TCBI in the LHC

Elias Métral and Nicolas Mounet

- **Past work and predictions**

- **Current work and predictions => PHD thesis of Nicolas Mounet on "The LHC coupled-bunch instability"**

- **Recommendations and future work**
  - **Nicolas Mounet**
  - **Raymond Wasef (5-month trainee, who started on 01/05/11) => HEADTAIL simulation studies of Landau damping through octupoles in the LHC**

PAST WORK AND PREDICTIONS (1/22)

- The TCBI was believed to be the most critical transverse instability, which could limit the nominal beam (25 ns etc.) to ~ half of its intensity per bunch (i.e. ~ 5E10 p/b) at 7 TeV/c without Transverse damper (TD)
- When we discuss TCBI in the LHC, one should disentangle between
  - Injection & mode HT mode 0 (more critical than at top energy) => TD with possible issue of gain over 20 MHz (see later, more critical at top energy)
  - Injection & mode HT mode 1 (or higher) => Chromaticity as low as possible + Landau Damping (LD) with possible issue of space charge shifting the stability curves from natural nonlinearities (depending on the transv. emitt.!)
  - Top energy & mode HT mode 0 => LD with possible intensity limit (1^{st} scenario studied) or TD with possible issue of gain over 20 MHz & noise in collision (2^{nd} scenario, which was thought to be OK in 2009)
  - Top energy & mode HT mode 1 (or higher) => Chromaticity as low as possible + LD from controlled octupoles

PAST WORK AND PREDICTIONS (2/22)

STABILITY DIAGRAM (1/3)

INJECTION

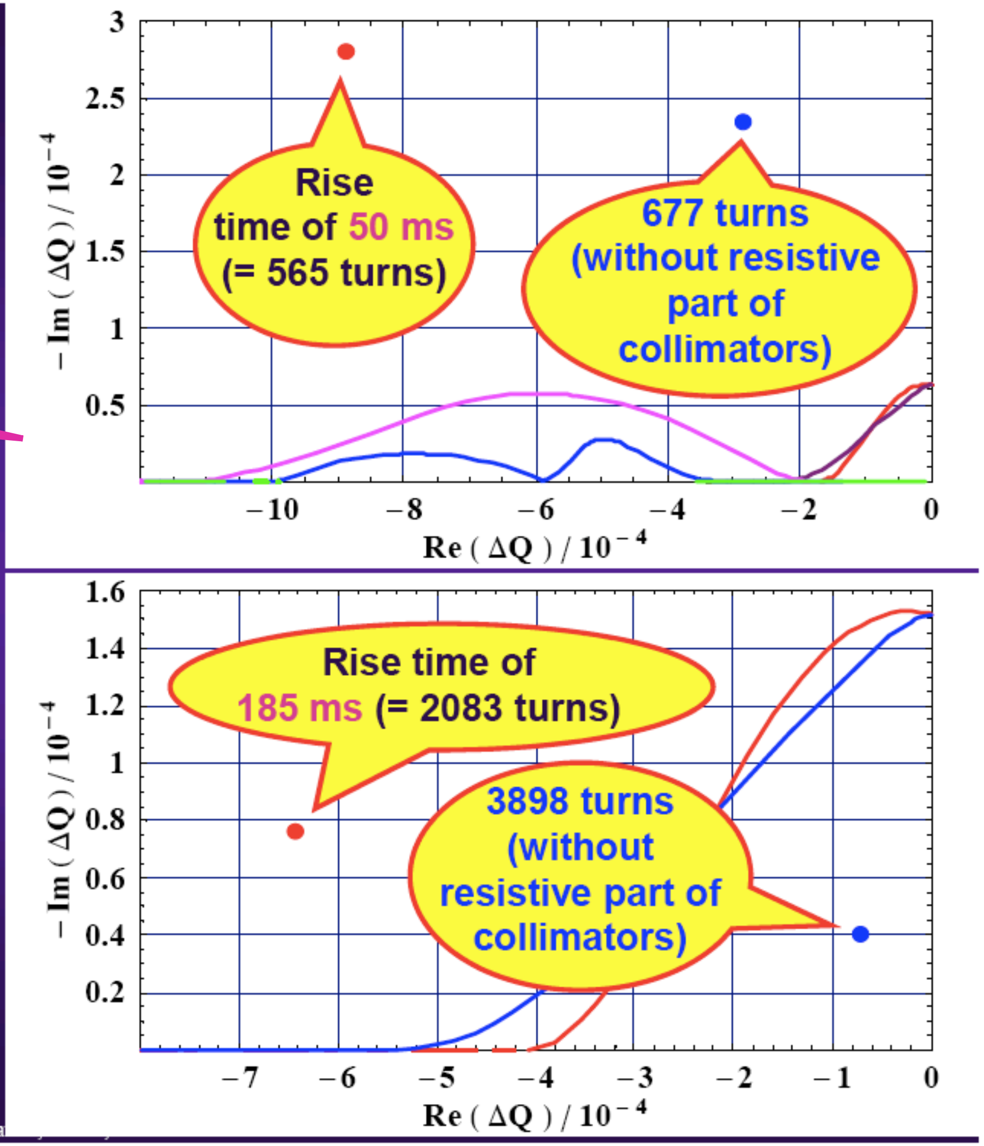
Should be the more critical cases

- Nominal case (25 ns bunch spacing and nominal intensity)

$T_{rev}^{LHC} \approx 89\ \mu s$

TOP ENERGY (after squeeze)

Reminder: - Im (ΔQ) / 10^{-4} = 1 $\Longrightarrow$ Rise time ≈ 1600 turns ≈ 140 ms



Elias Métral, Conceptual Design Review LHC Phase II Collima

PAST WORK AND PREDICTIONS (3/22)

TRANSVERSE FEEDBACK (1/2)

- The transverse feedback system should be able to damp instability rise-times of (We take a safety margin of a factor 2 compared to what was computed in the previous slides)

  - AT INJECTION ENERGY
    - ~ 280 turns (i.e. ~ 25 ms) for nominal intensity
    - ~ 190 turns (i.e. ~ 17 ms) for ultimate intensity

  - AT TOP ENERGY (AFTER THE SQUEEZE)
    - ~ 1040 turns (i.e. ~ 93 ms) for nominal intensity
    - ~ 705 turns (i.e. ~ 63 ms) for ultimate intensity

PAST WORK AND PREDICTIONS (4/22)

TRANSVERSE FEEDBACK (2/2)

- According to W. Hofle:
  - In the SPS ~ 20 turns damping is achieved in the vertical plane on a regular basis
  - The normal operating mode of the feedback should be at gains corresponding to 20-40 turns damping

    $\Longrightarrow$ It seems therefore feasible to damp the foreseen instability rise-times both at injection and top energy
  - The issue of the noise at top energy: K. Ohmi et al. (PAC 2007, LHC Project Report 1048) has estimated from numerical calculations that we can run in the LHC at a gain of 0.1 (10 turns damping) with a monitor resolution of 0.6% of σ and still have a luminosity life-time of one day. The corresponding required resolution is 7.2 μm at 450 GeV (σ = 1.2 mm) and 1.8 mm at 7 TeV (σ proportional to $\gamma^{-1/2}$). If the gain can be reduced, then the requirement for the monitor resolution can be relaxed. The improvement in monitor resolution required for LHC when compared with the SPS can be achieved due to the increased number of bits used and the higher signal power available from the coupler type pick-up

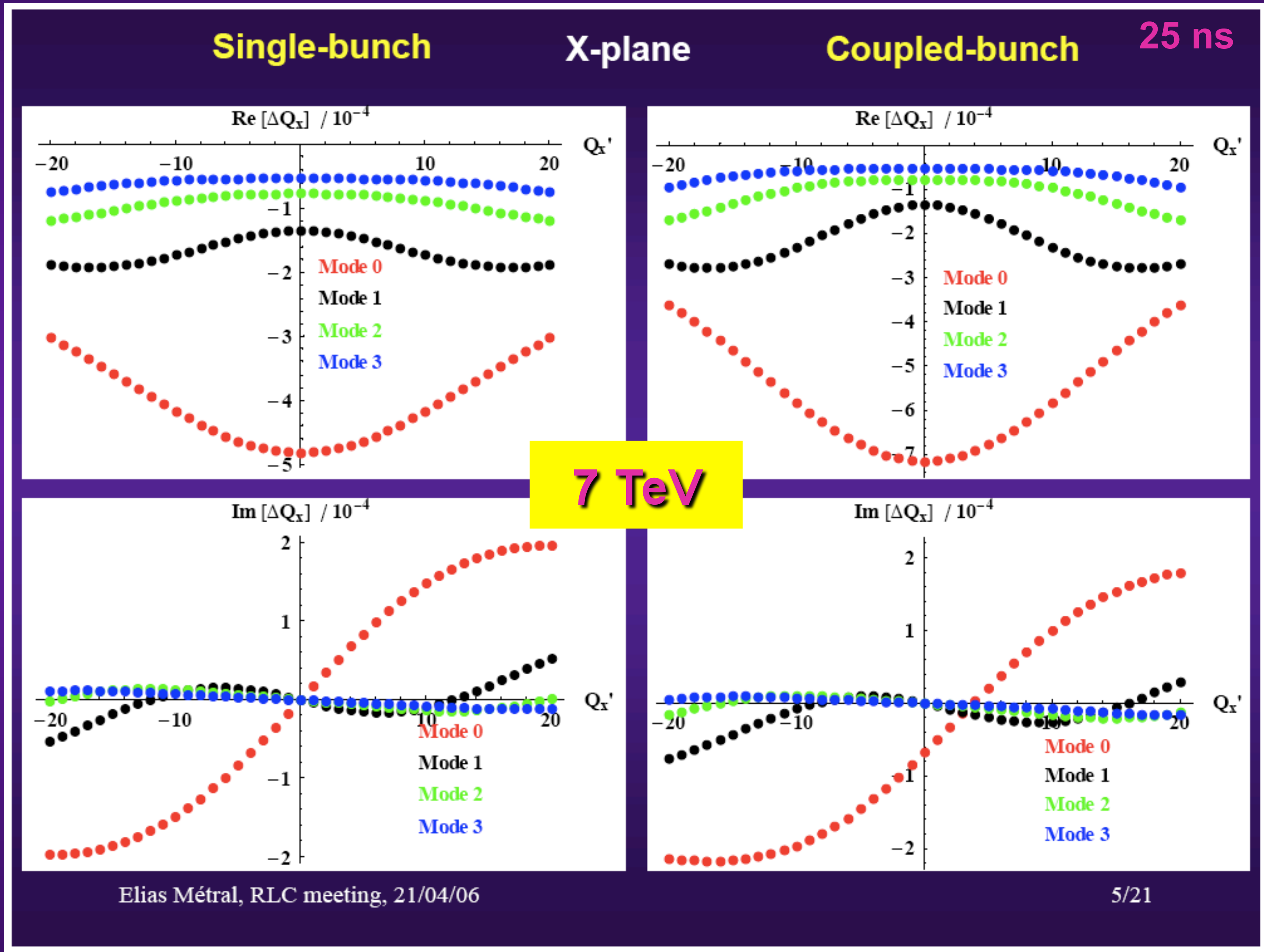
PAST WORK AND PREDICTIONS (5/22)

CONCLUSION AND OUTLOOK

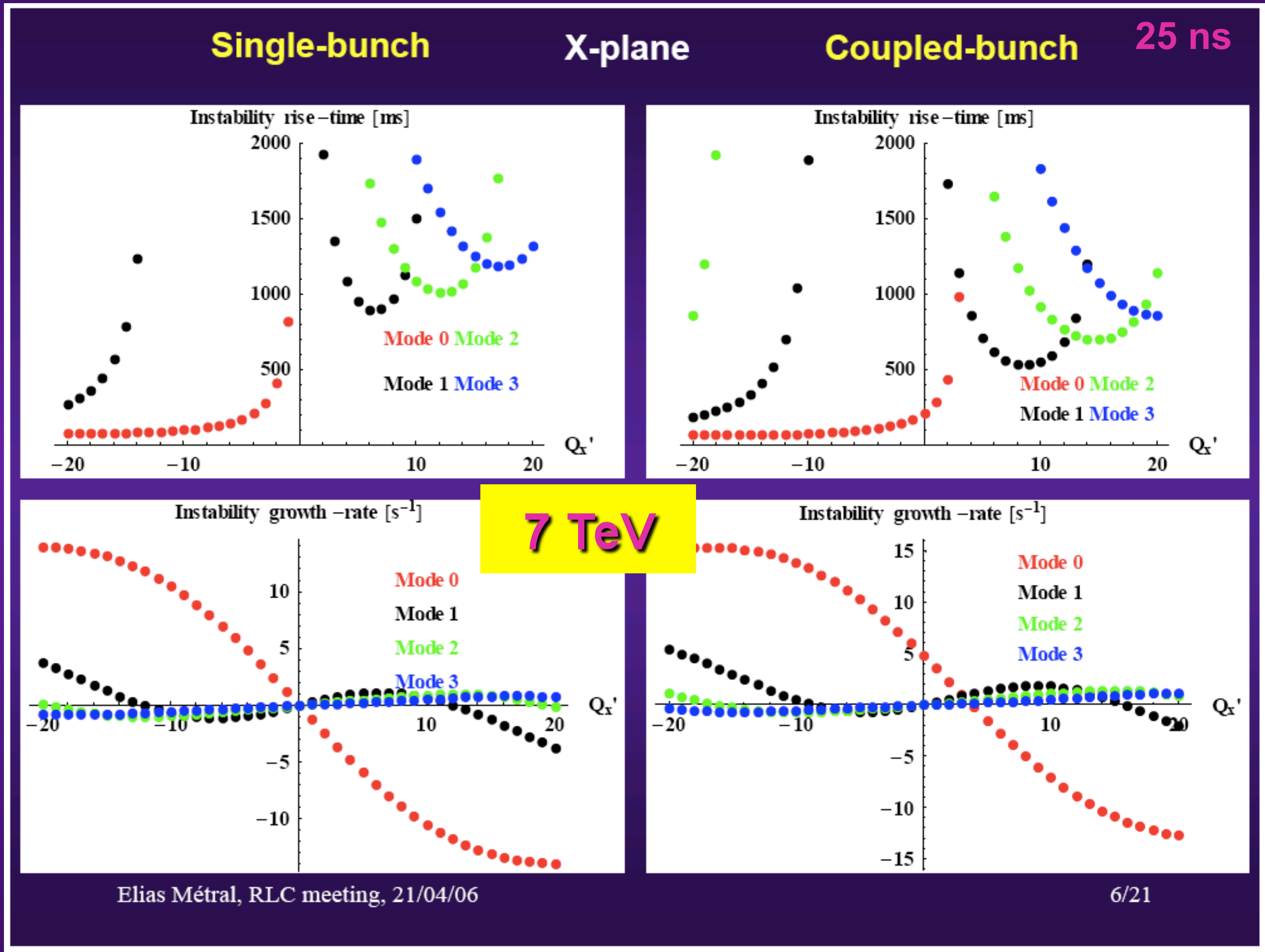
- **Theory of "wall" impedance**
  - Similar results obtained from several formalisms in the low-frequency regime (assuming infinitely long pipe), as well as with simulations and measurements
  - Next steps (Nicolas Mounet):
    - Study of transition between the 2nd and 1st frequency regime
    - Multi-bunch $\Longrightarrow$ Wave velocity ≠ Beam velocity
    - Finite length (preliminary results revealed "no" changes: Tbc)
    - Extension of HEADTAIL code to multi-bunch
- **Strategy for the stabilization of the transverse coupled-bunch instab.**
  - Transverse feedback: at injection and top energy (seems OK)
  - If pb $\Longrightarrow$ Landau octupoles (up to a certain intensity limit)
- **Phase 2: Copper and copper coated ceramics collimators are studied**
- **The best way to reduce the collimator impedance remains to open the gaps and reduce the total length of the collimators!**

Elias Métral, Conceptual Design Review LHC Phase II Collimation, CERN, 02-03/04/2009 17/17

PAST WORK AND PREDICTIONS (6/22)



PAST WORK AND PREDICTIONS (7/22)

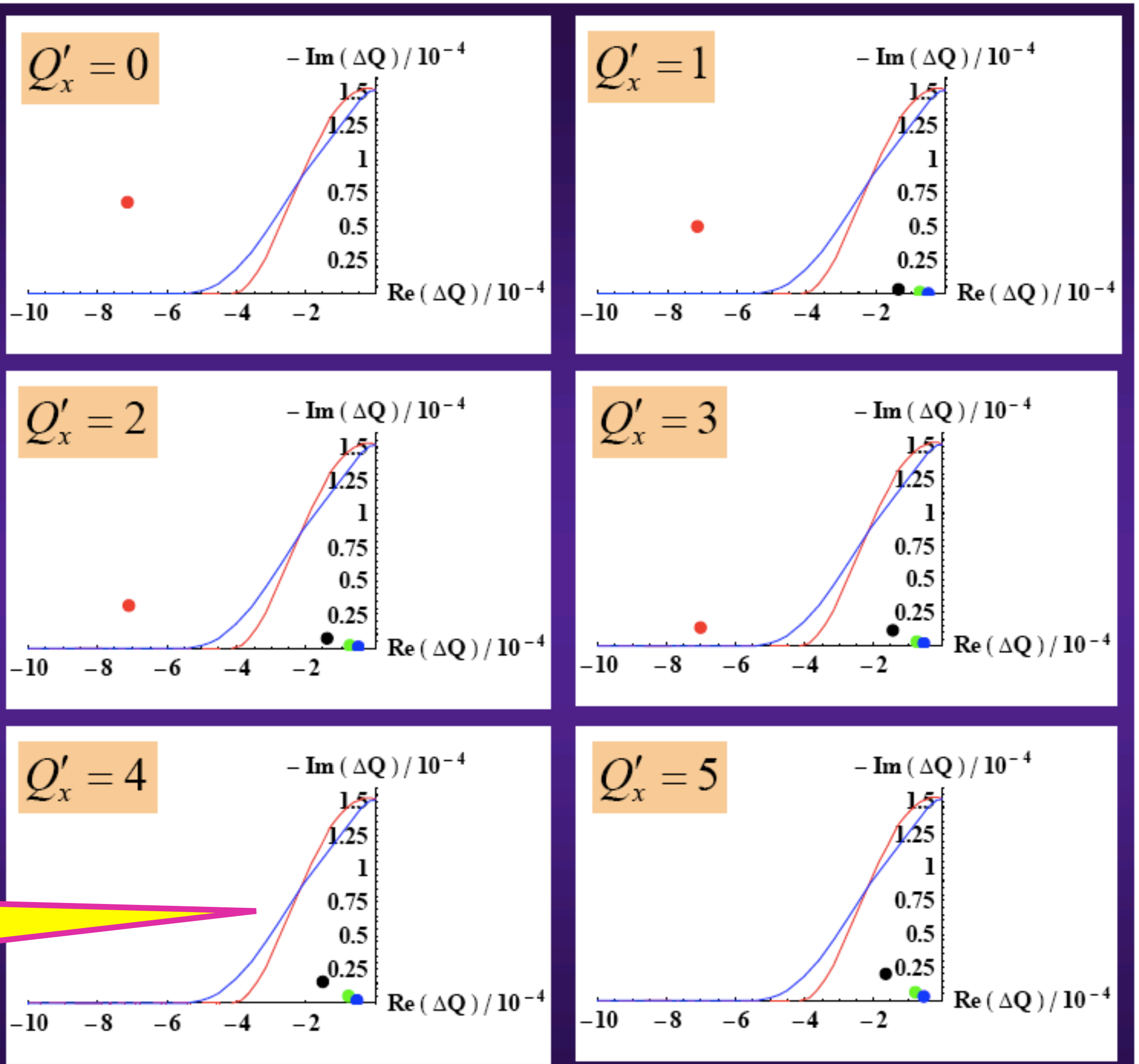


PAST WORK AND PREDICTIONS (8/22)

Stability diagrams (X-plane)

7 TeV

Mode 0
Mode 1
Mode 2
Mode 3

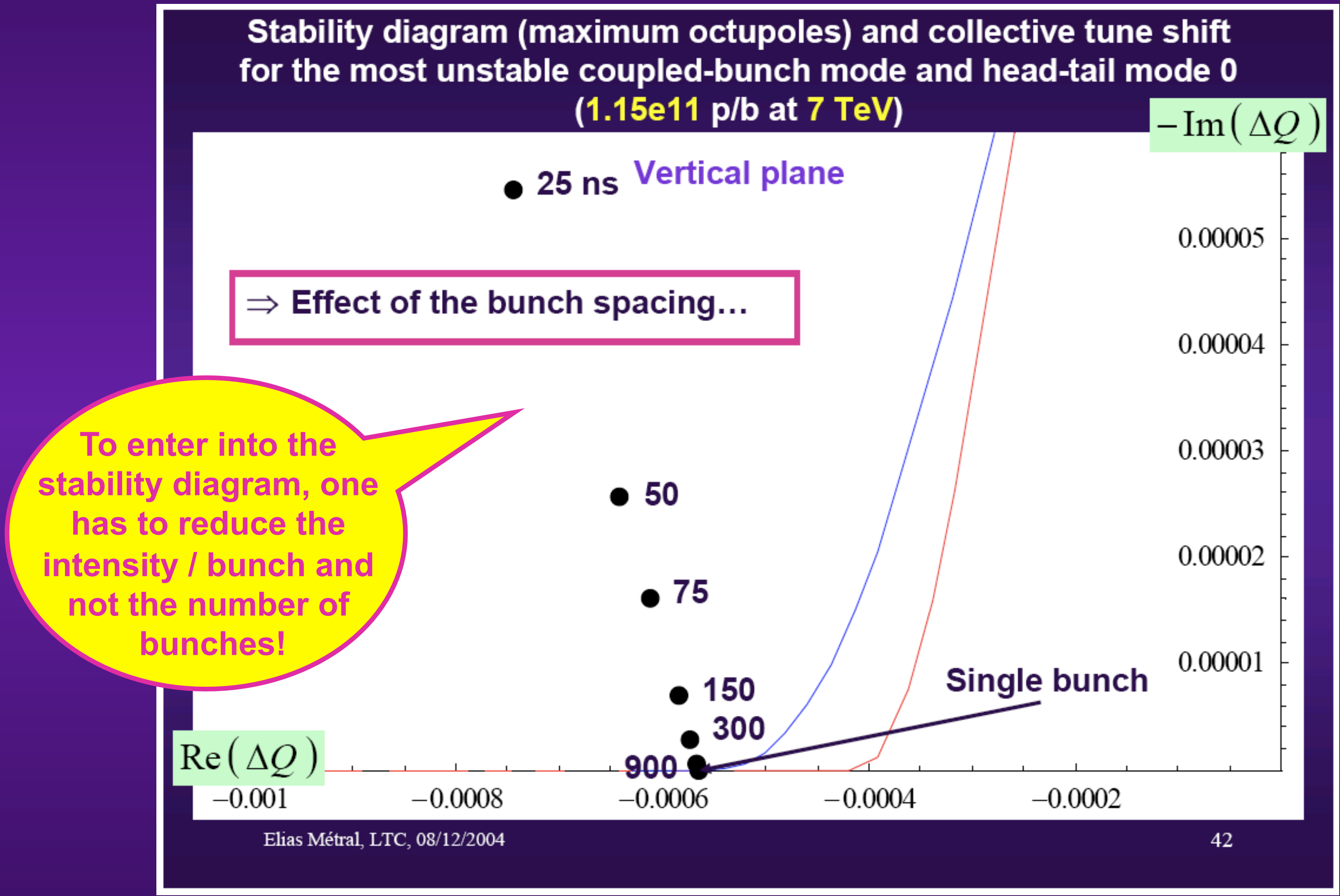


Stability diagrams are proportional to the transverse emittance!

Elias Métral, RLC meeting, 21/04/06

7/21

PAST WORK AND PREDICTIONS (9/22)



PAST WORK AND PREDICTIONS (10/22)

- **Remark concerning the stability diagrams**
  - **=> Should be a conservative but realistic approach**

From the LHC design report (page 104)

$a = 270000\,\mathrm{m}^{-1}$ and $b = -175420\,\mathrm{m}^{-1}$, with $c = b/a = -0.65$. Given the nominal beam emittance at 7 TeV $\varepsilon = 0.5\,\mathrm{nm}$, the corresponding maximum detuning at $1\,\sigma$ rms is $\Delta Q_{1\sigma} = a\varepsilon = 1.35 \times 10^{-4}$ in each plane. Landau damping for a pseudo-parabolic betatron distribution with $J_x + J_y \leq 5\sigma^2$, as discussed in [36, 37] is assumed. This is a somewhat conservative assumption, valid for a scraped beam with no tails beyond $3.2\,\sigma$. The

  - **Several cases with more tails were studied in Stability diagram for Landau damping with a beam collimated at an arbitrary number of σ (http://cdsweb.cern.ch/record/733611/files/ab-2004-019.pdf)**

    => More stability could be achieved (as Landau damping heavily depends on then tails), but the tails are no so well controlled…

PAST WORK AND PREDICTIONS (11/22)

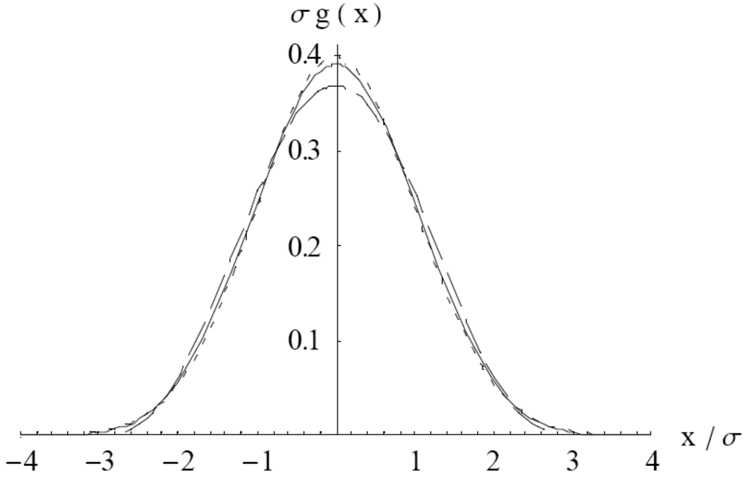


Figure 1: Transverse beam profile for the 15th order distribution (full curve), the quasi-parabolic distribution (dashed curve) and the Gaussian distribution (dotted curve).

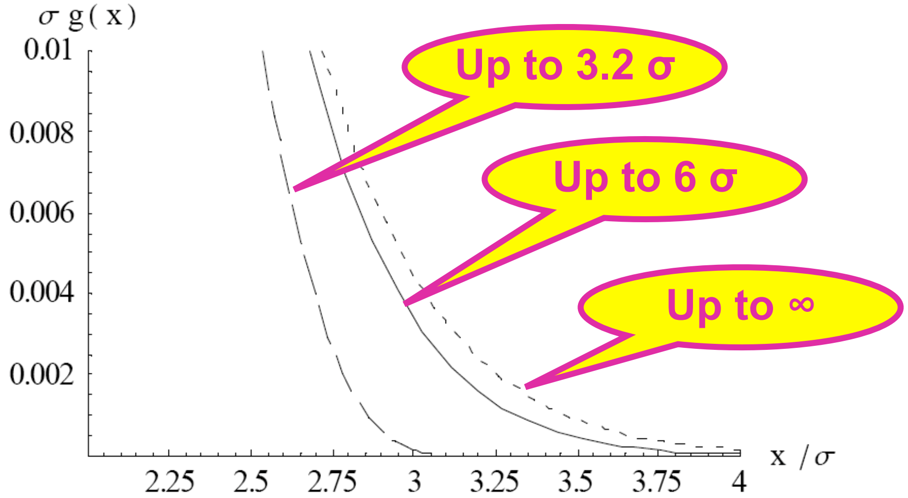


Figure 2: Zoom of the tails of the transverse beam profiles for the 15th order distribution (full curve), the quasi-parabolic distribution (dashed curve) and the Gaussian distribution (dotted curve).

PAST WORK AND PREDICTIONS (12/22)

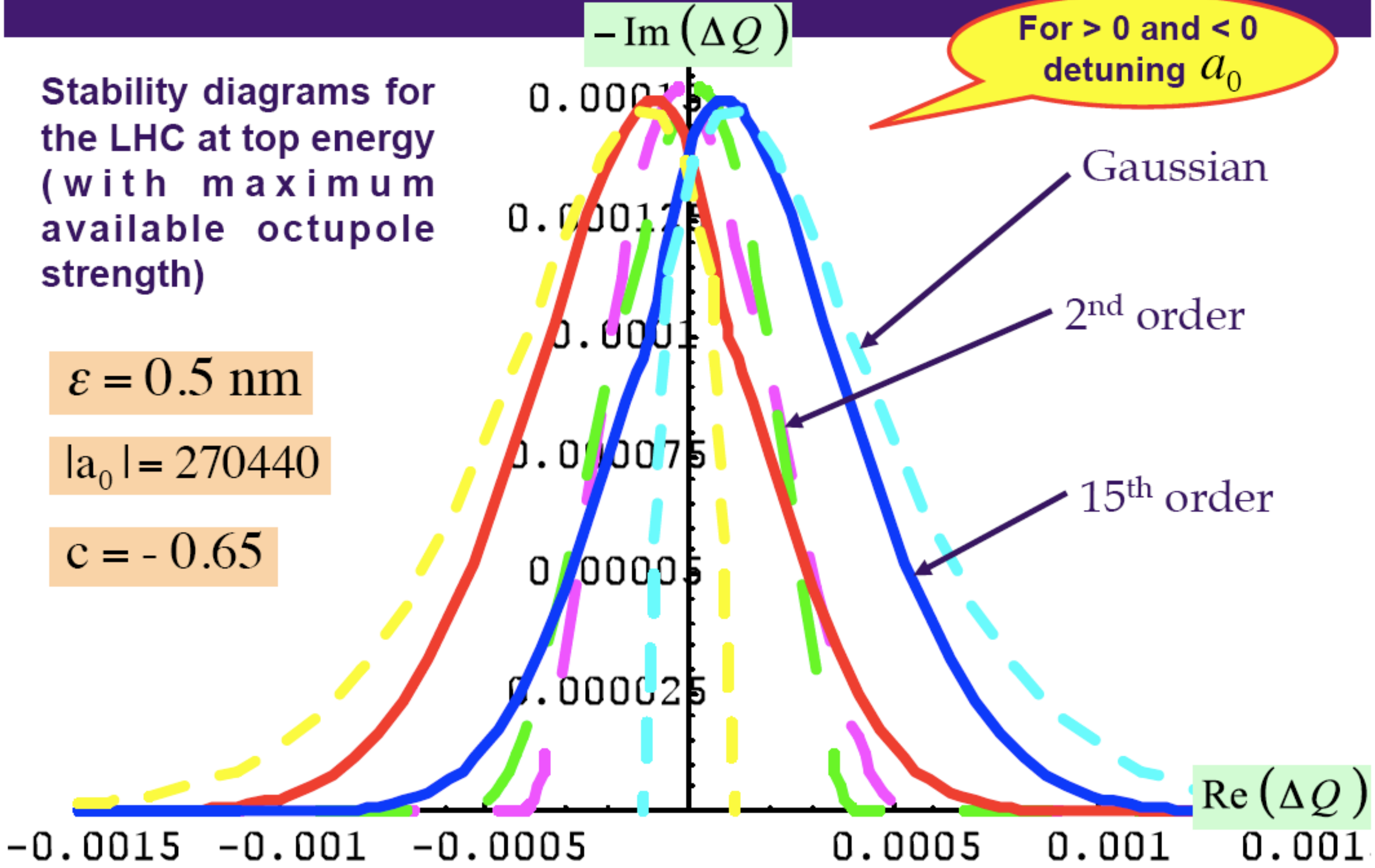
LANDAU DAMPING FOR A BEAM COLLIMATED AT AN ARBITRARY NUMBER OF SIGMAS (11/17)

Stability diagrams for the LHC at top energy (with maximum available octupole strength)

$\varepsilon = 0.5$ nm

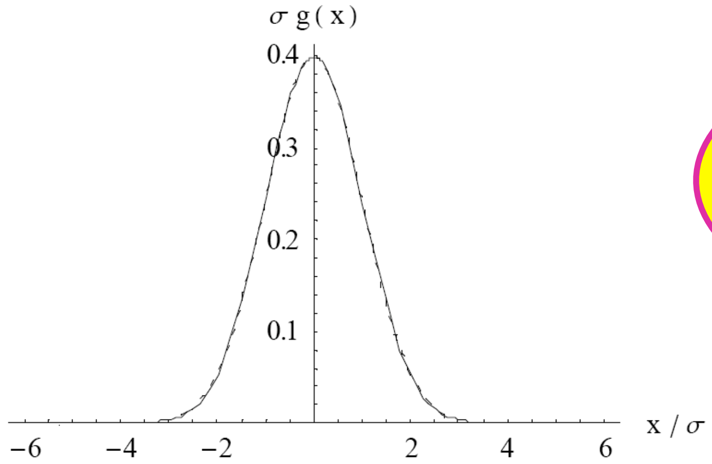
$|a_0| = 270440$

$c = -0.65$



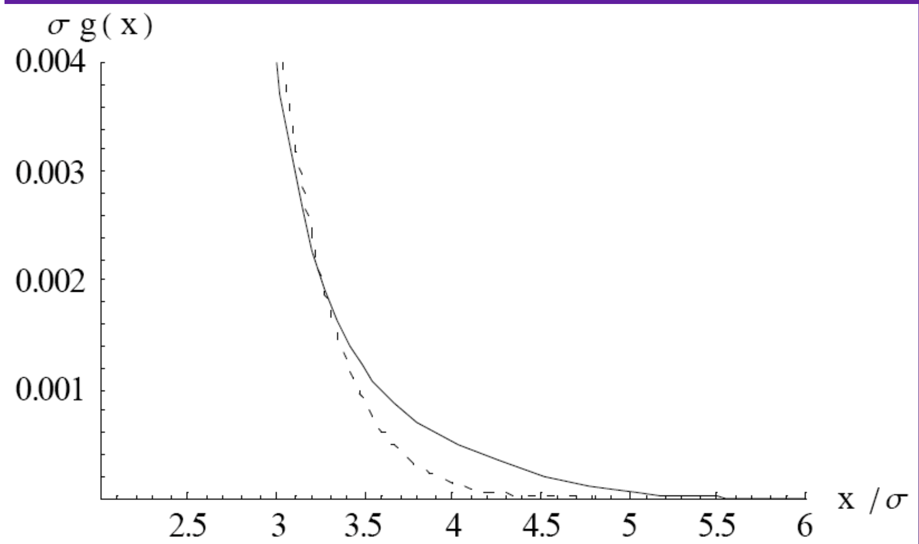
Elias Métral, USPAS2009 course, Albuquerque, USA, June 22-26, 2009 66/114

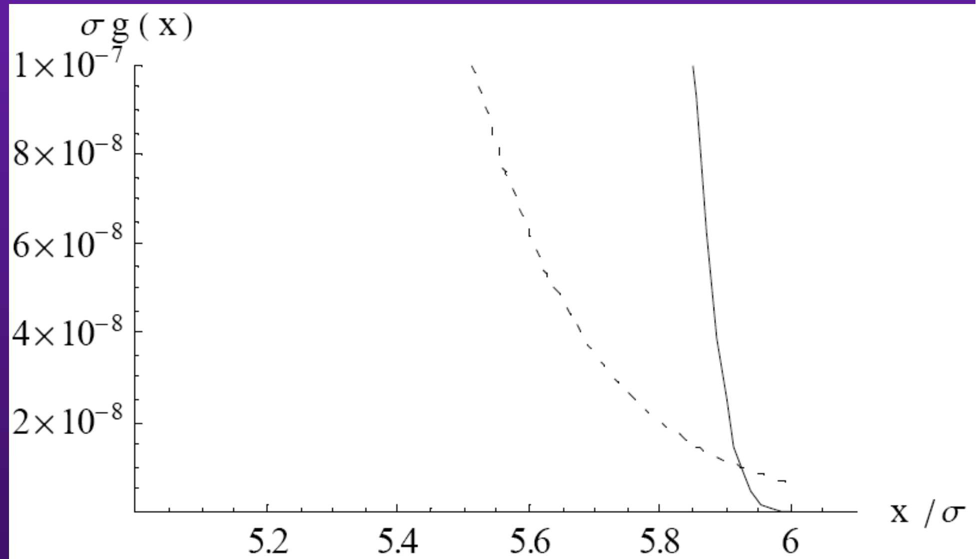
PAST WORK AND PREDICTIONS (13/22)



Up to 6 σ but with tails more populated than Gaussian

Figure 4: Transverse beam profile for the case n = 16 and p = 2 (full curve) and the Gaussian distribution (dotted curve).





PAST WORK AND PREDICTIONS (14/22)

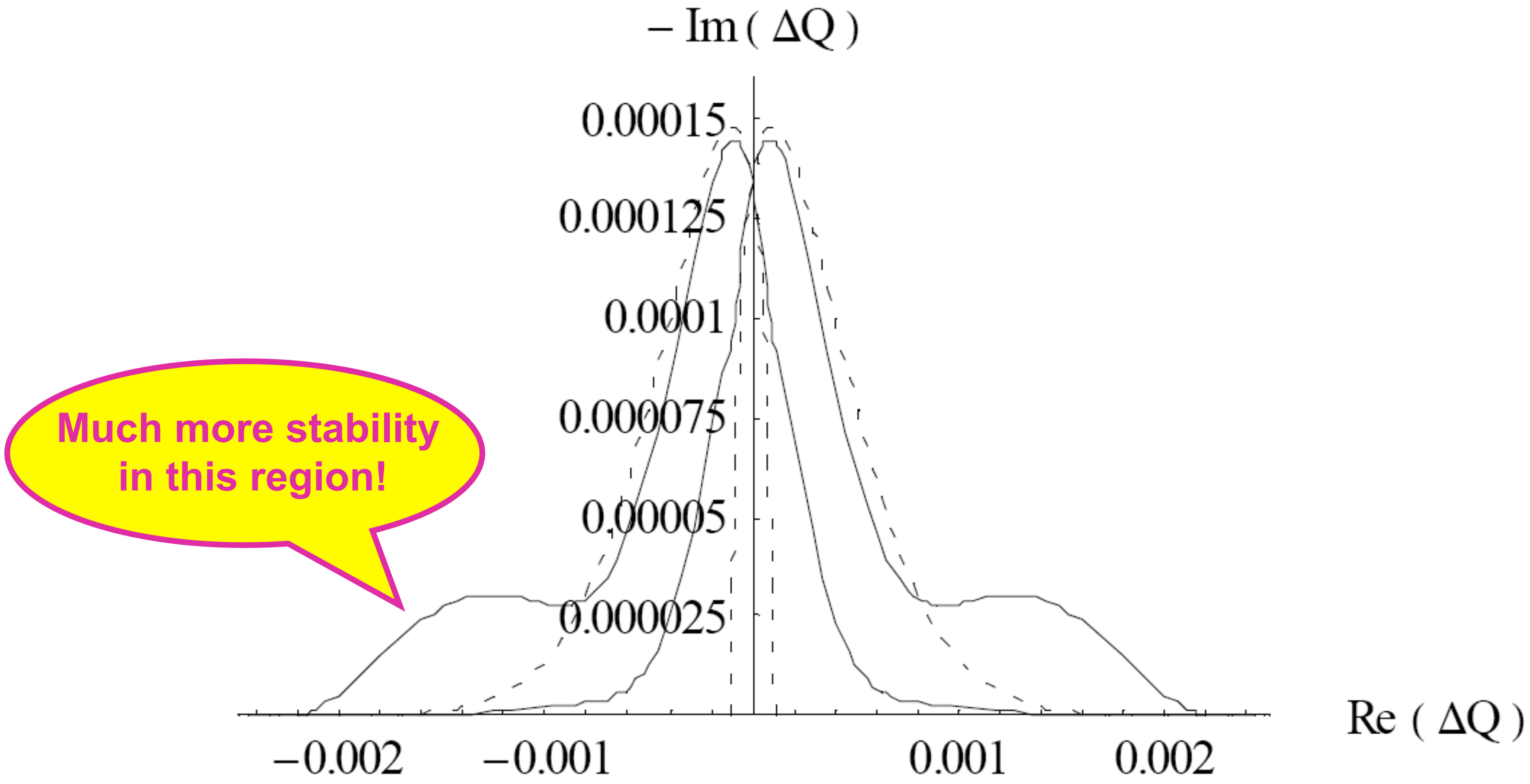
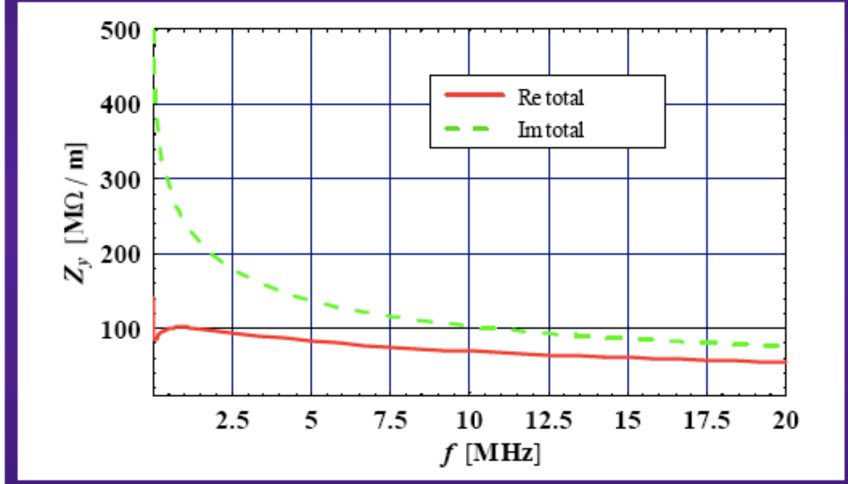


Figure 7: Stability diagrams (positive and negative detunings a_0) for the LHC at top energy (7 TeV) with maximum available octupole strength, for the case n = 16 and p = 2 (full curve) and the Gaussian distribution (dotted curve).

PAST WORK AND PREDICTIONS (15/22)

ZOOM (between 8 kHz and 20 MHz) OF THE LHC TRANSVERSE IMPEDANCE AT TOP ENERGY (AFTER THE SQUEEZE)

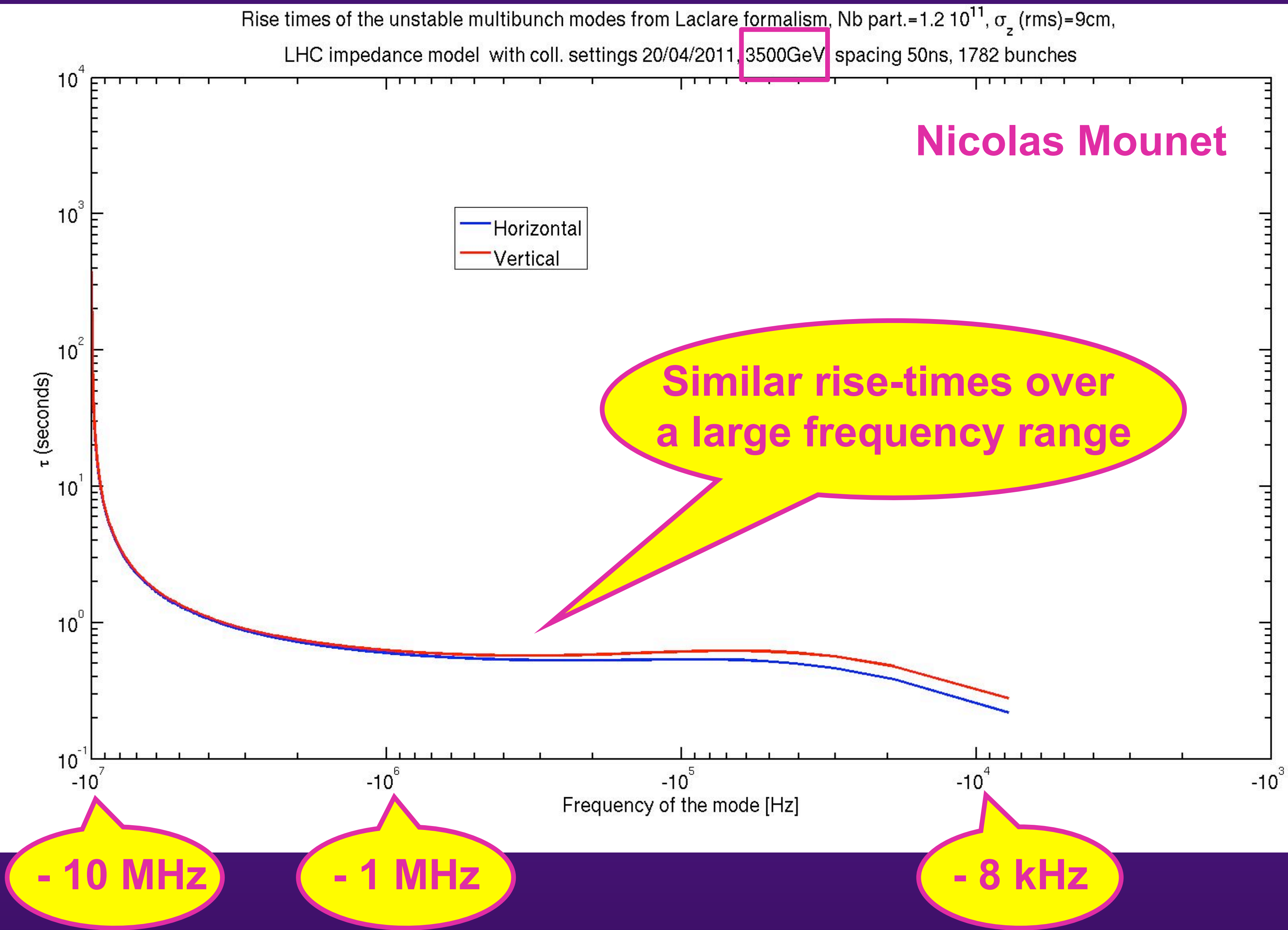


- The value of the real part of the impedance at 8 kHz (1st unstable betatron line) is ~ 141 MΩ/m
- The value of the real part of the impedance at 20 MHz (frequency limit of the transverse damper) is ~ 55 MΩ/m
- The ratio between the two values is only ~ 2.6 (it would have been 50 in the case of the classical resistive-wall theory!)

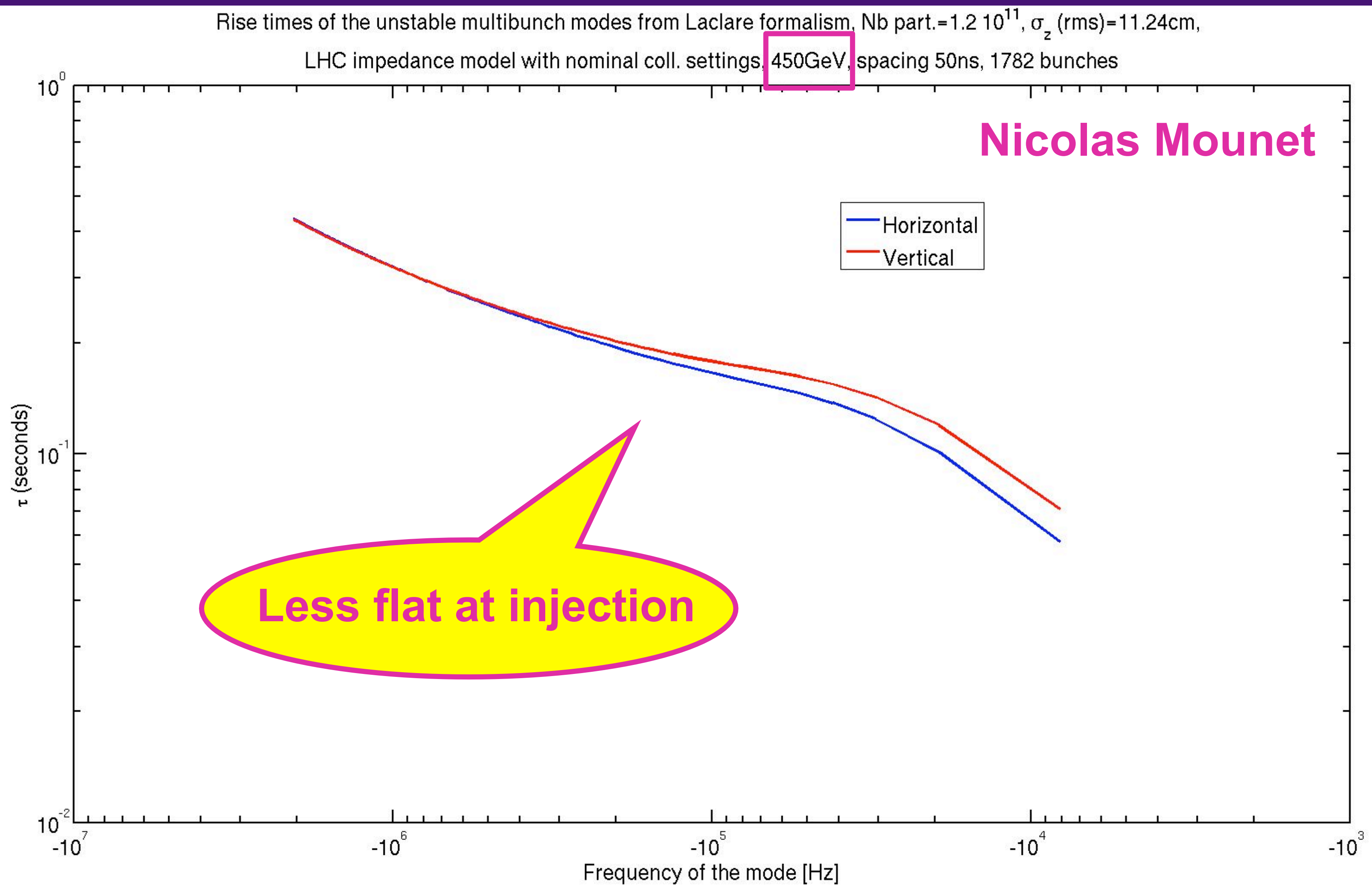
Of importance for the transverse feedback:
if the gain of the power amplifier rolls off rapidly when approaching 20 MHz, there might be some problems there… (seems OK)

Elias Métral, Conceptual Design Review LHC Phase II Collimation, CERN, 02-03/04/2009 6/17

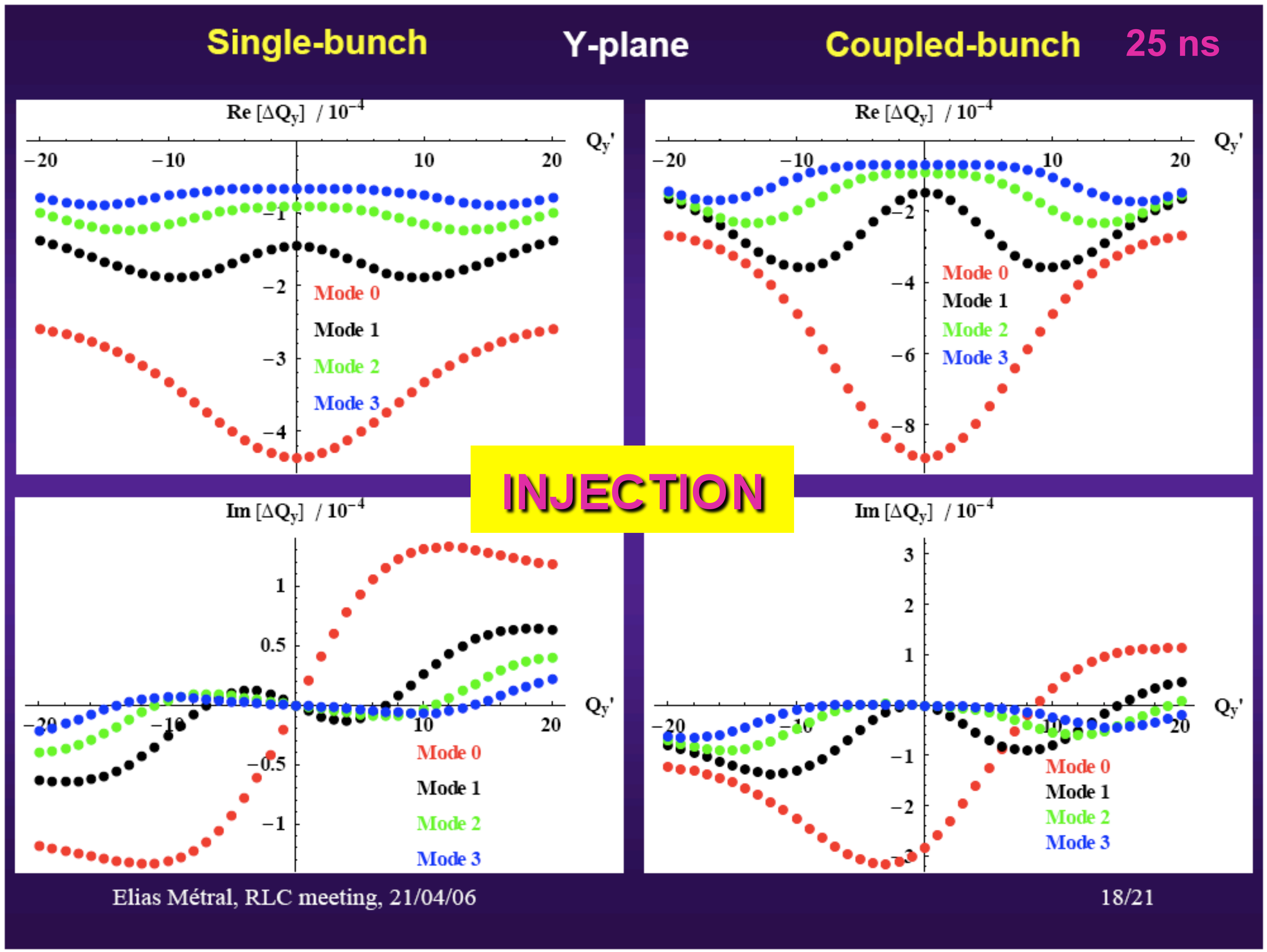
PAST WORK AND PREDICTIONS (16/22)



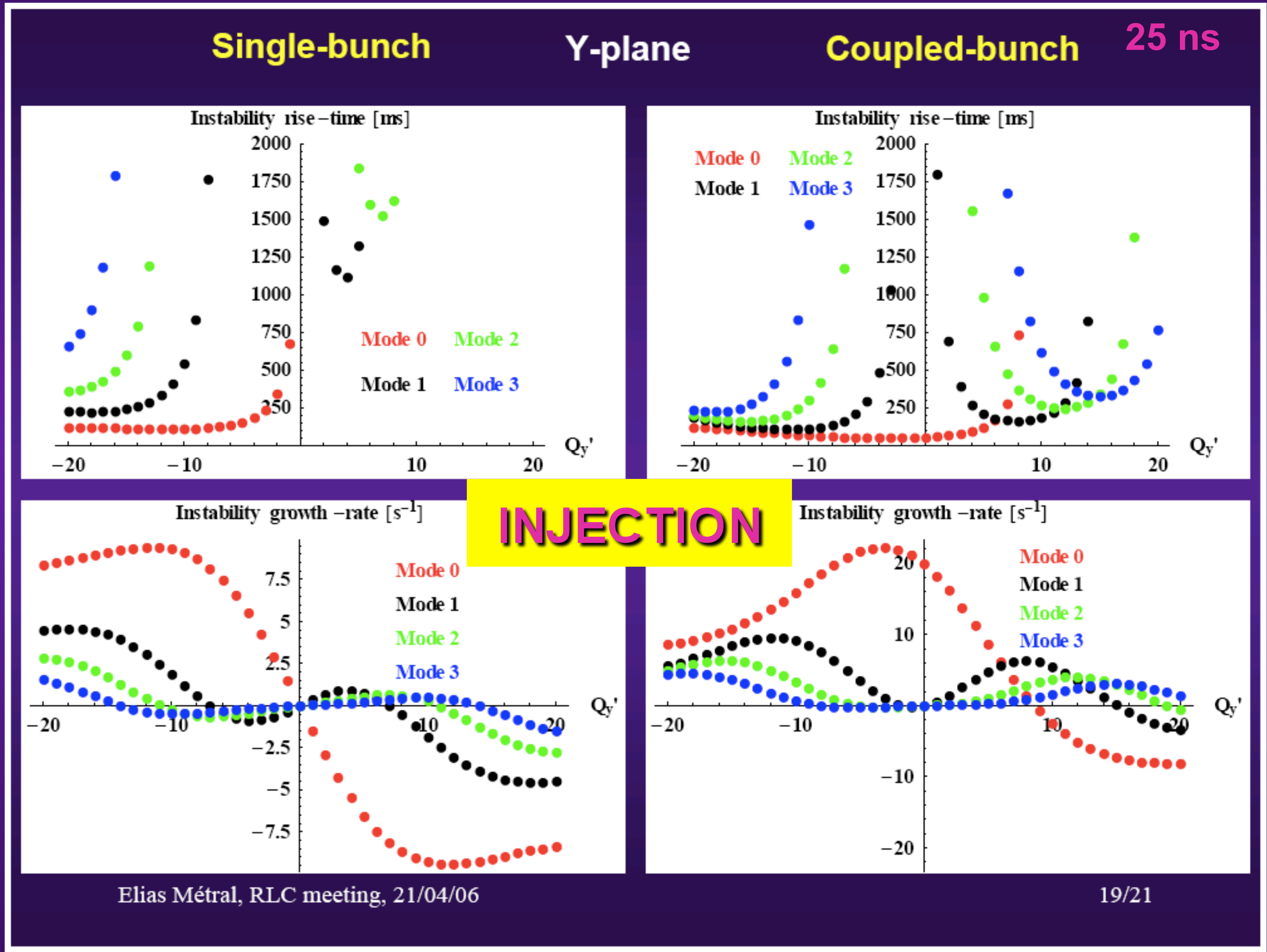
PAST WORK AND PREDICTIONS (17/22)



PAST WORK AND PREDICTIONS (18/22)



PAST WORK AND PREDICTIONS (19/22)

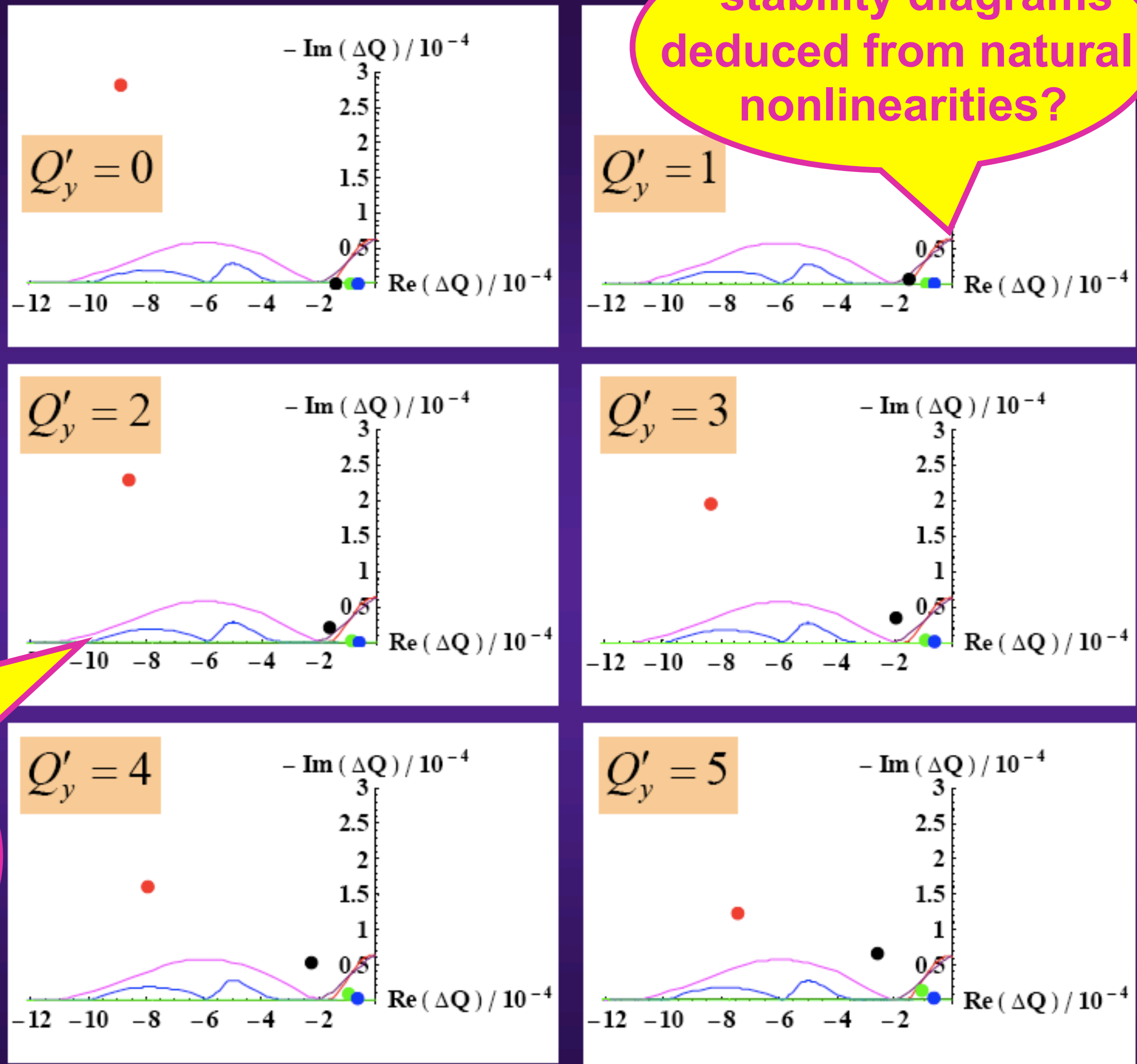


PAST WORK AND PREDICTIONS (20/22)

Stability diagrams (Y-plane)

INJECTION

Mode 0
Mode 1
Mode 2
Mode 3



~ stability diagrams deduced from natural nonlinearities?

One additional complexity: Shift of the stability diagrams due to SC (2D) => Some additional LD comes from the long. profile (Ng)

Elias Métral, RLC meeting, 21/04/06 20/21

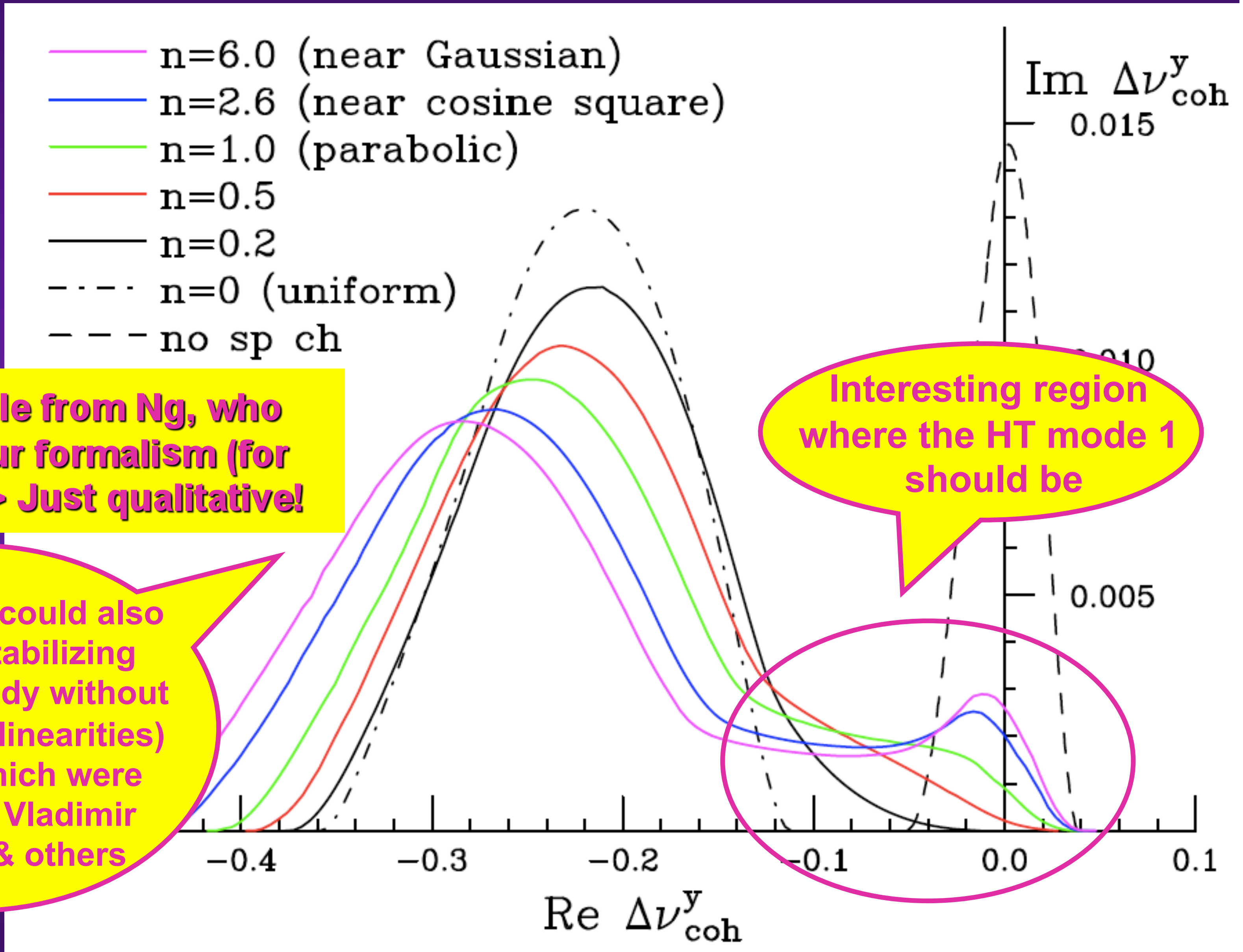
PAST WORK AND PREDICTIONS (21/22)

From the LHC design report (page 104)

tail modes with $m > 0$ are smaller than or equal to 0.85×10^{-4} in absolute value. The natural nonlinearities of the magnetic lattice still compatible with an adequate dynamic aperture correspond to a maximum detuning of 2×10^{-3} at $6\,\sigma$ [39], *i.e.*, about 0.56×10^{-4} at $1\,\sigma$. This provides Landau damping of coherent modes having

=> If the natural nonlinearities are very small (and DA better) and if the transverse emittances are smaller than nominal => We could add more Landau damping (see later), which could relax a little bit the constraint on the low chromaticity (not to excite too much the HT mode 1)

PAST WORK AND PREDICTIONS (22/22)



One example from Ng, who extended our formalism (for Fermilab) => Just qualitative!

In fact there could also be some stabilizing effects (already without external nonlinearities) for HOM which were studied by Vladimir Kornilov & others

CURRENT WORK AND PREDICTIONS (1/3)

- Nicolas extended the HEADTAIL code to multi-bunch operation (to study any filling pattern, which is not easily computable)
- For the case of equi-populated equi-spaced bunches => Similar results as Sacherer or Laclare (which we used in the past)
- Several predictions made and in particular for a train of 36 bunches both at injection energy and 3.5 TeV (and also for LD) => Nicolas could present all his results at some point
- 1st MD last Sunday at both injection and 3.5 TeV => Data being analyzed
- Some interesting info => The instability rise time is not that different (within a factor ~ 2-3) for a single train of 36 bunches spaced by 50 ns and all the machine (~ 1700 bunches, if possible…) => It will/should be a bit more critical when injecting more bunches (or using trains of 72 instead of 36, or 108 instead of 72, or 144 instead of 108) but not that much!

CURRENT WORK AND PREDICTIONS (2/3)

- **Some numbers for 3.5 TeV (from Nicolas):**

  - For one train of 36 50ns-bunches, rise times around 0.9 s in x, between 1 s and 1.4 s in y.
  - For a fully filled machine (1782 50ns equidistant bunches), rise times around 0.4 s in x and 0.6 s in y (~ a factor two below).
  - The later barely change when considering a linear bucket and dipolar impedance only, which can be compared to Sacherer formula (0.38 s in x, 0.47 s in y) and Laclare's formalism (0.36 s in x, 0.45 s in y).

CURRENT WORK AND PREDICTIONS (3/3)

- **Some numbers for 450 GeV (from Nicolas):**

  - For a fully filled machine (1782 50ns equidistant bunches), dipolar impedance only and linear bucket, rise times around 60 ms in x and 70 ms in y, tune shifts of ~ $-6\ 10^{-4}$ (Laclare: resp. 58 ms, 71 ms and $-8\ 10^{-4}$, and Sacherer: resp. 61 ms, 75 ms and $-7\ 10^{-4}$). Low frequency mode along the bunch train.
  - For one train of 36 50ns-bunches, rise times significantly higher for the last (most critical) bunch (~150 ms in x, ~ 250 ms in y), but also depend on the position along the train (larger at the head of the train) → quite different from situation at 3.5TeV.
  - Difference between 480b physics scheme and 1020b scrubbing scheme: 1020b seems significantly more critical, and the modes along the bunch train seem quite different between the two cases (low frequency mode along the full train for 1020b, higher frequency mode in each batch for 480b).

As suspected by Gianluigi => Importance of the TD gain adjustment at high *f* !

RECOMMENDATIONS AND FUTURE WORK (1/2)

- **RECOMMENDATIONS:**
  - Keep the chromaticity as low as possible (for HT mode 1 or HOM) both at low and top energy
  - TD work on the issue of the gain over 20 MHz (for 25 ns => 10 MHz for 50 ns) as it should normally rapidly roll off
  - In case some more LD would be needed at injection (i.e. if we can not continue and reduce the chromaticity), we could perhaps use the octupoles with very low current (few A => min and max current being followed up with Massimo) or the octupolar spool-pieces for the local b4 correction of the SC dipoles (also followed up with Massimo)
  - Comparison with some observations in 2011 => Seems in relatively good agreement (at least qualitatively) up to now… To be followed up to have more quantitative results (MDs etc.)

RECOMMENDATIONS AND FUTURE WORK (2/2)

- **FUTURE WORK**
  - **Follow-up and close collaboration with OP**
  - **Nicolas**
  - **Raymond Wasef**
    - **The theoretical curves for Landau damping have never been benchmarked with a simulation code => Plan to do this with HEADTAIL**
    - **Check in particular the effect of the transverse beam profile**