
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

# COLLECTIVE EFFECTS: STATUS AND PLAN

**Elias Métral**

**for the WP2 Task 2.4 and all the people working on collective effects and high-intensity issues.**
**Many many thanks! (20 + 5 min talk, 25 slides)**

- **Introduction**
- **The 5 main activities of Task 2.4 in 2012**
- **Conclusion**

# INTRODUCTION AND 2012 ACTIVITY IN TASK 2.4 (1/2)

- **Considerable increase of LHC luminosity in 2011 and 2012**
  - *Peak luminosity record: ~ 7.7E33, i.e. 77% of design luminosity*
  - *4 / 7 = 57% of design energy*
  - *½ number of bunches (50 ns spacing instead of 25 ns): 1374 b*
  - *~ 1.6 $10^{11}$ p/b within ~ 2.2 μm (transv. r.m.s. norm. emittance)*
  - **Bunch brightness: ~ (1.6 / 1.15) × (3.75 / 2.2) ~ 2.4 times larger than nominal => ~ 2.4 times more critical for octupoles current**
  - **Tight collimators' settings in 2012 => Larger impedances and more critical instabilities (factor ~ 2.3 compared to 2011) => ~ 2.3 more octupoles needed**
  - **Change of octupoles sign in July (see later why) => ~ 65% more current needed (assuming Gaussian transverse distribution)**

**=> Factor ~ 9 more octupoles current needed!**

- **3 types of instabilities perturbed the intensity ramp-up**

# INTRODUCTION AND 2012 ACTIVITY IN TASK 2.4 (2/2)

- ITEM 1): Definition of the work packages and distribution among the various collaborators and institutes
- ITEM 2): Intra-Beam Scattering (IBS) studies for the current LHC, nominal LHC and HL-LHC, and setting-up of a benchmarking case with all the IBS contributors
- ITEM 3): Evaluation of the impedance budget for the crab cavities to be installed in the HL-LHC, and dedicated impedance studies for other equipments
- ITEM 4): Follow-up of the LHC performance and participation to the LHC Machine Developments (MDs) via beam experiments in order to improve the understanding of collective effects in the present machine and assess our predictive power for the HL-LHC in terms of intensity limitations
- ITEM 5): Development of new ideas to push the machine performance

# ITEM 1): TASK 2.4 ORGANIZATION

- All the information related to the Task 2.4 (objectives, description of the work, sub-tasks, milestones, deliverables, person-months from the collaboration, work breakdown structure, Gantt chart, mailing list of 29 people, meetings, publications, inputs needed, questions raised, etc.) can be found at the following link:

  https://espace.cern.ch/HiLumi/WP2/task4/SitePages/Home.aspx

- This web page is maintained by the Task leader and 3 Task 2.4 meetings took place until now

# ITEM 2): IBS (1/4)

- **Studies have been finalized and presented at the occasion of a Task 2.4 meeting, revealing no major issues with the current HL-LHC parameter set => Full report under publication, from**

***Michaela Schaumann, John Jowett and Roderik Bruce***

- **A benchmarking case was also set-up to benchmark with other IBS codes in other labs**

# ITEM 2): IBS (2/4)

*Michaela Schaumann et al.*

- **IBS growth rates**

| Spacing | 25 ns | | 50 ns | |
|---|---|---|---|---|
| $E$ [GeV] | 450 | 7000 | 450 | 7000 |
| $\beta^*$[m] | 11 | 0.1 | 11 | 0.1 |
| $\alpha_{IBS,l}$ [1/h] | 0.096 | 0.060 | 0.124 | 0.075 |
| $\alpha_{IBS,x}$ [1/h] | 0.096 | 0.065 | 0.103 | 0.069 |
| $\alpha_{IBS,y}$ [1/h] | $-6.4 \times 10^{-4}$ | $-1.5 \times 10^{-6}$ | $-6.9 \times 10^{-4}$ | $-1.6 \times 10^{-6}$ |

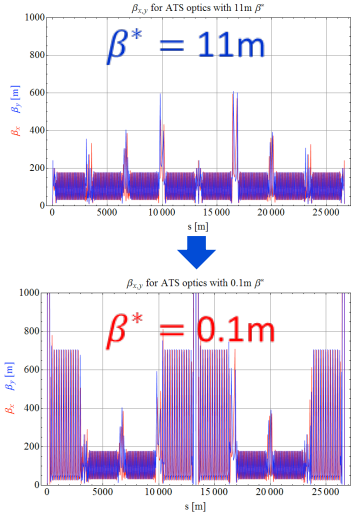
  - Calculations done with MADX and CTE (Collider Time Evolution) programs at injection (450 GeV) and collision (7 TeV) energy for various optics and beam parameter options => Both codes are in good agreement
  - 2 ATS Optics version considered: ATS-V6.503 and SLHCV3.1b
  - CTE simulations have included the evolution of beam parameters and luminosity with self-consistent IBS calculations, including non-Gaussian longitudinal distributions and losses from the RF bucket, radiation damping and the loss of intensity due to luminosity production ("burn off")

Michaela Schaumann et al.

# ITEM 2): IBS (3/4)

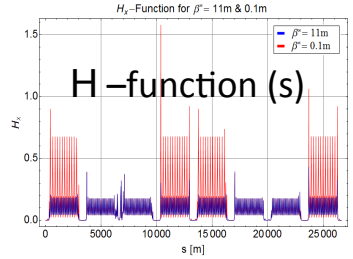
## Effect of the ATS Squeeze on IBS Growth Rates

### β-Function (s)

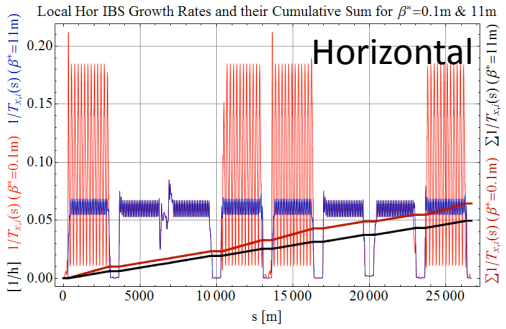


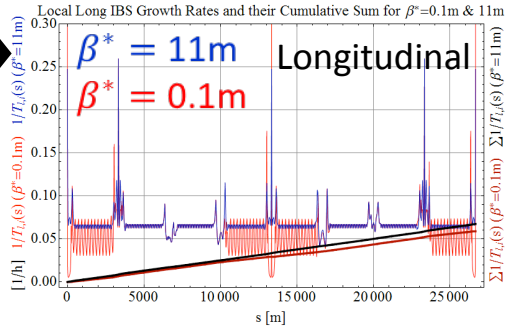

Squeeze creates high $\beta$-values in the arcs around IP1&5 for $\beta^* \leq 0.4$m.

Increase in $\mathcal{H}$ –func.




### Local IBS Growth Rates (s)

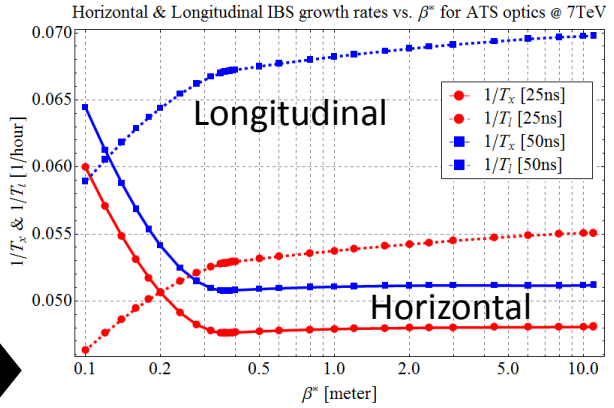



Increased IBS contribution for $\beta^* = 0.1$m in high $\beta$-regions.

Accumulated/average IBS rate:
- horizontal increase,
- longitudinal reduction. (dark red lines)

### IBS Growth Rates ($\beta^*$)



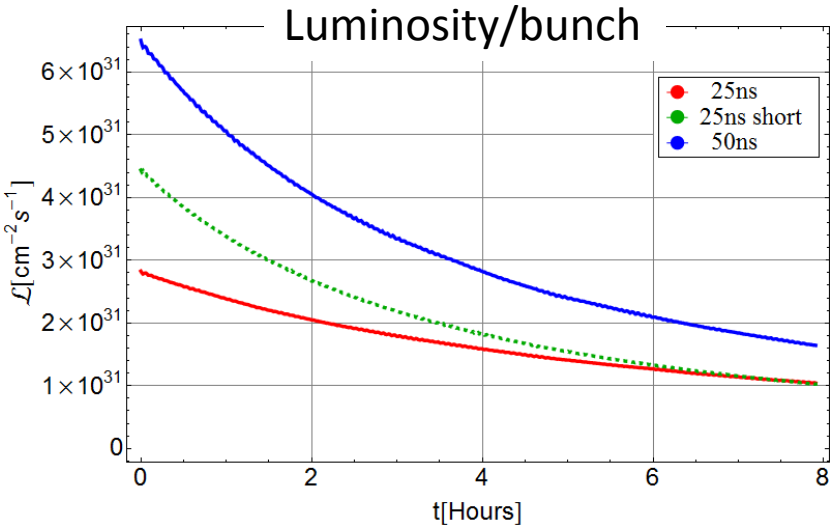

Horizontal growth rate (solid line) increases with $\beta^*$ smaller ~0.4m:
- due to strong dependence on the $\mathcal{H}$ –function.

Longitudinal growth rate (dashed line) improves with smaller $\beta^*$:
- dependence on lattice parameters is less dominant.

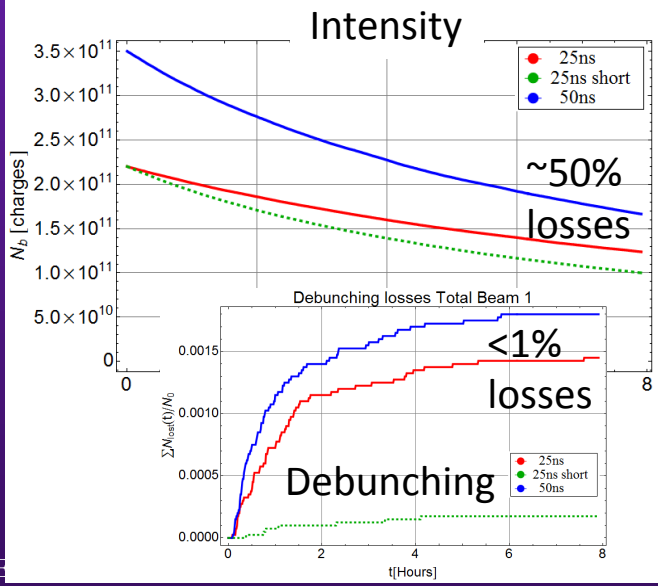
*Michaela Schaumann et al.*

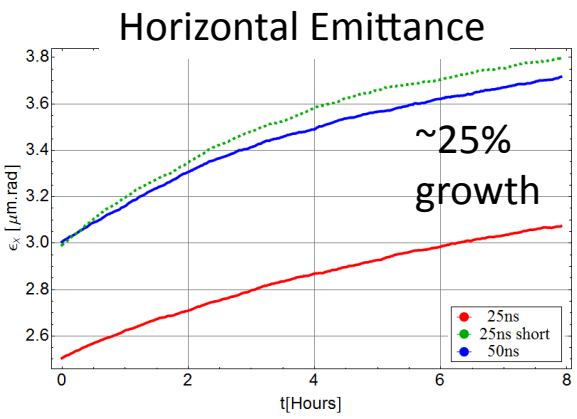
# ITEM 2): IBS (4/4)

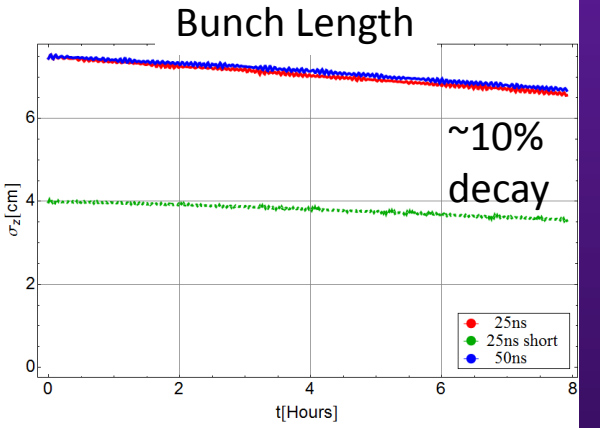
## Beam and Luminosity Evolution




- Simulations done with CTE
- Virtual luminosity evolution - no crab cavities and levelling
- Radiation damping has positive effect on emittance growth and leads to reduction of bunch length
- Intensity losses are dominated by luminosity burn off – debunching losses are negligible
- 50ns beam produces more luminosity thanks to the higher initial bunch intensity



# ITEM 3): IMPEDANCE STUDIES (1/2)

- Will be discussed in detail during the talk of *Benoit Salvant*
- In particular, work was done by some collaborators
  - Vacuum chamber in the CMS experiment

    *Rainer Wanzenberg and Olga Zagorodnova (DESY)*
  - Broad-band kicker for SPS intra-bunch feedback system

    *Mikhail Zobov et al. (LNF INFN)*
- Some guidance for the impedance budget of the Crab Cavities was already given in 2011 at LHC-CC11 workshop by *Alexey Burov (LARP-LTV)* and the different so-called compact Crab Cavity prototypes have been designed and built following these recommendations
- Following the 2011 LHC run with issues identified for some components with RF fingers, a dedicated task force was set up in 2012 to review all these equipments (see http://emetral.web.cern.ch/emetral/LRFF/LRFF.htm) => Recommendations should be made by the end of the year (both for the LHC and HL-LHC)

# ITEM 3): IMPEDANCE STUDIES (2/2)

- RF heating of some equipments is worrisome => Closely followed up and more MDs are needed to assess all the possible future limitations

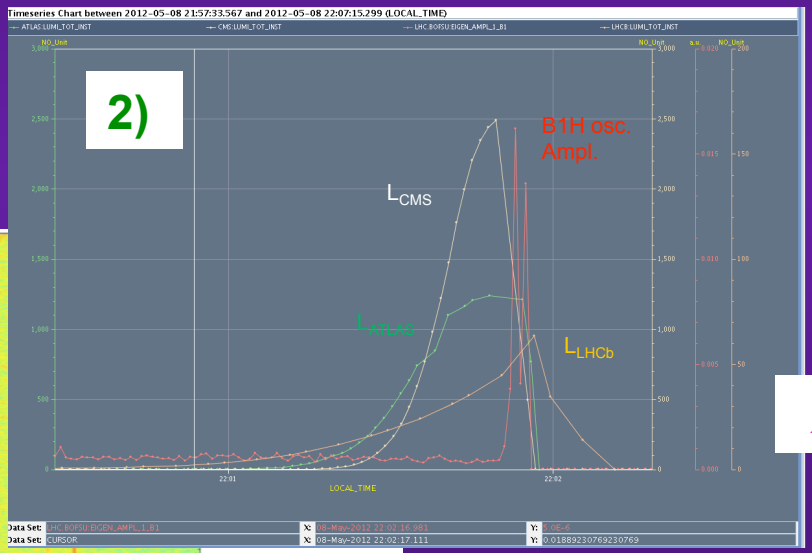
*Benoit Salvant*

- Some successful impedance reductions have however been already achieved, as for instance on one of the modules forming the injection kicker, but further modifications will be required for the HL-LHC era

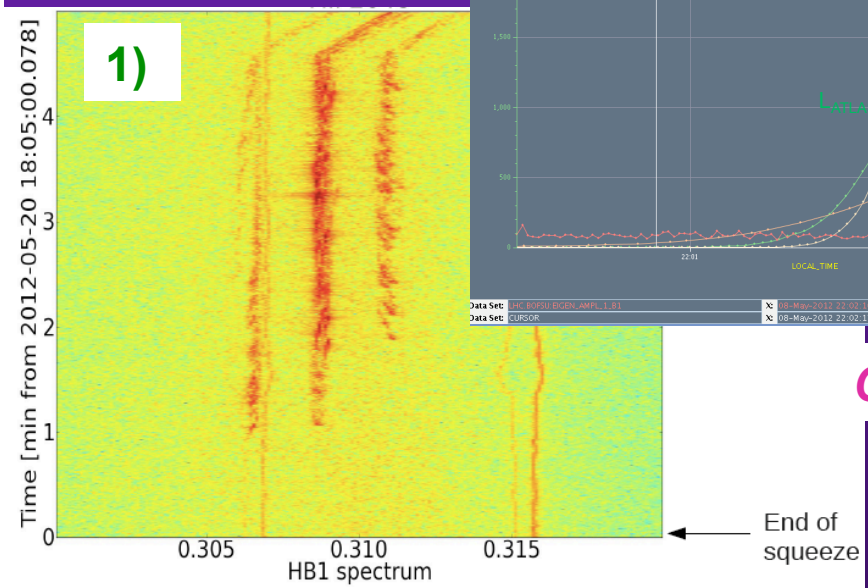
*Hugo Day and Mike Barnes*

# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (1/11)

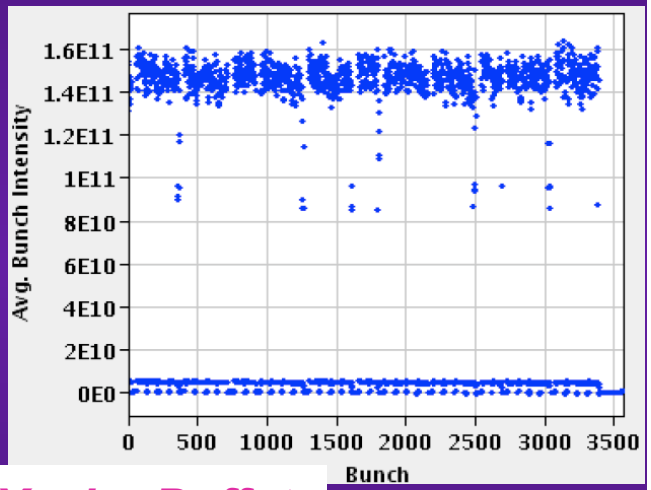
- **3 types of instabilities perturbed the intensity ramp-up:**
  - 1) during or at the end of the squeeze process
  - 2) during the collapsing process (putting the beams into collision)
  - 3) in collision (during the levelling process with parallel separation in LHCb, but for some specific bunches only)



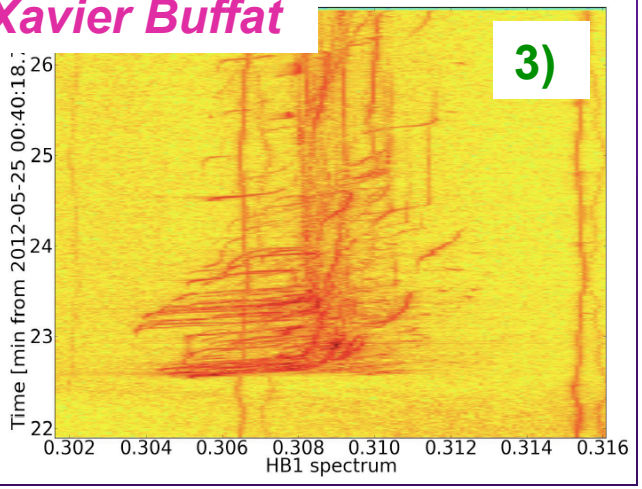

*Xavier Buffat*




*Gianluigi Arduini*




*Xavier Buffat*



# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (2/11)

- **Concerning 2) and 3), possible explanation => Landau octupoles (with negative sign) and beam-beam long-range fought against each other**
  - **For this reason the polarity of the Landau octupoles was changed in July, as proposed by *Stephane Fartoukh*. Studies also from *Xavier Buffat et al.***
  - **Furthermore, the gain of the transverse damper was increased to about its maximum damping rate (50 turns) and the chromaticity (initially kept to a few units) set to ~ 15-20 units**
  - **Since then the beam dumps linked to the instabilities disappeared and the intensity could be increased, but then instabilities at the very the end of the squeeze reappeared (mainly B1V. With the other sign, it was mainly in H…)**
  - **More Landau octupoles' current is needed during the physics fills (i.e. with 2 beams) than in dedicated MDs with only one beam. In particular, the octupole current used in operation is close to its maximum value of 550 A, which is currently a major concern for HL-LHC => Ongoing studies:**
    - **Two-beam effects such as two-beam impedances: MD foreseen (using "cogging"), proposed by *Stephane Fartoukh***
    - **Interplays impedances / beam-beam effects => See talk from *Simon White***

# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (3/11)

- **Organization and detailed analysis of the single-beam MDs (still ongoing) by** ***Nicolas Mounet***

| Fill Number | date | time | beam(s) present | stage | beam affected | bunches affected by losses | Instab. Plane | intensity per bunch | number of bunches |
|---|---|---|---|---|---|---|---|---|---|
| 2744 (MD) | 19/06/2012 | 11:48:00 PM | 2 | before squeeze | 2 | **beginning of batches** + some in the middle of batches + complete 12 bunches batch | V | 1.50E+011 | 1380 |
| 2771 (MD) | 23/06/2012 | 07:06:00 PM | 2 | after squeeze | 2 | all over the place | V | 1.43E+011 | 1380 |
| 2771 (MD) | 23/06/2012 | 08:19:00 PM | 2 | after squeeze | 2 | close to the end of trains plus a few in the middle | V | 1.40E+011 | 1380 |
| 2771 (MD) | 23/06/2012 | 08:49:00 PM | 2 | after squeeze | 2 | all over the place | V | 1.40E+011 | 1380 |
| 2771 (MD) | 23/06/2012 | 09:55:00 PM | 2 | after squeeze | 2 | all over the place | V | 1.37E+011 | 1380 |

note: emittance measured at injection → then +0.5 mm.mrad for B2H (from V. Kain, CMAC talk, Aug 2012), the rest + 10% (~arbitrary - see also same talk)

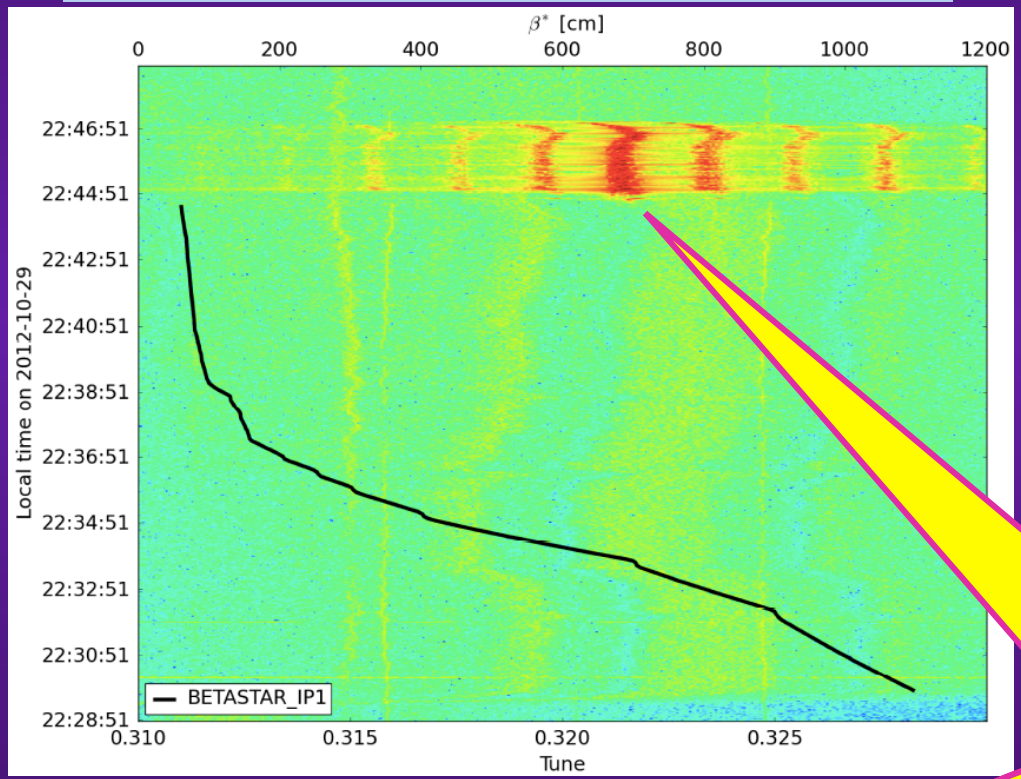
| focusing octupole current [A] | Qx/Qy | Q'x/Q'y | emit x/y [mm.mrad] | ADT damping time x/ y [turns] (rate [omega_s]) | Total bunch length [ns] | Headtail mode number | Rise time [s] | Instability visible on available ADT data ? |
|---|---|---|---|---|---|---|---|---|
| -100 | 0.28/0.31 | 8.35 +/- 0.05<br>4.1 +/- 0.3 | 2 ? / 2 ? | 100 / 200 (0.7 / 0.35) | 1.2 | -1 (BBQ) | 6.3 (BBQ) | no |
| -20 | 0.308/0.32 | 11 +/- 2<br>4 +/- 0.5 | 2 / 2 | 50 / 100 (1.4 / 0.7) | 1.23 | 0 ? (BBQ) | 20 (BBQ) | no |
| -240 | 0.308/0.32 | -1.9 +/- 1.3<br>-5 +/- 0.5 | 2 / 2 | 50 / 100 (1.4 / 0.7) | 1.24 | -1 ? (BBQ) | 14 (BBQ) | no |
| -60 | 0.308/0.32 | 8 +/- 2<br>1 +/- 0.5 | 2 / 2 | 50 / 100 (1.4 / 0.7) | 1.26 | -2 ? (BBQ) | 16 (BBQ) | no |
| -400 | 0.308/0.32 | 2.8 +/- 0.6<br>2.4 +/- 0.6 | 2 / 2 | inf / inf (0 / 0) | 1.26 | -1 ? (BBQ) | 3.6 (BBQ) | no |

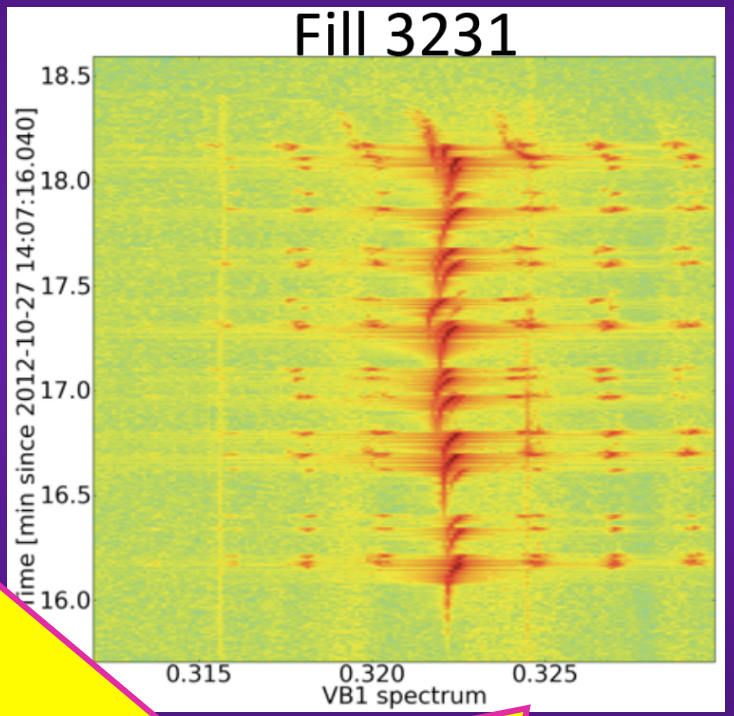
# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (4/11)

- **Example of current instability (with the new, positive sign of the Landau octupoles), max. damper gain and chromas at ~ 15-20 units**

Fill 3238 (Monday 29/10 evening)

*Tatiana Pieloni*



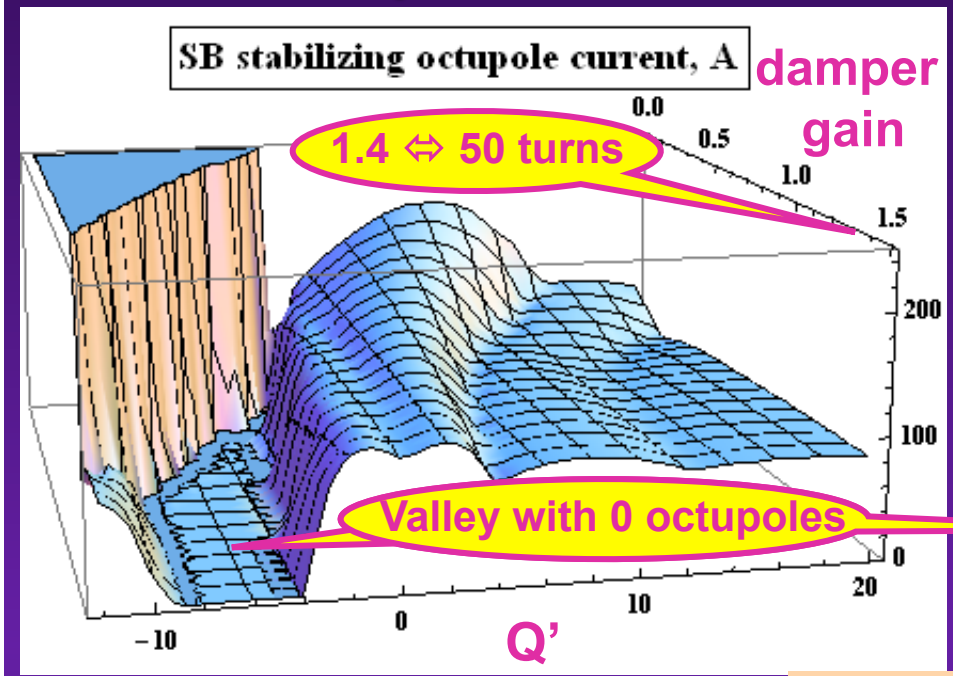

*Nicolas Mounet*

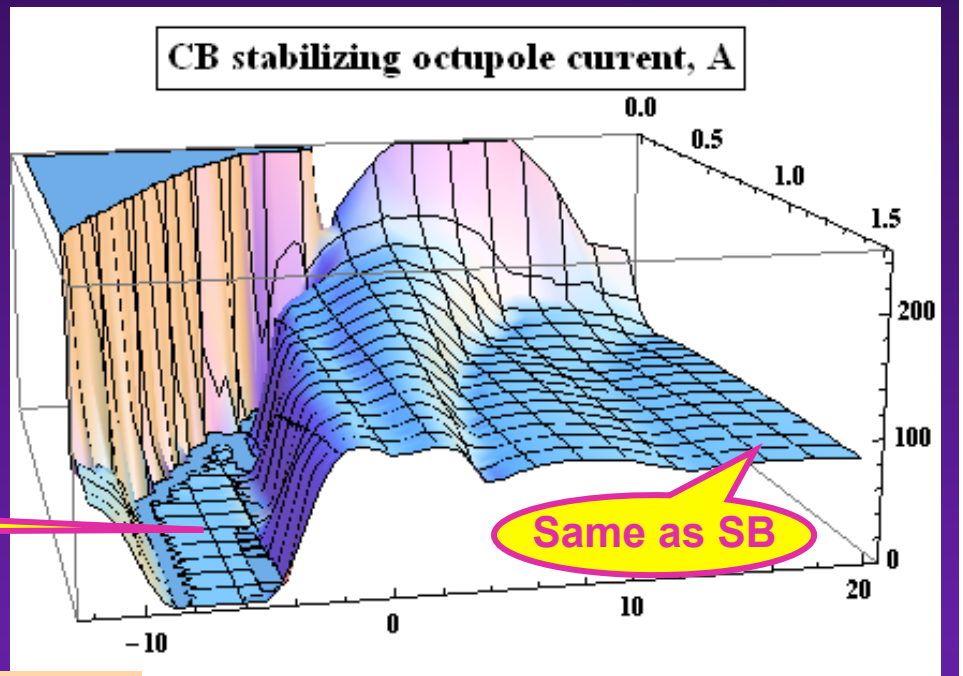
**Very reproducible => At the end of the squeeze (β* = 0.6 m), after ~ 16 min from the start of the squeeze**

# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (5/11)

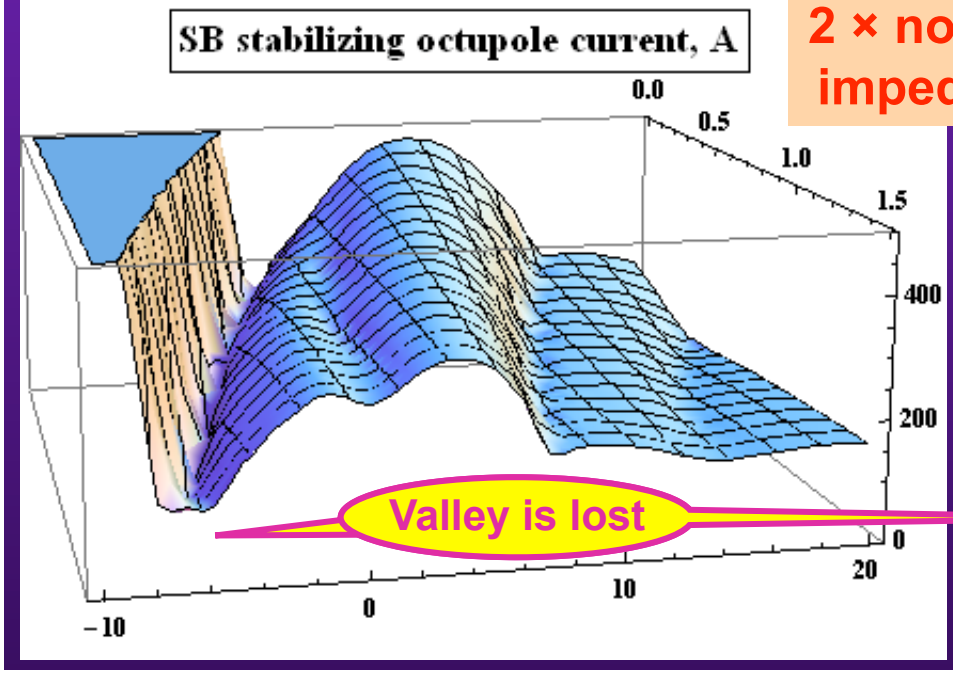
- The new values of the transverse damper gain and chromaticity were suggested after a new analytical approach => Nested Head-Tail (NHT) Vlasov Solver developed *Alexey Burov (LARP-LTV)*
- It assumes arbitrary multi-bunch beam with arbitrary train structure, arbitrary impedance, arbitrary frequency profile of the damper gain, arbitrary transverse and longitudinal nonlinearities and beam-beam collision scheme. The corresponding functions are supposed to be provided in any form
- The program computes all the relevant coherent modes with their head-tail, radial and couple-bunch structure for a given gain amplitude and beam chromaticity
- After that, the threshold strength of the Landau elements is computed by means of pre-calculated stability diagrams
- The NHT is under construction, being extended, upgraded and anti-bug checked day after day

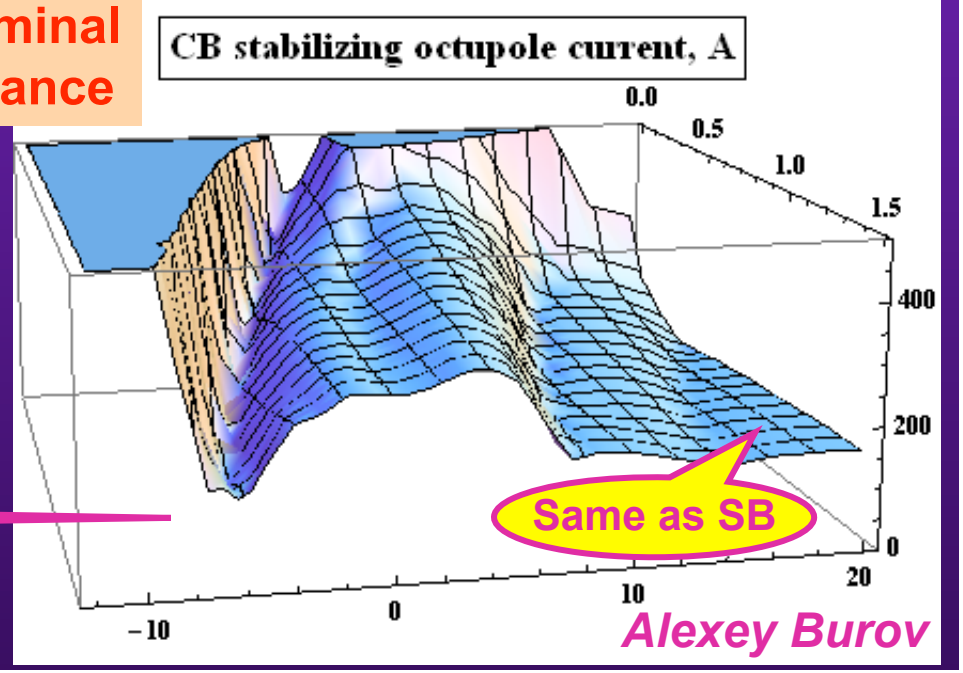
# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (6/11)




2 × nominal impedance




*Alexey Burov*

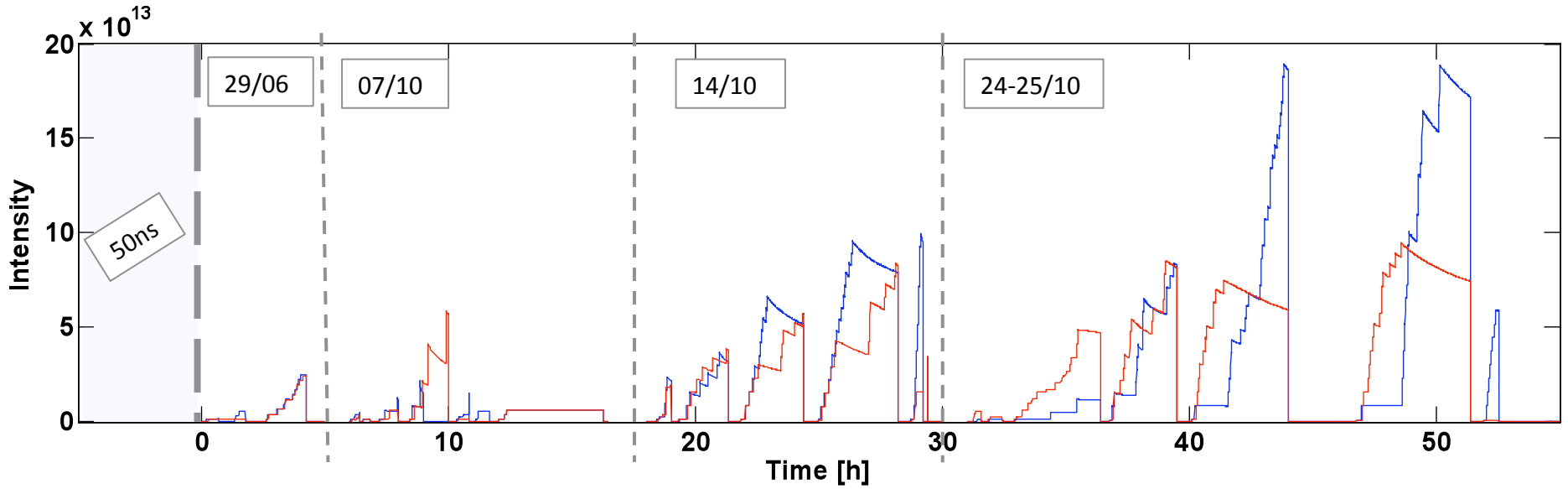
# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (7/11)

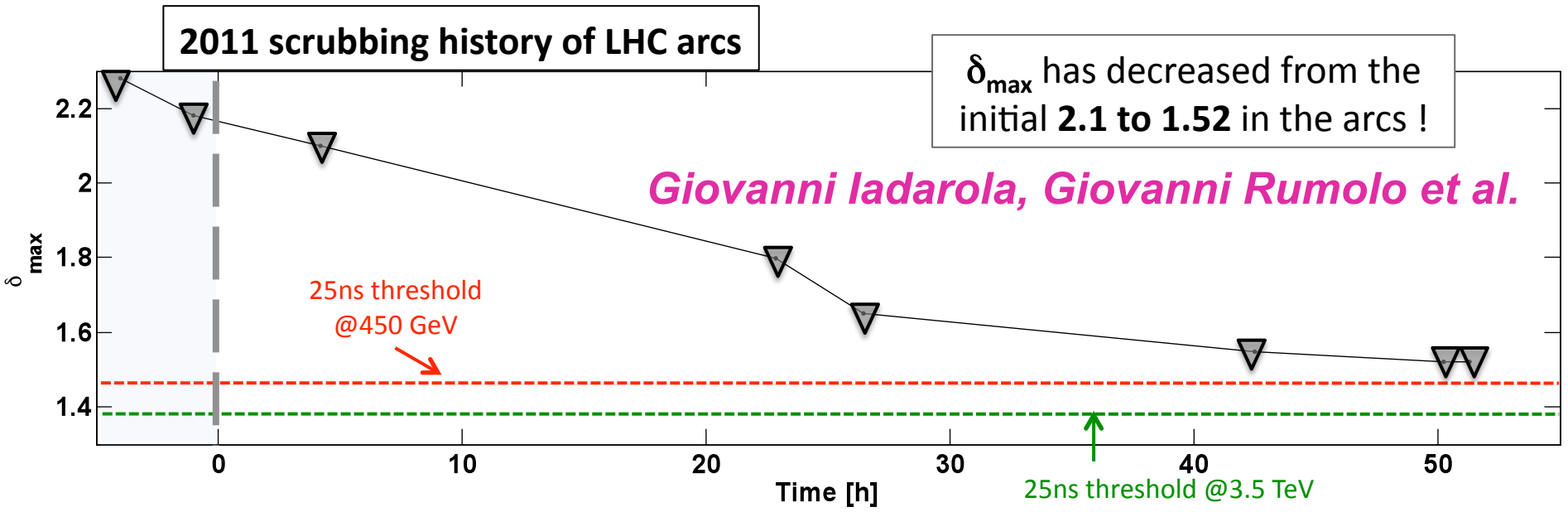
- **Finally, initial tests with bunches spaced by 25 ns (instead of 50 ns as used now) were encouraging with respect to the mechanisms linked to electrons cloud, but this beam still needs to be studied in more detail in the LHC to identify possible bottlenecks**

- **In parallel, the operating experience with electron cloud clearing electrodes at DAFNE has been reviewed, revealing a very beneficial impact of clearing electrodes**

# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (8/11)

- **ECLOUD studies in the LHC with 25 ns beam**



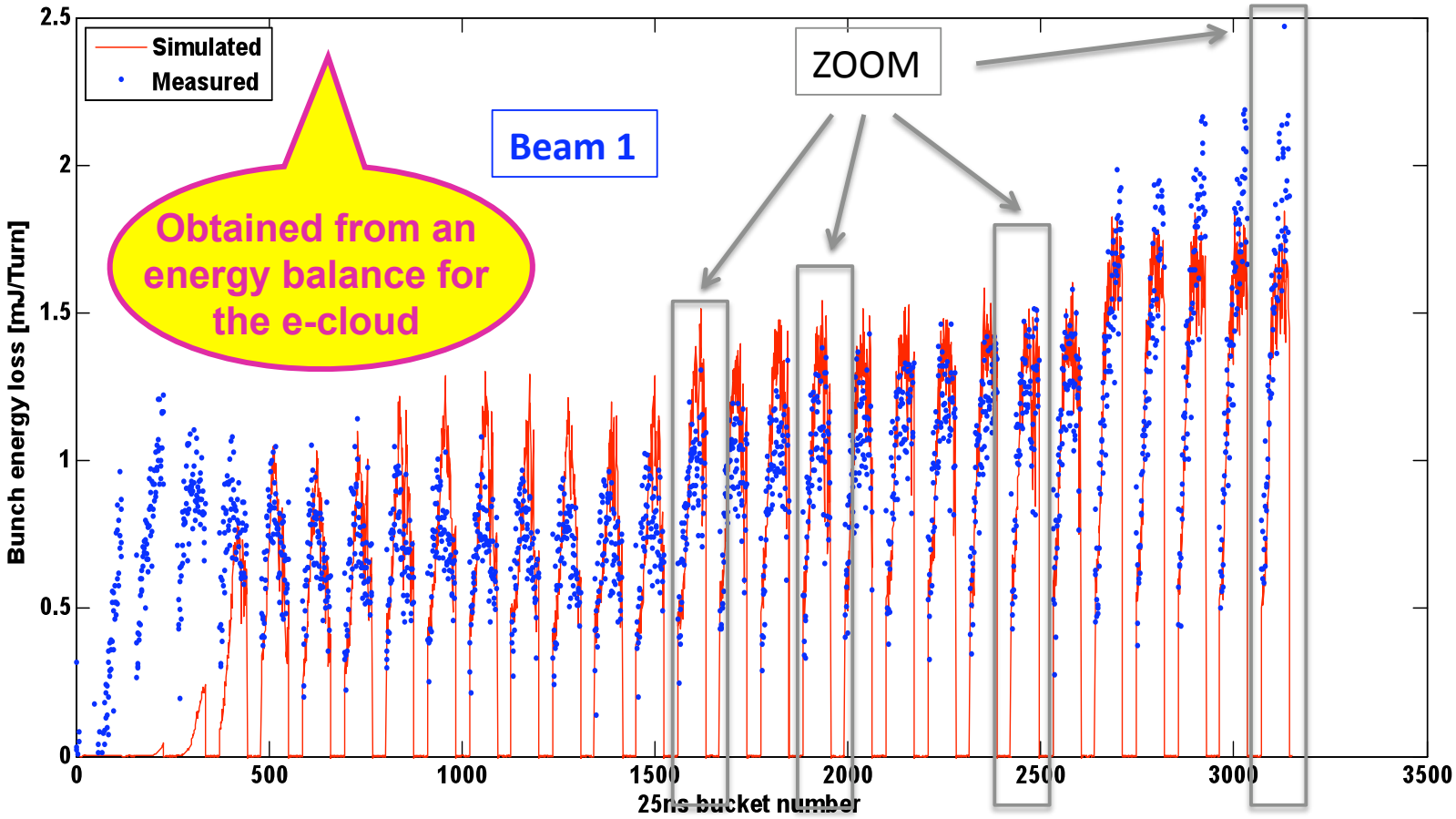

$\delta_{max}$ has decreased from the initial **2.1 to 1.52** in the arcs !

***Giovanni Iadarola, Giovanni Rumolo et al.***

# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (9/11)

Simulations → $\delta_{max}$ fixed to **1.5** (added 2e9p$^+$/m uncapt. beam)

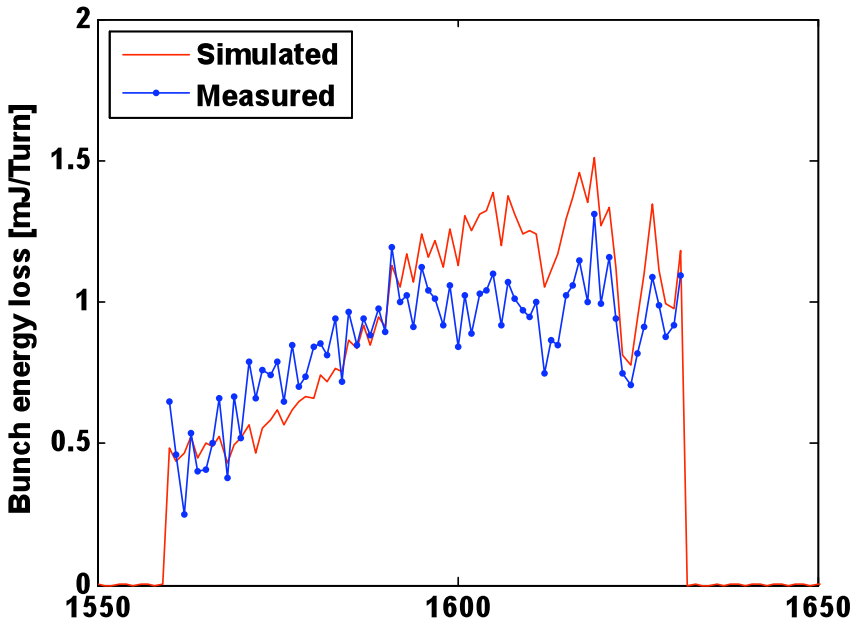
Measurements → the energy loss per bunch is obtained from the stable phase shift

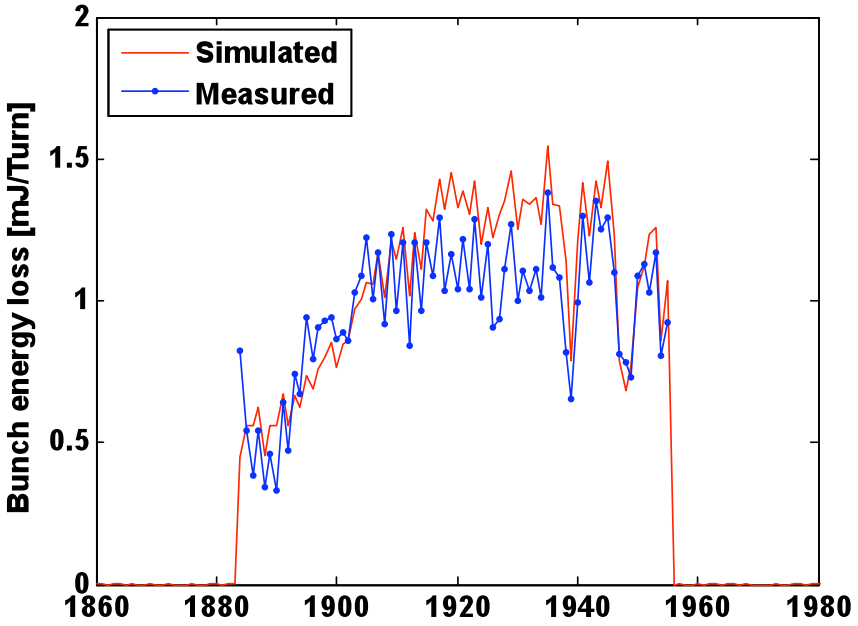


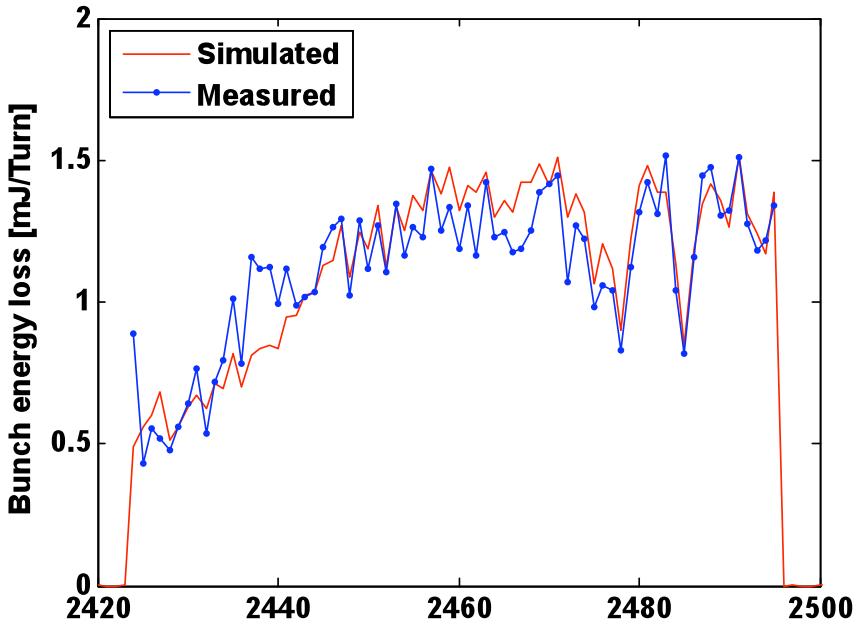

*G. Iadarola, G. Rumolo, J.E. Muller, E. Shaposhnikova et al.*

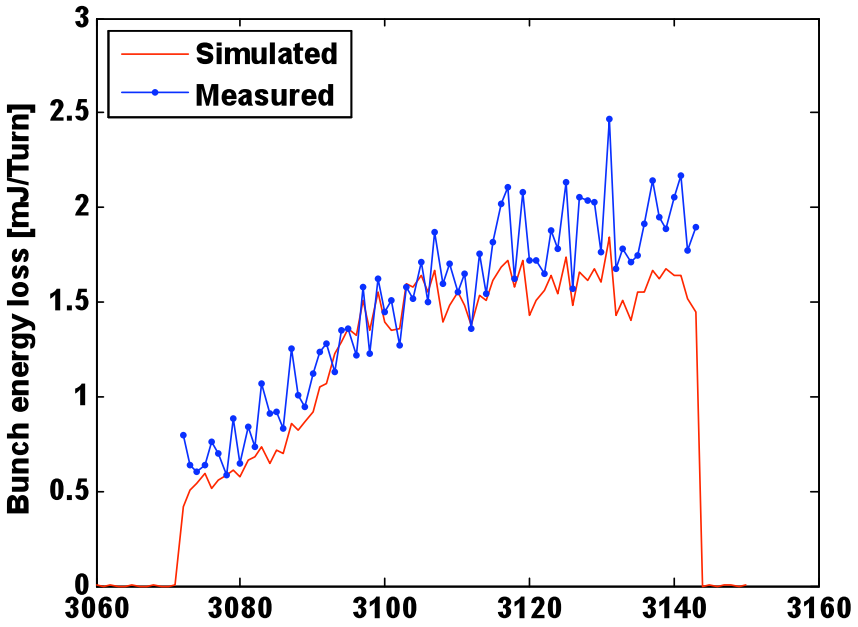
# ITEM 4): FOLLOW-UP OF THE CU

*G. Iadarola, G. Rumolo,*
*J.E. Muller, E. Shaposhnikova et al.*



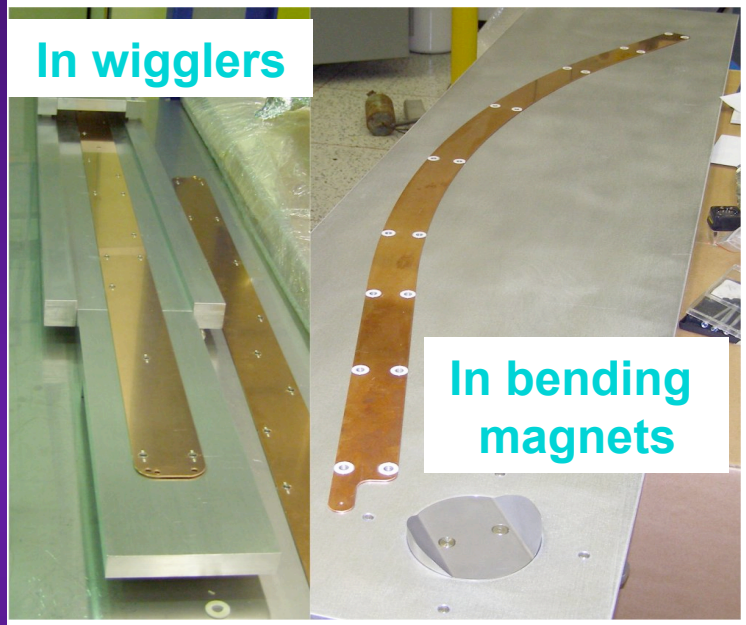



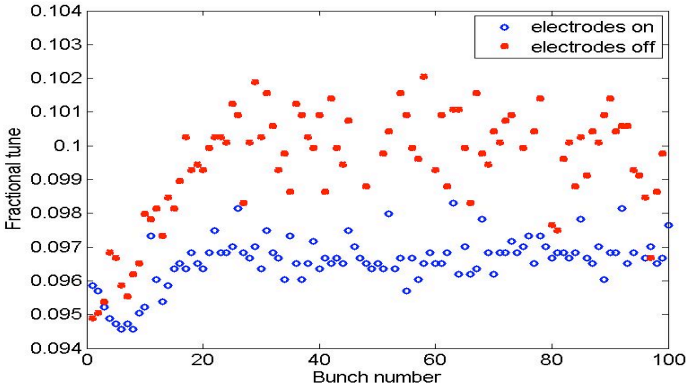
# ITEM 4): FOLLOW-UP OF THE CURRENT LHC (11/11)

- **E-cloud clearing electrodes at DAΦNE**

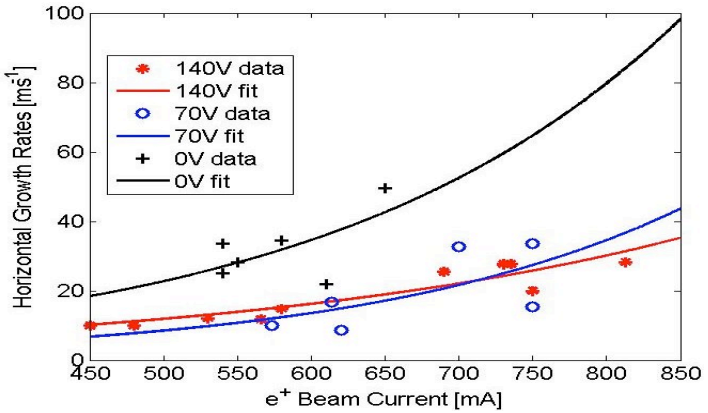
*Mikhail Zobov et al.*



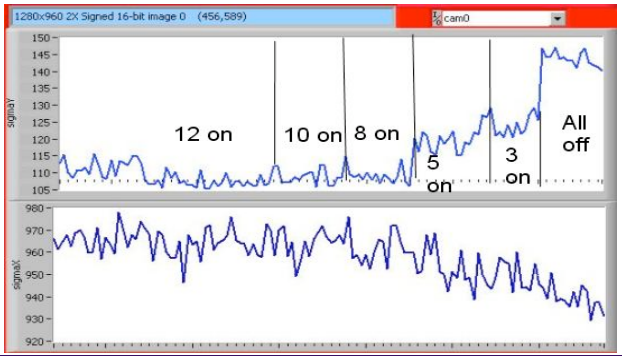

**Lower tune spread**




**Weaker instability**




**No transverse blow up**



# ITEM 5): NEW IDEAS

- The use of circular modes and flat emittance beams has been proposed by *Alexey Burov (LARP-LTV)*, as an alternative plan, which seems promising and deserves to be studied in more details
  - Conventional X / Y betatron oscillations can be referred to as a planar optics
  - Instead of X / Y eigenmodes in uncoupled case, we may have clockwise / counter-clockwise optical modes = Circular optics
  - To have circular optics => Focusing has to be rotationally invariant in the transverse plane
  - 2 possible applications, which need to be studied in detail (IBS issues, preservation of circular optics, etc.)
    - Space charge => Limit from bigger emitt. (circular) vs. smaller emitt. (planar)!
    - Luminosity => Inversely proportional to the sqrt of smaller emittance

# CONCLUSION (1/3)

- Even if there were neither deliverables nor milestones foreseen for this reference period, the overall progress of the various activities is satisfactory
- Next steps
  - Try and understand the cause of the instability at the end of the squeeze and all the means to raise the intensity threshold => Important MDs in past block #3 and next block #4 before the long SD *N. Mounet et al.*
  - Impedance model for HL-LHC (still several scenarios for collimators)
  - 2 big current issues/questions: RF heating? and octupoles' current?
- The 2 milestones MS29 and MS30 are for month 24 (01/11/2013) and month 30 (01/05/2014), with initial estimates of the machine impedance and intensity limitations, respectively
- The deliverable D2.4 attached to Task 2.4 is a report expected for month 36 on (01/11/2014) on "Beam intensity limitations"

# CONCLUSION (2/3)

- Going from 4 TeV to 7 TeV => Factor 7/4 = 1.75 in energy
- With the same settings for the collimators (in mm) and same materials
  - Impedance will be the same and the transverse instabilities will be ~ 1.75 times less critical
  - BUT, the effect of the octupoles will be (7/4)^2 ~ 3.1 times more critical

    => The overall situation should be 1.75 more critical. As 550 A is the maximum octupoles' current, it means that it corresponds to a maximum value of ~ 300 A at 4 TeV
- For collimators closer to the beam => Situation will be worse!
- For higher brightnesses (intensities / emittances) => Situation will be worse!

# CONCLUSION (3/3)

- **In the future, if we can't have enough octupoles' current, we might want to**
  - **Come back to the previous sign of the octupoles. 1st, one would like to check if with the high chromaticities and transverse damper gain the situation is better than before => MDs requested but not approved**
  - **Reduce the time during which we have the critical situations => Go faster through the colliding process**
  - **Use beta star levelling (see beam-beam talk) to profit from the huge beam beam head-on tune spread**
  - **Increase the bunch length to have more (longitudinal) Landau damping helpful for transverse instabilities**
  - **Optimize collimators settings and beta star**
  - **…**


The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.