Impedance and beam stability lessons learned form the 2010-2011 operation of the LHC and their implications for the HL-LHC project

Elias Métral (25 + 5 min talk, 46 slides)

Many thanks to all the people who worked on these subjects in the past (at CERN or elsewhere) and in particular to Benoit Salvant, Nicolas Mounet and Hugo Day for the recent studies

- **Introduction and predictions**
- **2010 and 2011 observations**
- **Benchmark of the theoretical stability diagram with HEADTAIL code for a Gaussian transverse bunch profile**
- **Current issue: heating here and there…**
- **Future issues expected: heating (?) + Loss of transverse Landau damping (from octupoles) for TCBI mode - 1**
- **Conclusion**

INTRODUCTION AND PREDICTIONS (1/11)

- **REMINDER:** (At least) 5 impedances are needed! => L + H dipolar + H quadrupolar + V dipolar + V quadrupolar!

- **Predictions**
  - **Longitudinal imaginary effective impedance:**

    PREDICTION

    - **Injection and 7 TeV: ~ 0.09 Ω**

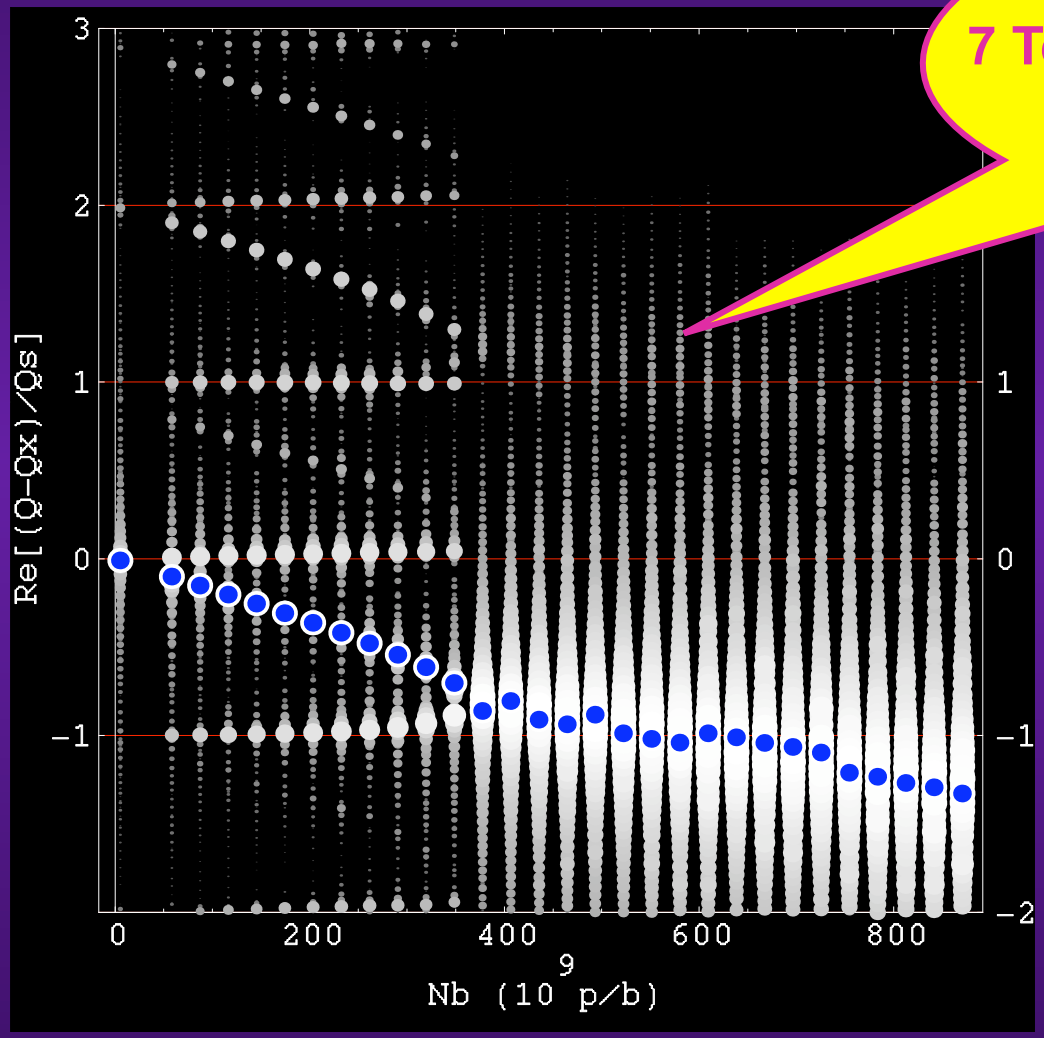
  - **Transverse imaginary effective impedance (dip + quad):**

    PREDICTION

    - **Injection: ~ 3 MΩ/m**
    - **3.5 TeV: ~ 7.5 MΩ/m**
    - **7 TeV: ~ 30 MΩ/m (i.e. > SPS!)**

Dominated by collimators

INTRODUCTION AND PREDICTIONS (2/11)



HEADTAIL simulations at 7 TeV => N_b^{th} ~ 3.5E11 p/b, i.e. a factor ~ 3 > nominal (for 0 chroma.)

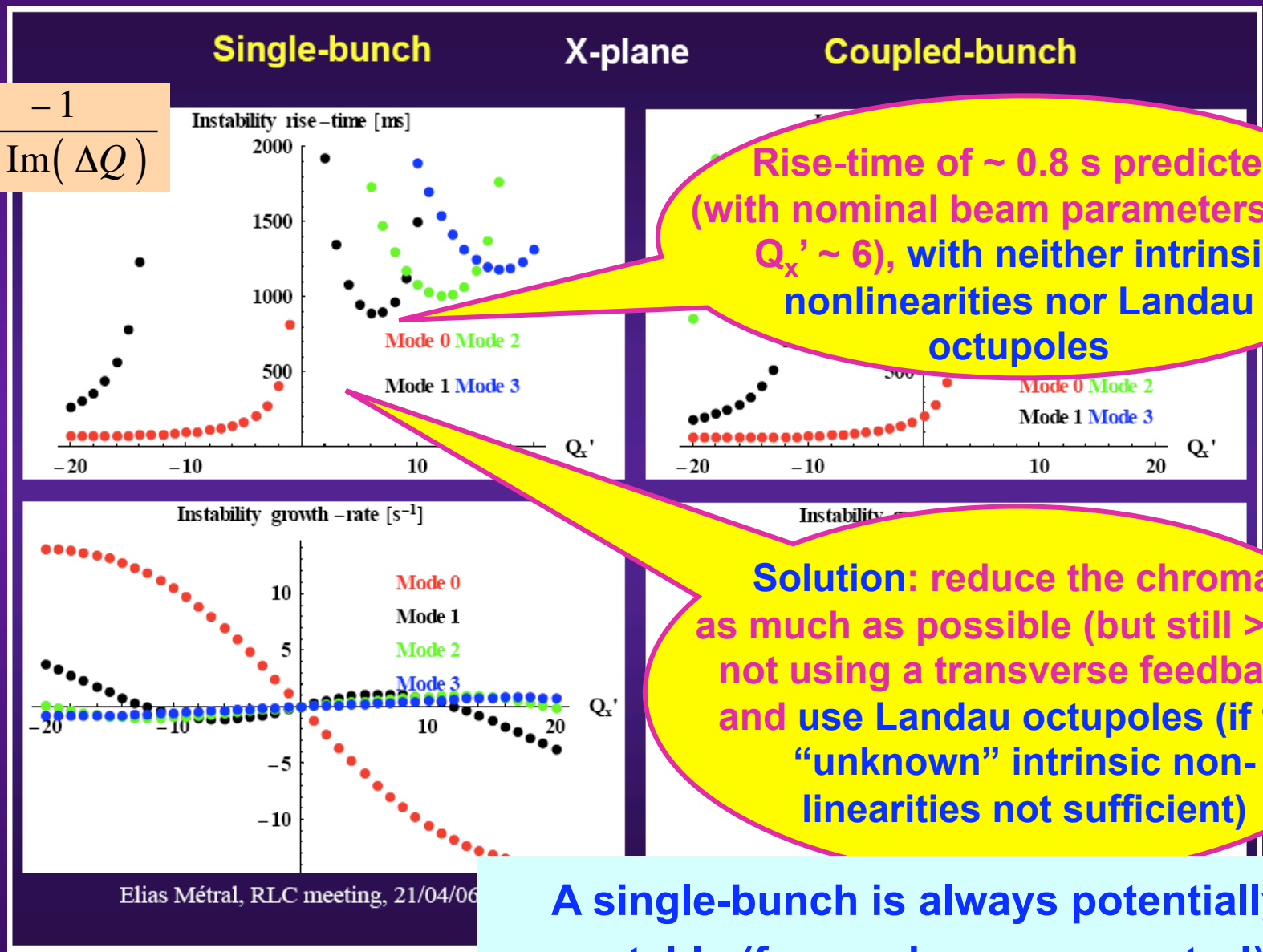
REMINDER

- **Contrary to other machines, the TMCI is more critical at top energy than at injection energy (factor ~ 7 there and also at 3.5 TeV) due to the fact that the transverse impedance increases with energy (collimators!)**

INTRODUCTION AND PREDICTIONS (3/11)

BUT… Chromaticity is never 0 in a machine => Example at 7 TeV

$$\tau = \frac{-1}{\omega_0 \, \mathrm{Im}(\Delta Q)}$$



Rise-time of ~ 0.8 s predicted (with nominal beam parameters and $Q_x' \sim 6$), with neither intrinsic nonlinearities nor Landau octupoles

Solution: reduce the chroma. as much as possible (but still > 0, if not using a transverse feedback) and use Landau octupoles (if the "unknown" intrinsic non-linearities not sufficient)

A single-bunch is always potentially unstable (for any beam parameter!)

INTRODUCTION AND PREDICTIONS (4/11)

$\Delta Q^{1\sigma}_{oct,spread} = 1.35 \times 10^{-4}$

TCBI mode 0 being damped by the transverse damper (which works very well!)

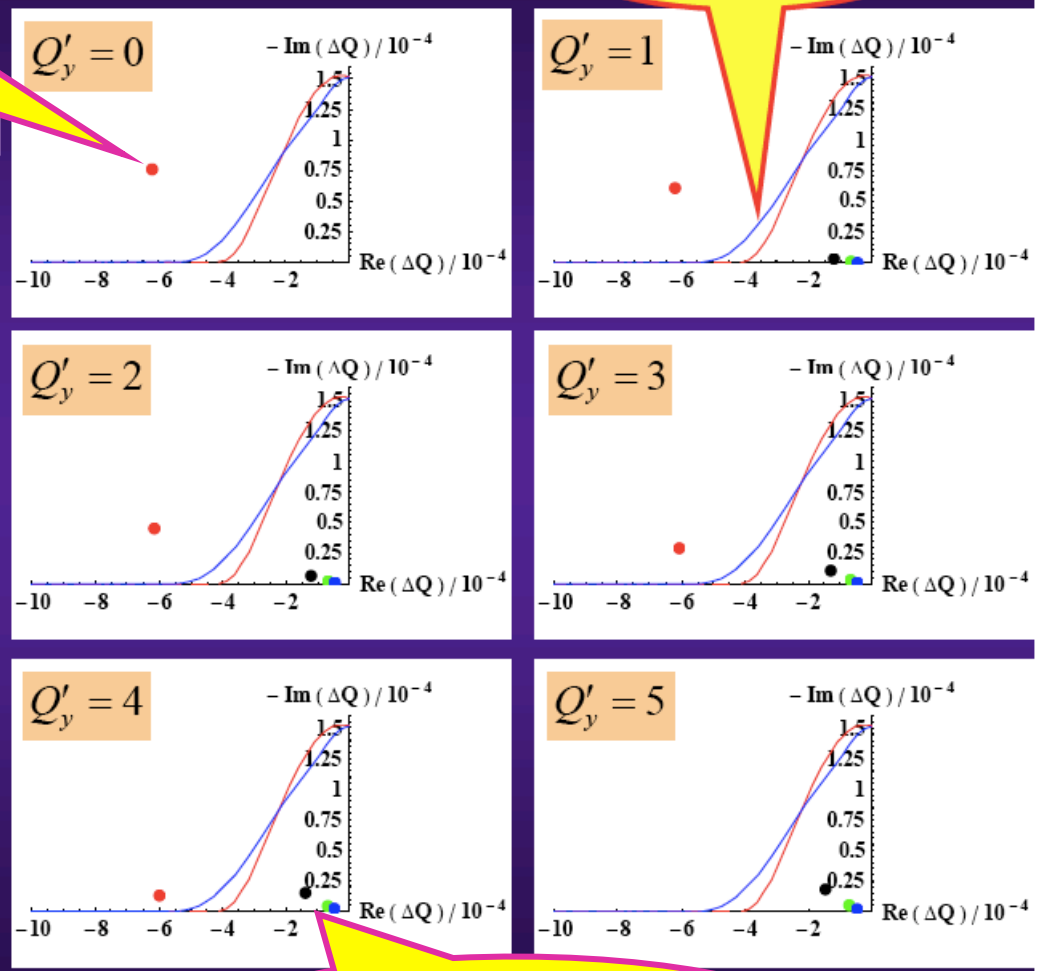
EFFECT OF CHROMATICITY

From Landau octupoles at max.

$Q'_{x,y} = 1 \Rightarrow f_{\xi_{x,y}} \sim 40$ MHz

TOP ENERGY

Reminder: Stability diagrams are proportional to transverse emittance => More critical for smaller emittance!



Mode 0
Mode 1
Mode 2
Mode 3

Elias Métral, LTC, 06/12/06

19/28

Higher order modes to be Landau damped!

INTRODUCTION AND PREDICTIONS (5/11)

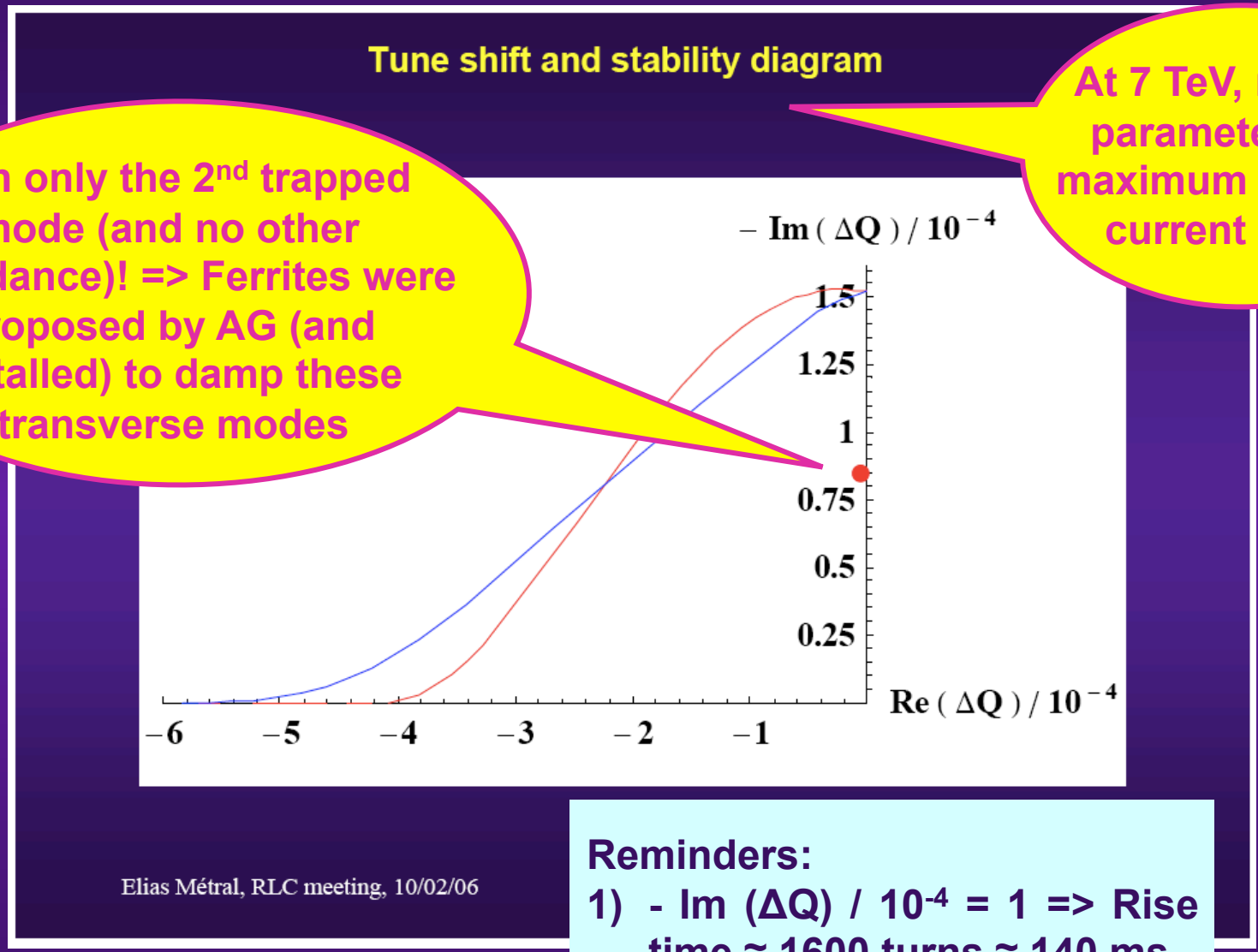
- At lot of effort has been devoted in the past to understand the resistive-wall impedance from the collimators (theory, bench measurements, simulations and beam-based measurements)
- Several equipments were studied also in detail by collaborators: Andrea Mostacci (beam screen), Bruno Spataro (Y-chambers), Rainer Wanzenberg (experiments beam pipe) etc. Many thanks!
- Other possible worries were the trapped modes in particular in the 2-beam (i.e. big) devices such as TCTVB => Was studied in detail by Alexej Grudiev

- AG computed the impedance of transverse modes in the TCTV (W jaw) for a (full) gap of 3 mm
- There are few of them
- The 2 most critical trapped modes are

$f_{r1} = 0.362$ GHz	$Q_1 = 1700$	$R_{y1} = 152.8$ MΩ/m
$f_{r2} = 0.443$ GHz	$Q_2 = 1080$	$R_{y2} = 173.8$ MΩ/m

Elias Métral, RLC meeting, 10/02/06 1/7

INTRODUCTION AND PREDICTIONS (6/11)



With only the 2nd trapped mode (and no other impedance)! => Ferrites were proposed by AG (and installed) to damp these transverse modes

At 7 TeV, nominal parameters and maximum octupole current (550 A)

Reminders:

1) - Im (ΔQ) / 10^{-4} = 1 => Rise time ≈ 1600 turns ≈ 140 ms
2) => Min. rise-time which can be damped by oct. ≈ 90 ms

INTRODUCTION AND PREDICTIONS (7/11)

- **Stability diagram analyses**
  - **Heavily depends on transverse profiles and their tails**
  - **Planned to check that with the HEADTAIL code (done in summer 2011, see later)**

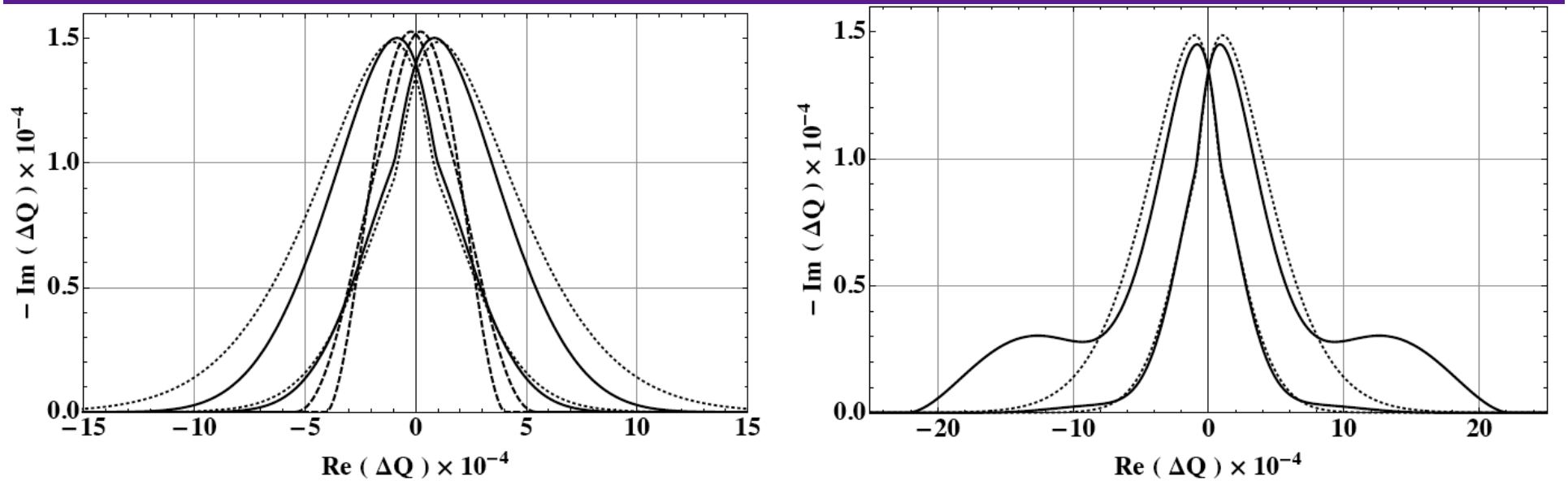


Fig. 4.8. Stability diagrams (for both positive and negative detunings a_0) for the LHC at top energy (7 TeV) with maximum available octupole strength: (Left) for the 2nd order (dashed curves), the 15th order (full curves), and the Gaussian (dotted curves) distribution; (Right) for the Gaussian distribution (dotted curve) and a distribution with more populated tails than the Gaussian (full curve).

INTRODUCTION AND PREDICTIONS (8/11)

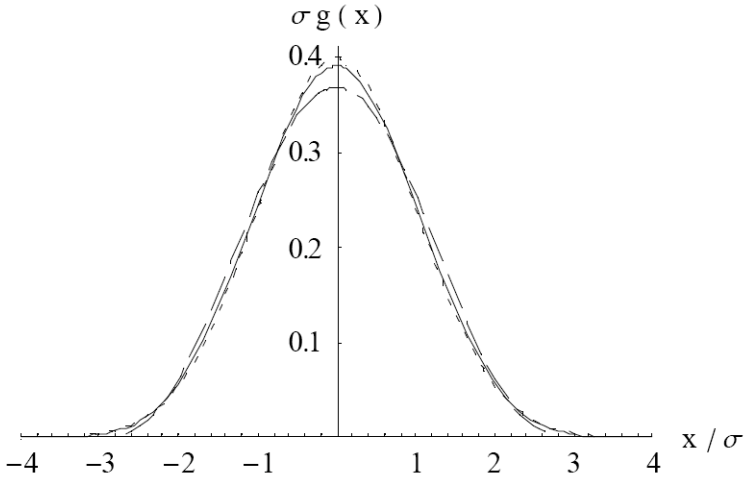


Figure 1: Transverse beam profile for the 15th order distribution (full curve), the quasi-parabolic distribution (dashed curve) and the Gaussian distribution (dotted curve).

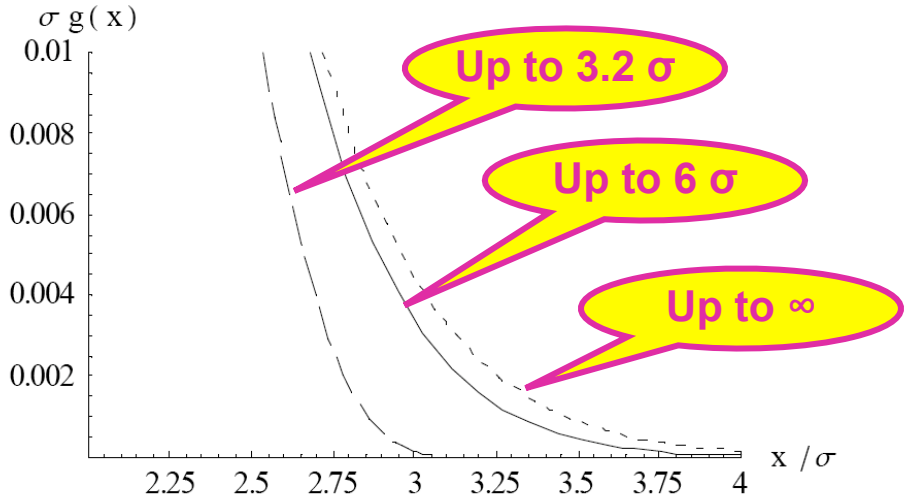
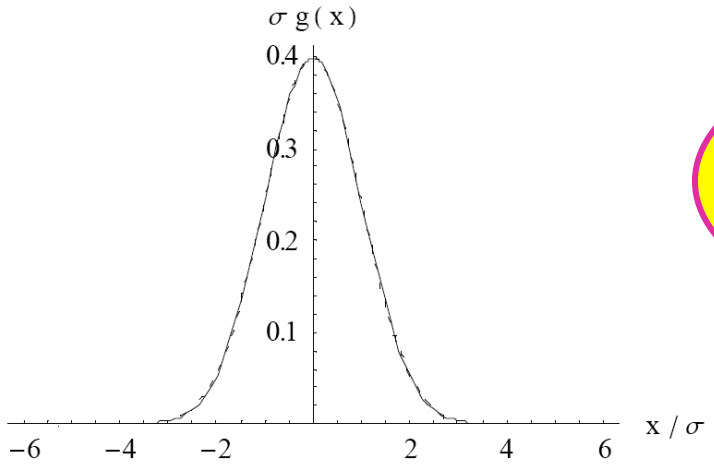


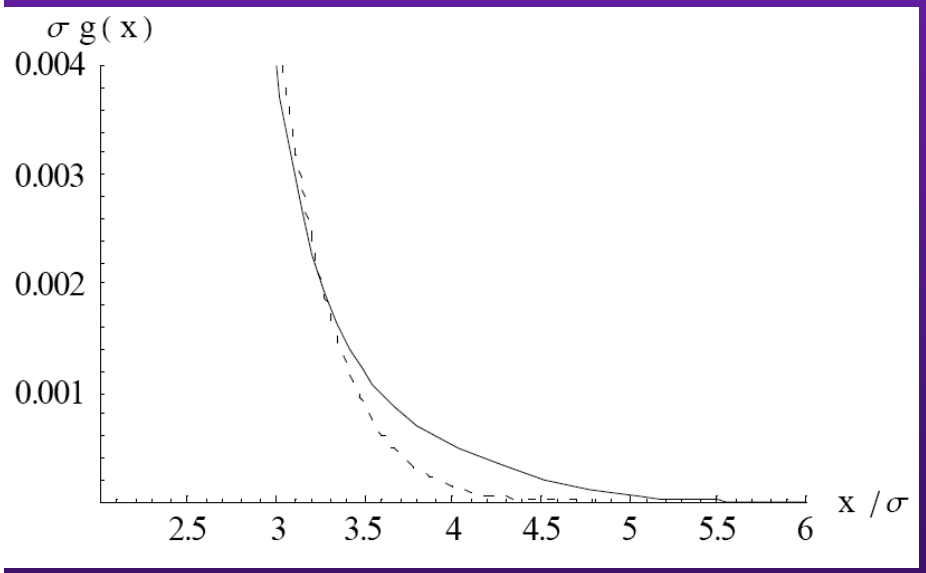
Figure 2: Zoom of the tails of the transverse beam profiles for the 15th order distribution (full curve), the quasi-parabolic distribution (dashed curve) and the Gaussian distribution (dotted curve).

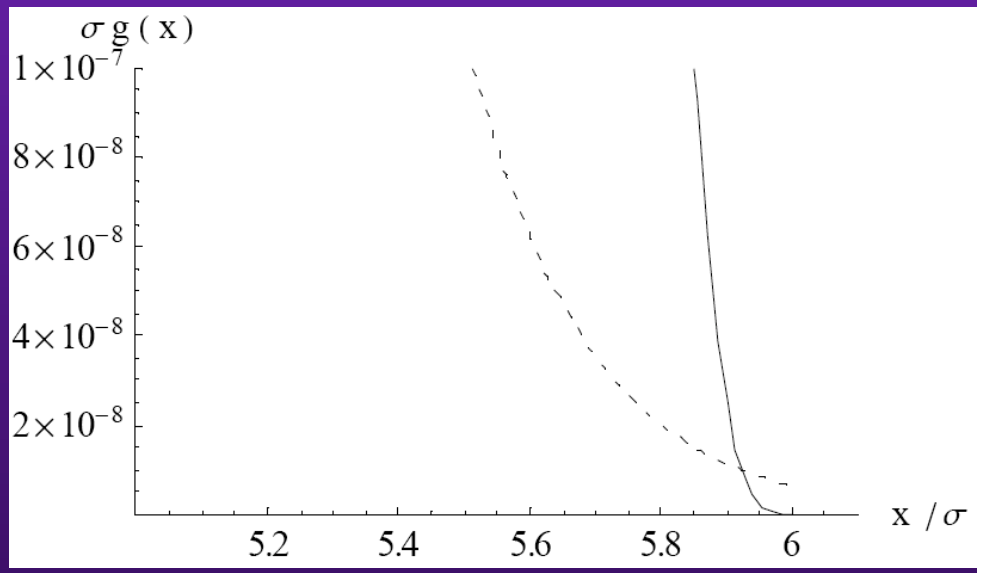
INTRODUCTION AND PREDICTIONS (9/11)



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).





INTRODUCTION AND PREDICTIONS (10/11)

- **Effect of SC at injection:**
  - **Incoherent tune spread: ~ - 1.3E-3 for nominal beam parameters (1.15E11 p/b and 3.5 microm) => If the intensity is higher (~ 1.45E11 p/b at the end of 2011 run) and/or if the transverse emittances are smaller (~ 2-2.5 microm at the end of 2011 run) => The incoherent tune spread was increased to ~ - 3E-3, i.e. close to synchrotron tune**
  - **Reminder: (nominal) incoherent synchrotron tune ~ 5.5E-3**
  - **Shift of the stability diagrams etc. => To be looked at in detail**
- **PHD thesis from Nicolas Mounet (to be defended in January 2012) on the LHC transverse coupled-bunch instability => Extension of the HEADTAIL code to multi-bunch operation**
- **Next step: study in detail the interplay with space charge etc. (collaboration with Alexey Burov and GSI in particular)**

INTRODUCTION AND PREDICTIONS (11/11)

- **ecloud:**
  - **Many studies in the past (Frank Zimmermann et al.) on heat load, fast single-bunch instability (to be cured by high chromaticity) etc.**
  - **Planned to rely on scrubbing run (as mentioned in the LHC Design Report)**

2010 OBSERVATIONS (1/9)

- **Many collective effects observed in 2010:**
  - **1st in Spring: Increasing the intensity / bunch**

  => SBI from impedance: Solved by octupoles (above ~ 2 TeV)
  - **2nd in Summer: Increasing # of bunches and changing Xing angle**

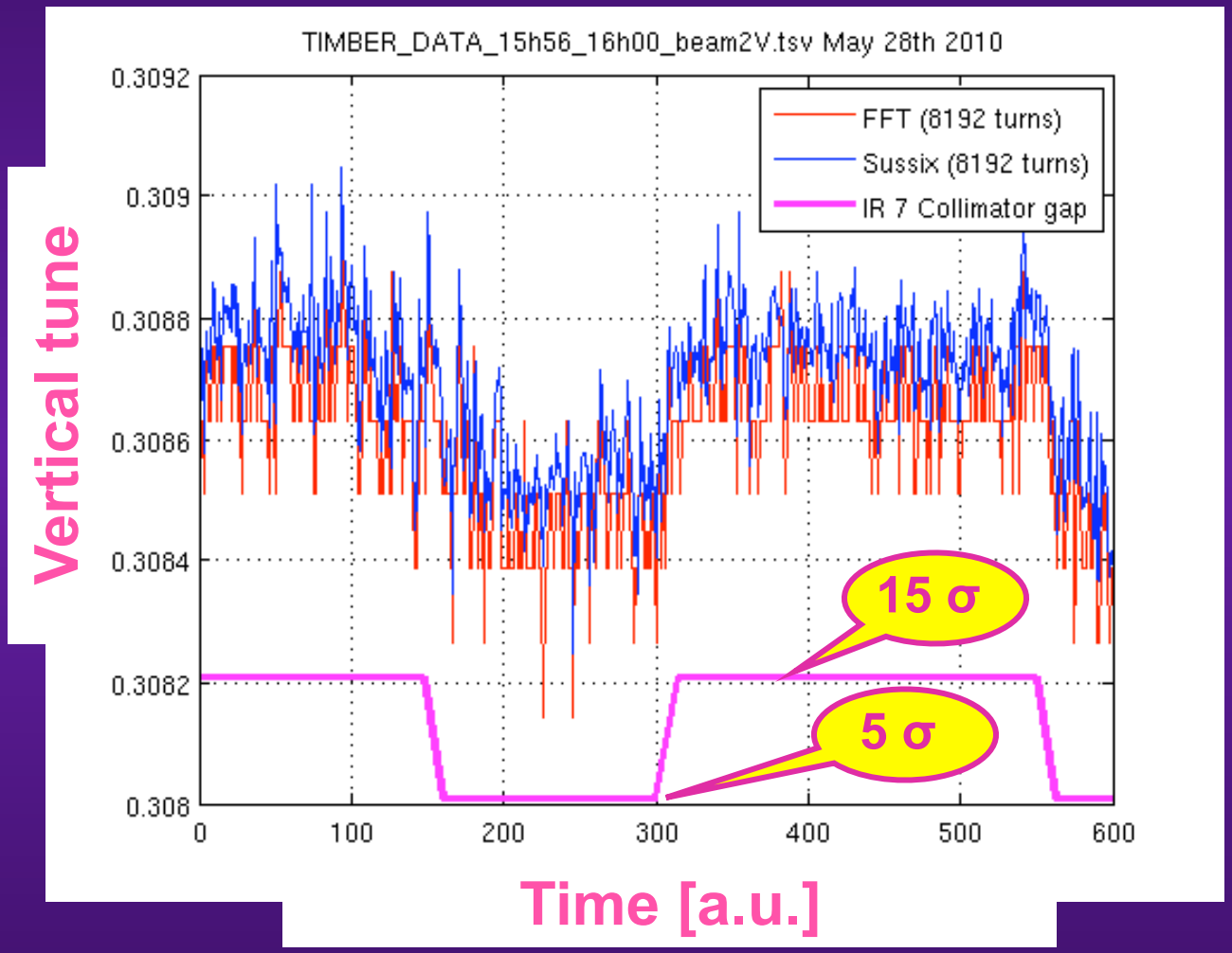
  => Beam-beam: HO alone OK but LR?
  - **3rd in Autumn: Reducing the batch spacing (150, 75 and 50 ns)**

  => Ecloud: 50 ns is the most critical

  => 50 ns scrubbing foreseen at the beginning of 2011

2010 OBSERVATIONS (2/9)

Moving IN and OUT all IR7 collimators at 450 GeV/c



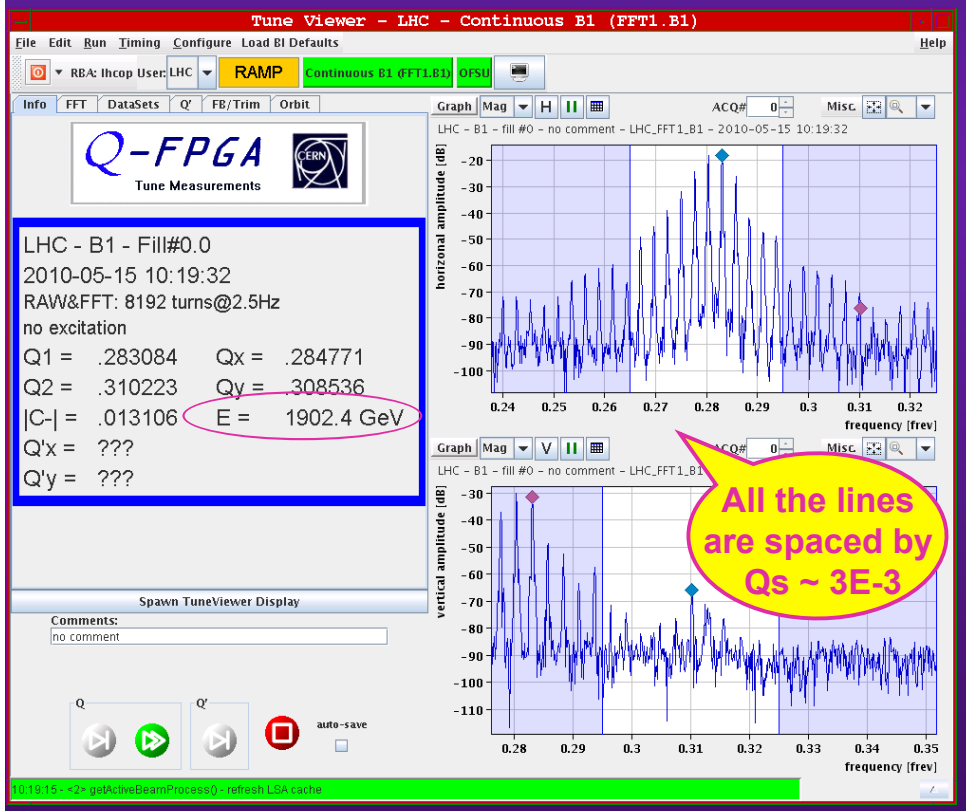
- ΔQ_y (meas.) ~ - 2.4 10^{-4}
- ΔQ_y (impedance model) ~ - 2.0 10^{-4}

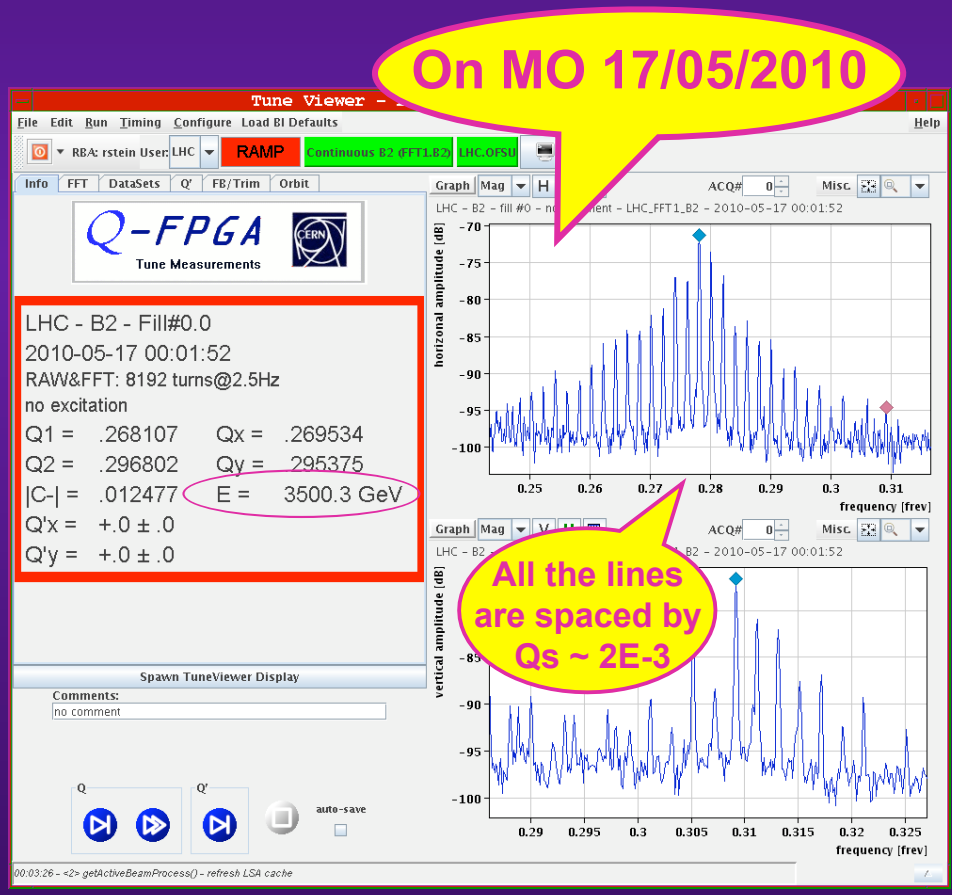
2010 OBSERVATIONS (3/9)

- A 1st ramp was tried with a single-bunch of ~ 1E11 p/b (on both B1 and B2) on SA 15/05/2010

=> Bunch unstable at ~ 1.8 TeV/c for B1 and ~ 2.1 TeV/c for B2

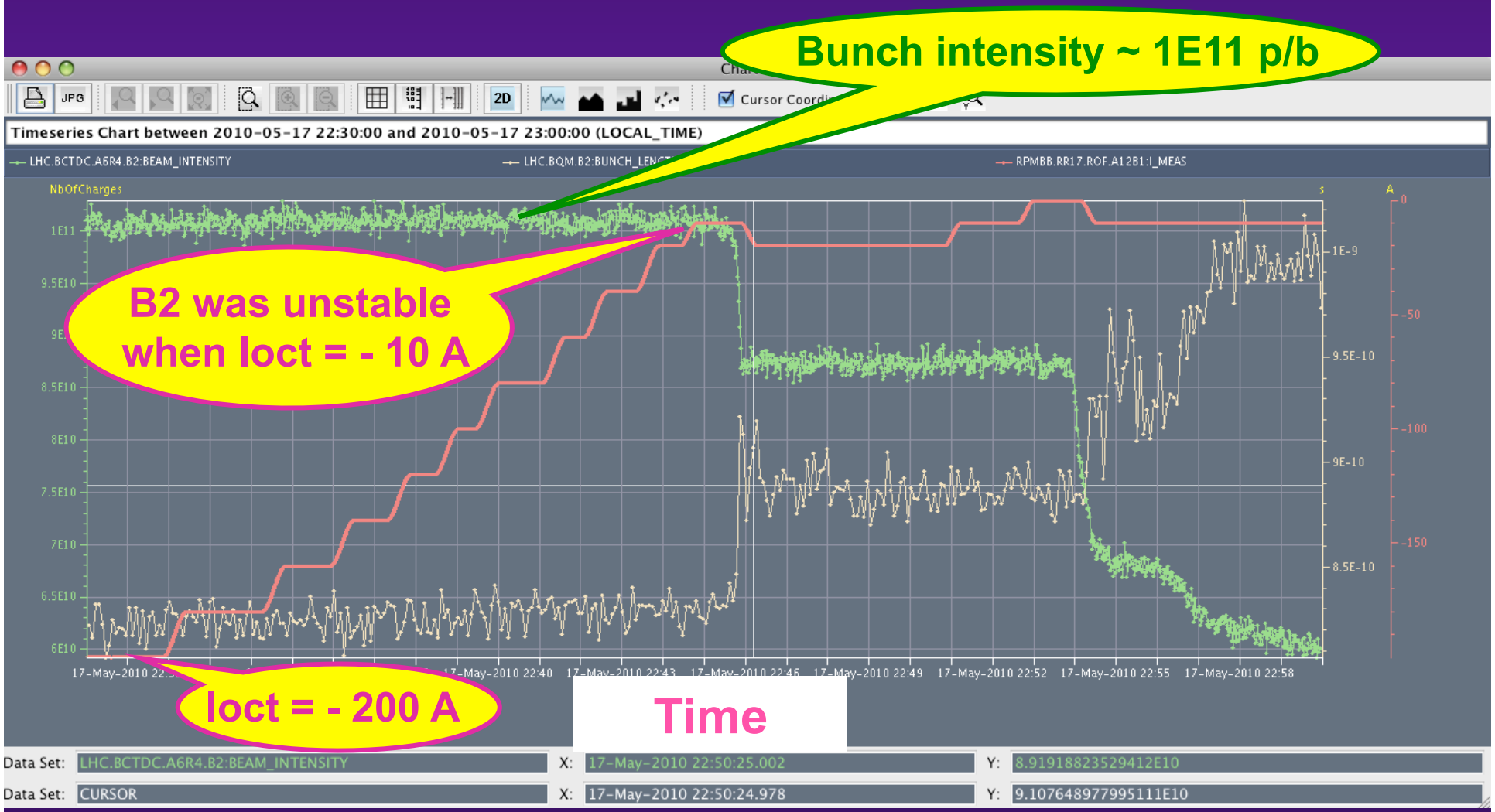
=> Famous "Christmas tree"





2010 OBSERVATIONS (4/9)

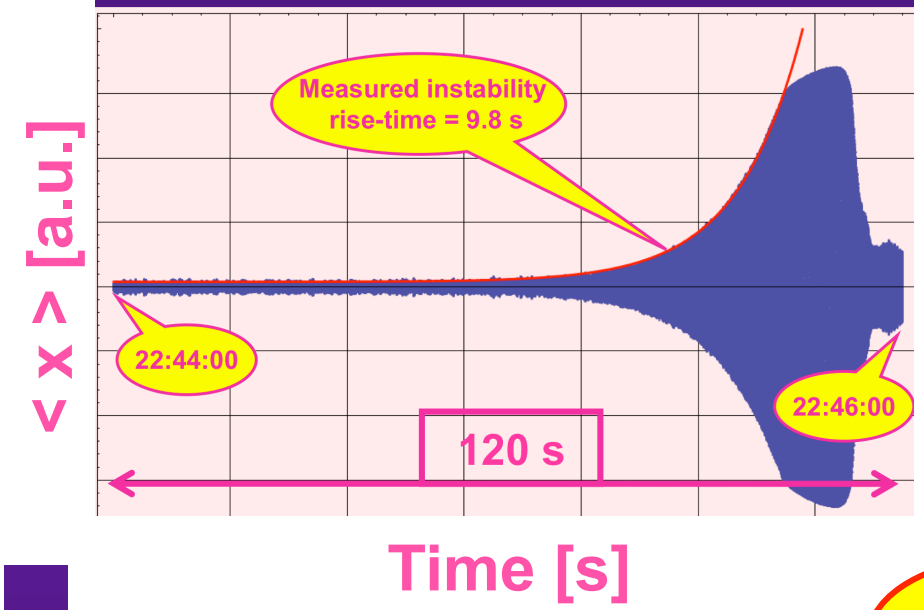
- Study on MO 17/05/10 at 3.5 TeV (acceleration with some octupole current, - 200 A ⇔ K3 = - 12 at 3.5 TeV, and then reduction by steps)



2010 OBSERVATIONS (5/9)

MEASUREMENTS

(17/05/2010 at 3.5 TeV)

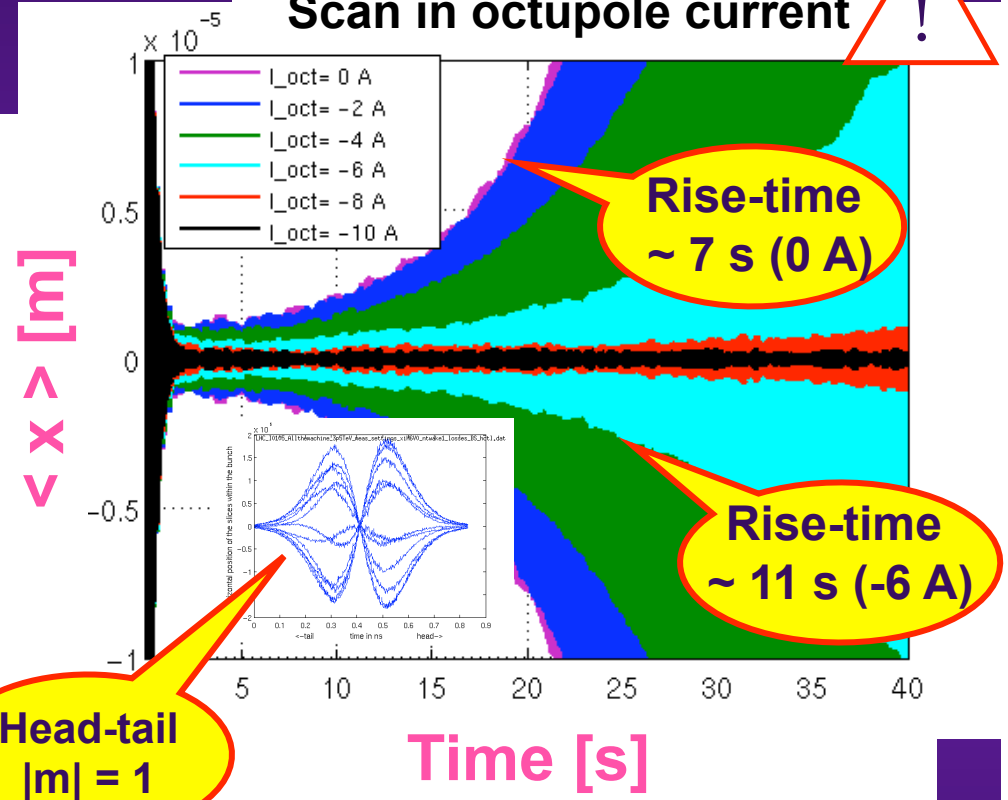


SIMULATIONS

All loct should be × by 2 (error found in HEADTAIL), Oct. 2011

!

Scan in octupole current

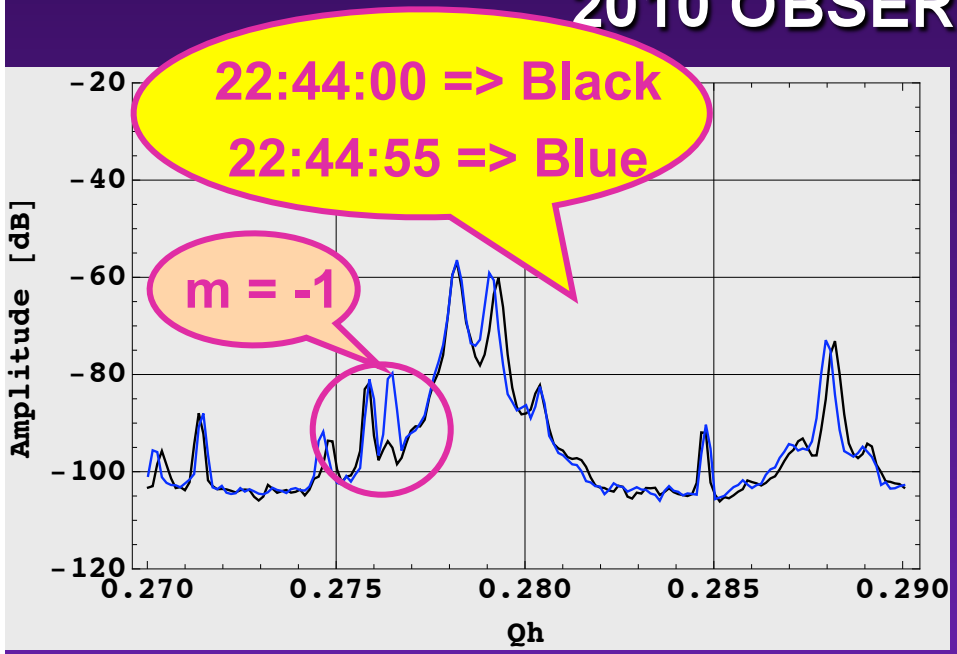


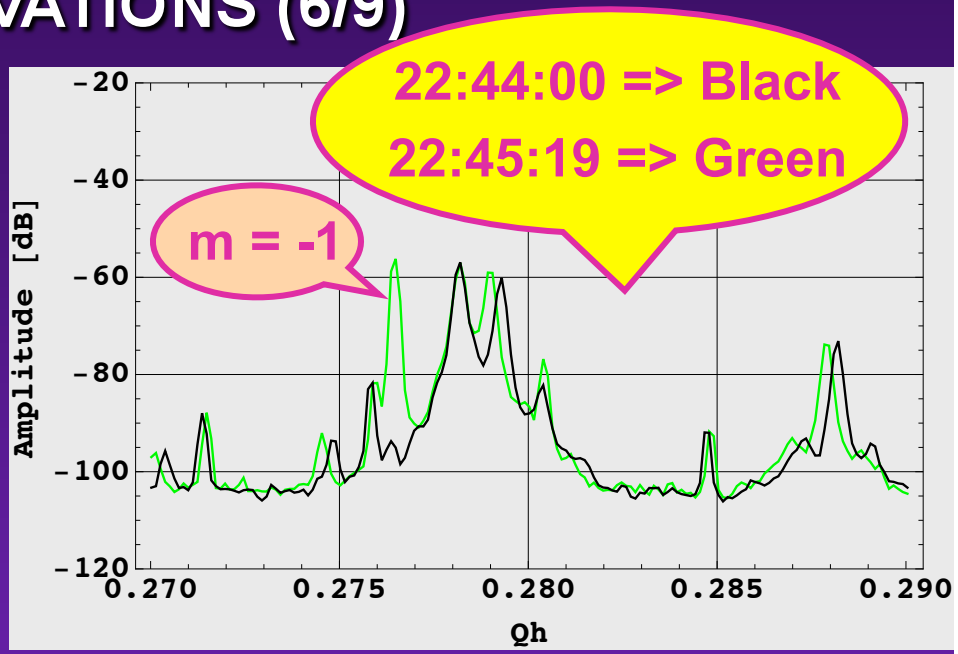
Head-tail |m| = 1

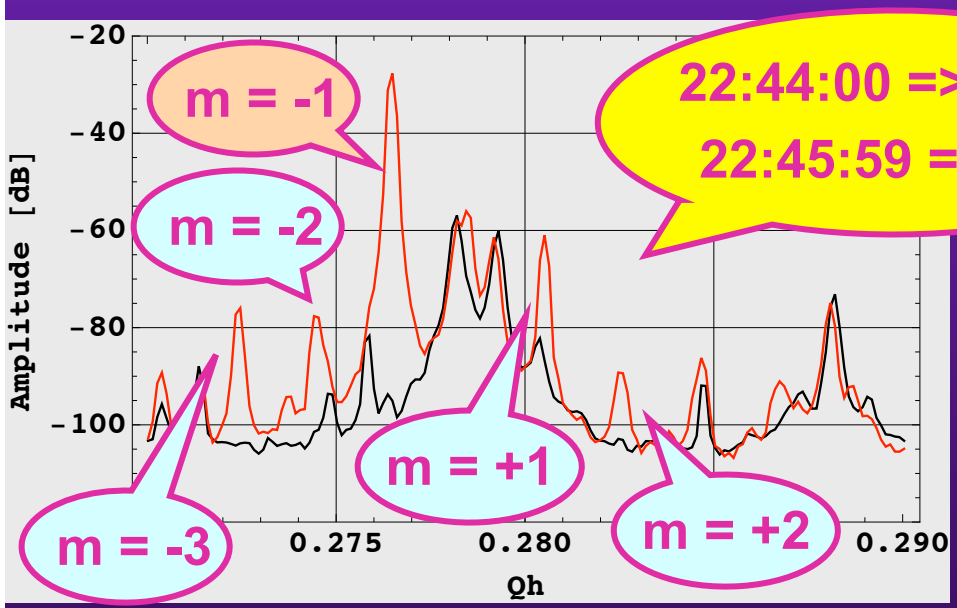
- Unstable bunch for I_{oct} = - 10 A => Rise-time ~ 10 s (with Q' ~ 6, epsx ~ 5 μm? as doubt on meas.)
- Bunch was stable for I_{oct} = - 20 A => -20 A < I_{oct} for stability < - 10 A

- Unstable bunch for I_{oct} > -10 A => Rise-time ~ 11 s for I_{oct} = - 6 A (with Q' ~ 6, epsx = 3.75 μm)
- Stable bunch for I_{oct} ~ -10 A

2010 OBSERVATIONS (6/9)







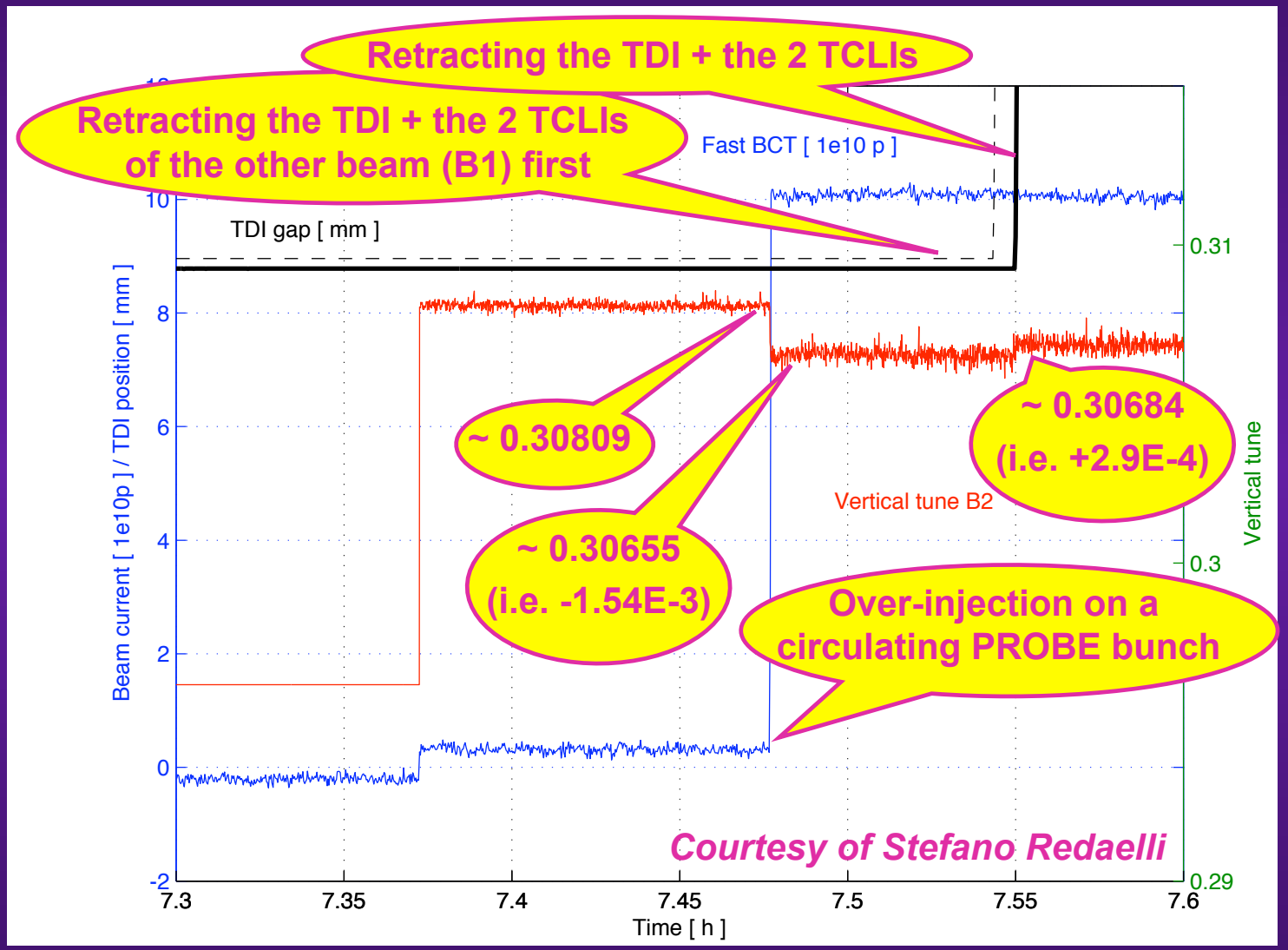
- **MEASUREMENTS => Mode m = -1 (at - Qs from the tune) clearly grows up alone (Qs ~ 2E-3) and the other head-tail modes follow afterwards**

2010 OBSERVATIONS (7/9)

- From LLD, Elena Shaposhnikova et al. estimated the longitudinal imaginary effective impedance to ~ 0.09 Ω (i.e. the predicted value, see slide 2!)
  - Instabilities observed at the beginning of the 2010 run with more critical parameters than nominal => Longitudinal blow-up used (SPS and LHC)
  - New theory from Alexey Burov being discussed

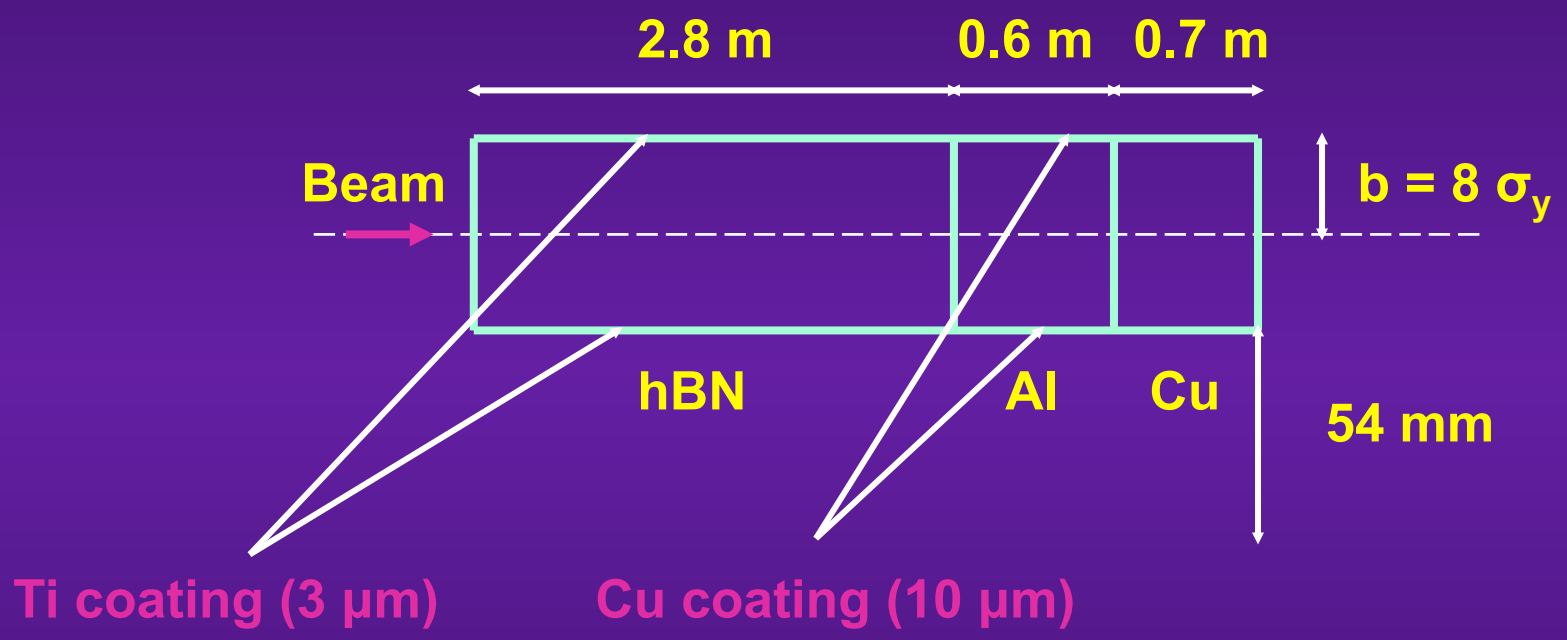
- In summary: (Very) good agreement between predictions and (first) measurements… EXCEPT 1 measurement: transverse coherent tune (from TDI + 2 TCLI) seems to be ~ 2 times larger than predicted

2010 OBSERVATIONS (8/9)



2010 OBSERVATIONS (9/9)

TDI



- **Question raised:** Was the Ti coating damaged? Reminder: Without the Ti coating, a higher transverse coherent tune shift by a factor ~ 3.5 is expected… To be followed up

2011 OBSERVATIONS (1/13)

- As the TCBI are more critical than the SBI, we soon needed to put octupoles at lower energies than ~ 2 TeV. Increasing the number of bunches even more and using very small emittances (< 2 microm), the octupoles'current needed to be increased earlier and earlier in the ramp, until we finally reached injection
- What happened at injection is not understood yet as some transverse BU was often observed for some of the injected batches => Seems there are some transient effects. To be followed up (but not a pb anymore for the moment)
- At the end of the 2011 run, we used the following octupoles' current: - 6 A at injection and - 200 A at 3.5 TeV/c => This corresponds to:

450 GeV/c

$$\Delta Q^{1\sigma}_{oct,spread} \approx 1.35\times10^{-4} \times \frac{6}{550} \times \left(\frac{7000}{450}\right)^2 \times \frac{2}{3.75} \approx 1.9\times10^{-4}$$

3.5 TeV/c

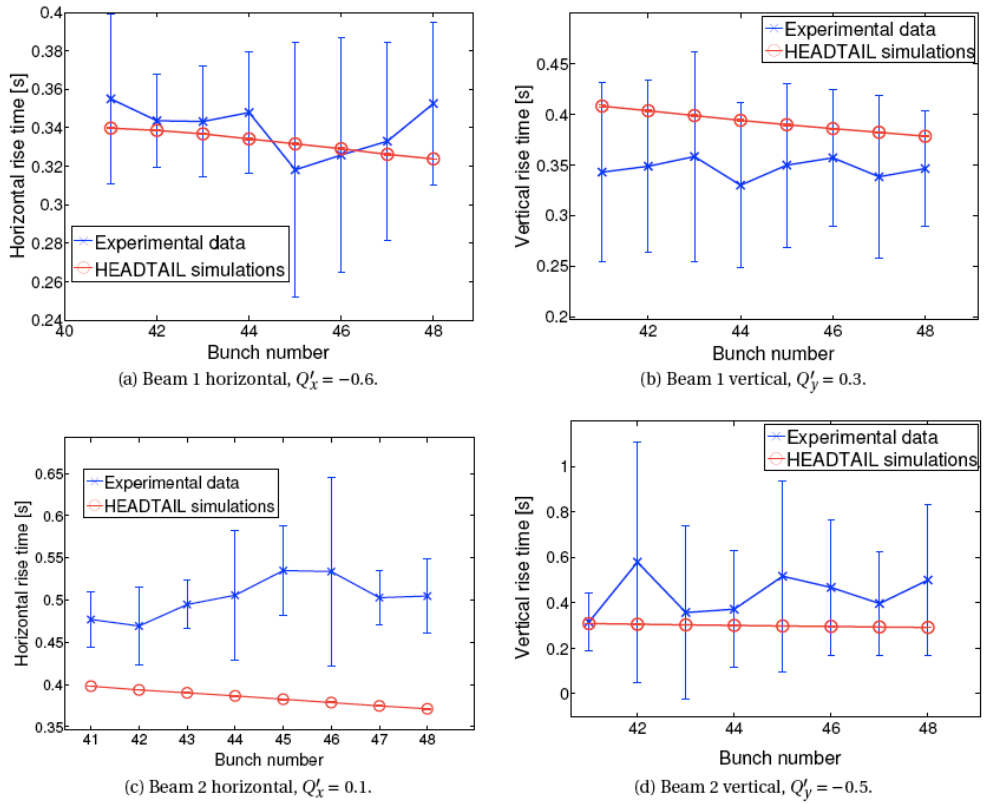
$$\Delta Q^{1\sigma}_{oct,spread} \approx 1.35\times10^{-4} \times \frac{200}{550} \times \left(\frac{7000}{3500}\right)^2 \times \frac{2.5}{3.75} \approx 1.3\times10^{-4}$$

2011 OBSERVATIONS (2/13)

- We made MDs to benchmark our predictions for the transverse coupled instabilities at injection and top energy => A (very) good agreement was obtained at 450 GeV/c (see below) while some discrepancies (~ 2-3 times worse in measurements) were observed at 3.5 TeV/c (believed to be due to bad estimates of the chromaticities) => To be followed up

Examples for 450 GeV/c

Nicolas Mounet's PHD thesis (being written) => Many nice results inside!



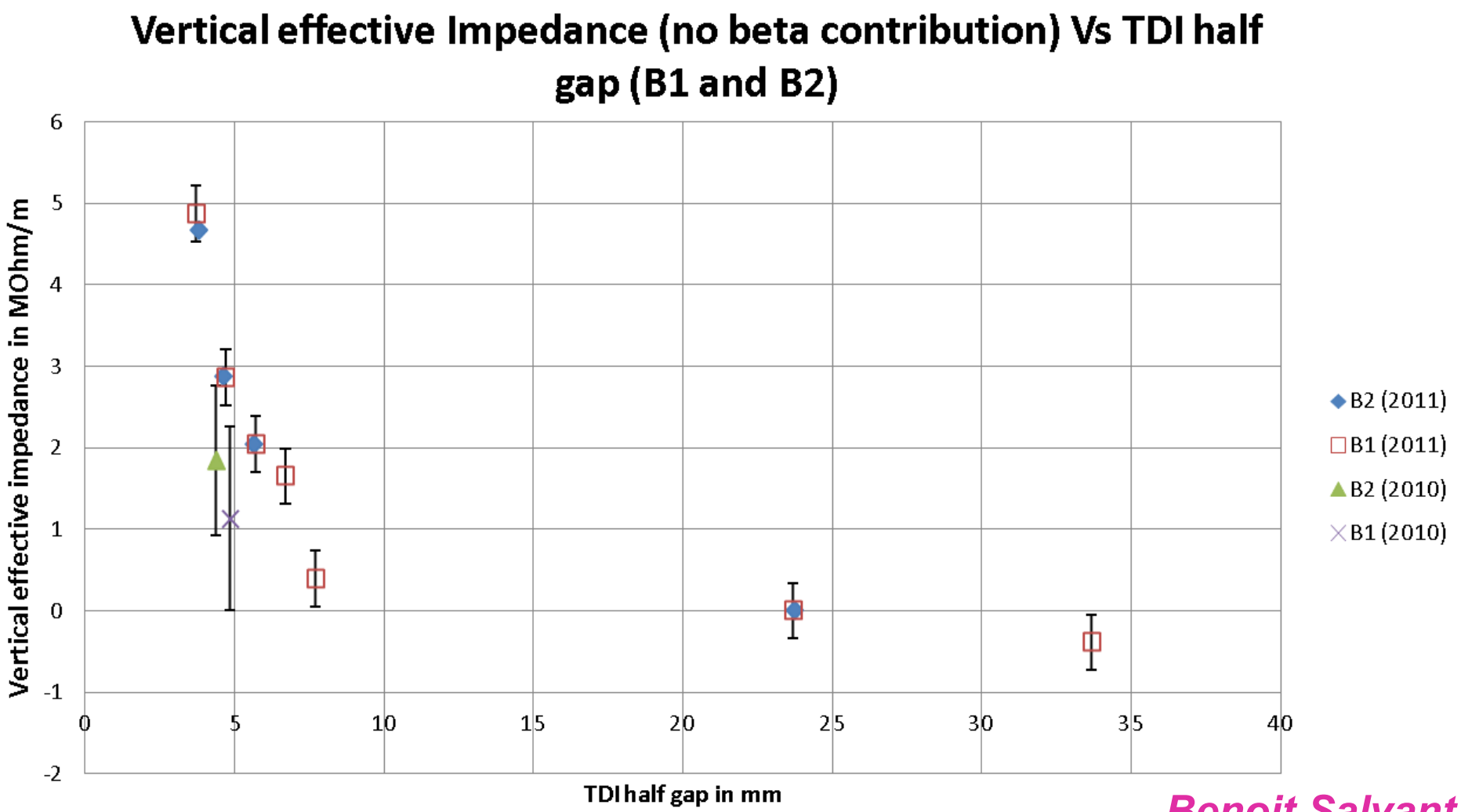
(a) Beam 1 horizontal, $Q'_x = -0.6$.
(b) Beam 1 vertical, $Q'_y = 0.3$.
(c) Beam 2 horizontal, $Q'_x = 0.1$.
(d) Beam 2 vertical, $Q'_y = -0.5$.

Figure 4.10: Rise times of the last 8 bunches of the train at injection energy, for various chromaticities, and comparison with HEADTAIL simulations.

2011 OBSERVATIONS (3/13)

- During some experiments it was shown that it was possible (with the operational settings) to inject and collide few bunches with ~ 2.5E11 p/b and transverse emittances of ~ 2-2.5 microm => No bad surprise at the moment concerning SB TMCI (predicted to be ~ 8E11 p/b at 3.5 TeV and ~ 3.5E11 p/b at 7 TeV for nominal collimators)
- TDI: New measurements in 2011 were made with higher intensities and therefore cleaner signals => Revealed that the measurements are ~ 3-4 times higher than predicted and that it could have degraded between 2010 and 2011 (see next slide)
  - => Could confirm our initial assumption that the Ti coating is damaged (BUT this is just an assumption and it still has to be confirmed!)
  - 3D simulations being performed to try and understand better the situation + heating issues (see later)

2011 OBSERVATIONS (4/13)

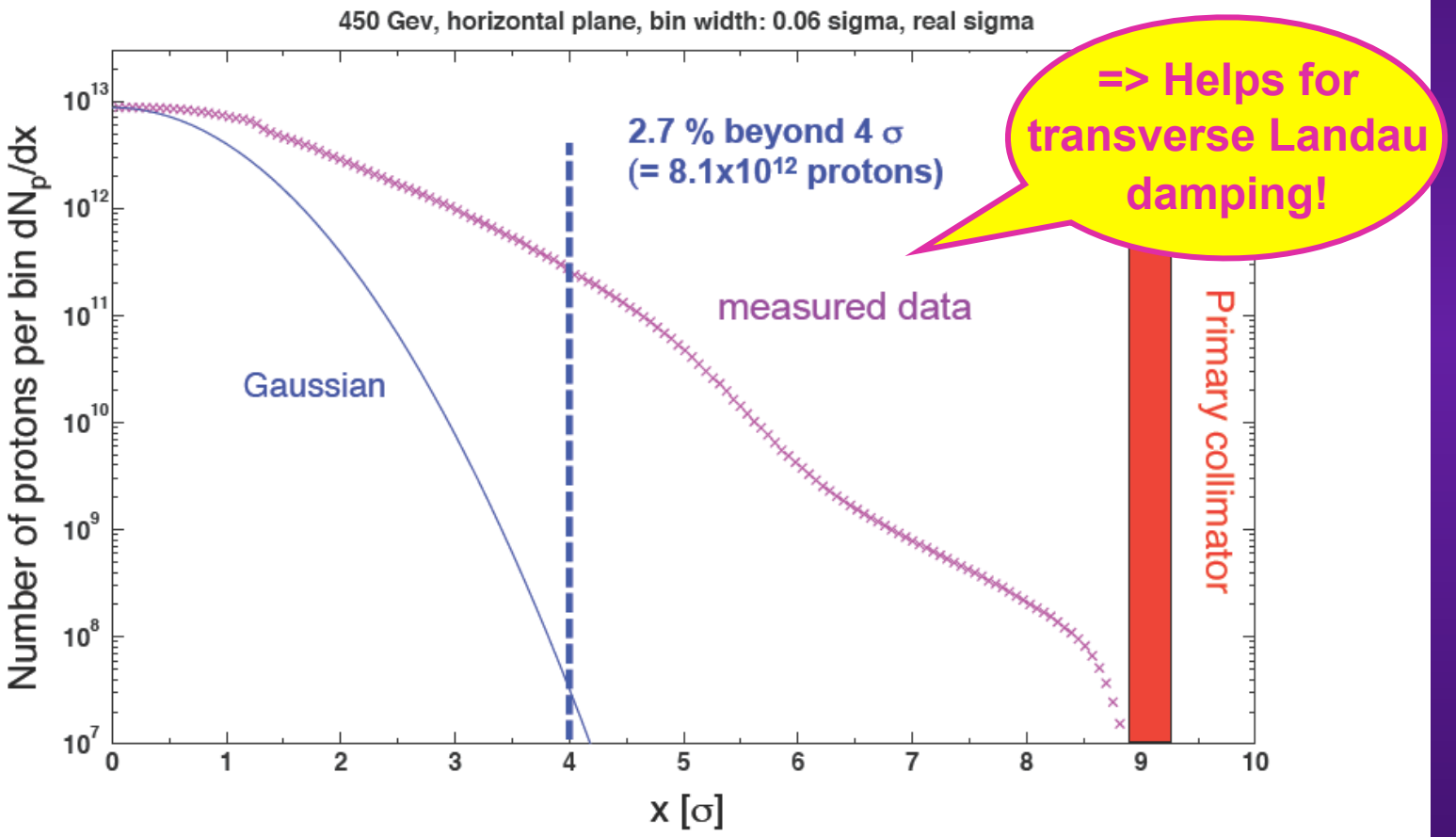


Benoit Salvant

2011 OBSERVATIONS (5/13)

Highly Populated Beam Tails

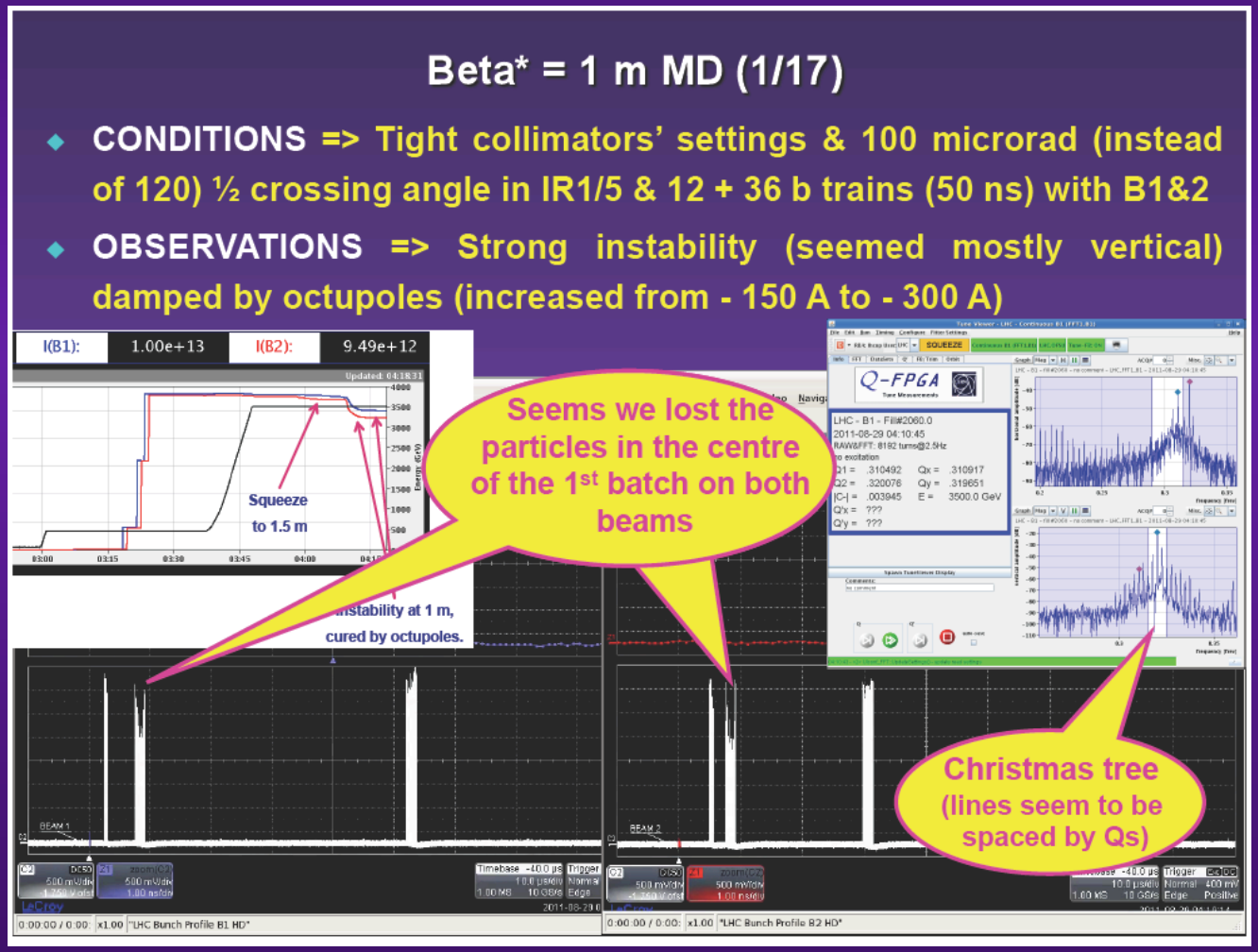
(horizontal plane, 450 GeV, total intensity 3×10^{14}p, real σ)



Florian Burkart, Nov. 2011 3

2011 OBSERVATIONS (6/13)

- **2 (main) observations of beam instabilities and losses during the 2011 run => 1st one (29/08/2011):**



=> Coherent oscillations with few seconds rise-times, 4-6 units in chroma.

=> "Could be" due to loss of Landau damping of TCBI of mode |m| = 1 + effects of BBLR

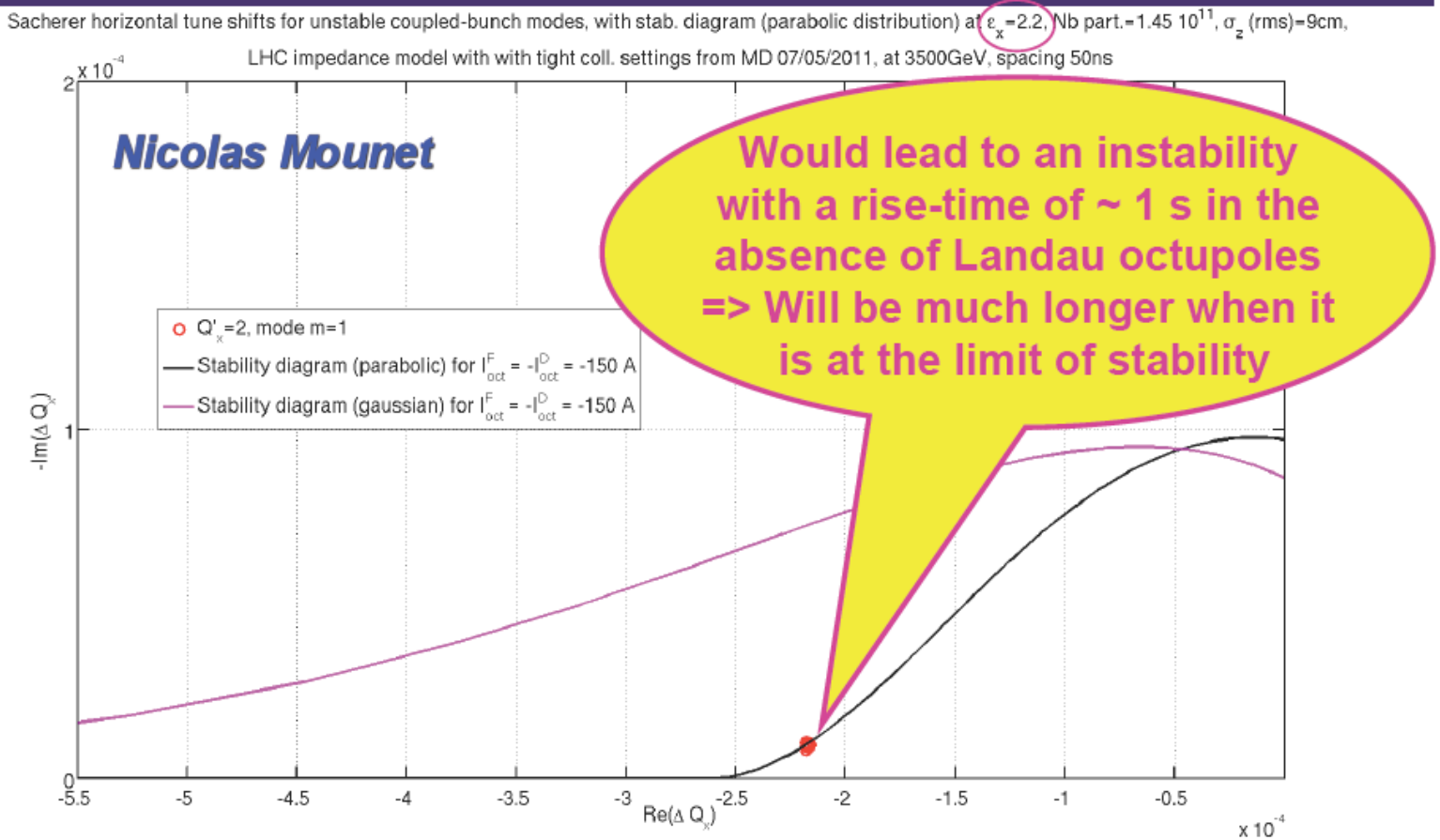
=> Solved by using nominal collimators and crossing angle

2011 OBSERVATIONS (7/13)

- **HOWEVER, continuously increasing the intensity per bunch (to ~ 1.45E p/b) led again to a similar instability at the end of the squeeze (17/10/2011):**
  - **Seems compatible with our predictions (see next slide) of loss of Landau damping of TCBI mode - 1**
  - **Was removed by increasing the octupole current slightly from - 150 A to - 200 A (it is good to increase the octupole current by small steps as it offers possibilities to check our predictions when the current is increased…)**
  - **Usual recommendation to keep the chromaticities as low as possible**

2011 OBSERVATIONS (8/13)

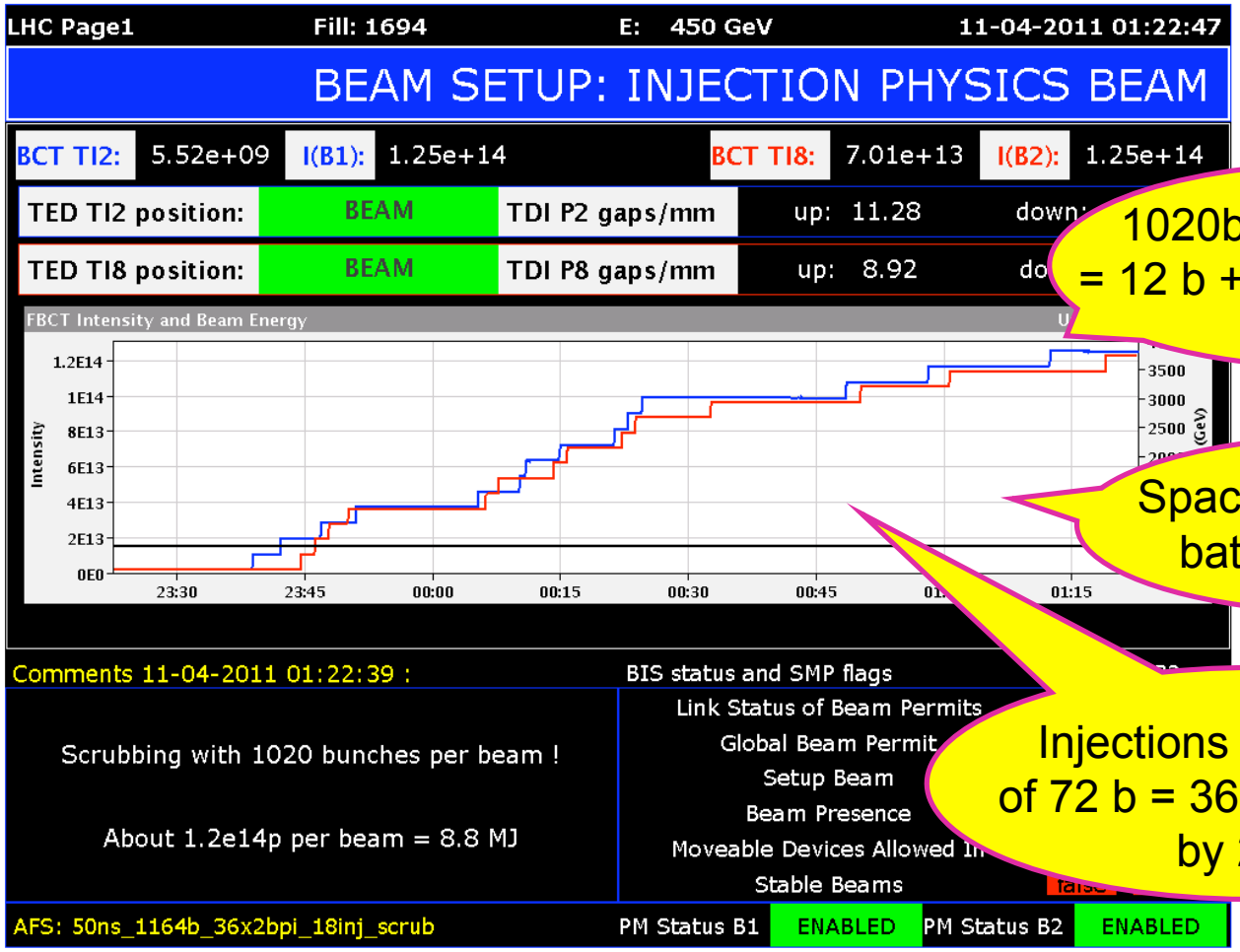
PREDICTIONS FROM OUR MODEL (2/2)



2011 OBSERVATIONS (9/13)

GOAL OF THE LHC SCRUBBING RUN => SCRUB and reach a "stable" situation with at least ~ 1000 bunches with 50 ns

=> ~ Done on Monday 11/04/11



1020b = 12b + 1008b
= 12 b + 14 × (36b + 36b)

Spacing between LHC batches = 1100 ns

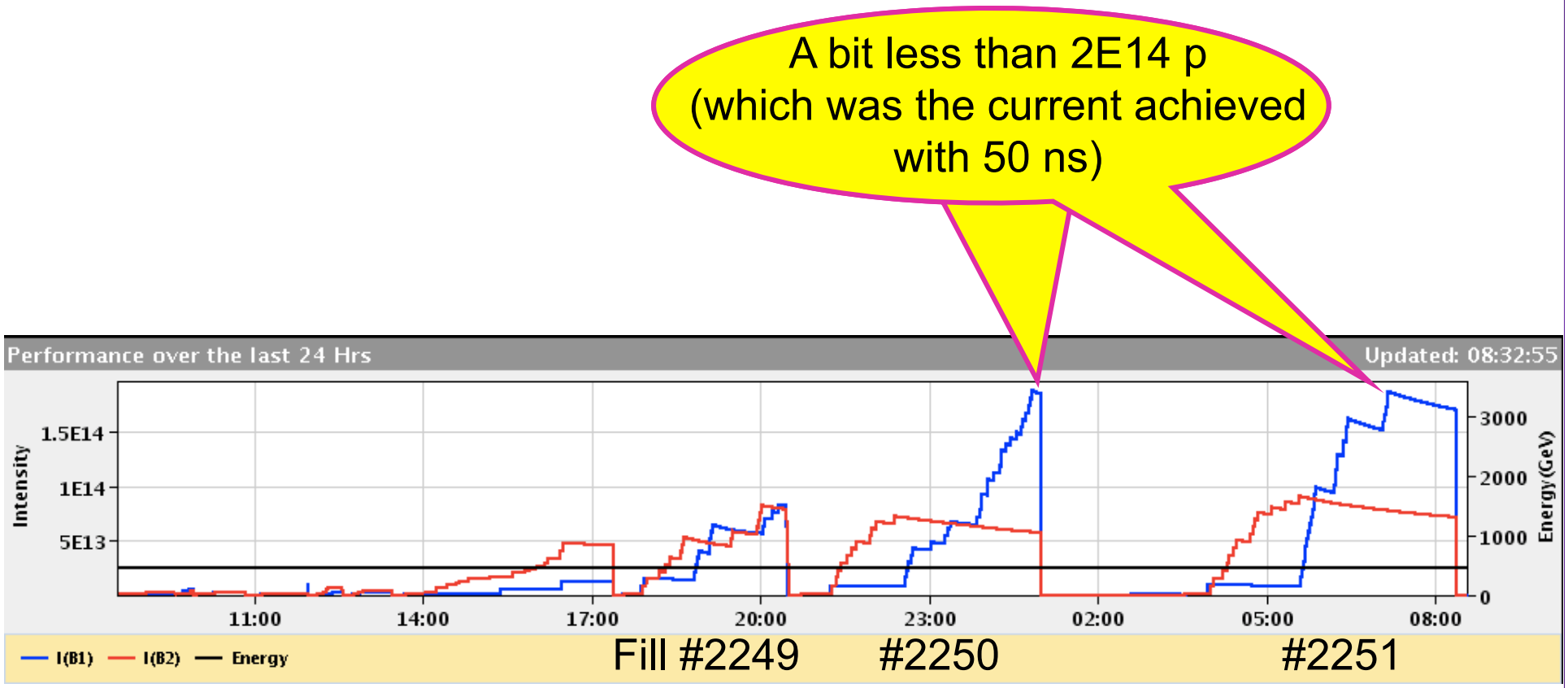
Injections from the SPS of 72 b = 36b + 36b spaced by 225 ns

2011 OBSERVATIONS (10/13)

GOAL OF THE LHC SCRUBBING RUN => SCRUB and reach a "stable" situation with at least ~ 1000 bunches with 50 ns

2011 OBSERVATIONS (11/13)

25 ns BEAM STUDIES IN THE LHC



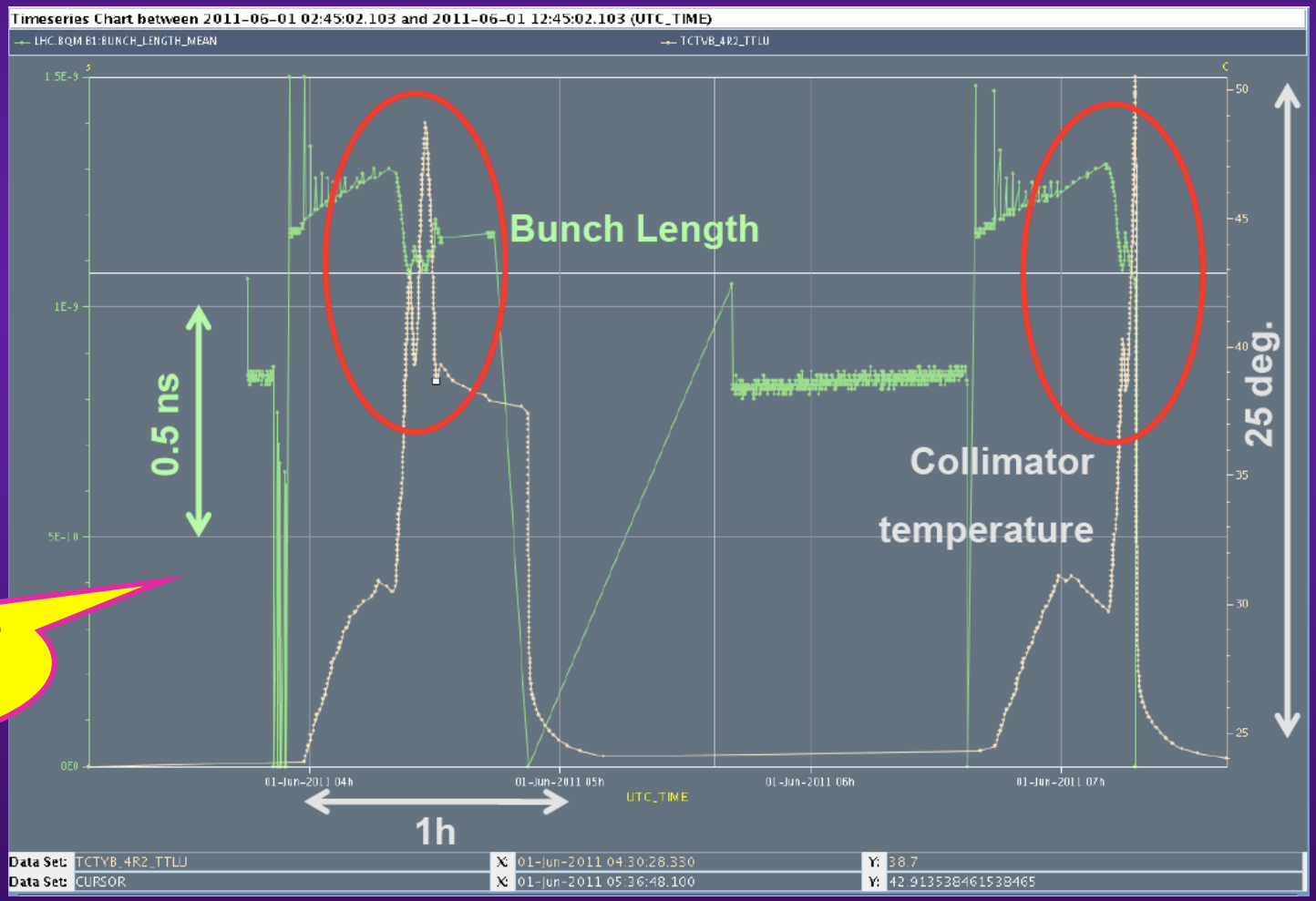
- **Reminder on strategy: Start first with high chromaticities (~ 15 units) to prevent the single-bunch TMCI-like instability from developing => Worked as foreseen by FrankZ & ElenaB in the past**

2011 OBSERVATIONS (12/13)

25 ns BEAM STUDIES IN THE LHC

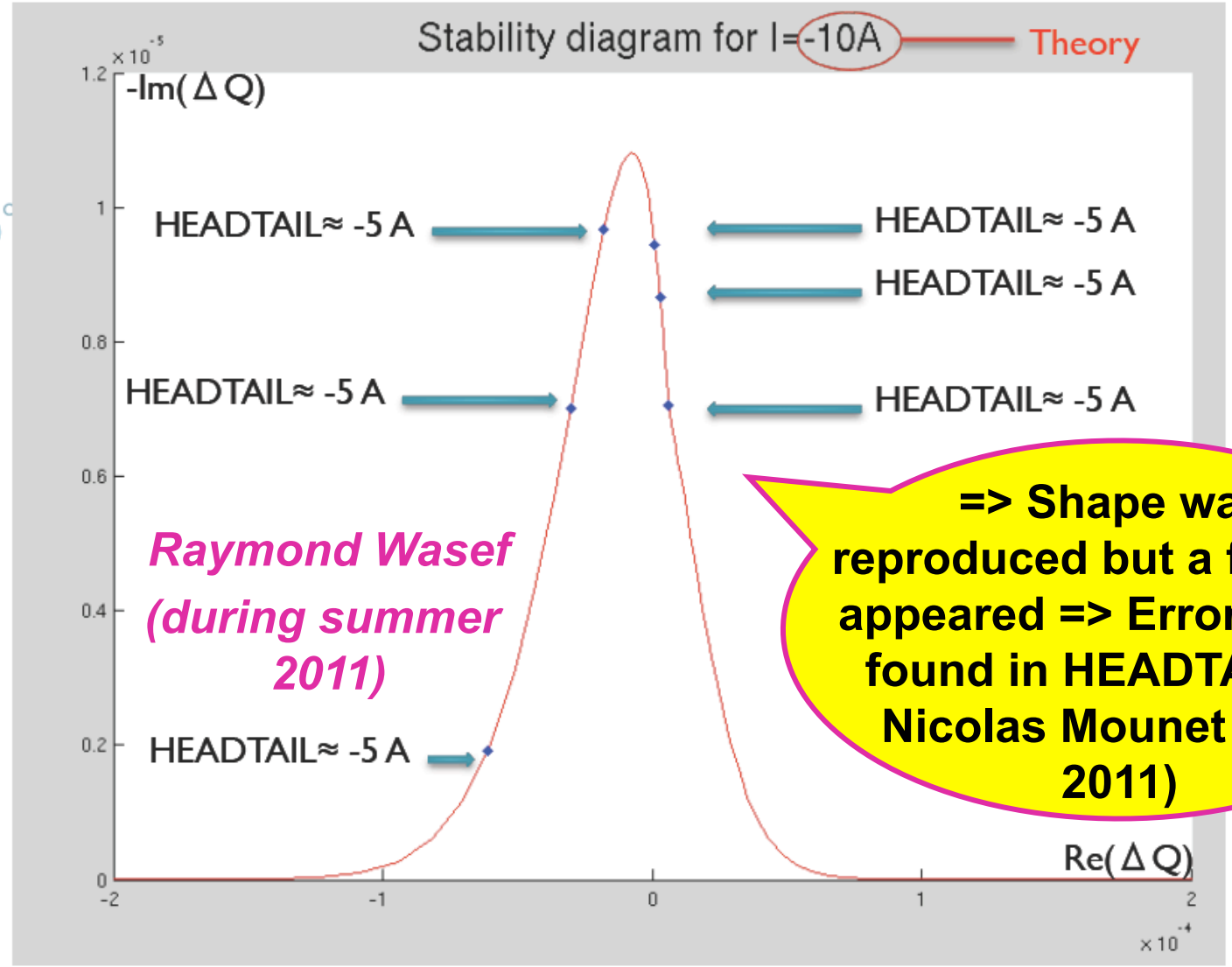
2011 OBSERVATIONS (13/13)

- **In summary: quite good results so far (as concerns beam stability and quality)… BUT heating observed here and there**



Example of the TCTVB_4R2

BENCHMARK OF THEORETICAL STABILITY DIAGRAM WITH HEADTAIL CODE FOR A GAUSSIAN BUNCH

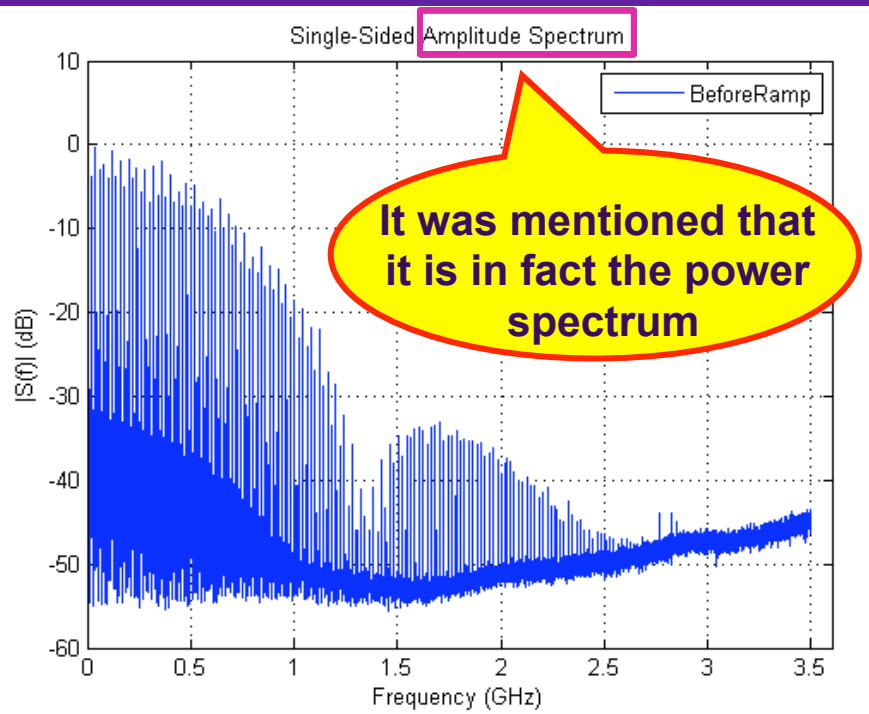


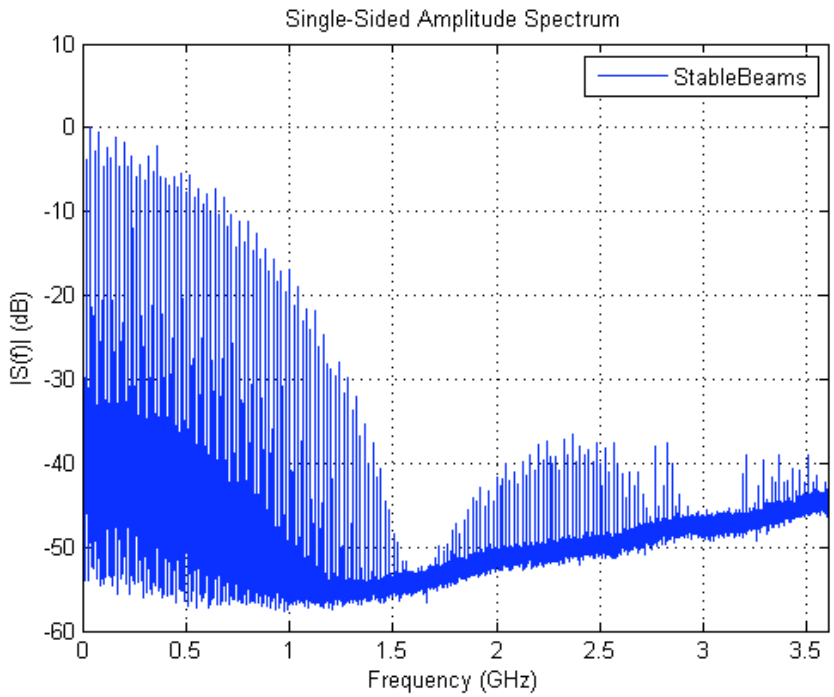
All points are stabilizing between -4A and -6A

CURRENT ISSUE: HEATING HERE AND THERE… (1/7)

- **Analyses ongoing**
  - **Trapped modes of some equipments re-studied. Ferrite issues?...**
  - **Understanding of measured bunch spectra => Discussions ongoing with RF colleagues etc.**

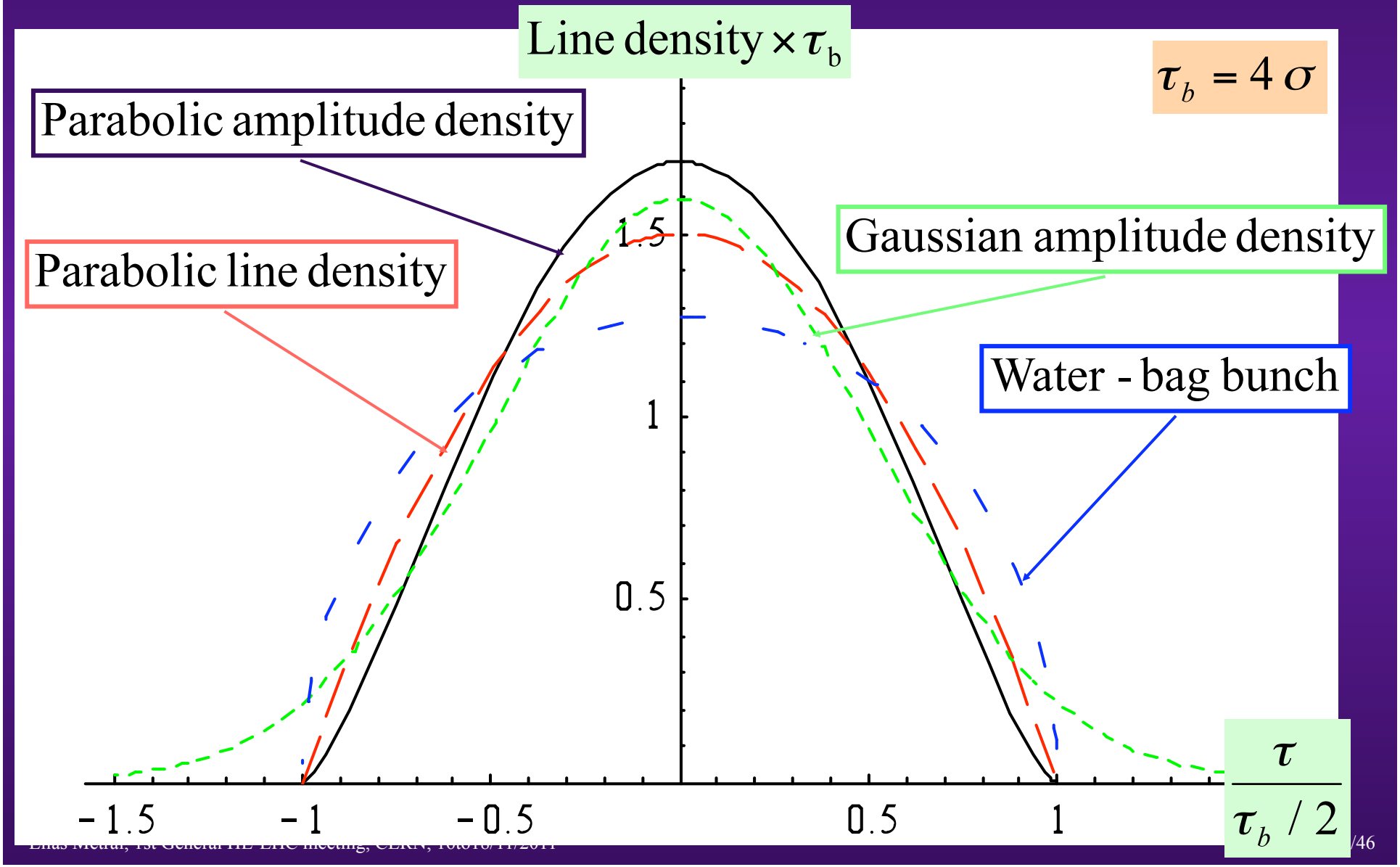
Measurements on B1 by Themis Mastoridis and Philippe Baudrenghien on fill # 2261 (Ralph Steinhagen obtained similar results in the past)



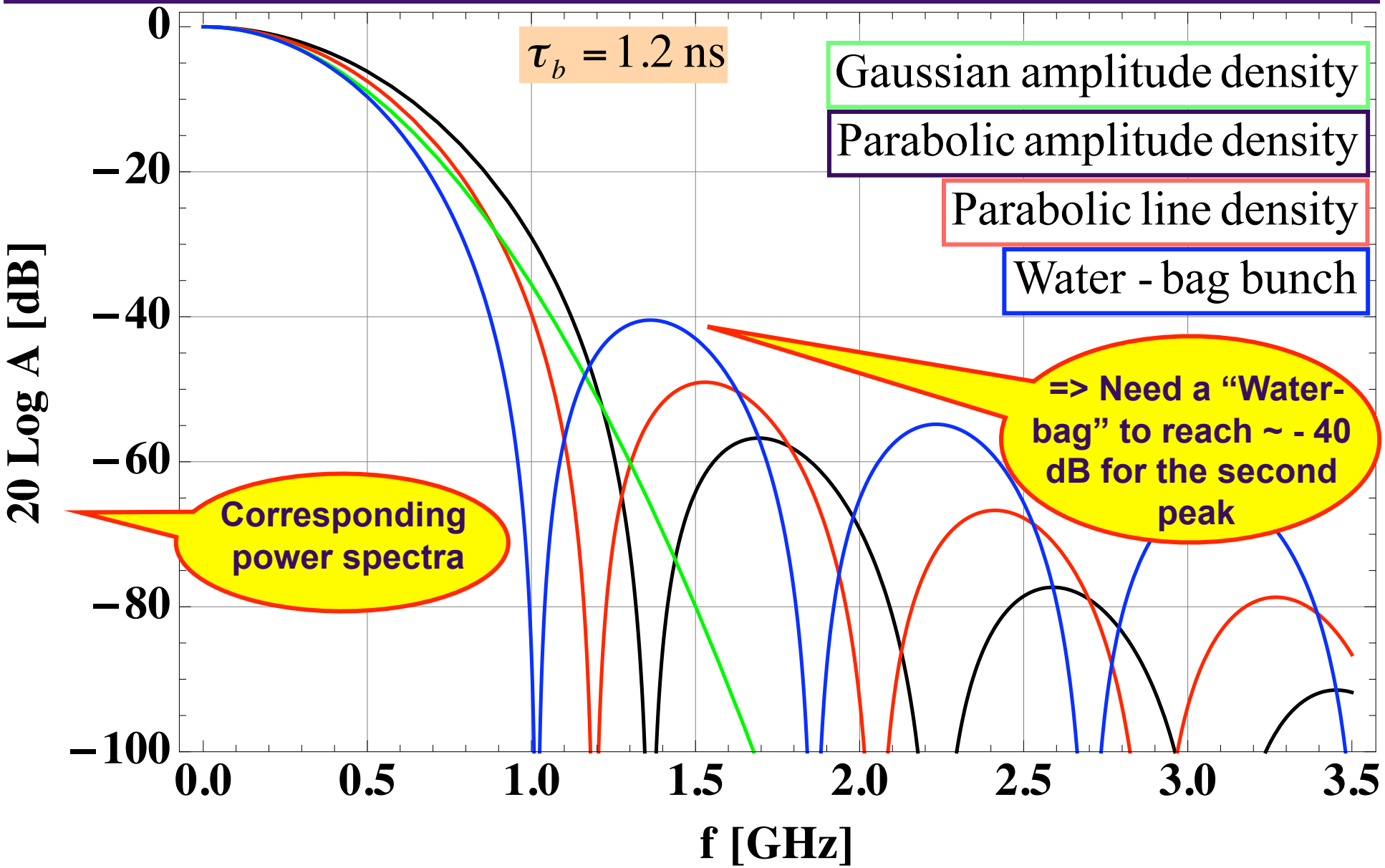


CURRENT ISSUE: HEATING HERE AND THERE… (2/7)

- **Can we (I) understand it?**

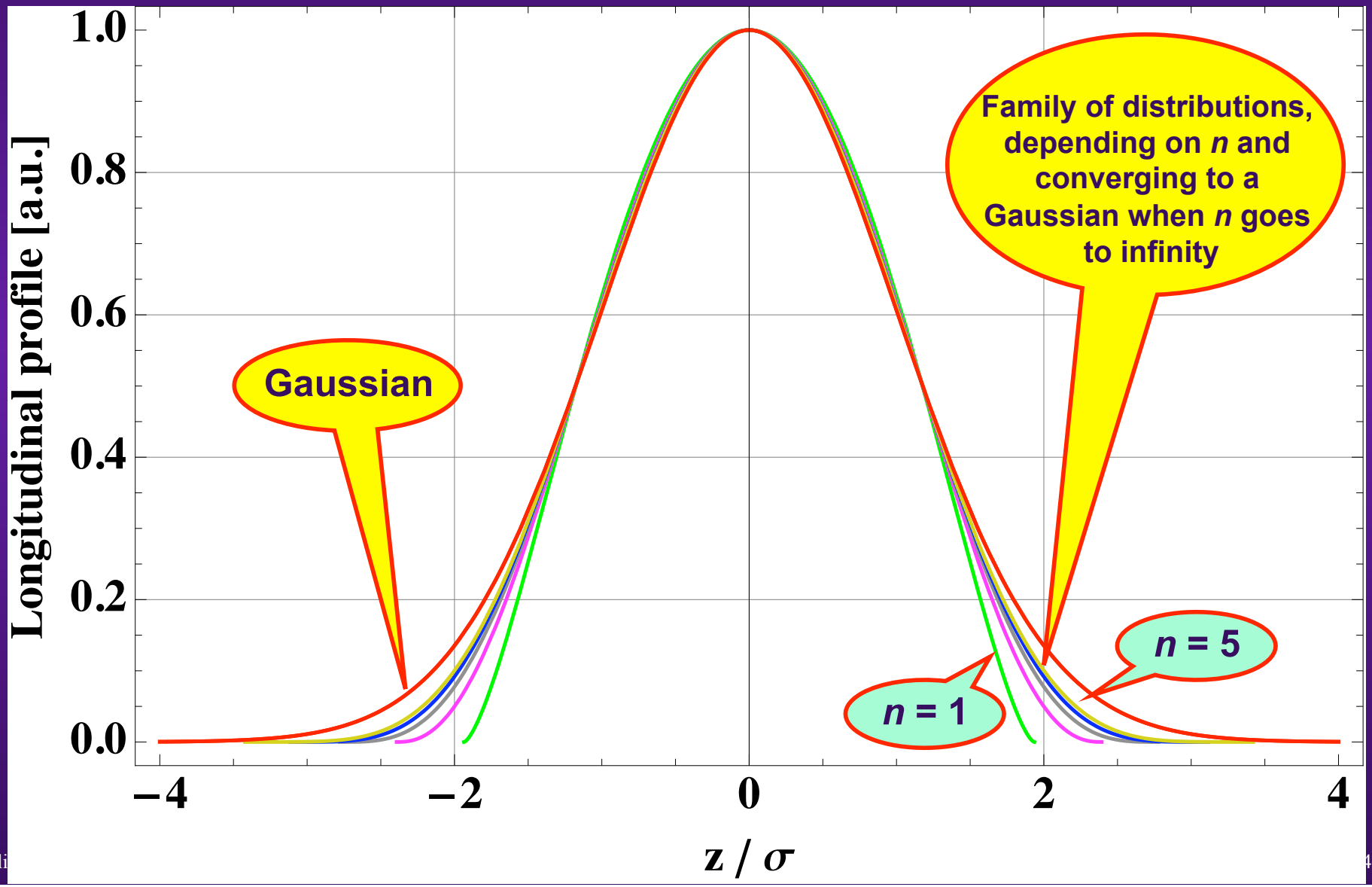


CURRENT ISSUE: HEATING HERE AND THERE… (3/7)

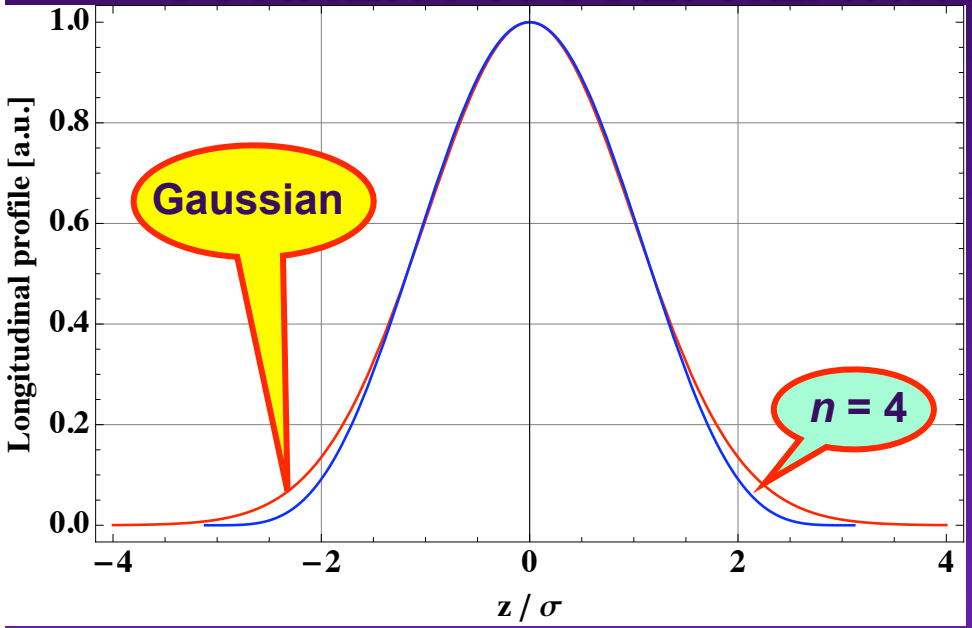


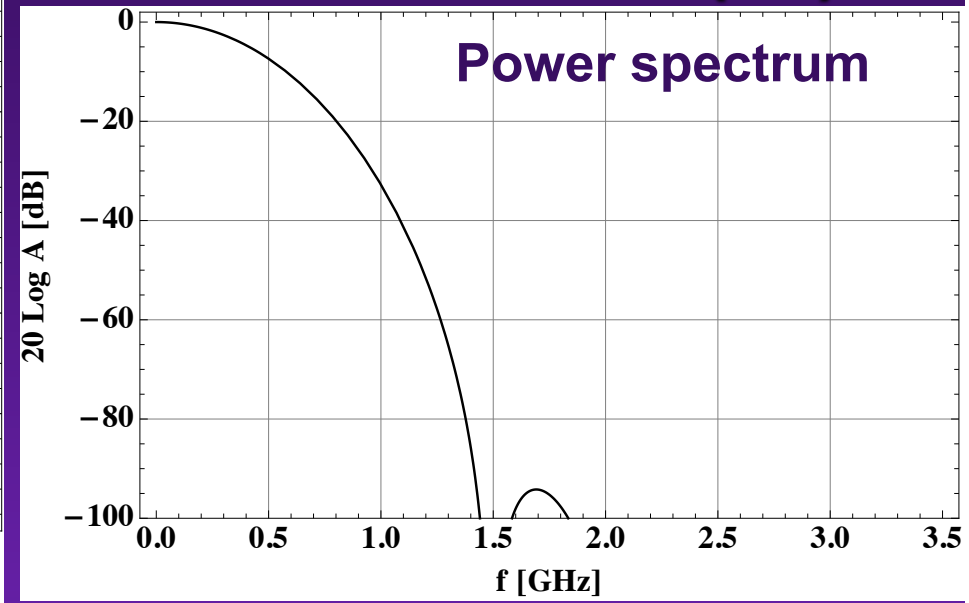
CURRENT ISSUE: HEATING HERE AND THERE… (4/7)

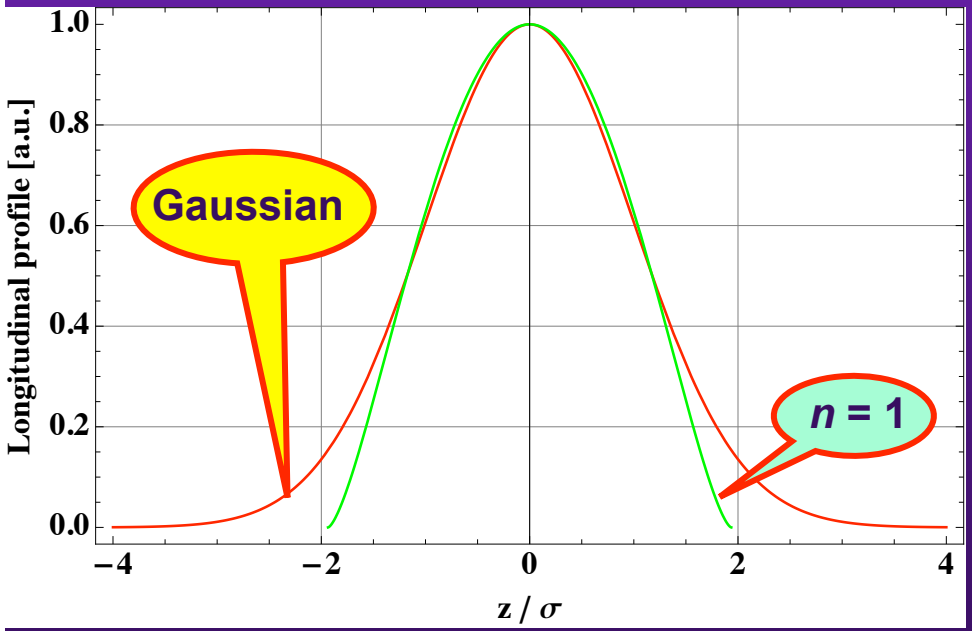
- **What happens to Gaussian-like distributions (but with finite tails)?**

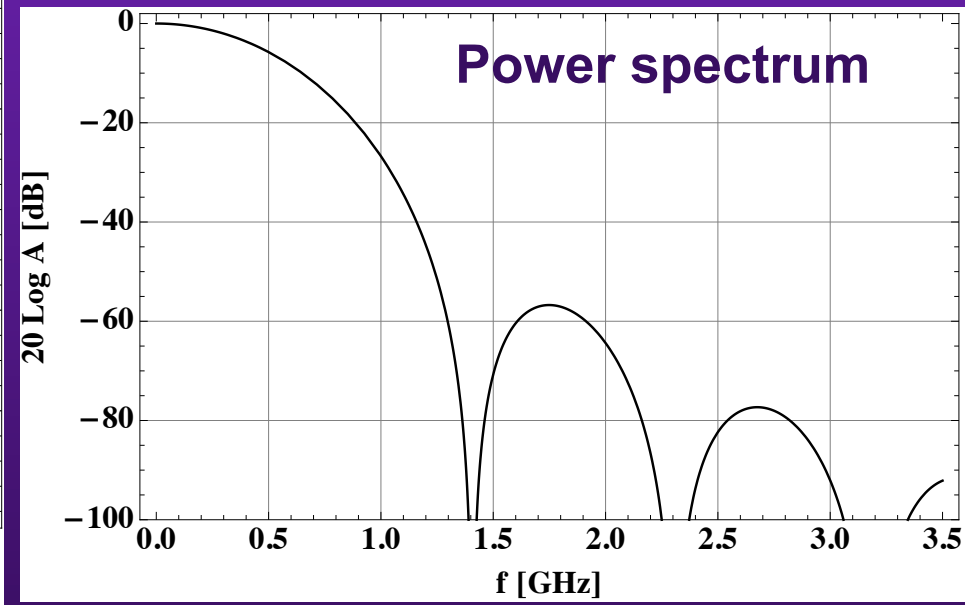


CURRENT ISSUE: HEATING HERE AND THERE… (5/7)

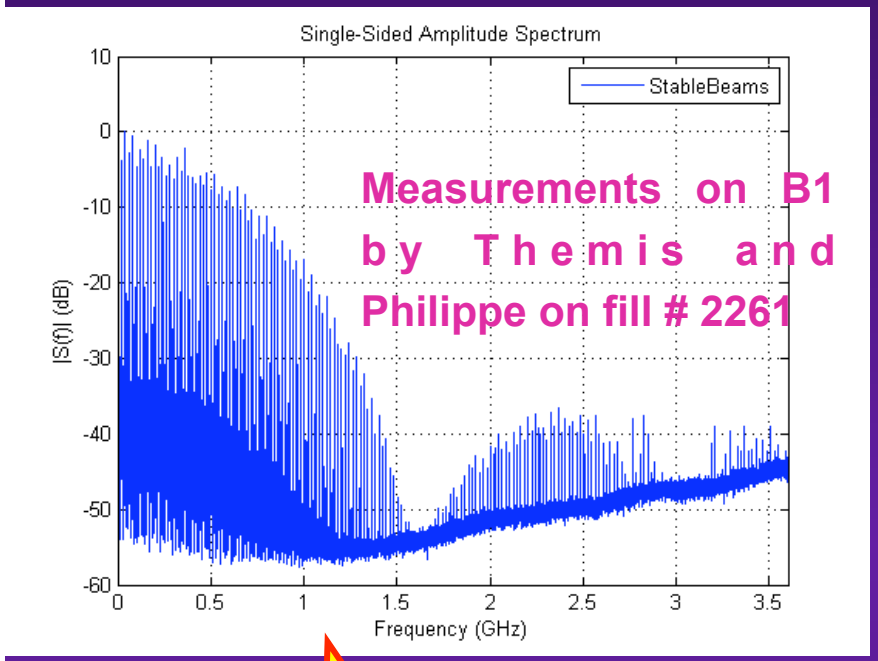


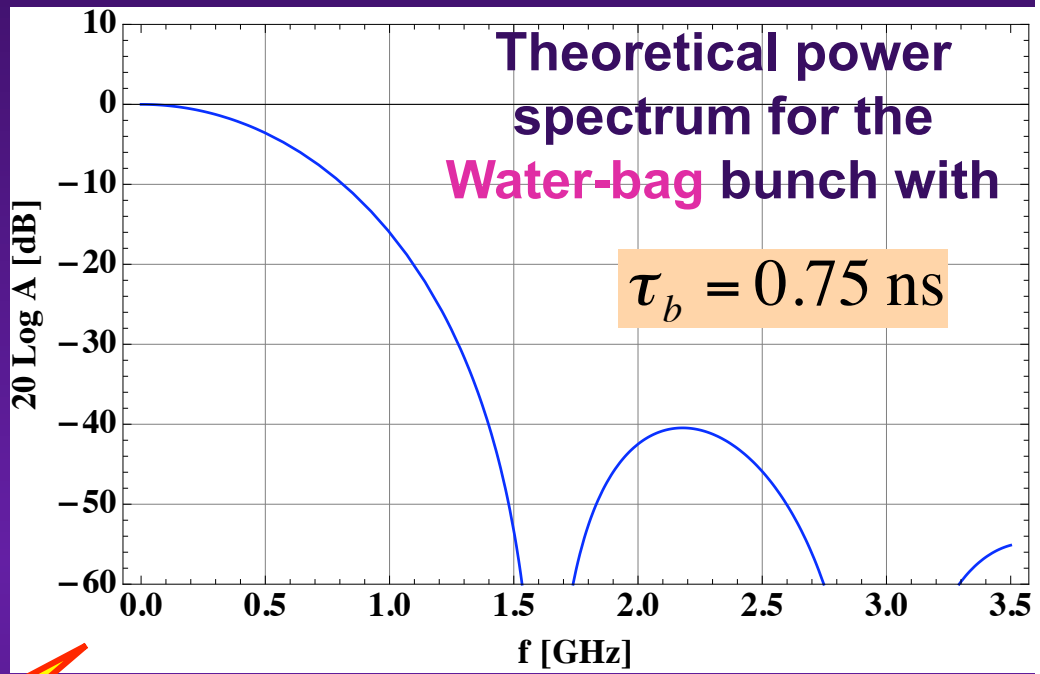




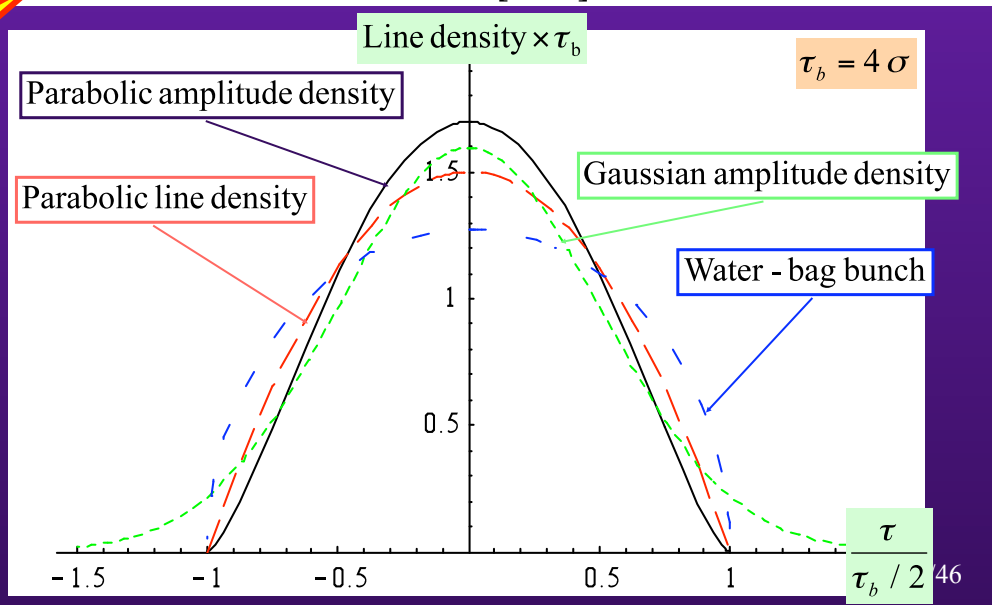


CURRENT ISSUE: HEATING HERE AND THERE… (6/7)





Best fitting (which seems quite good!) of this measurement is obtained with the Water-bag on the right



CURRENT ISSUE: HEATING HERE AND THERE… (7/7)

- **According to the analysis done by Themis Mastoridis from BQM data, it seems that the bunch spectra together with the BQM data are consistent with a bunch distribution close to a Water-bag with a full bunch length at the base close to 0.75 ns (which corresponds to 1.1 ns from the BQM).**

  => To be followed-up

- ***Reminder (from Themis Mastoridis): The BQM reports the full-width at half maximum (FWHM) scaled by sqrt(2/ln(2)). The scaling is set to report a 4-sigma width assuming a Gaussian bunch***

FUTURE ISSUES: HEATING (?) + LOSS OF TRANSVERSE LANDAU DAMPING (1/2)

- **Heating** => Identify all the sources and find ways of mitigation (damping of some trapped modes and/or change of the bunch spectrum etc.) => Ongoing

- **Loss of transverse Landau damping of TCBI mode - 1:**
  - It seems we need ~ - 200 A at the end of the squeeze to keep the beam stable with 50 ns beam (1380 b), ~ 1.45E11 p/b with ~ 2-2.5 microm

    => We still have some margin: Factor F = 550 / 200 = 2.7
  - In the short future (at 3.5 TeV): If/when the impedance will increase by more than factor ~ F (with tighter collimators' settings), and/or the transverse emittances will decrease by more than factor ~ F and/or the intensity will increase by more than factor ~ F, Landau damping from octupoles should be lost

FUTURE ISSUES: HEATING + LOSS OF TRANSVERSE LANDAU DAMPING (2/2)

- In the medium future (at 7 TeV) => Nicolas Mounet:
  - For 50 ns beam, 1.5E11 p/b within 2 microns (Qprime ~ 2), and nominal collimators => Beam should be stable (~ 400 A needed)
  - For 50 ns beam, 1.5E11 p/b within 2 microns, and tight collimators' settings discussed at some point => Beam should be unstable (~ 800 A would be needed)

- In the long future (HL-LHC at 7 TeV):
  - For 25 ns beam (with 2E11 p/b within 2.5 microm) or 50 ns beam (with 3.3E11 p/b within 3.0 microm) => Should be close to the limit for nominal collimators' settings

CONCLUSION (1/2)

- The ADT (transverse damper) is working extremely well to damp the TCBI mode 0 => It helped also in the past to fight the hump
- Until now it was possible to run with chromaticities as low as possible (1-2 units) => There is no need to increase it (except during scrubbing run due to ecloud TMCI-like fast instability)
- Landau octupoles are needed to damp the SBI and TCBI mode - 1 and they are used since injection (- 6 A) till stable beams (- 200 A)
- In the longitudinal plane, emittance blow-up is used
- The 50 ns scrubbing run went very well and first studies with 25 ns are very encouraging for future operation with 25 ns beam
- Main concern at the moment: heating observed here and there
  - Work on many impedances ongoing
  - Possible work on bunch spectrum (to avoid the 2nd – 3rd peaks, if needed)?

CONCLUSION (2/2)

- **Possible future issues:**
  - **Heating?**
  - **Loss of transverse Landau damping for TCBI mode - 1 if the collimators' settings are closer than nominal**
  - **(Assuming that the ADT will always damp the TCBI mode 0…)**

- **I will be the task leader of task 2.4 (Collective Effects Studies) within WP2 (on Accelerators Physics) of the HL-LHC project and I am impatient to work with all the interested collaborators to start this great adventure and try to push forward the LHC performance!**