

PRESENT UNDERSTANDING OF THE INSTABILITIES OBSERVED AT THE LHC DURING RUN I AND IMPLICATIONS FOR HL-LHC

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**Thanks to ICE section, WP2 Task 2.4 and all the people working / helping on our collective effects and high-intensity issues
(30 + 5 min talk)**

- ◆ **Introduction**
- ◆ **Everything started well in 2010...**
- ◆ **What happened in 2011?**
- ◆ **What happened in 2012?**
- ◆ **Conclusion**



INTRODUCTION

- ◆ **Did we make some progress during Run I and since last year's annual meeting?**

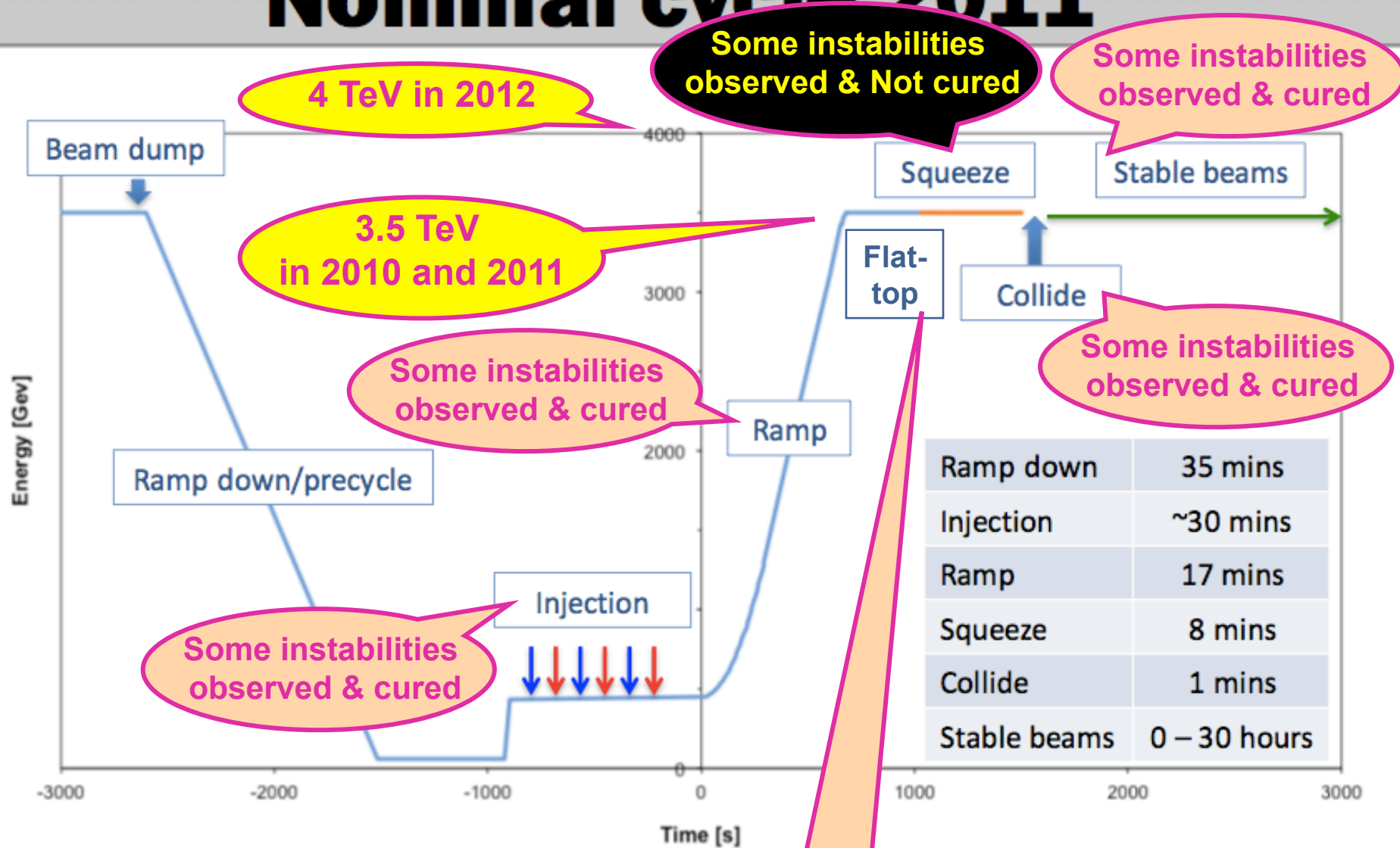
YES, A LOT!

- ◆ **Do we understand our main limitation at the end of last year at the end of the betatron squeeze (EOSI = End-Of-Squeeze Instability)?**

NO! (not yet...)

=> Need therefore to consider alternative scenarios for post-LS1 and HL-LHC, while continuing to try and understand it...

Nominal cycle 2011



Some instabilities observed & Not cured

Some instabilities observed & cured

4 TeV in 2012

3.5 TeV in 2010 and 2011

Some instabilities observed & cured

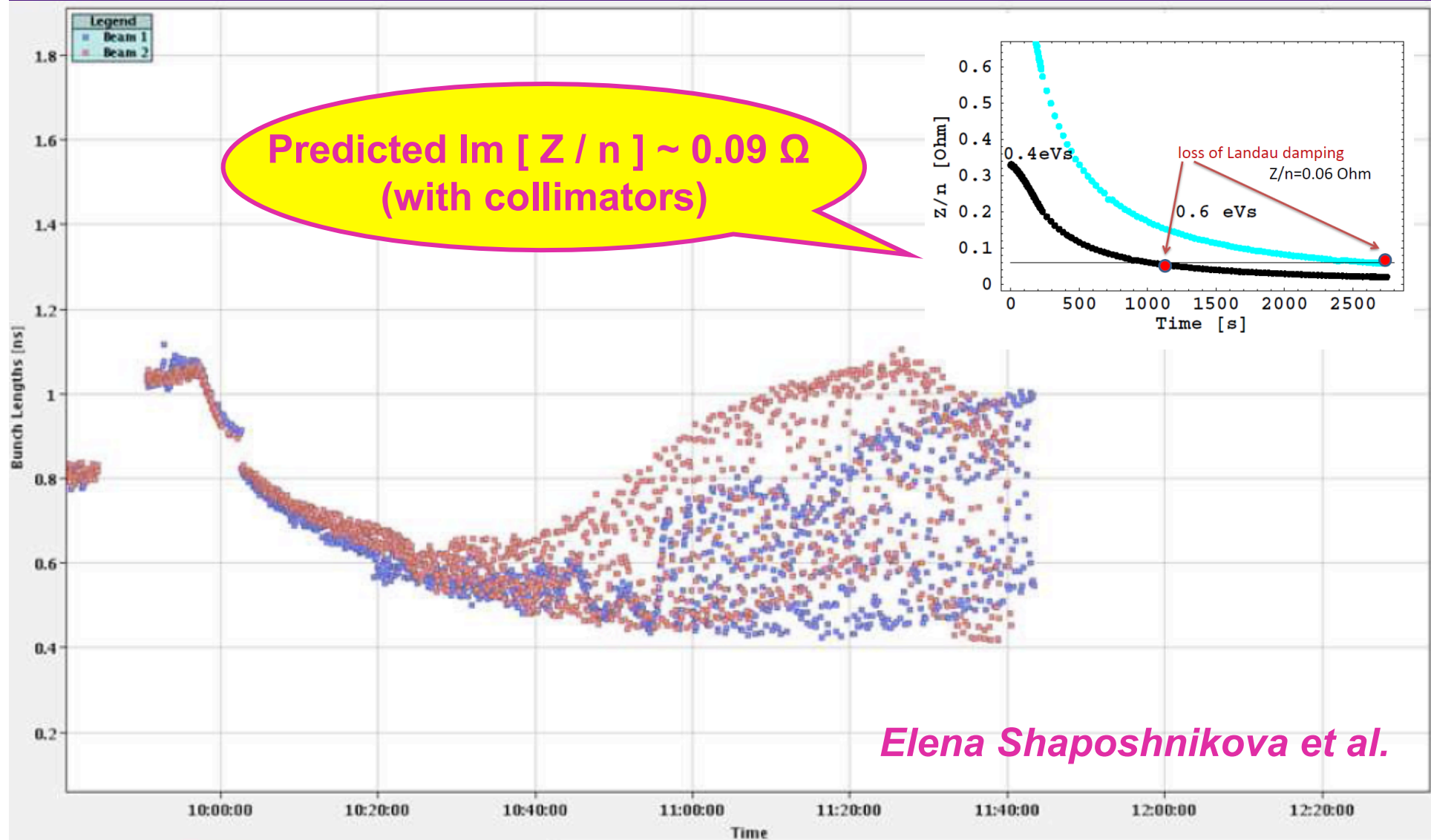
Some instabilities observed & cured

Some instabilities observed & cured

Some instabilities observed & cured

EVERYTHING STARTED WELL IN 2010... (1/6)

- ◆ 1) Loss of longitudinal Landau damping during LHC acceleration when longitudinal emittance too small (\sim as predicted...)



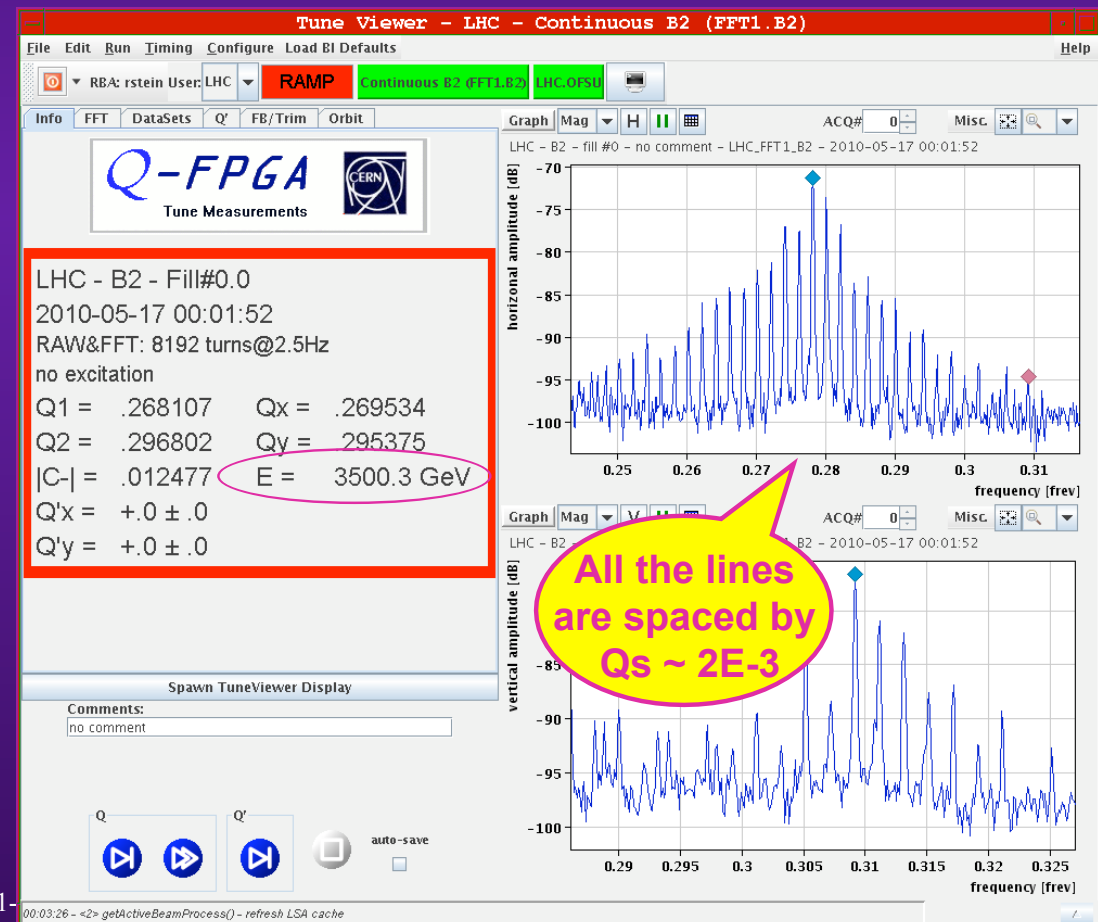
EVERYTHING STARTED WELL IN 2010... (2/6)

- ◆ 2) 1st ramp tried with single-bunch of $\sim 1E11$ p/b (both B1 and B2) on SA 15/05/2010 without Landau octupoles

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

=> Famous “Christmas tree”

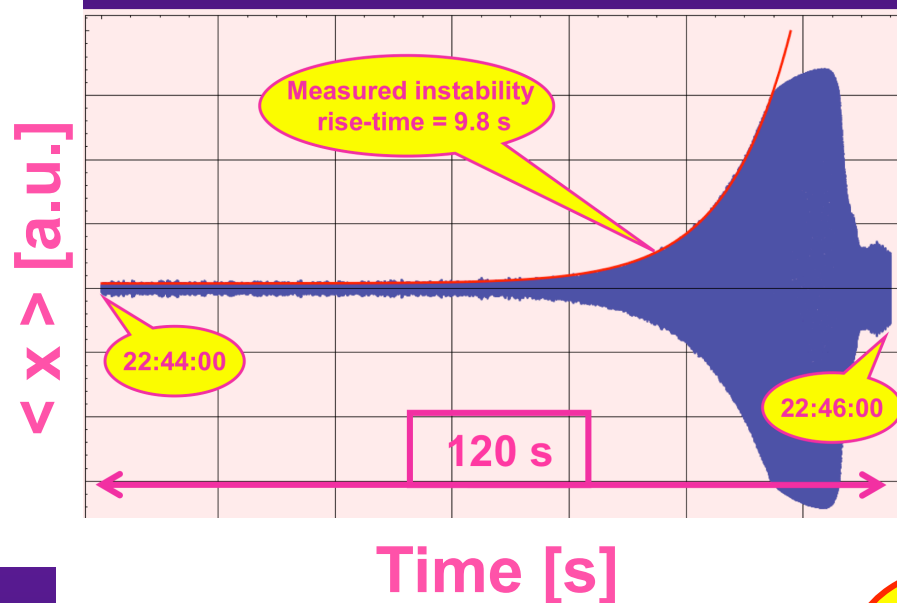
Dedicated study
on MO 17/05/2010
at 3.5 TeV



EVERYTHING STARTED WELL IN 2010... (3/6)

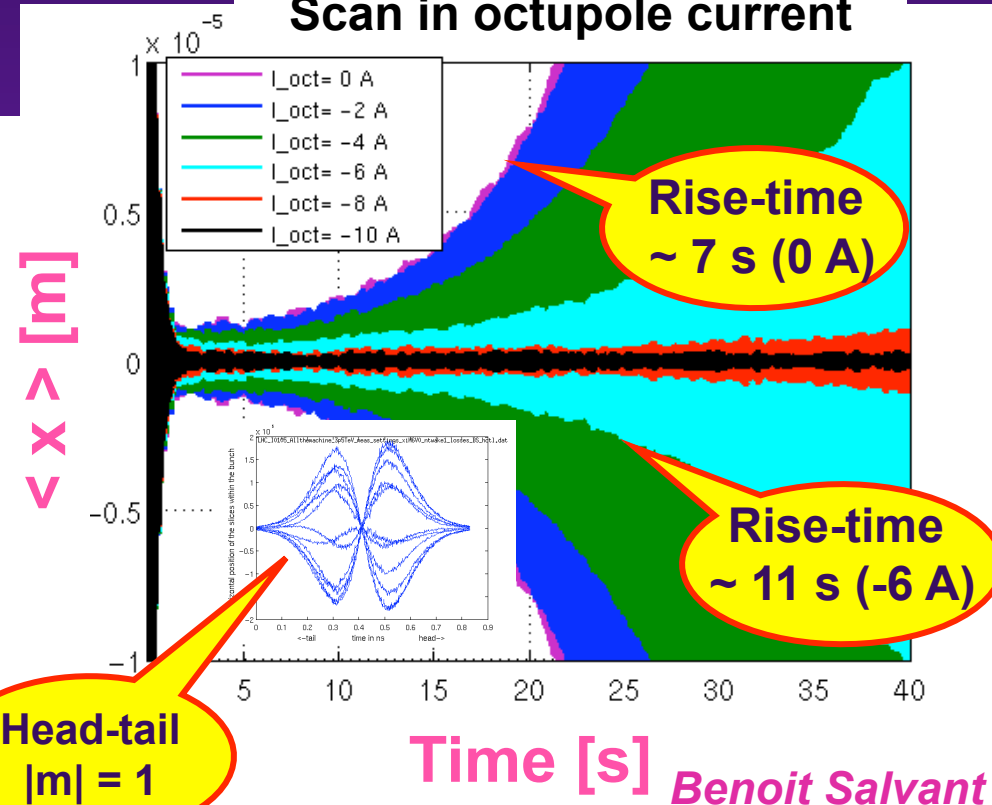
MEASUREMENTS

(17/05/2010 at 3.5 TeV)



SIMULATIONS

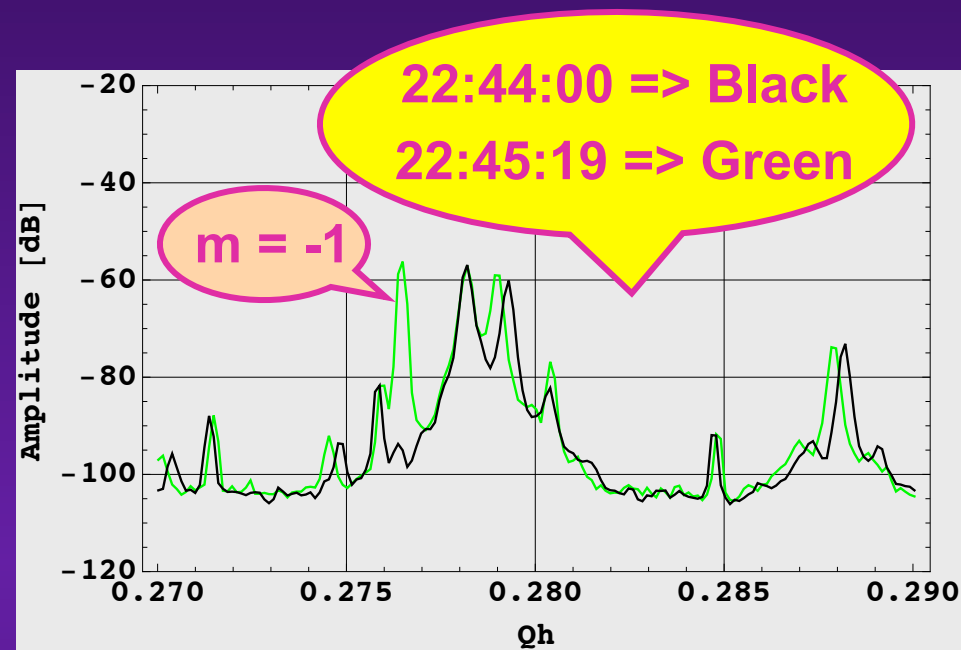
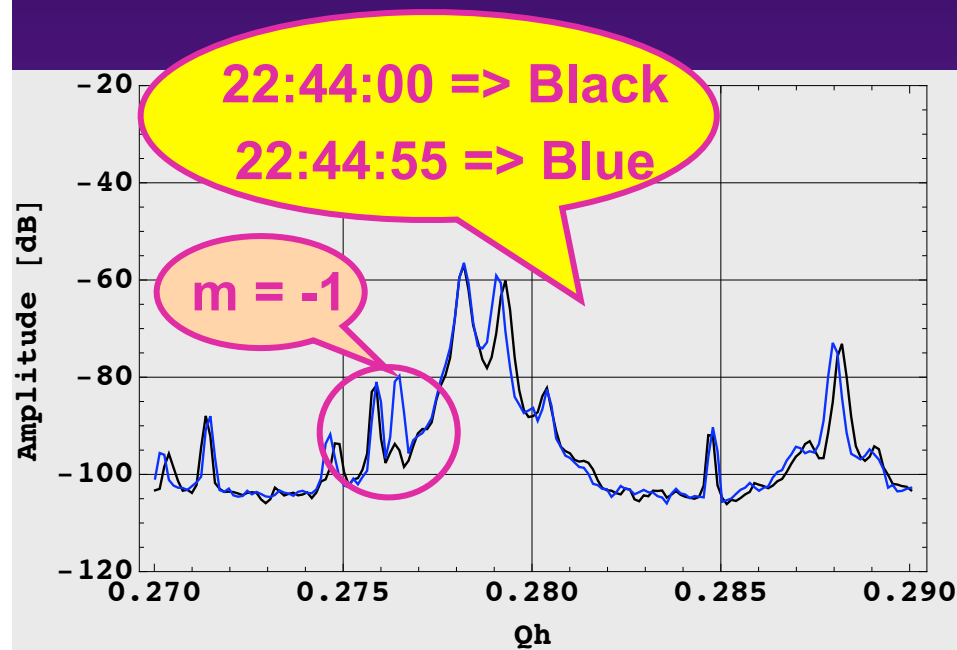
Scan in octupole current



- Rise-time ~ 10 s
- $-20 \text{ A} < I_{oct}$ for stability $< -10 \text{ A}$

- Rise-time ~ 10 s
- Stability for $I_{oct} \sim -10 \text{ A}$

EVERYTHING STARTED WELL IN 2010... (4/6)



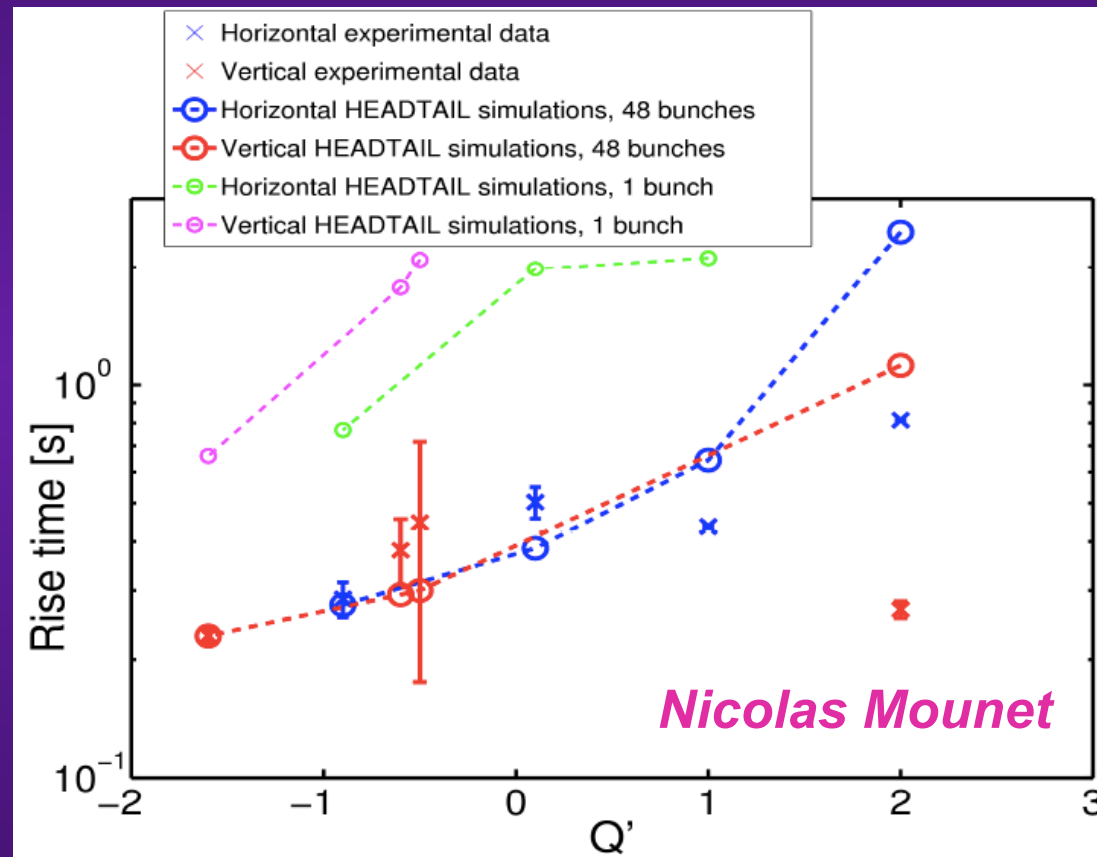
Estimation of the rise-time in frequency domain

~ 24 dB in 24 s => ~ 9 dB in ~ 9 s

=> Instability rise time ~ 9 s (consistent with time domain)

EVERYTHING STARTED WELL IN 2010... (5/6)

- ◆ 3) TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)
 - Good agreement at 450 GeV



- ~ 2-3 faster rise-times observed at 3.5 TeV (but uncertainty on chromaticities...)

EVERYTHING STARTED WELL IN 2010... (6/6)

- Landau octupoles used at 3.5 TeV to stabilize the beam

LOD = - LOF

Landau octupole current [A]	Beam 1	Beam 2
HEADTAIL predictions (Gaussian bunch)	120	100
Measurements	60	70

Nicolas Mounet

- Simulations more critical (but uncertainty on chromaticities, transverse profile - measured by collimation team - different from Gaussian, etc.) => Reasons exist for that and some explanation can be found!

=> Everything was for the best in the best of all possible worlds...

WHAT HAPPENED IN 2011? (1/4)

◆ Everything continued ~ well with nice measurements on impedance, beam-beam and e-cloud

■ Impedance

N. Mounet et al.

- Always within factor ~ 2-3 (tune shifts, rise-times) and sometimes even better than predicted (instability thresholds)

■ Beam-Beam

W. Herr, T. Pieloni et al.

- PACMAN effects (loss pattern, orbits) clearly visible and ~ as expected; coherent beam-beam modes as expected
- HO tune spread \gg nominal can be achieved

■ E-cloud

G. Rumolo, G. Iadarola et al.

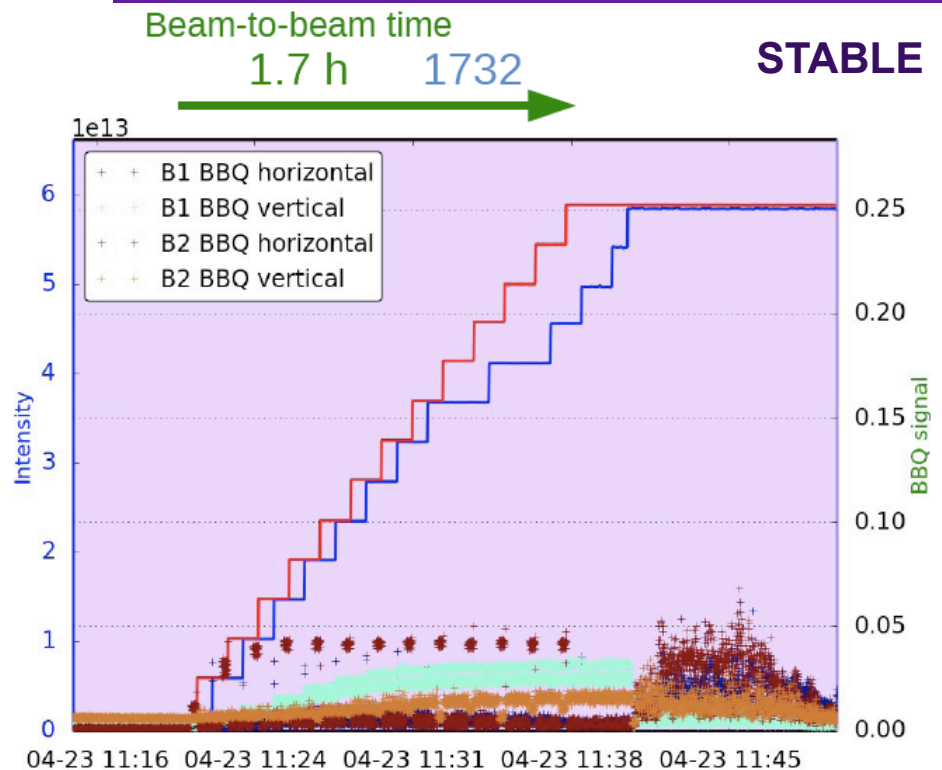
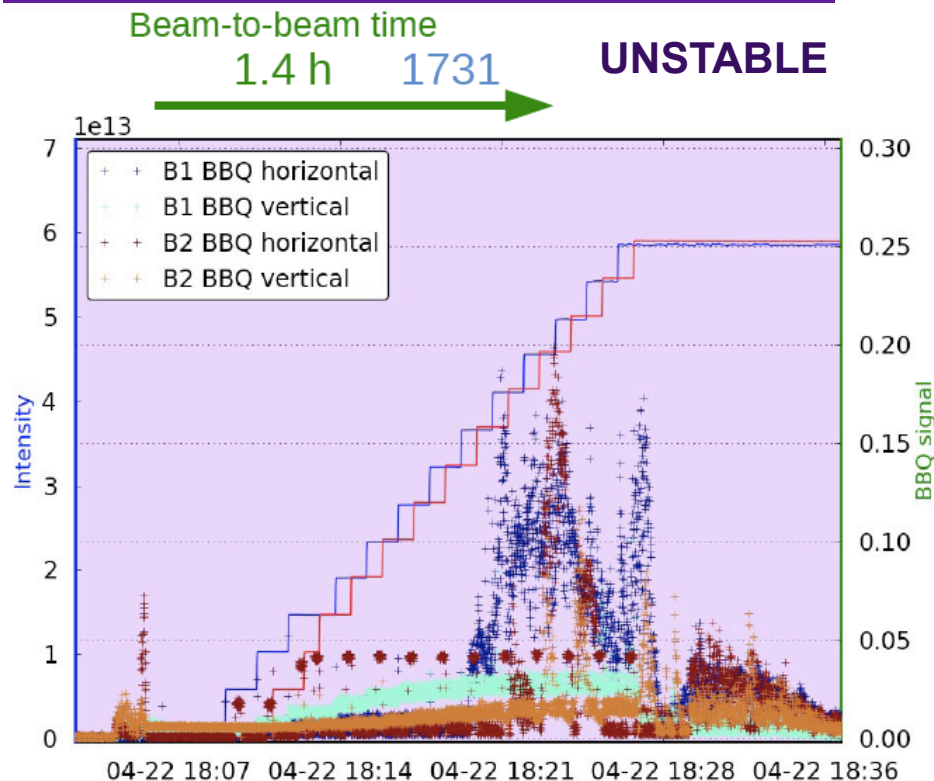
- Fast instability damped by large chroma (~ as expected)
- Nice decreases of SEYs (scrubbing history); nice meas. & sim. of energy loss / bunch (stable phase shift)

WHAT HAPPENED IN 2011? (2/4)

- ◆ 09/06/2011 => Some octupoles added also at injection due to BBQ activity and emittance BU on some batches (LOF = - 6.5 A > fill 1865) => OK afterwards (2011 and 2012) but never optimized
 - Changing the sign of LOF (in 2012, see later) and going from - 6.5 A to + 6.5 A also worked

Kevin Li

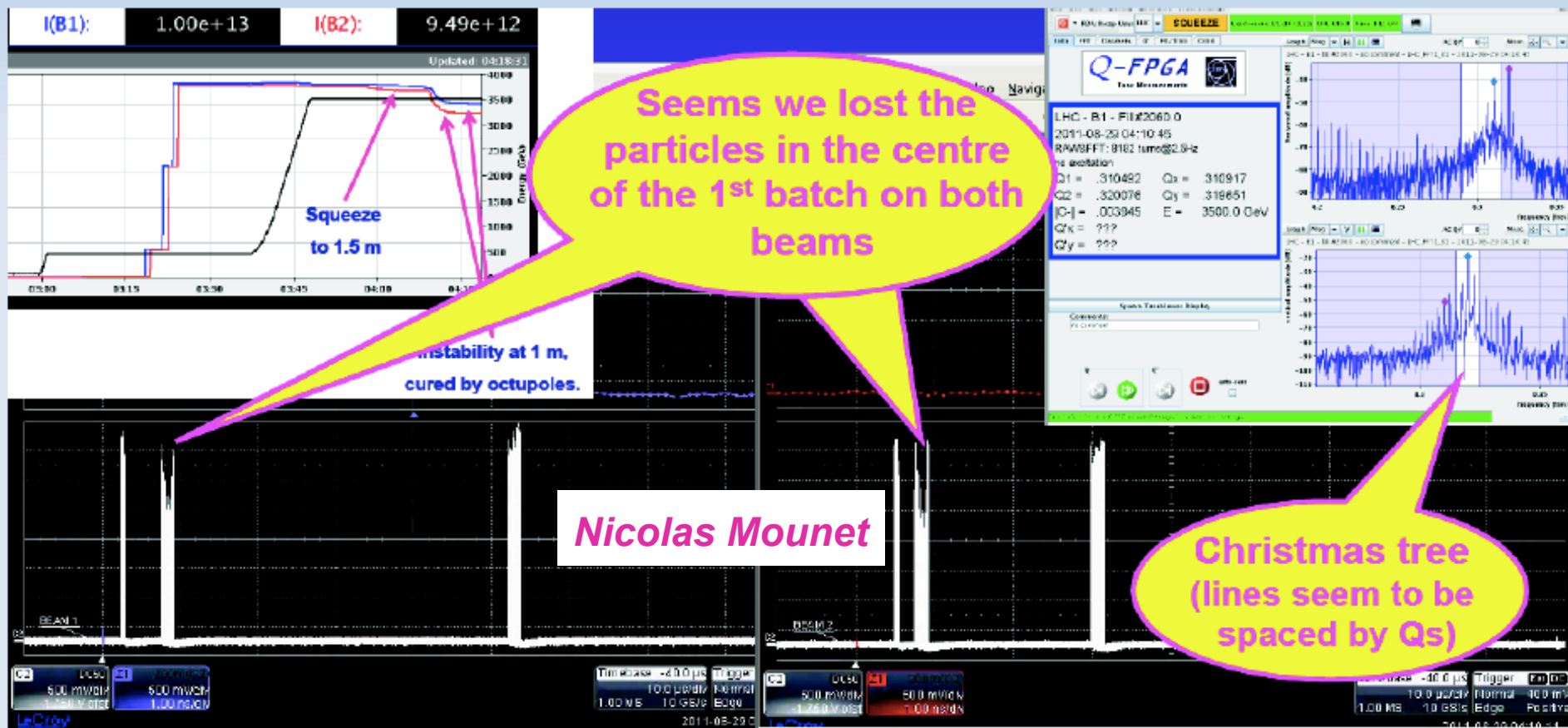
Hints towards e-cloud



WHAT HAPPENED IN 2011? (3/4)

◆ What happened on 29/08/2011?

- Ramp 12+2*36 bunches (50ns), **tight collimator settings**, squeeze to $\beta^*=1$ m, **100 μ rad crossing angle** (i.e. 7.7σ for the long-range beam-beam separation, vs. 9.3σ in physics fills with $\beta^*=1$ m, as done later)



WHAT HAPPENED IN 2011? (4/4)

- ◆ At the end of the 2011 run, a **Landau octupoles current of ~ -200 A in squeeze was needed for beam stability, which was much bigger than predicted... assuming known beam parameters such as chromaticities, etc.**
- ◆ **Why? => Was not understood...**

WHAT HAPPENED IN 2012? (1/13)

- ◆ **The 2012 run was devoted to the LHC exploitation but also to explore the LHC performance limits => Busy period for us!**
- ◆ **Machine and beam parameters**
 - 4 TeV
 - Tighter collimators' settings
 - 60 cm β^* in IP1&5
 - $\frac{1}{2}$ number of bunches (50 ns spacing): 1374 b
 - $\sim 1.6E11$ p/b within $\sim 2.2 \mu\text{m}$
 - ~ 10 cm rms bunch length for beam-induced RF heating reasons

WHAT HAPPENED IN 2012? (2/13)

- ◆ **Reminder: Knobs available to damp transverse coherent instabilities**
 - Transverse tunes and tune split between the 2 beams
 - Coupling between the transverse planes
 - Chromaticities (value and sign)
 - (Landau) octupoles (value and sign) to increase Landau damping
 - (ADT) transverse damper (gain and bandwidth: not fully flat / bunch-by-bunch or flat / bunch-by-bunch)
 - Bunch length and / or longitudinal profile

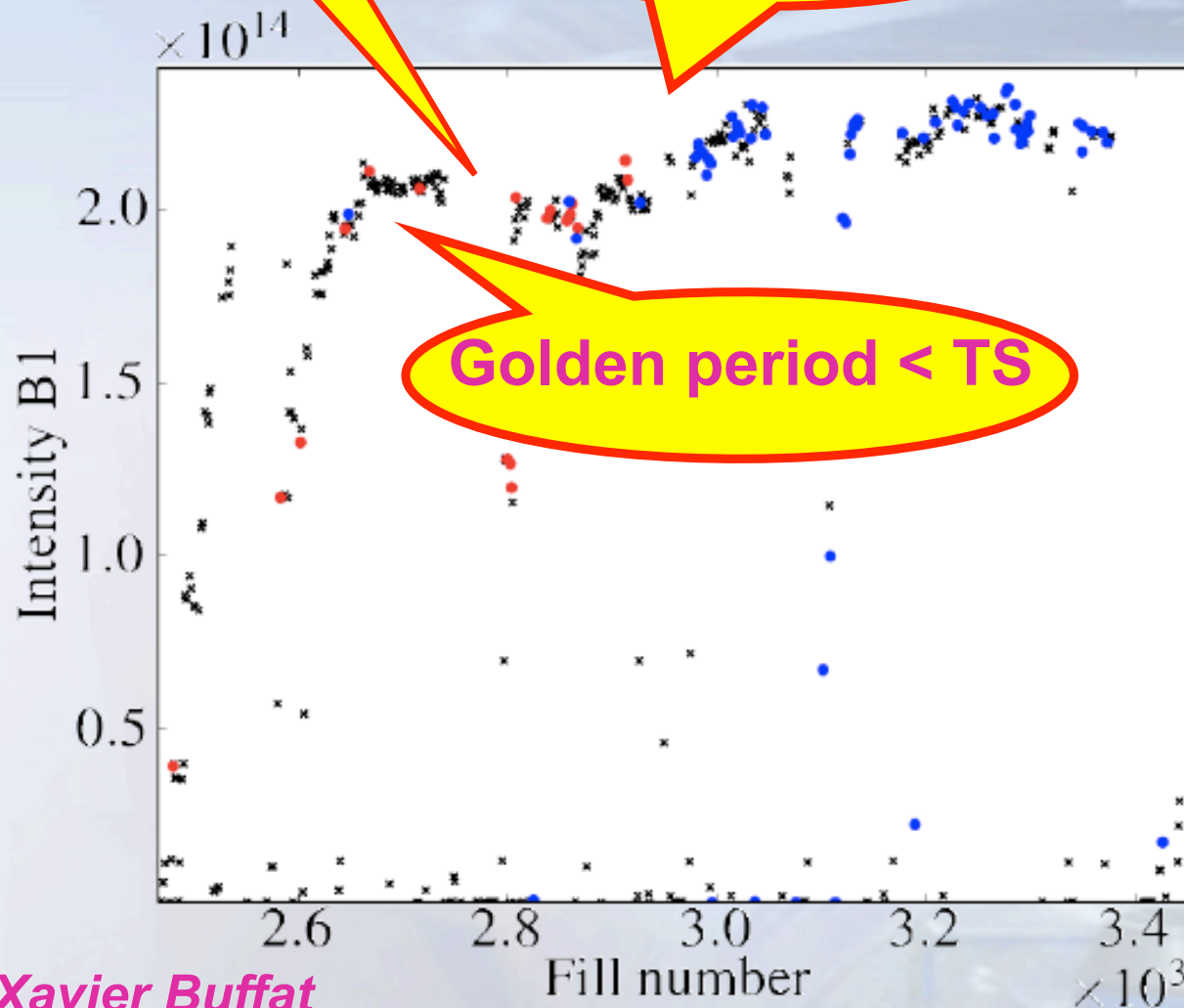
WHAT HAPPENED IN 2012? (3/13)

Proposed by
S. Fartoukh

Technical Stop
(TS)

Run clearly split in
2 (< and > MYC)

Golden period < TS



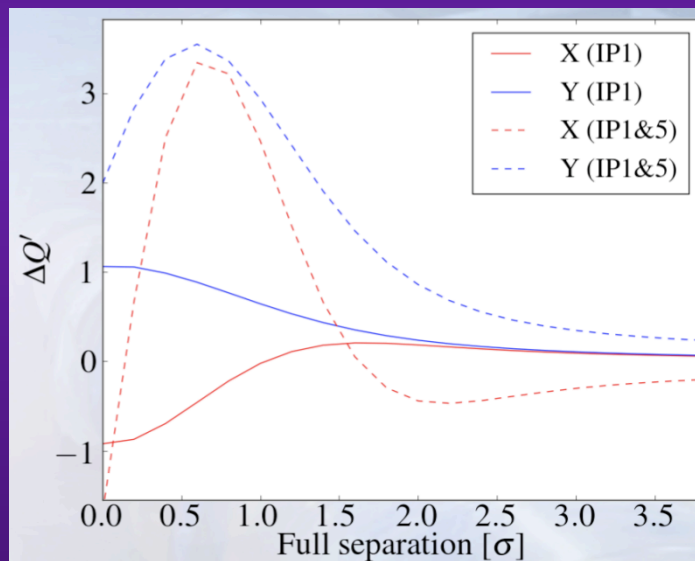
Xavier Buffat

- ◆ MYC = Middle of the Year Change = Change to “LOF > 0 (on 07/08/12 – Fill 2926) + high chroma + higher damper gain in the vertical plane”
- ◆ In red: BBQ activity during colliding process (adjust or stable beams)
- ◆ In blue: BBQ activity during / after the squeeze => EOSI

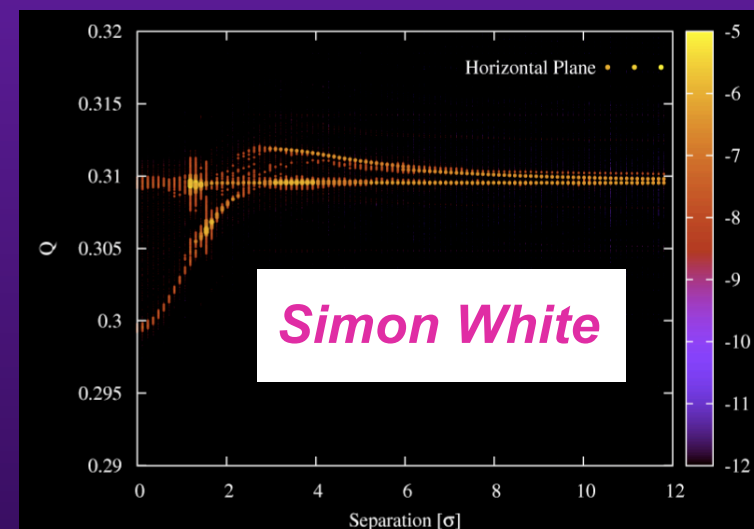
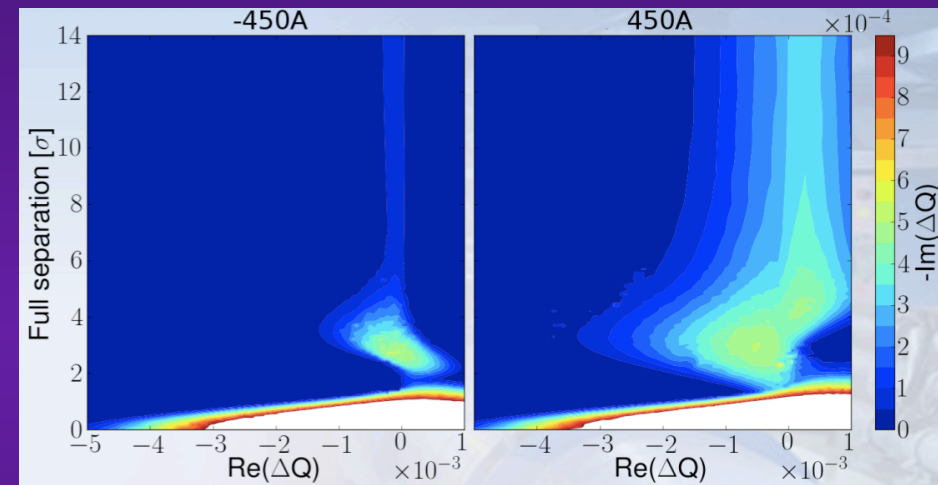
WHAT HAPPENED IN 2012? (4/13)

- ◆ **Stability of beams colliding with an offset is critical around 1-2 σ full separation. Observed in operation and dedicated experiments. Confirmed by models, with 3 mechanisms critical in this area**

Xavier Buffat



Tatiana Pieloni



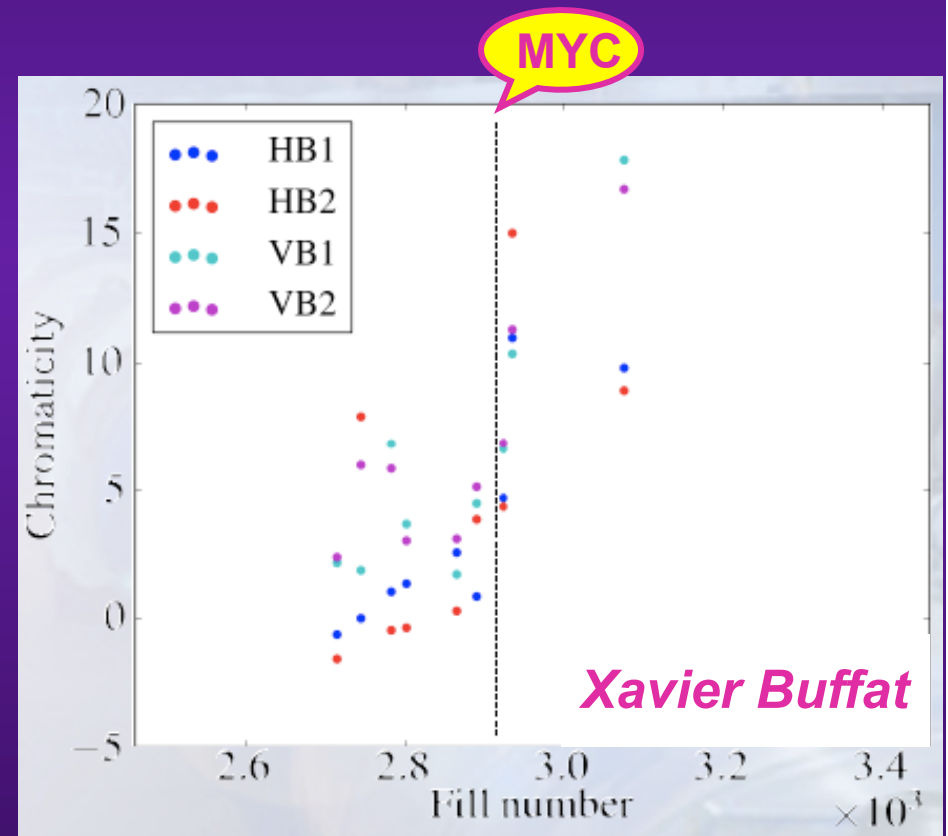
Simon White

WHAT HAPPENED IN 2012? (5/13)

- Main issue: Difficult to disentangle between the 3 mechanisms
- H-plane was more critical => Due to chromaticity?

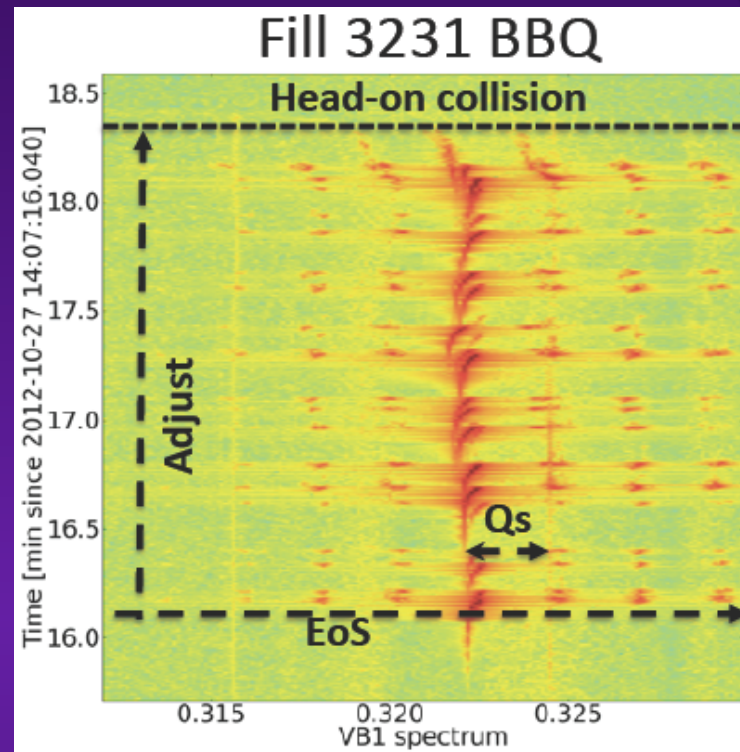
- Summary

- Many dumps < MYC
- **Situation > MYC: was OK**
- LOF < 0? => Should have several means to fight against instabilities (high chroma; asynchronous collision process)



WHAT HAPPENED IN 2012? (6/13)

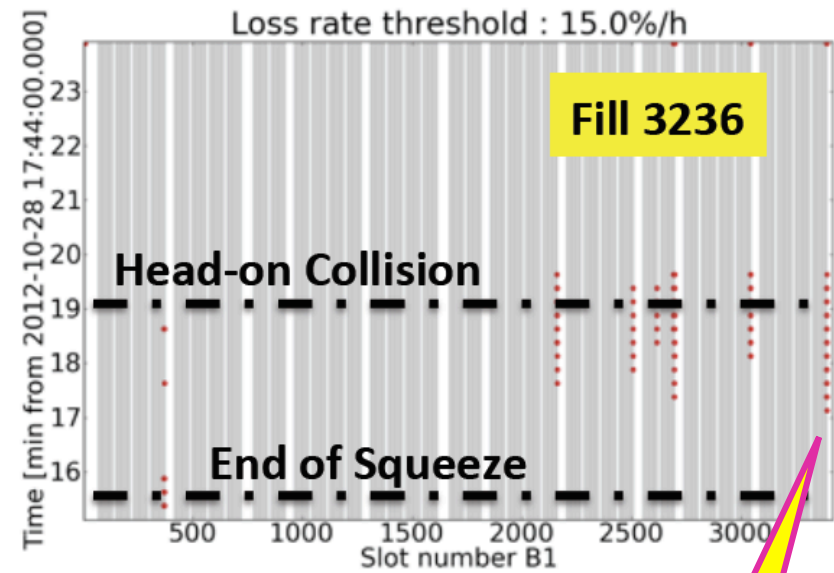
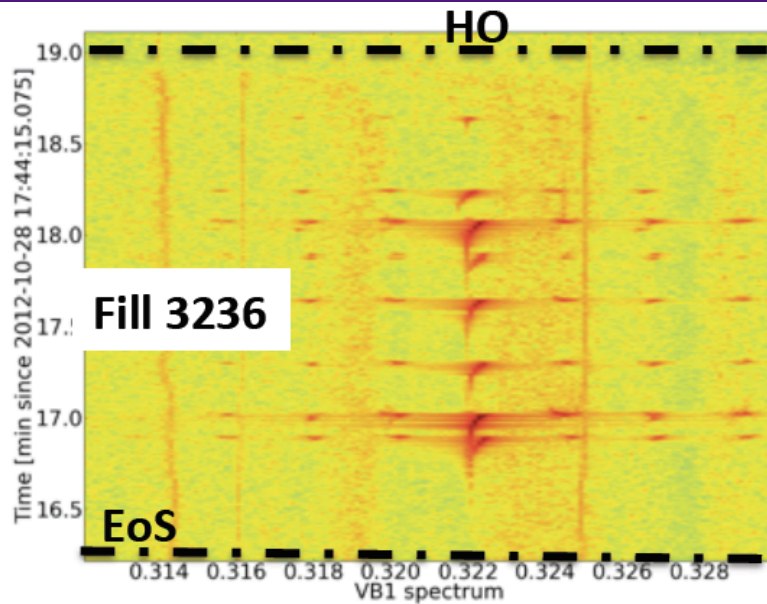
◆ EOSI



Tatiana Pieloni

- **More instabilities > MYC => Was NOT OK!**
- Very reproducible at the end of the squeeze > Fill 2980
- Clear pattern > MYC whereas less clear < MYC
- Mostly B1V > MYC (plane changed with MYC)
- **More critical at the end of the batches**

WHAT HAPPENED IN 2012? (7/13)



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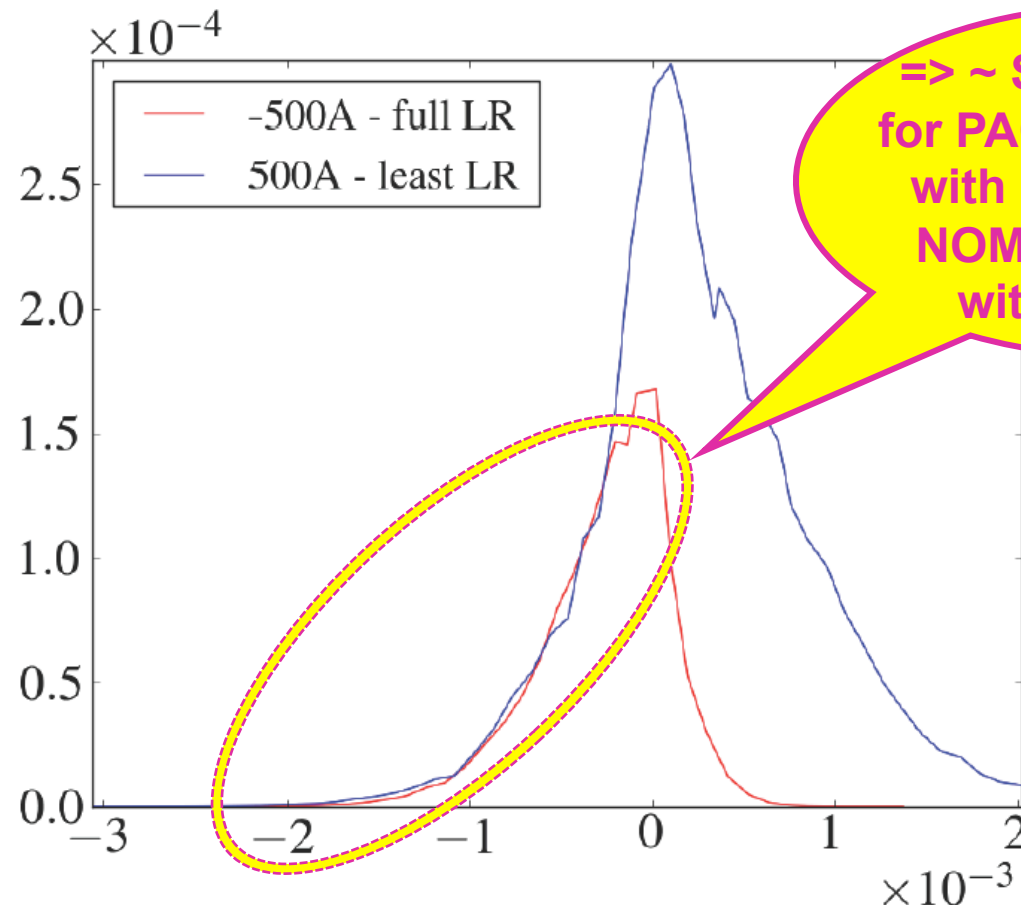
End of
batches

WHAT HAPPENED IN 2012? (8/13)

- Effect of change of sign of LOF

Xavier Buffat

End of squeeze Stability diagrams:
change of octupoles PACMAN bunches

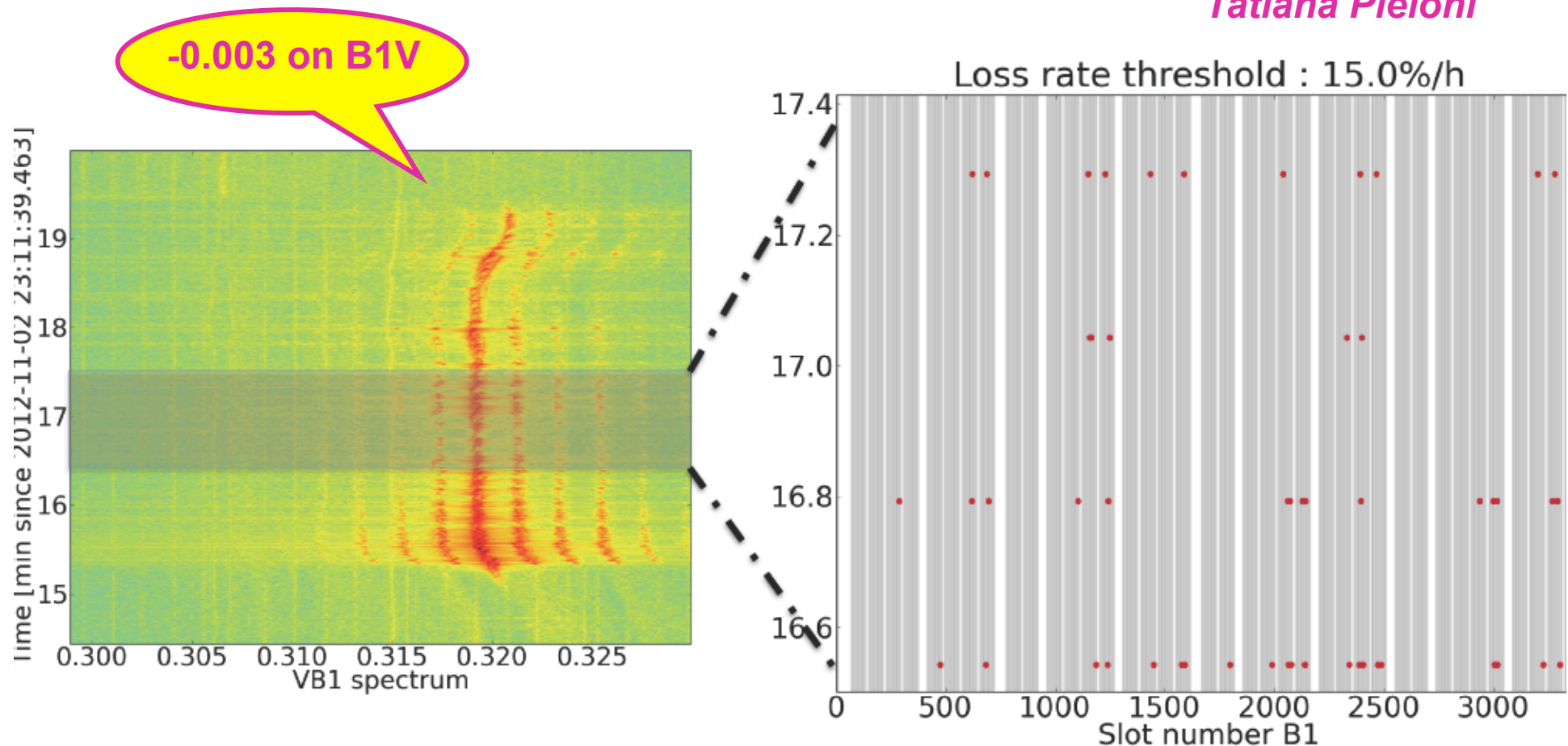


WHAT HAPPENED IN 2012? (9/13)

- Tune splits => Several fills tested and the loss pattern seemed to change (at least in some cases) => Moved towards the centre bunches, as expected in some models (Simon White)

Fill 3259 tune split at end of squeeze:

Tatiana Pieloni

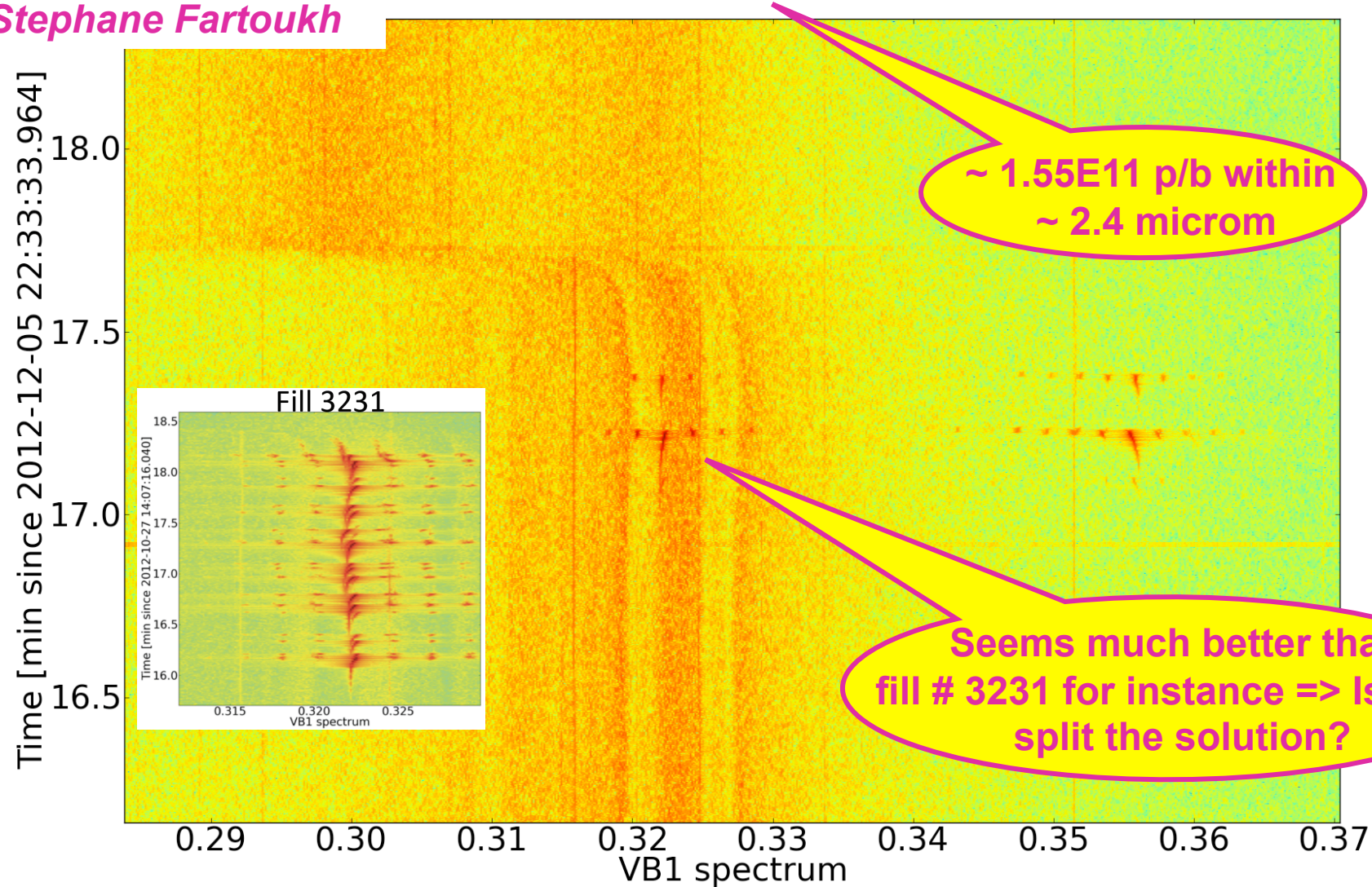


WHAT HAPPENED IN 2012? (10/13)

Fill # 3378 => Tune split: -0.005 on B2H and B2V

Tatiana Pieloni

Stephane Fartoukh



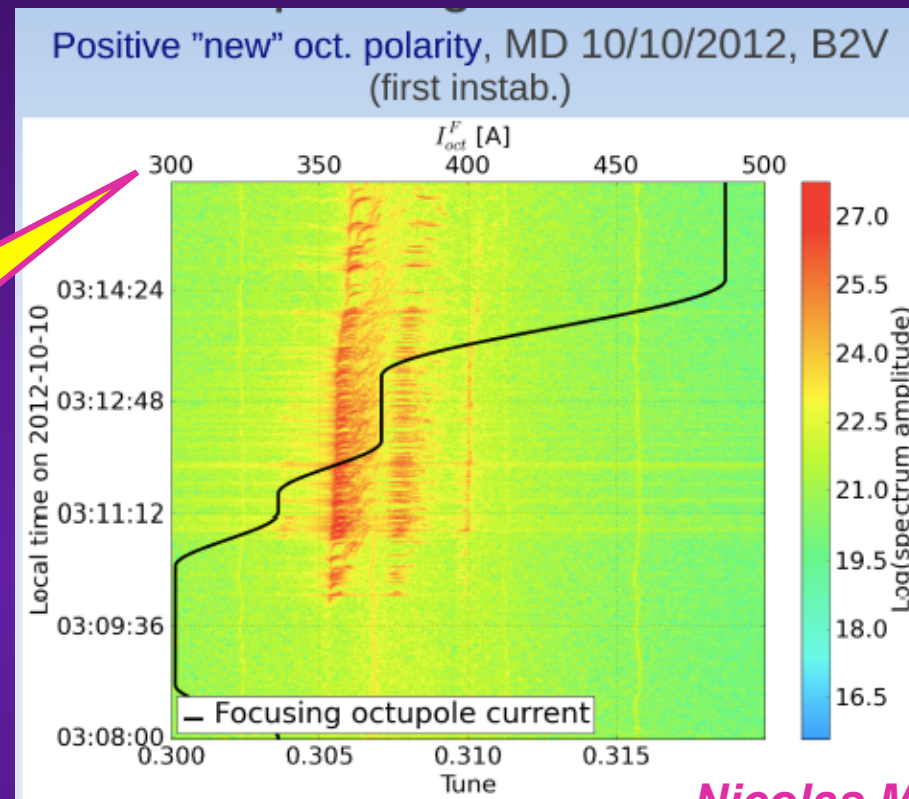
WHAT HAPPENED IN 2012? (11/13)

- **Cogging MD (Stephane Fartoukh et al.)**
 - **After an instability (reducing the LOF), the beam could not be stabilized again by re-increasing the LOF**
 - **BBQ signal disappeared when the cogging process started (tune split introduced!)**
- **Global summary => Seems that tune splits are doing something and that a coupling between the 2 beams exist... Still discussions...**

WHAT HAPPENED IN 2012? (12/13)

◆ 1-beam instabilities

Threshold LOF ~ 300 A
and then not possible to re-
stabilize the beam



Nicolas Mounet

■ Issues

- MDs done on B2 only (EOSI mostly B1V > MYC)
- Impedance model (tune shift) not studied at high chroma (which has been used > MYC)

WHAT HAPPENED IN 2012? (13/13)

■ Global summary

- Several features observed which are similar to the ones observed with the EOSI (tails of batches more critical; hockey sticks)
- Several features observed which are similar to the ones observed during the cogging MD (beam could not be saved by octupoles once unstable, etc.)
- **LOF < 0 better from both model and measurements**

=> Is the EOSI due to increase of impedance during the squeeze and / or some coupling between the 2 beams?

- Ongoing improvement of our impedance model
- Need to study in more detail the tune split

CONCLUSION (1/3)

◆ Great success for the LHC performance

- $\sim 1.6E11$ p/b instead of nominal $1.15E11$ p/b $\Rightarrow + \sim 40\%$
- $\sim 2.2 \mu\text{m}$ instead of nominal $3.75 \mu\text{m}$ $\Rightarrow - \sim 40\%$

\Rightarrow Bunch brightness: $\sim (1.6 / 1.15) \times (3.75 / 2.2) \sim 2.4$ times larger than nominal!

- Both transverse damper and Landau octupoles are needed and work well!

◆ However,

- EOSI could not be cured (not understood yet) \Rightarrow Potential worry for future operation at higher energy, higher beam intensity and higher beam brightness
- Remains to be seen what will happen at 7 TeV (instead of 4) and with 25 ns (instead of 50 ns)... \Rightarrow Ecloud!

CONCLUSION (2/3)

- ◆ **Lot of effort devoted to study the main mechanisms and interplay between them**
 - Impedance, octupoles and ADT (and BBLR)
 - Octupoles and beam-beam (BBLR & BBHO)
 - Impedance and beam-beam (BBLR & BBHO)
 - Effect of octupoles and beam-beam (BBLR & BBHO) on chroma
 - **Alexey Burov** developed a 3-beam instability model to explain the EOSI with e- at the IT => Difficult at the moment to explain (quantitatively) the EOSI by this mechanism
- ◆ **Experience from 2012 => “Full” understanding not possible**
 - Frequent and simultaneous changes of beam parameters
 - Non-conclusive measurements
 - Different interpretation of measurements and observations

=> Systematic measurements needed

CONCLUSION (3/3)

- ◆ **Might not have enough transverse Landau damping in the future**
 - More octupoles needed (and $\text{LOF} < 0$ better for 1-beam). ATS optics will help
 - Use BBHO tune spread as soon as possible (but we need to reach this point...)
 - Decrease the impedance
 - Recent idea / proposition from **Alexej Grudiev** to help us having more transverse Landau damping => **RF quadrupole (to provide longitudinal spread of betatron tune)**
 - A ~ 1 m long cryomodule with three 800 MHz SC pillbox cavities in IR4 could provide enough tune spread for Landau damping of a mode with $\Delta Q_{\text{coh}} \sim 2\text{E-}4$ at 7 TeV
 - Under study if this can really help us (beam dynamics)
 - Then, possible design, prototype, etc.