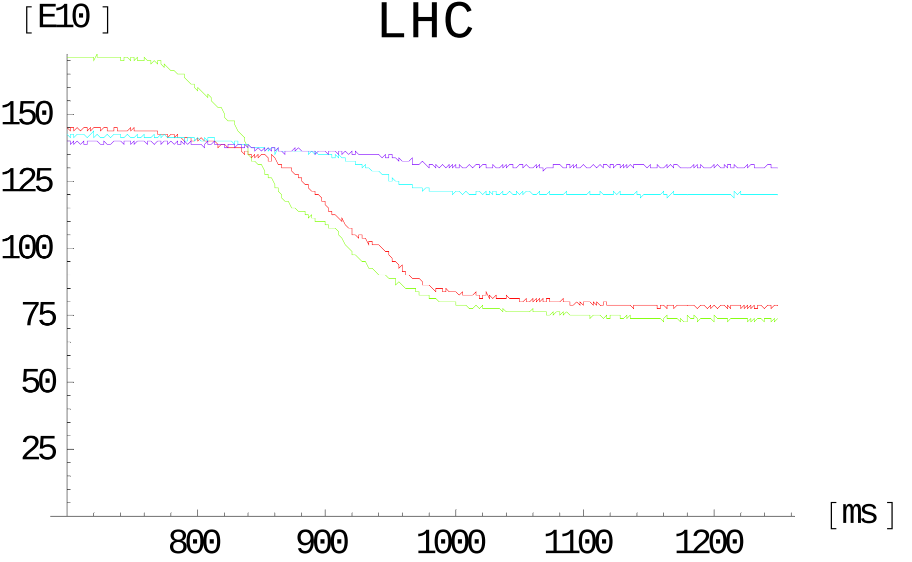
OUTLOOK

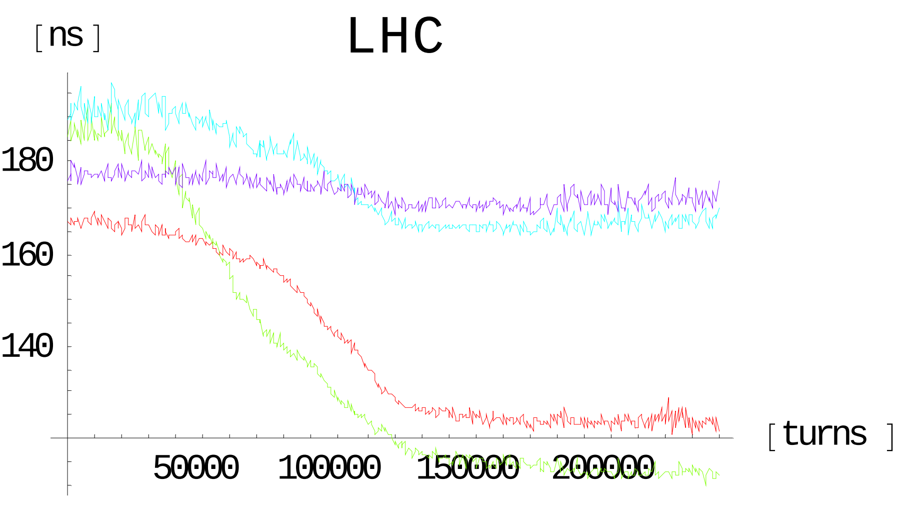
Trapping phenomena are an important subject in high intensity machines as well as in rings with electron clouds [14]. We presented here the status of the present understanding: simple formulae for asymptotic beam loss and rms emittance growth have been found. Scaling laws for trapping induced rms emittance growth are possible and will be studied in details in the near future. The chromaticity also plays an important role: the CERN-PS experiment modeling has been considerably improved by including the chromaticity bringing the beam loss prediction to 50% of that found in the experiment. The remaining discrepancy will be the subject of future studies, which should include fully self-consistent simulations.

Space charge driven resonance phenomena (6/6)

Beam losses on the PS injection flat-bottom (2006) ⇒ Space charge driven resonance trapping phenomena

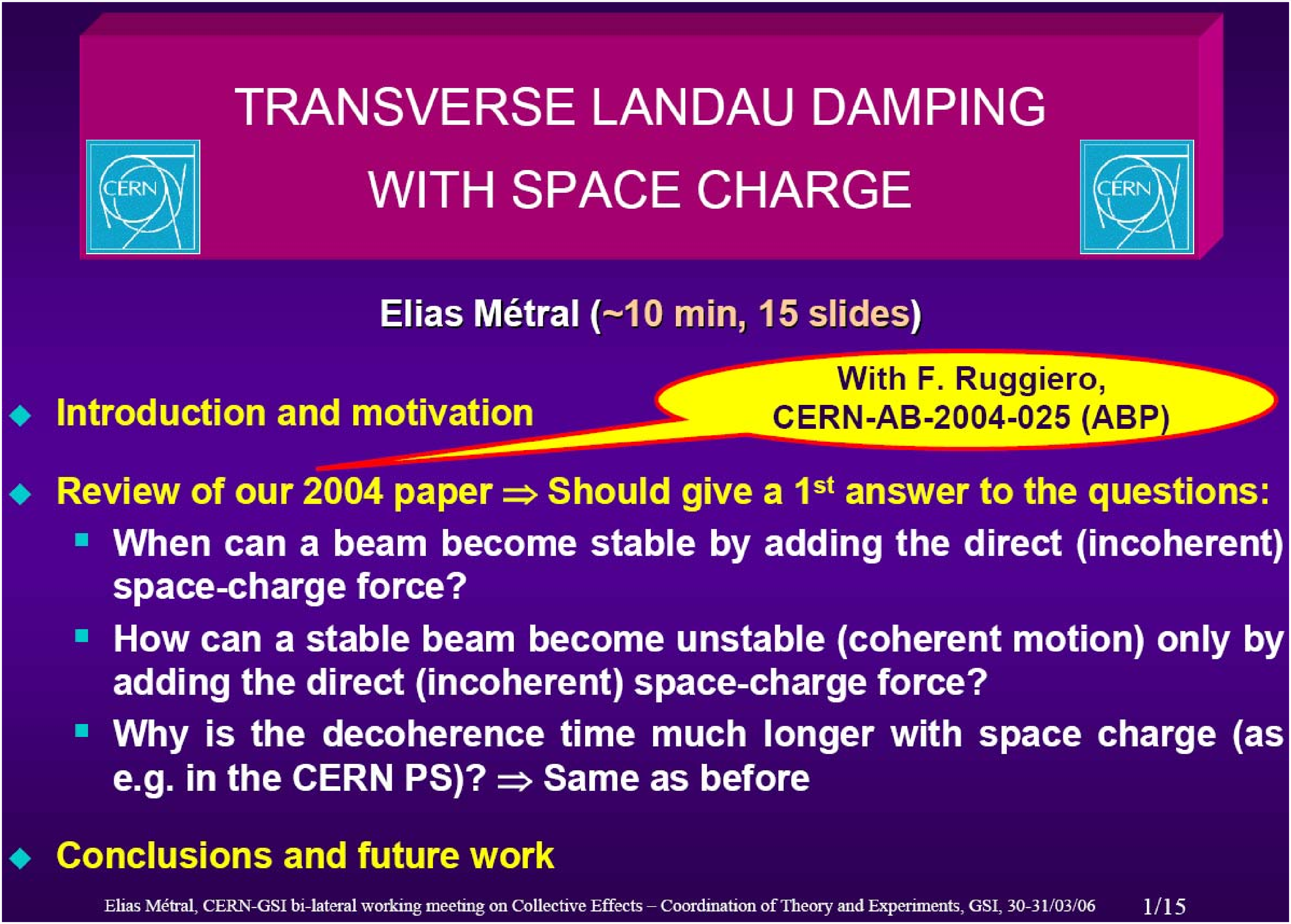






Courtesy S. Hancock

Transverse Landau damping with space charge (1/6)



TRANSVERSE LANDAU DAMPING WITH SPACE CHARGE

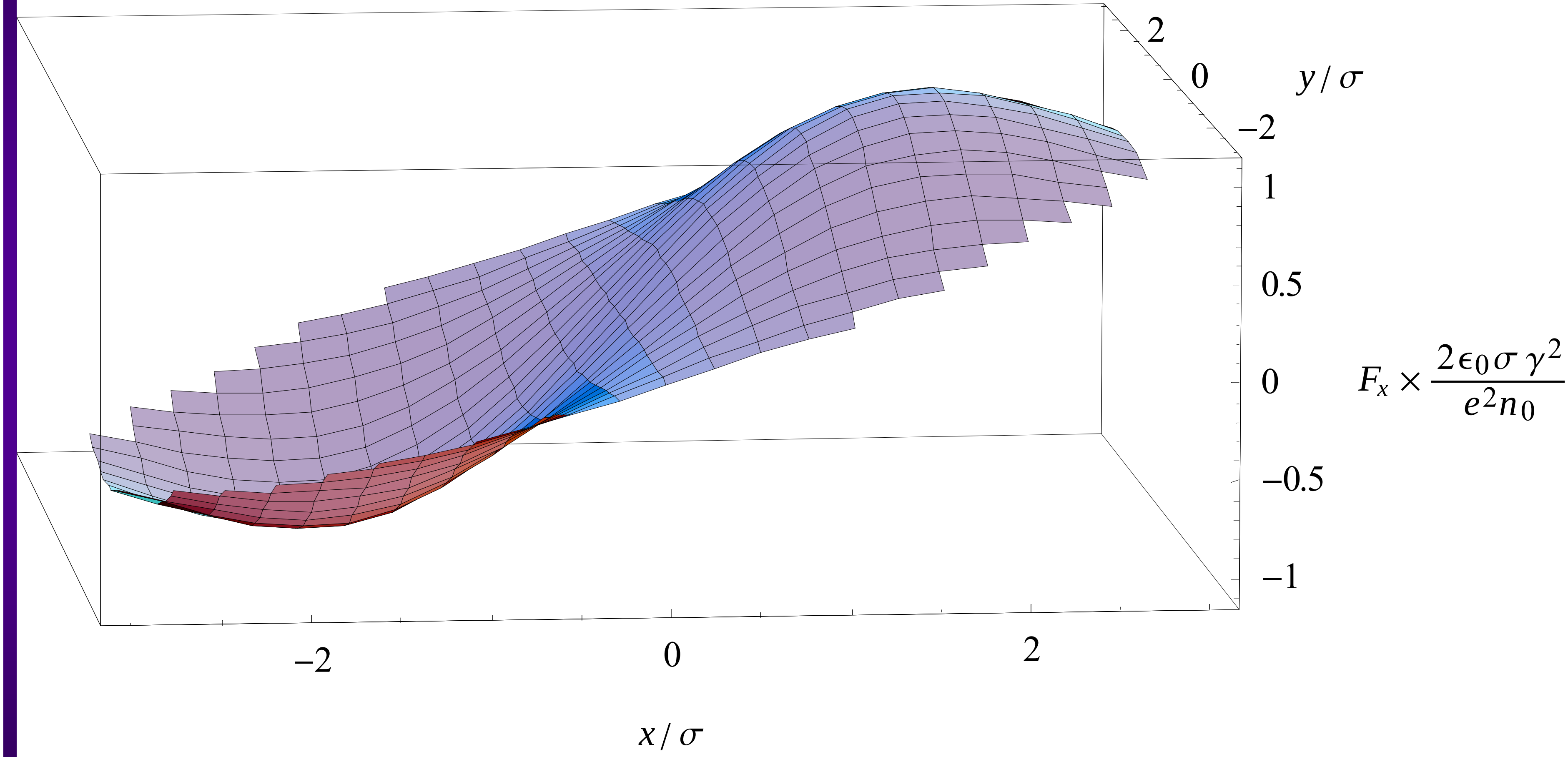
Elias Métral (~10 min, 15 slides)

With F. Ruggiero, CERN-AB-2004-025 (ABP)

- Introduction and motivation
- Review of our 2004 paper ⇒ Should give a 1st answer to the questions:
  - When can a beam become stable by adding the direct (incoherent) space-charge force?
  - How can a stable beam become unstable (coherent motion) only by adding the direct (incoherent) space-charge force?
  - Why is the decoherence time much longer with space charge (as e.g. in the CERN PS)? ⇒ Same as before
- Conclusions and future work

Transverse Landau damping with space charge (2/6)

Space-charge force

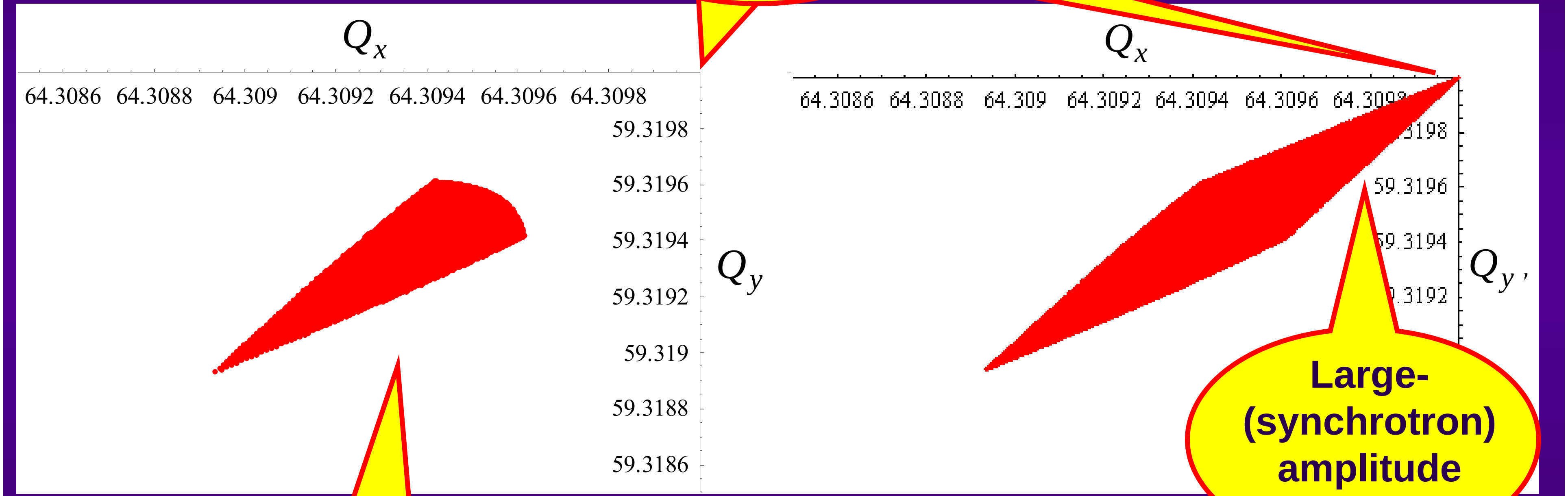


Transverse Landau damping with space charge (3/6)

Case of the LHC at injection

2D tune footprint

3D tune footprint



Low-intensity working point

Large-(synchrotron) amplitude particles

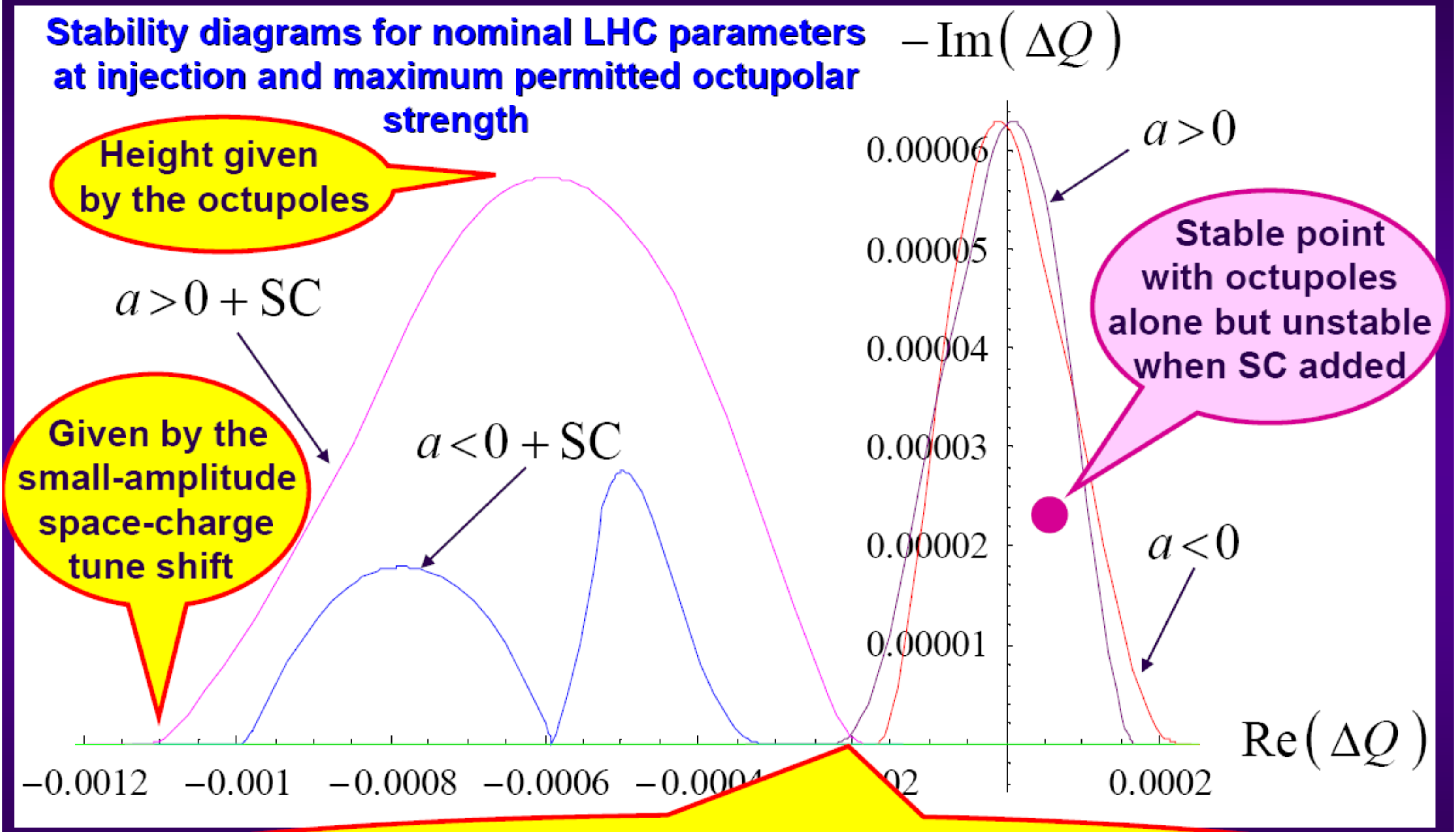
This case has been studied analytically

Transverse Landau damping with space charge (4/6)

REVIEW OF OUR 2004 PAPER (10/10)

- Analytical stability diagrams derived in the approximate case

Stability diagrams for nominal LHC parameters at injection and maximum permitted octupolar strength



Height given by the octupoles

Given by the small-amplitude space-charge tune shift

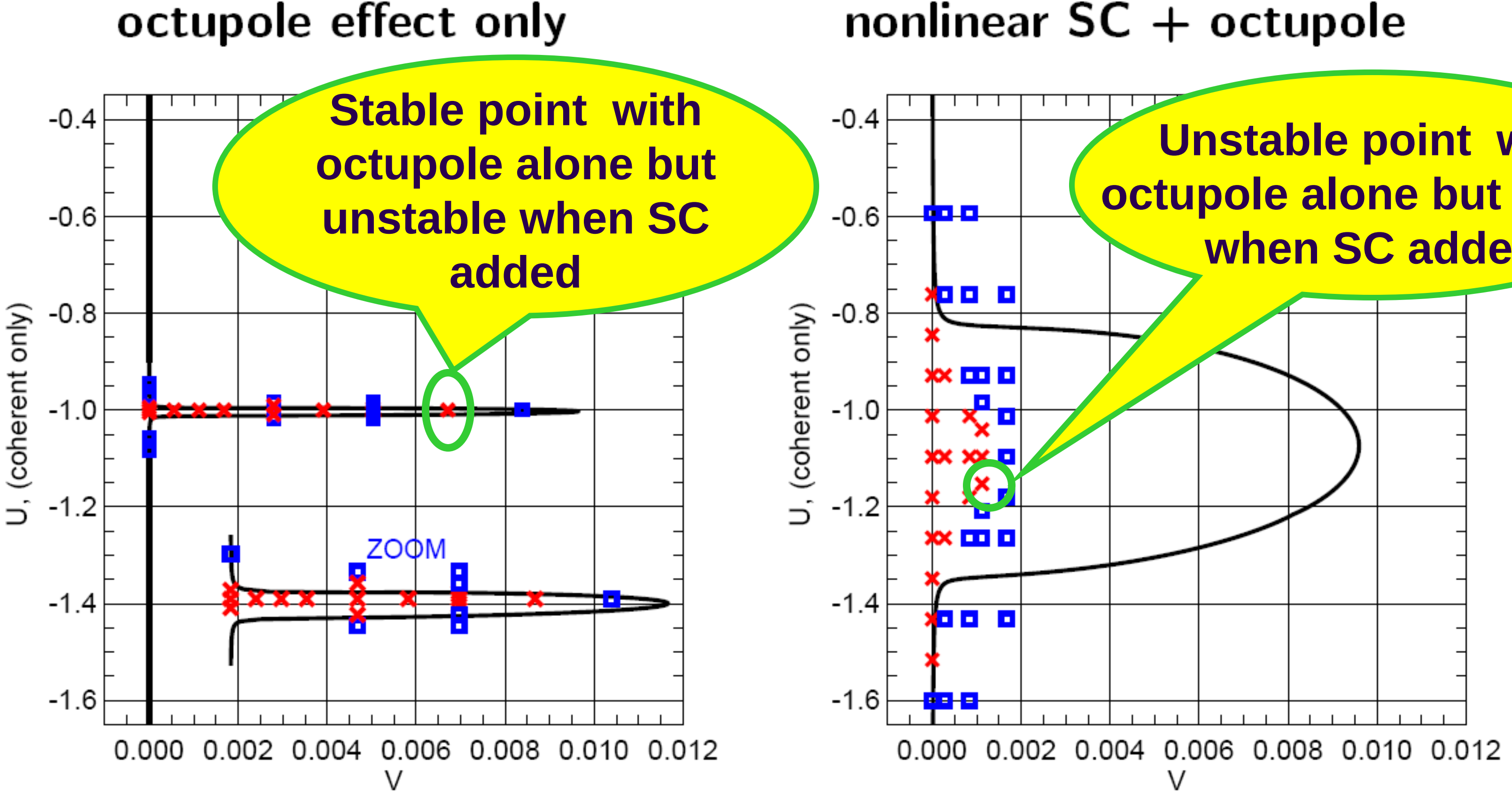
Stable point with octupoles alone but unstable when SC added

Given by the large-amplitude space-charge tune shift + octupoles
$\Longrightarrow$ Will move to the right with longitudinal motion

Transverse Landau damping with space charge (5/6)

GSI **COMPARISONS WITH SIMULATIONS**

From HB2006



octupole effect only

nonlinear SC + octupole

Stable point with octupole alone but unstable when SC added

Unstable point with octupole alone but stable when SC added

PATRIC **simulations:** □ ↦ **no damping**

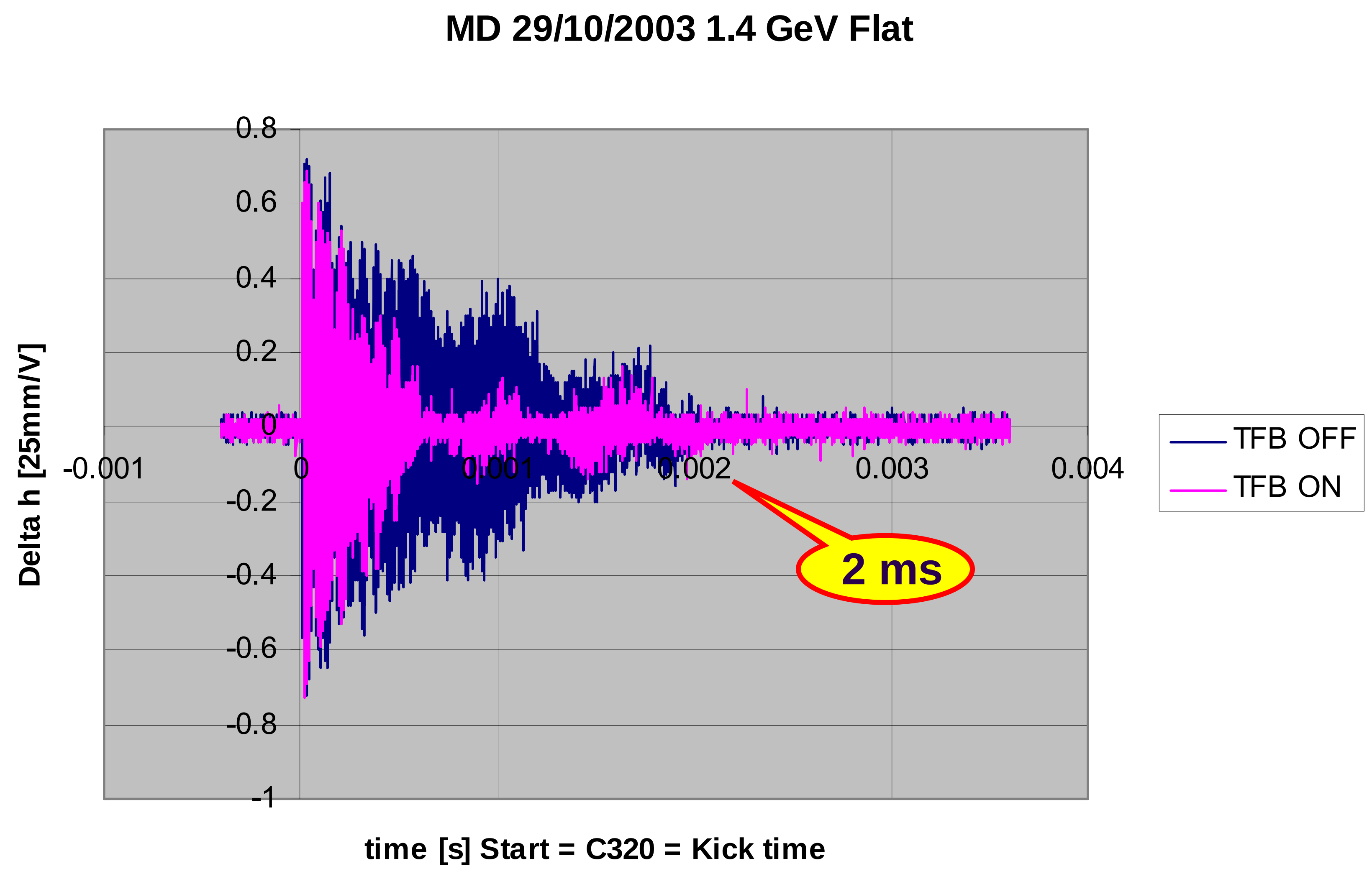
× ↦ $\overline{x}(t)$ **damped**

Transverse Landau damping with space charge (6/6)

- Interesting new PATRIC simulations by V. Kornilov et al. seem now in good agreement with Mohl&Schonauer1974 theory (which we extended with FR) ⇒ End (at least qualitatively) of a long-standing problem…
- What is in addition in the extended theory and not (yet) in the previous simulations
  - 2-dimensional betatron tune spread ⇒ In the absence of space charge the stability diagrams from Berg&Ruggiero are recovered
  - 2 stability diagrams in the presence of both space charge and octupoles: same or opposite sign of the detuning with amplitude
  - Stability diagrams plotted in the complex tune diagram (instead of the LNS coefficients U and V) ⇒ Much more convenient in practice
- Future (collaboration) work: Make the PATRIC (and HEADTAIL) simulations for the PS, LHC… at injection?

Decoherence without and with space charge at PS injection (1/4)

Measurements from F. Blas with a nominal LHC bunch



Decoherence without and with space charge at PS injection (2/4)

HEADTAIL simulations from E. Benedetto (PHD thesis)

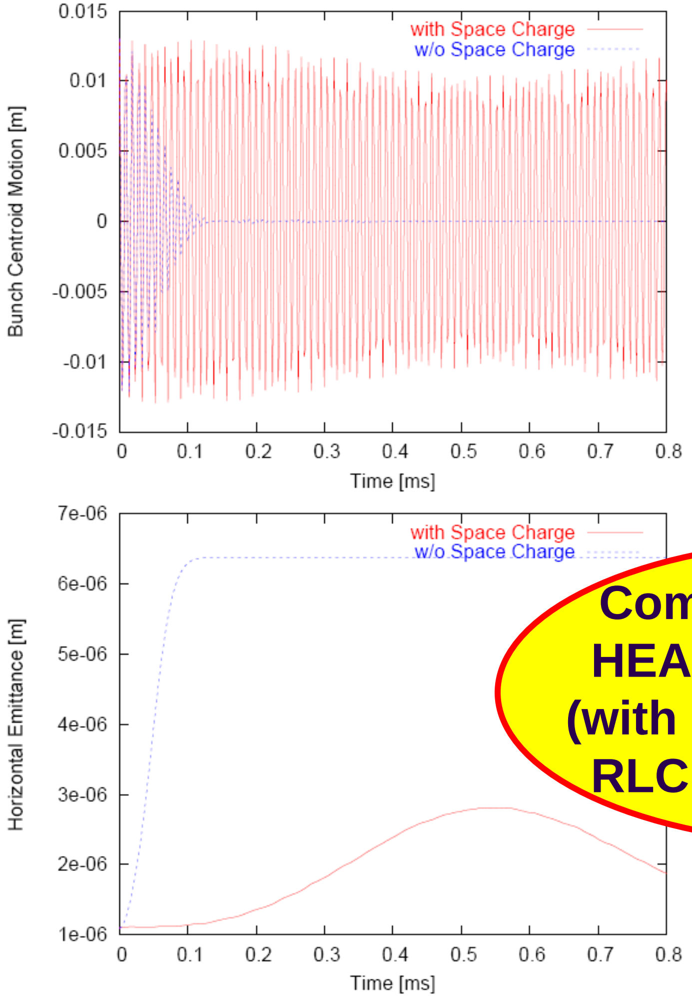
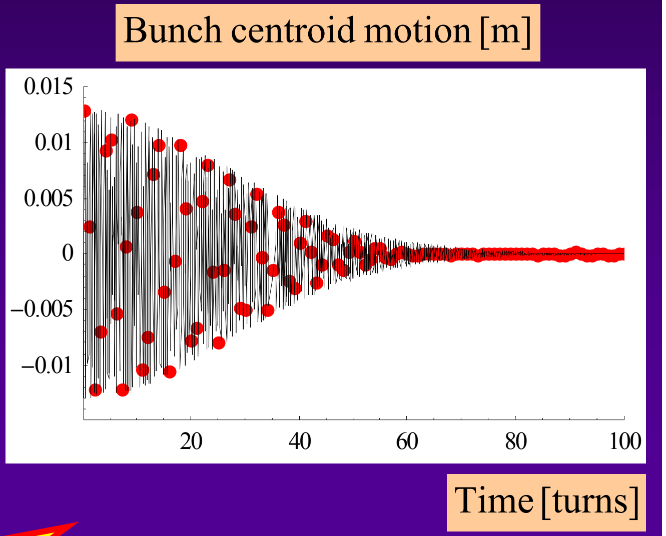
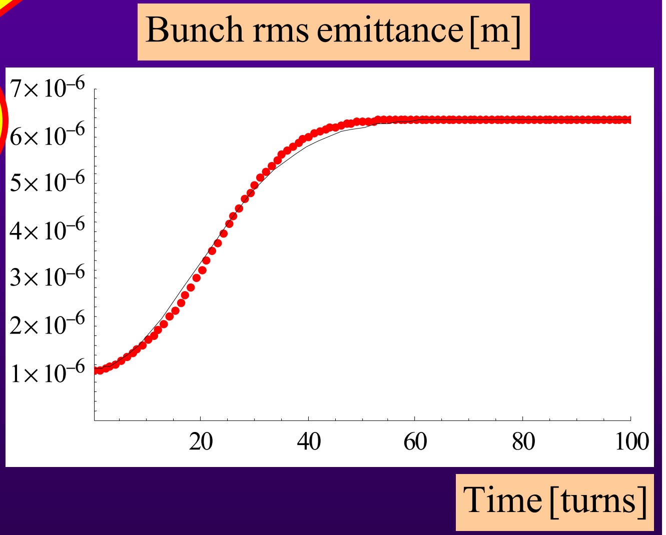


Figure B.1. Simulations with HEADTAIL. Horizontal bunch centroid (top) and emittance (bottom) vs. time during the first 0.8 ms in PS. An initial offset $x_0 = 0.013$ is given to the bunch. The two curves refer to simulations with space–charge taken into account or not.

Comparison between HEADTAIL and theory (with chromaticity only), RLC meeting 18-02-05





Decoherence without and with space charge at PS injection (3/4)

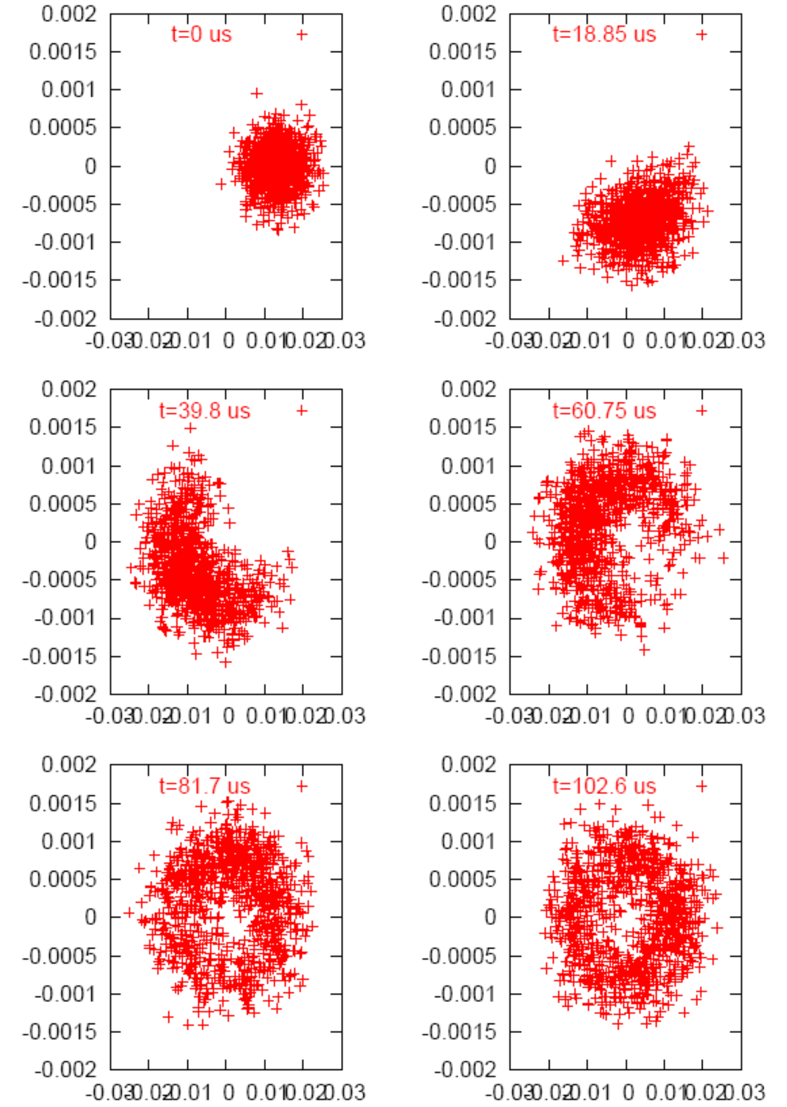


Figure B.2. Horizontal phase space at different time steps (in μs). Simulations do not include space charge effects.

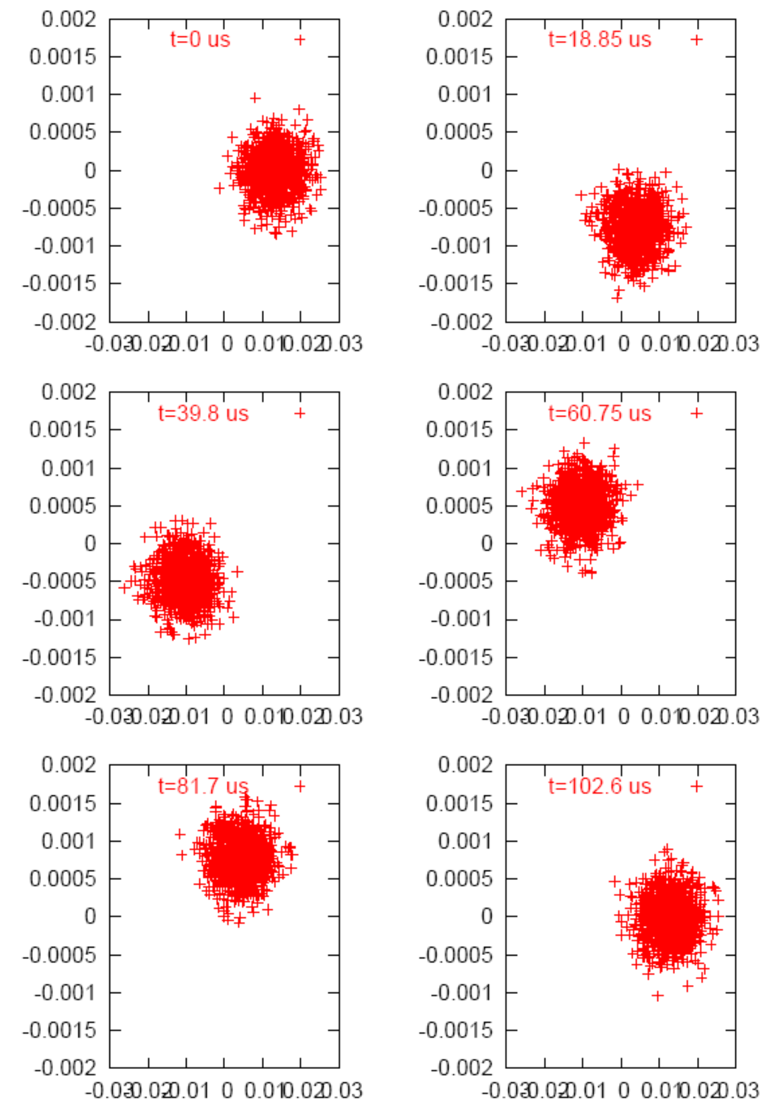


Figure B.3. Horizontal phase space at different time steps (in μs). Simulations include particles tune shift due to space–charge.

Decoherence without and with space charge at PS injection (4/4)

Note: HEADTAIL simulations from G. Rumolo + F. Zimmermann in SPS (Practical User Guide for HEADTAIL, 2002)

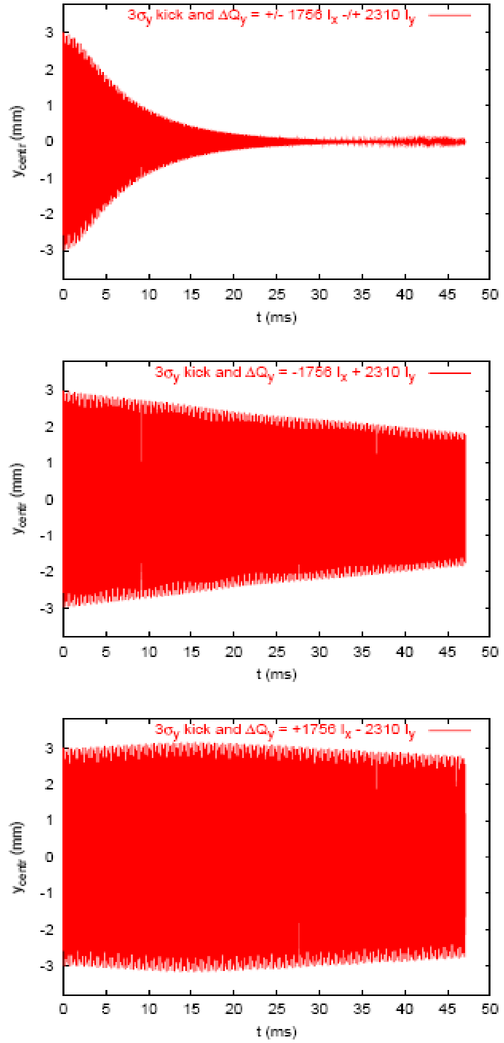


Figure 13: Vertical centroid evolution of an SPS bunch kicked to an amplitude of $3\sigma_y$. Detuning with amplitude is included in all the simulations; space charge only in the two lower pictures.

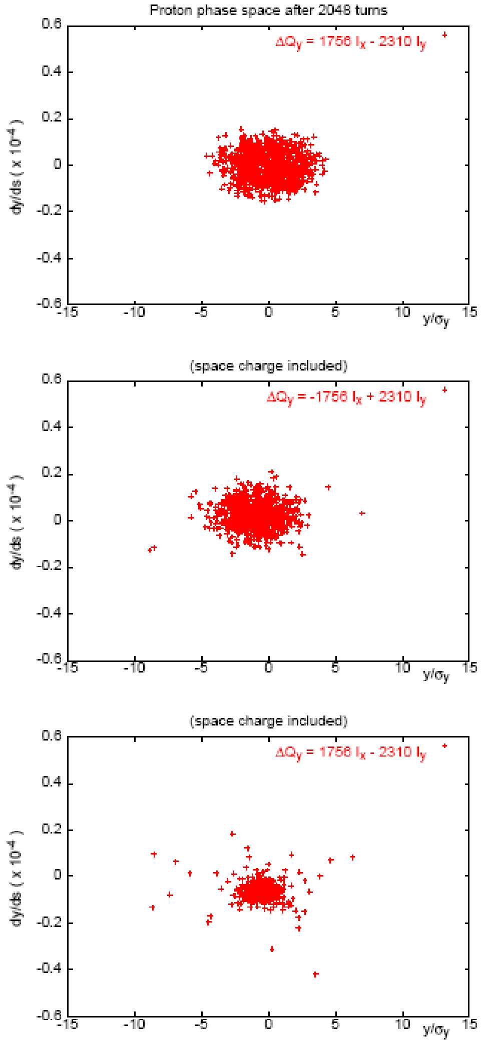


Figure 14: Vertical phase space of an SPS bunch initially kicked to an amplitude of $3\sigma_y$ after 2048 turns. Only amplitude dependent detuning (upper figure); with space charge and amplitude detuning of opposite signs (lower figures).

Possible experiments in the PSB-PS to benchmark the SC codes? (1/2)

- Study the emittance sharing/exchange mechanism with unsplit and split (by 1 integer) transverse tunes in the PSB
  - The Montague resonance works only near $Q_x = Q_y$
  - Emittance transfer with linear coupling works near $Q_x = Q_y +$ any integer
  - We could measure for the first time (to my knowledge) in the same machine with unsplit and split tunes to disentangle the space charge effect from the linear coupling effect
  - Another proposition from A. Franchi (PHD thesis): Suppress the space charge driven emittance exchange using "normal quadrupoles to detune the machine and make the beam cross the resonance with an effective speed such to prevent any exchange and mismatch" $\Longrightarrow$ To be tested

Possible experiments in the PSB-PS to benchmark the SC codes? (2/2)

- Study the PS low energy resistive-wall instability (large incoherent space charge tune spread of ~ 0.3) ⟹ We started this already with Benoit et al.

- Effect of external nonlinearities (both signs of the detuning coefficients) + space charge on Landau damping mechanism and decoherence ⟹ Coherent tune inside or outside the incoherent tune spread to be studied

- Use the flat bunches (a la Christian) to reduce the SC tune spread at PS injection, to move the working point and perhaps reduce the losses on the long injection flat bottom ⟹ (Rapidly) tested in the past and not conclusive at that time… But we should perhaps try it again

  ⟹ Giuliano could make the corresponding simulations to see if and how flat bunches can help