A Brief Survey of Beam Instabilities at the LHC

G. Rumolo

Based almost 100% on the Chamonix material of **Kevin Li**!

With the input of G. Arduini, H. Bartosik, X. Buffat, L. Carver, G. Iadarola, L. Mether, E. Métral, N. Mounet, T. Pieloni, S. Redaelli, A. Romano, G. Rumolo, B. Salvant, M. Schenk, R. Tomás

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Outline

⇒ Brief history of instability observation in LHC

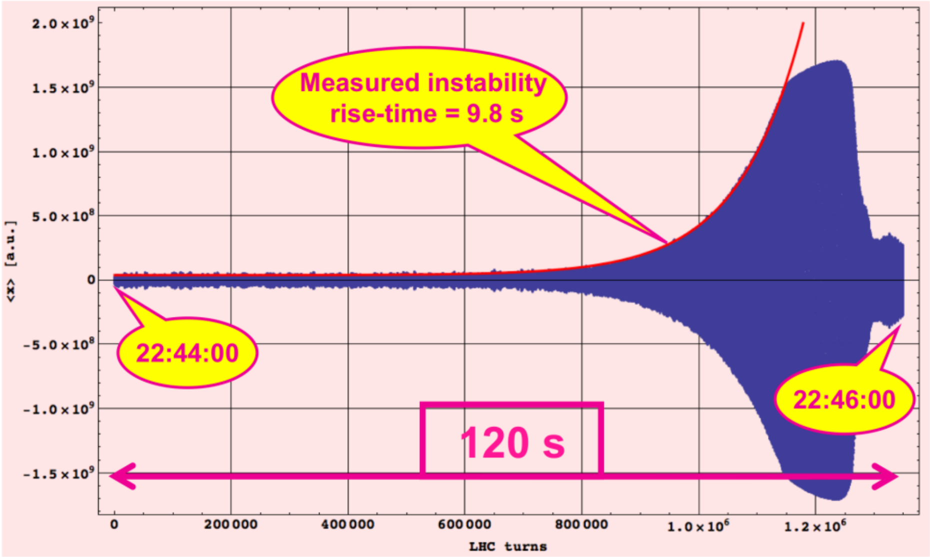
⇒ 2015-2016:

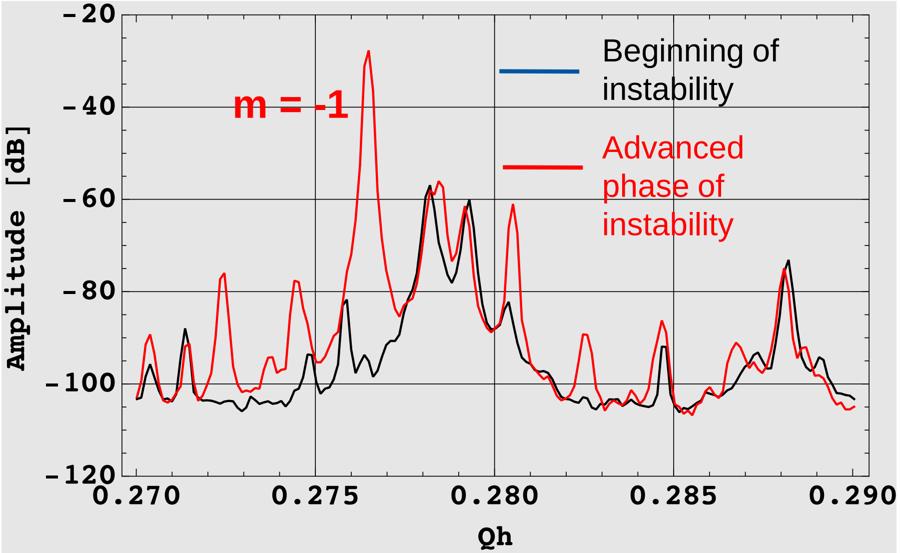
- 25 ns beam and 6.5 TeV
- LHC hypercycle and types of instabilities observed
- Role of electron cloud

⇒ Lesson learnt and open questions

Recap of LHC operation over the years

- 2010-2011
  - Bunch spacing gradually decreased from 150 ns to 50 ns
  - Nominal bunch intensity (1.2e11 p/b)
  - Transverse emittance gradually decreased from 2.5 to 1.2 μm at injection
  - Single bunch instabilities observed during early commissioning phase over the ramp suppressed with octupoles
  - In general, beams stable except residual ecloud effects in 2011(?)!





Courtesy E. Métral

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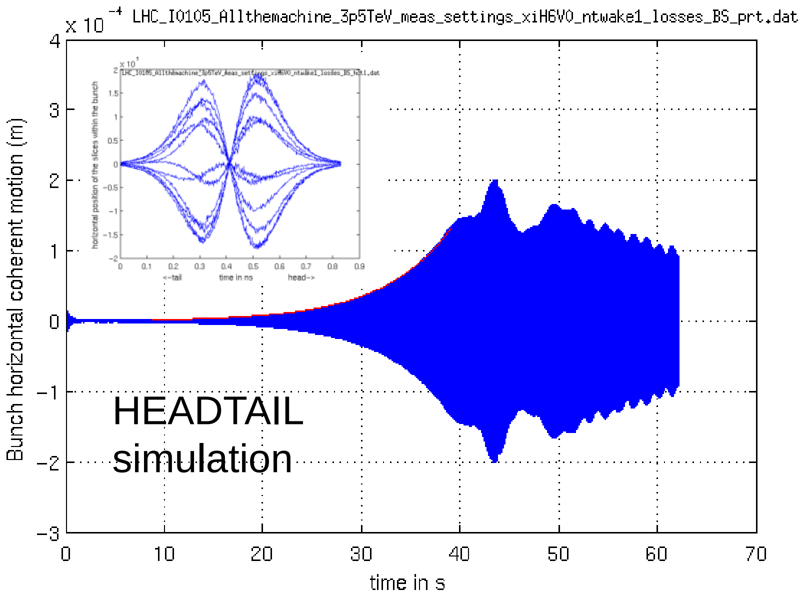

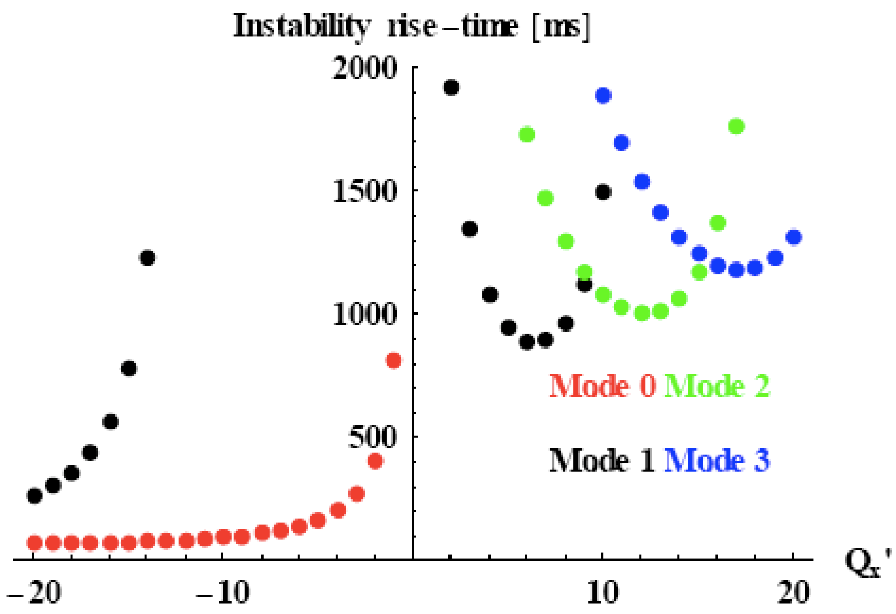

Question still being addressed: why did it only appear at ~2 TeV ?

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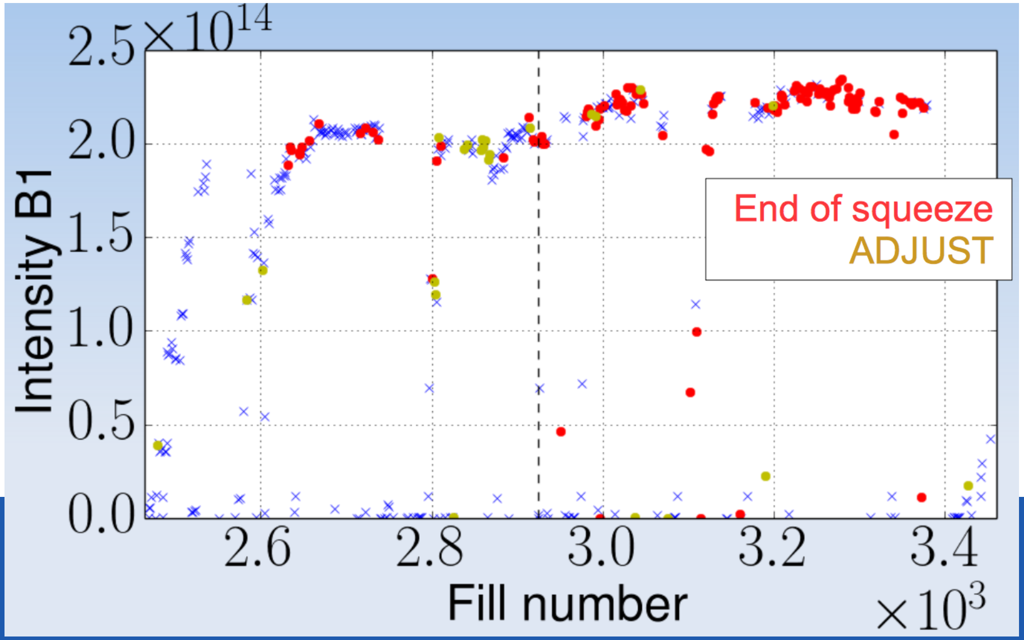
- 2012
  - 50 ns operation in almost fully ecloud-free environment
    - Ecloud only in uncoated interaction regions, notably the triplets
  - Bunch intensity increased up to 1.7e11 p/b (1.7 μm emittance at injection)
  - Many instabilities mainly observed at top energy (4 TeV) before colliding

Recap of LHC operation over the years

2012 Instabilities

- Mainly observed in the phases just before going into colliding beams (betatron squeeze and adjust)
- First part of the year (before Fill #2950)
  - Low positive chromaticity (~2 units) and negative polarity of octupoles
  - Many fills without instabilities, but impact of instabilities important, when present
- Second part of the year (after Fill #2950)
  - High positive chromaticity (~15 units) and positive polarity of the octupoles
  - Instabilities were observed at the end of the squeeze, continuing through ADJUST, stabilised by head-on collision – no large impact of instabilities



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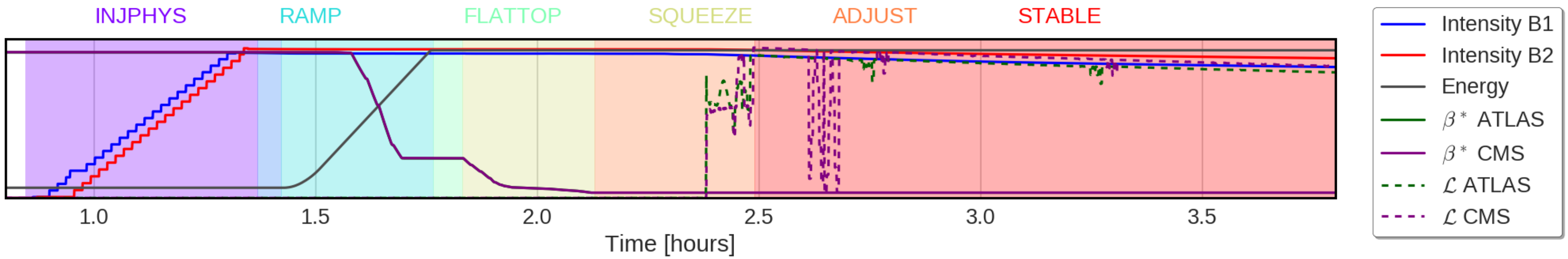
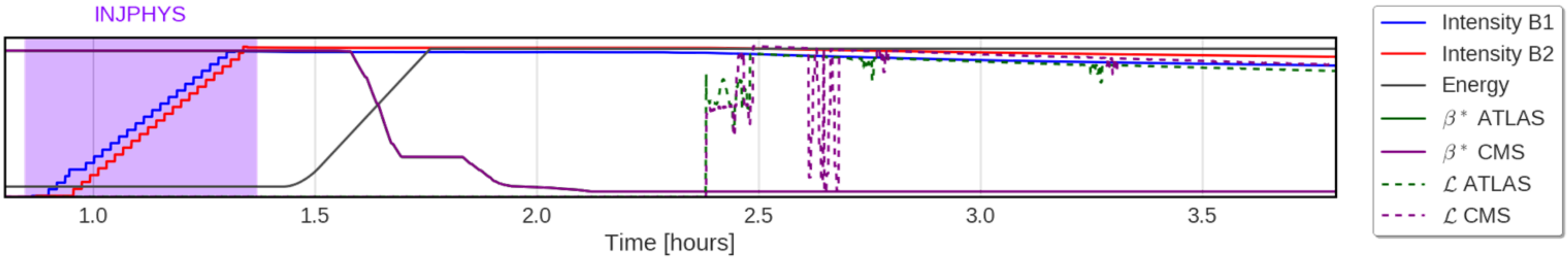
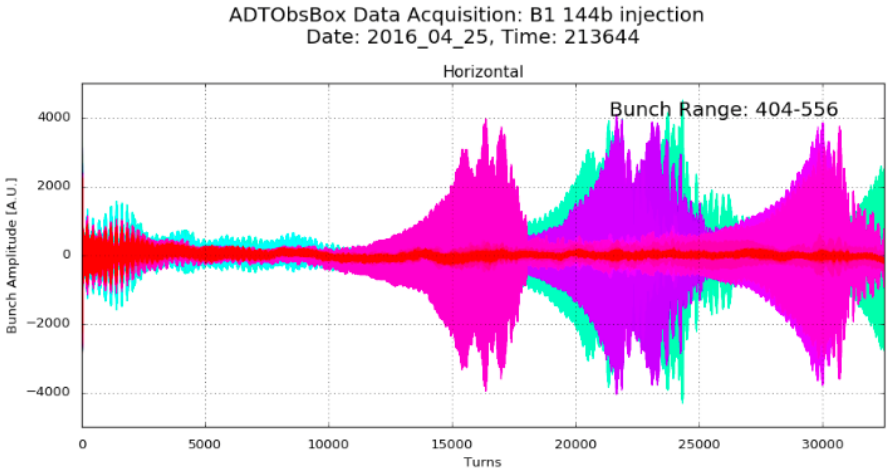
- 2015-2016
  - 25 ns operation with strong electron cloud
  - Nominal bunch intensity (1.2e11 p/b)
  - Transverse emittance gradually decreased from 2.7 to 1.6 μm at injection
  - Focus of the next slides …

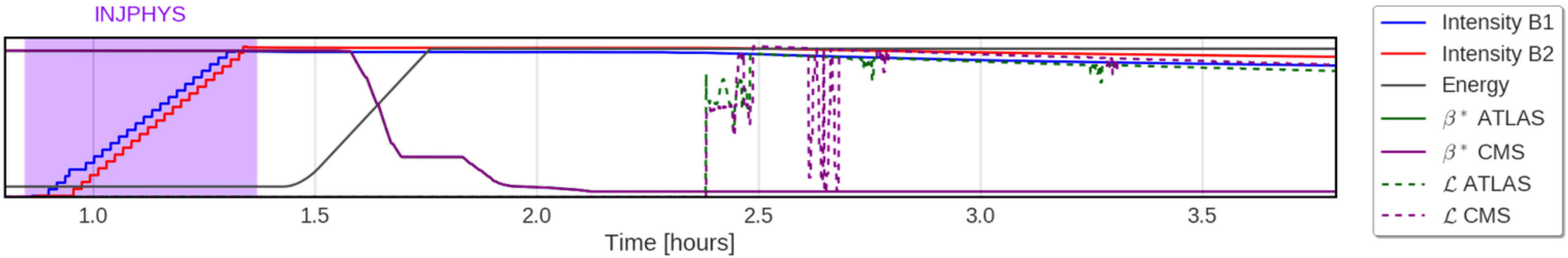


- **Injection**
  → Up to 23 injections for 2220 bunches, **crucial phase for instabilities**, **incoherent blow-up** observed
- **Ramp**
  → Roughly 20 minutes of combined ramp and squeeze, beam typically stable, mainly **incoherent blow-up** observed
- **Flat-top**
  → Uncritical, beta* at 3 m, beam stable
- **Squeeze**
  → Down to 40 cm, very dynamic phase, highly relying on good control of machine parameters – some issues with instabilities when **linear coupling** not well corrected, surge of strong **non-linearities** now blurring the workspace
- **Adjust**
  → Long-range beam-beam comes into play, instabilities sporadically observed
- **Stable/colliding beams**
  → Luminosity production, **instabilities observed** and vanished later during the year – possible mechanism related to electron cloud identified

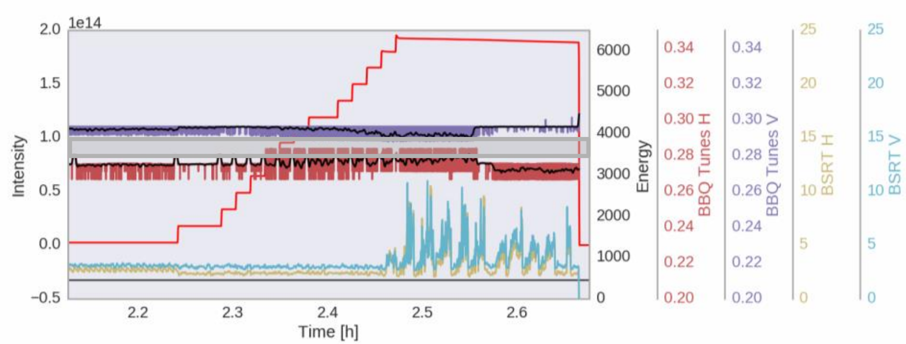


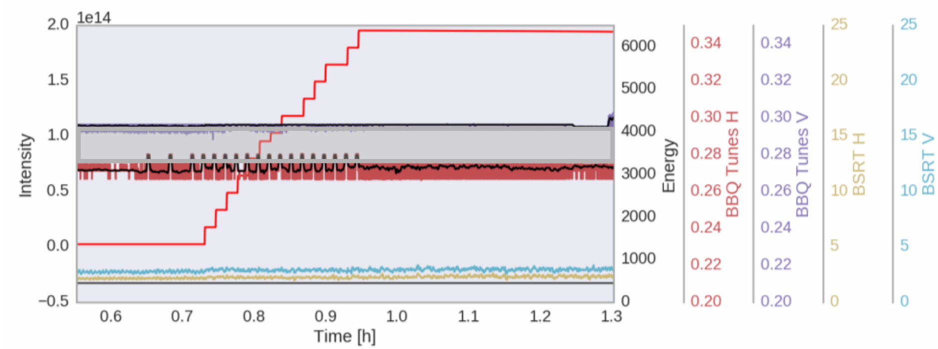
- Electron cloud instability determines the machine settings at injection
- **Key lesson:** machine settings for stable operation in **e-cloud dominated environment**
  - Tunes farther from third order resonance – (0.27, 0.295) instead of (0.28, 0.31) – to better accommodate electron cloud tune spread
  - Chromaticities of 20/20 and octupoles at 10 A for 2.5 μm emittance, high gain for the transverse damper





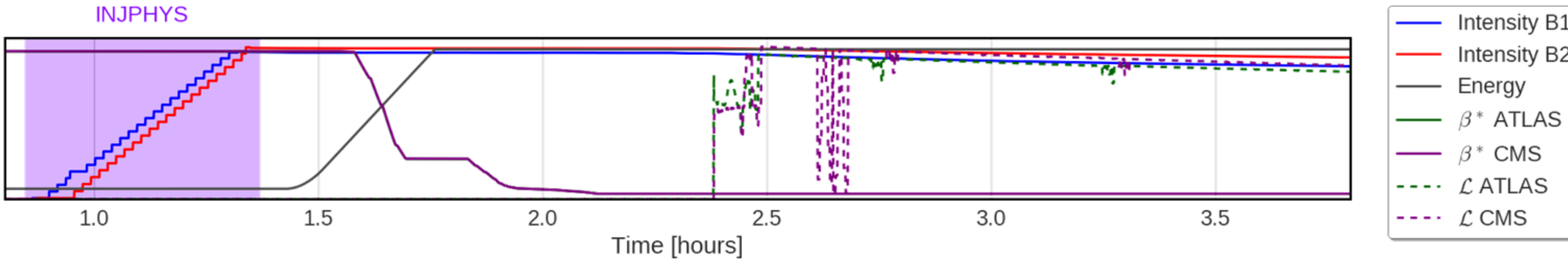
- Not enough, if tunes drift close to each other, coupling makes beam unstable (loss of Landau damping)





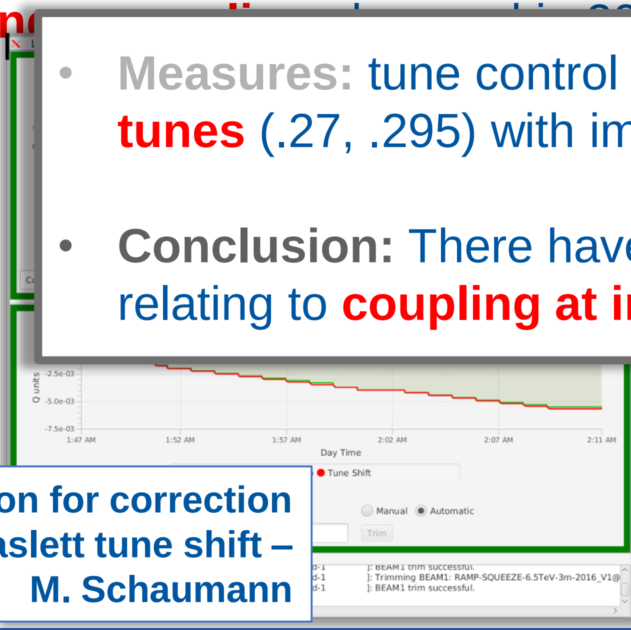
- Fill 4642 with **uncorrected** tune drift → blow-up during injection
- Coupling C- for these fills was below 0.004

- Fill 4643 with **tune correction** → no blow-up
- Measurement, monitoring and **correction of tunes** and **coupling** are crucial especially during injection

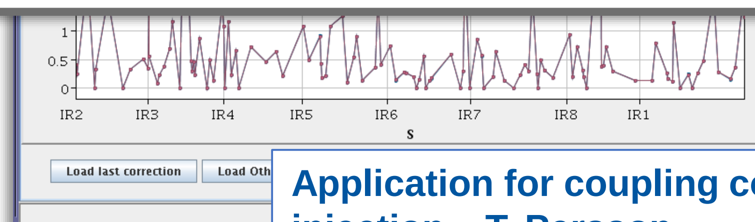


- Not enough, if tunes drift close to each other, coupling makes beam unstable (loss of Landau damping)
- Two **vital applications** have been in put in place to **prevent the issues with lin**

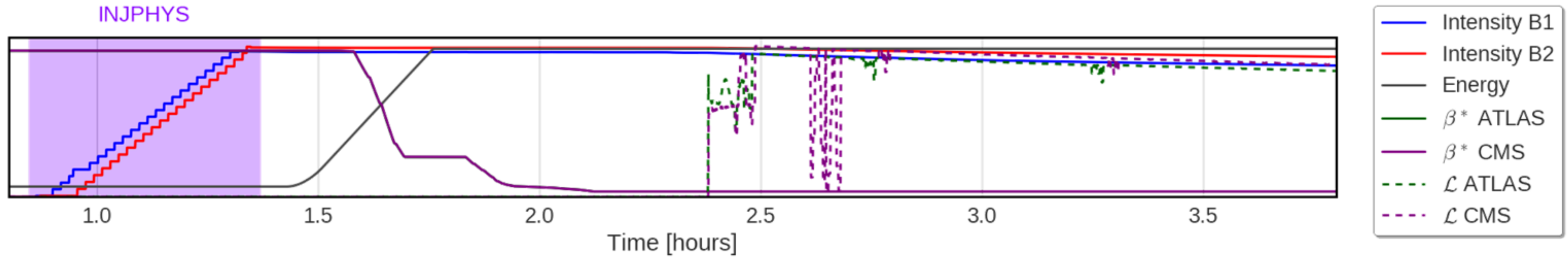
- **Measures:** tune control with coupling correction + **e-cloud tunes** (.27, .295) with improved separation.
- **Conclusion:** There have been **no issues** with instabilities relating to **coupling at injection** in 2016

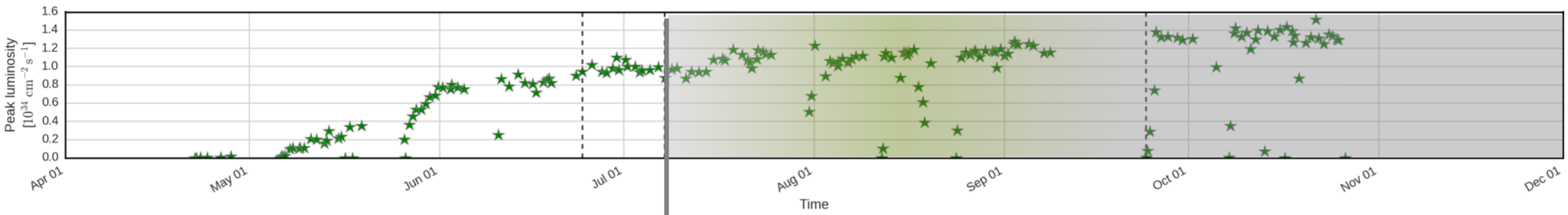


Application for correction for Laslett tune shift – M. Schaumann



Application for coupling correction at injection – T. Persson





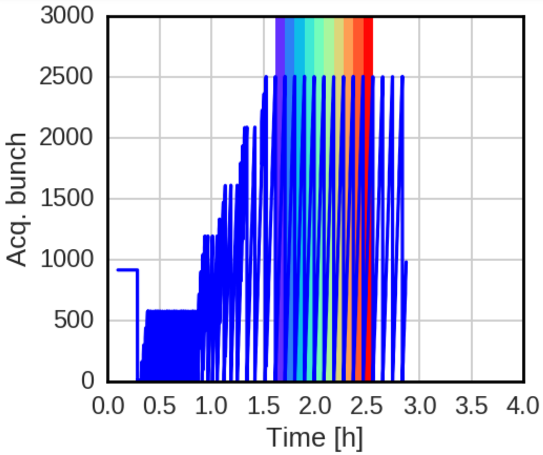
BCMS beam (low emittance variant of 25 ns beam)

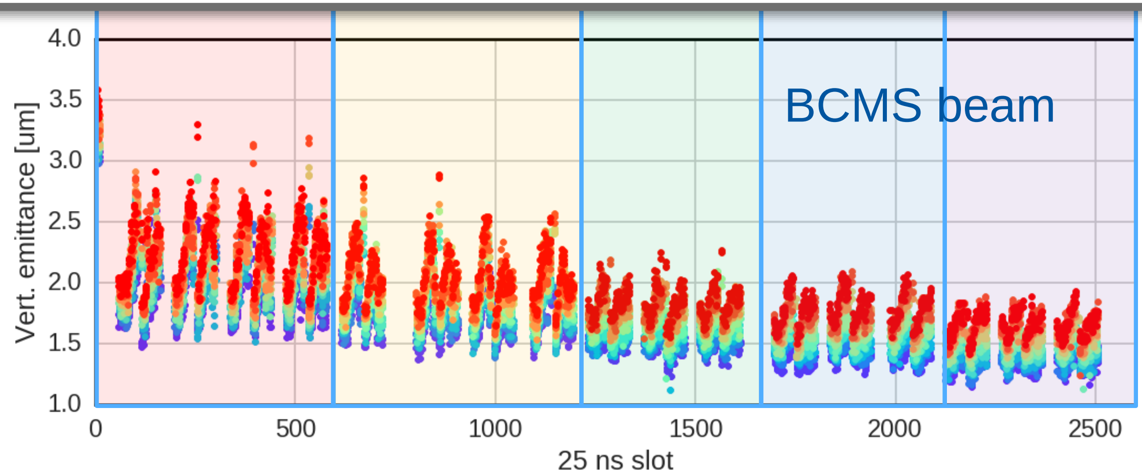
- Reduction of transverse emittance from injectors (BCMS beam) awakened beam instabilities
- Strong blow-up required an increase in octupole current to 40 A (by a factor 2)
- The **required machine settings** to ensure beam stability were confirmed in a **dedicated study**

Octupole knob	-1.5	-1.5	-2.5	-2.5	-3.0
Damper gain	normal	double	double	normal	normal

Fill 5217: B2, started on Thu, 18 Aug 2016 13:21:28

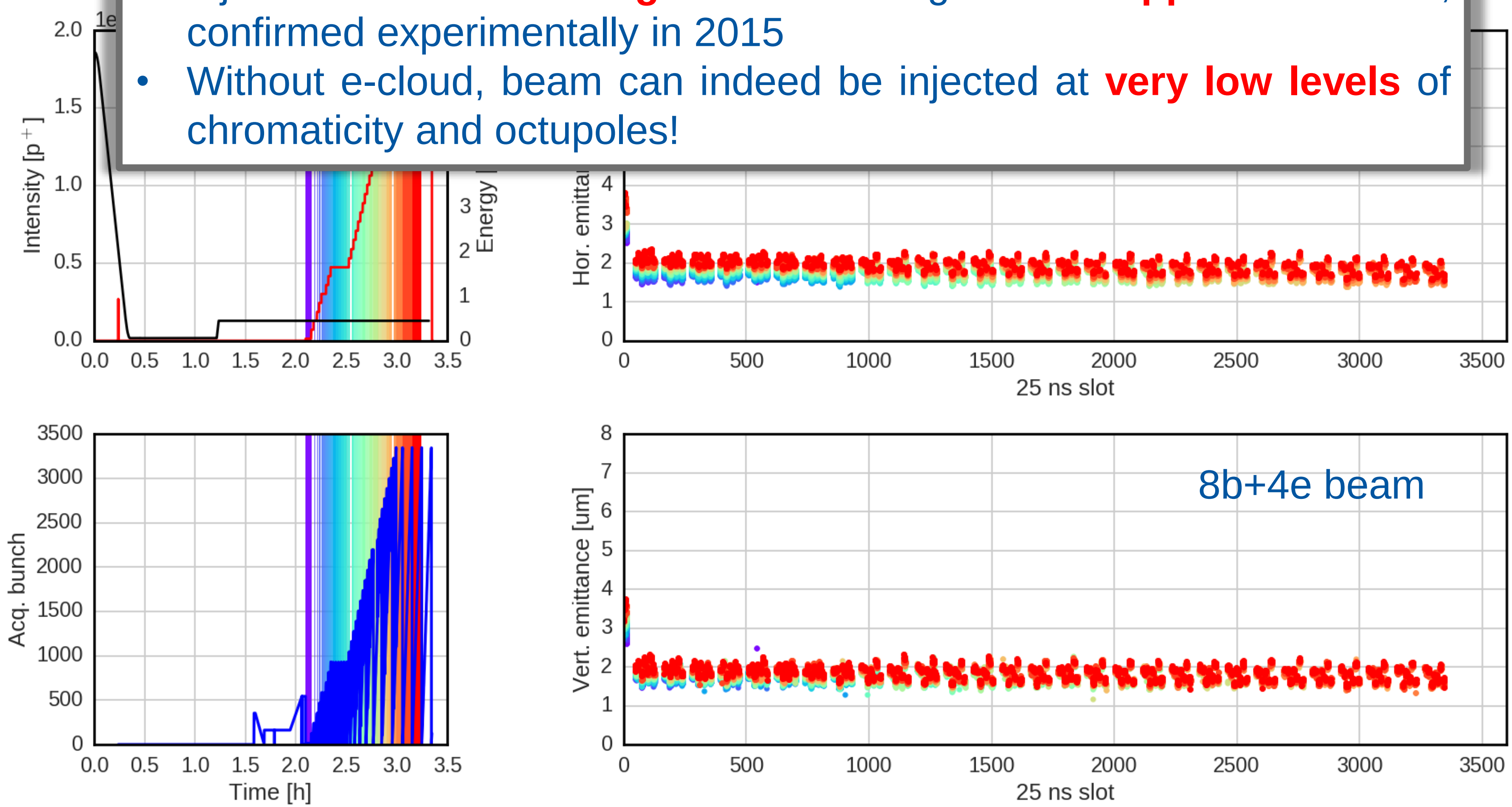
- **Signature:** strong **blow-up of BCMS beam** at injection
- **Measures:** increase octupole current from **19.5 A to 40 A** (damper gain has little impact)
- **Conclusion:** running at increased octupole currents renders the **BCMS beam stable** with no critical impact on beam lifetime





Octupole knob	-0.5	-1.0	-1.0	-1.0	-2.0	-4.0	-4.0	-4.0
Chromaticity	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15

- Injection of **8b+4e filling scheme** designed to **suppress e-cloud**, confirmed experimentally in 2015
- Without e-cloud, beam can indeed be injected at **very low levels** of chromaticity and octupoles!



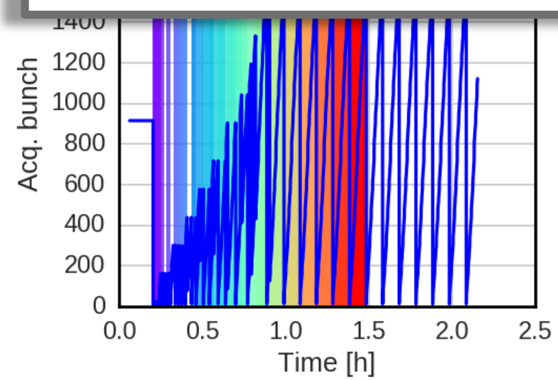
Octupole knob	-0.5	-1.0	-1.0	-1.0	-2.0	-4.0	-4.0	-4.0
Chromaticity	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15

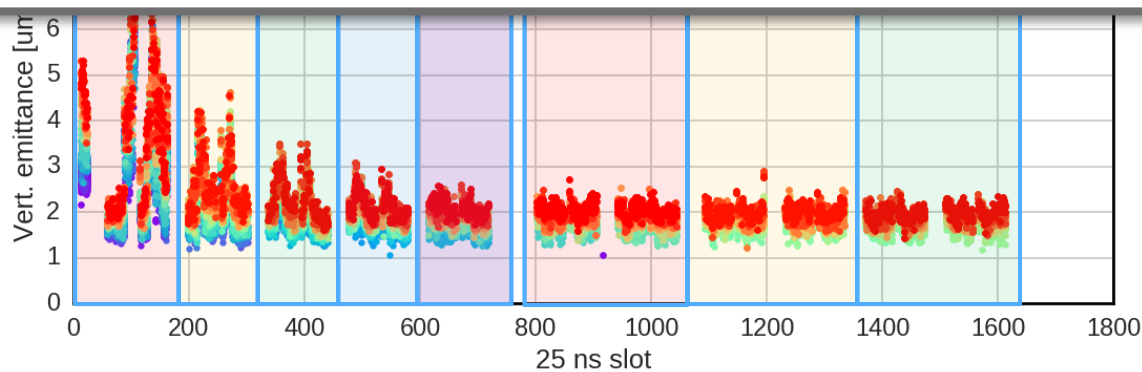
Fill 5372: B1, started on Thu, 06 Oct 2016 17:44:53

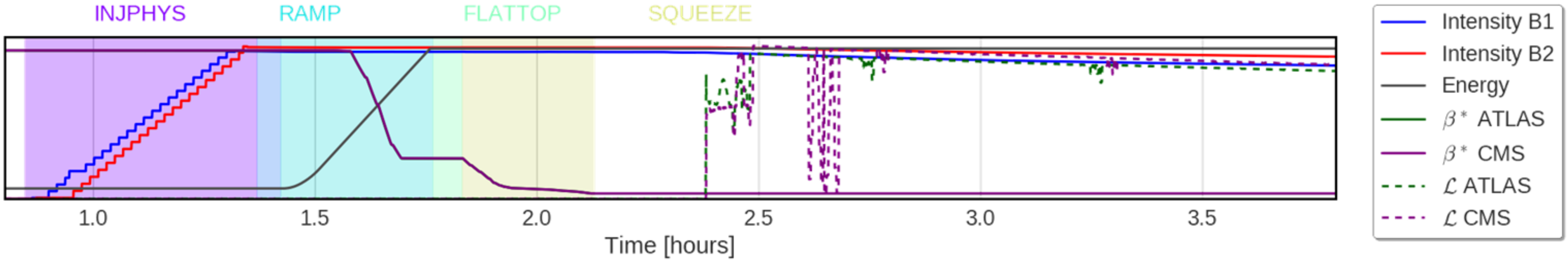
- **Signature:** the **8b+4e scheme** allows for **stable operation** at very low levels of chromaticity and octupoles – the BCMS continues to blow up

- **Measures:** adjust machine parameters, in particular **chromaticity**, to stabilizing regime

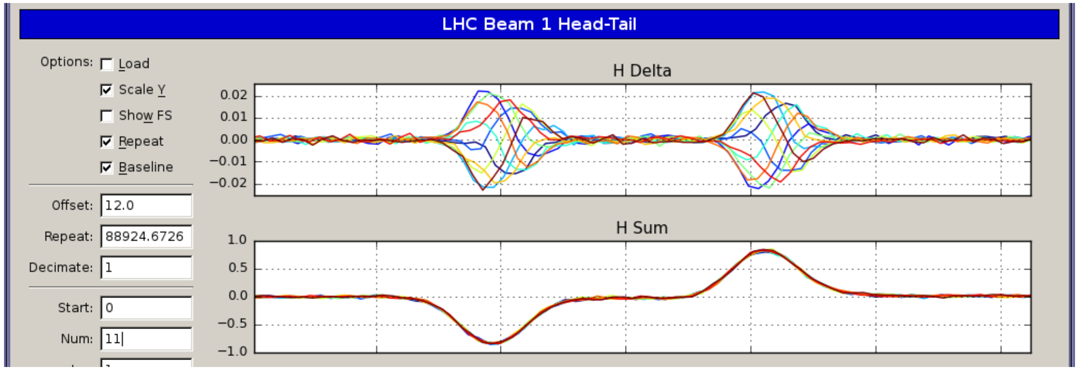
- **Conclusion:** **e-cloud still present in 2016** and **defining the machine settings** at injection (and throughout the cycle) with practically **no margins** – **chromaticity** being the **main knob** as was already **expected from simulations**

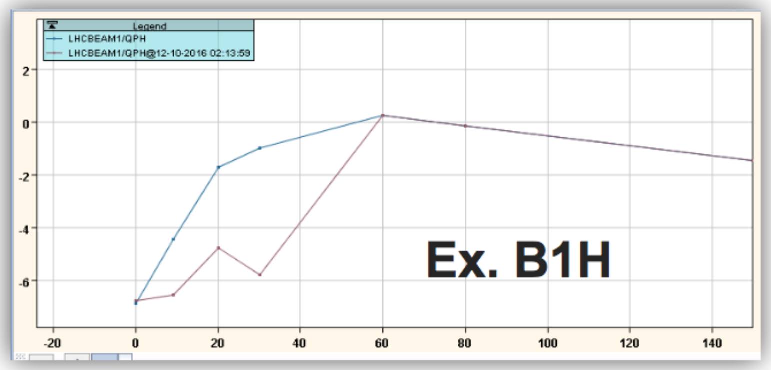


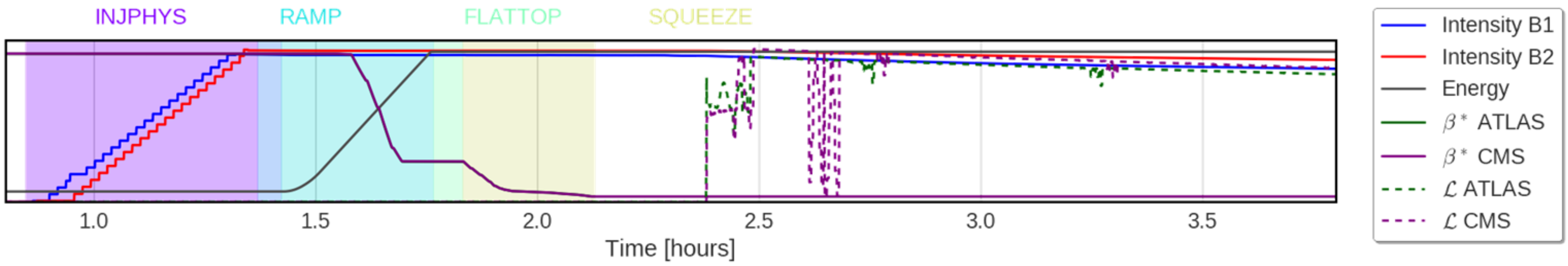




- Only instabilities observed at **beginning of ramp** were due to overcorrected snapback right after an MD block







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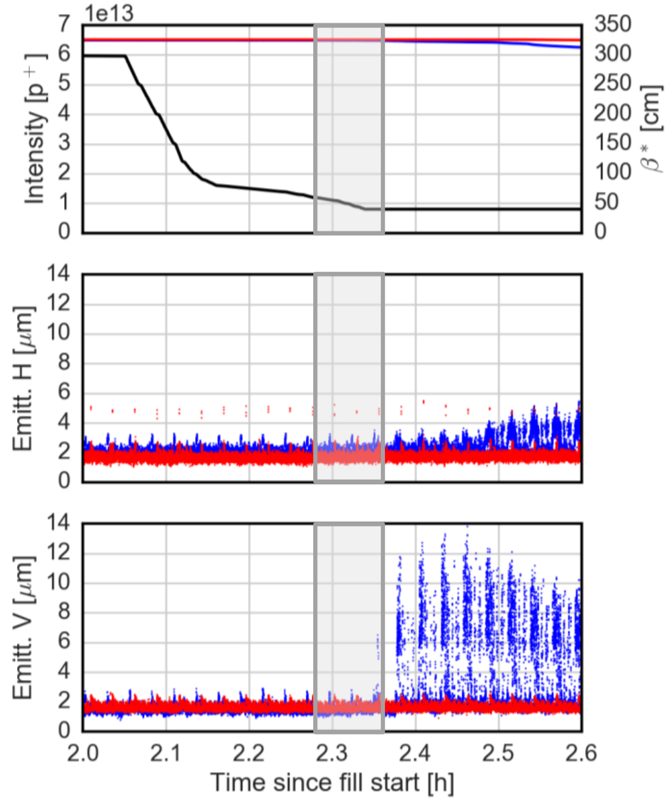
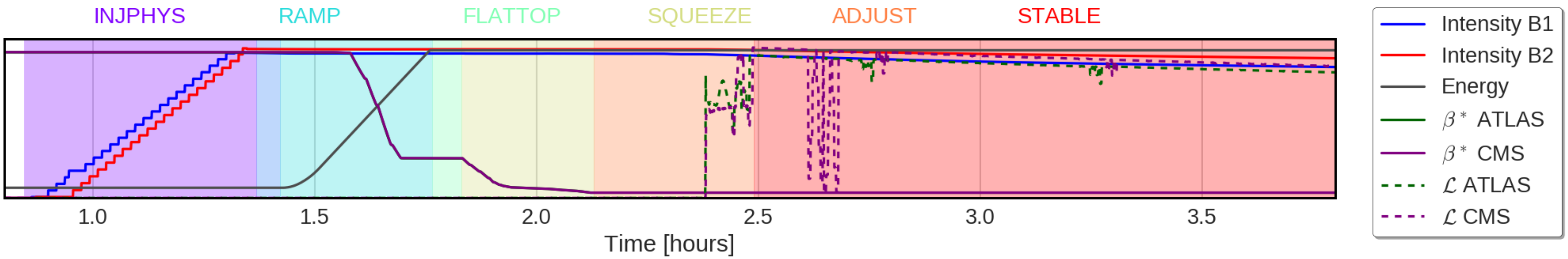
- Coupling **during the squeeze is critical** due to reduced tune separation
  - Losses and **emittance blow-up** in beam 1 right after squeeze
  - Coupling not well corrected caused instabilities after a Technical Stop
  - $|C^-|$ re-measured by OMC team: **~5e-3 at end of squeeze**





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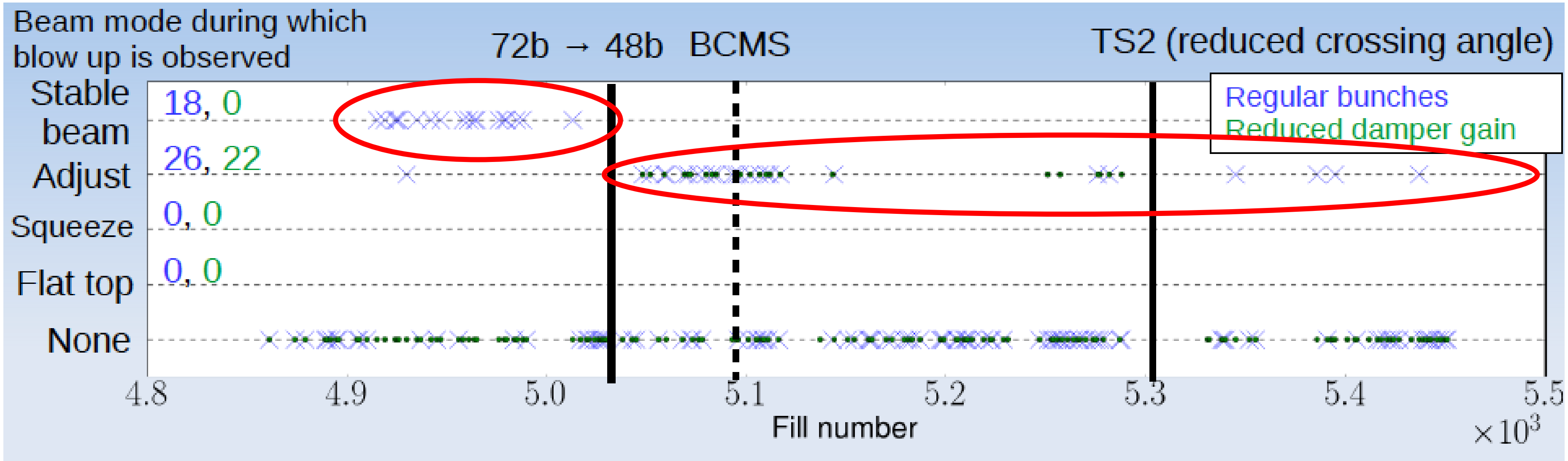
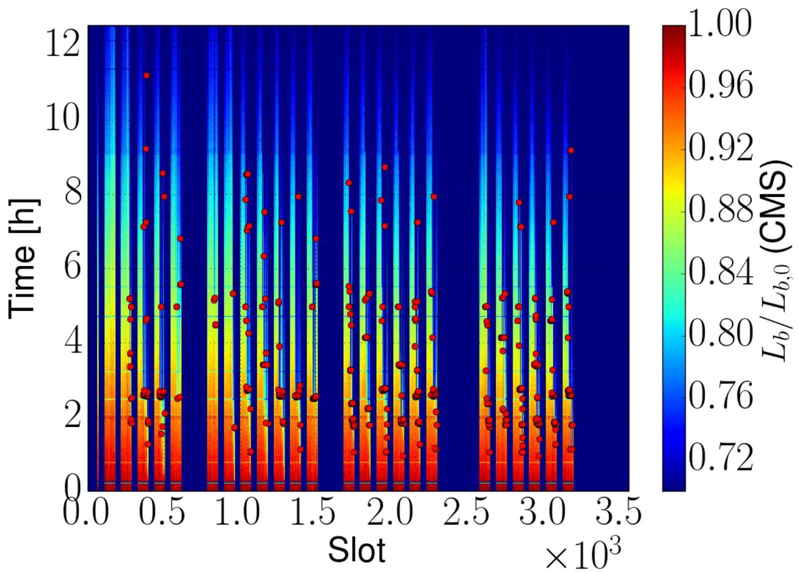
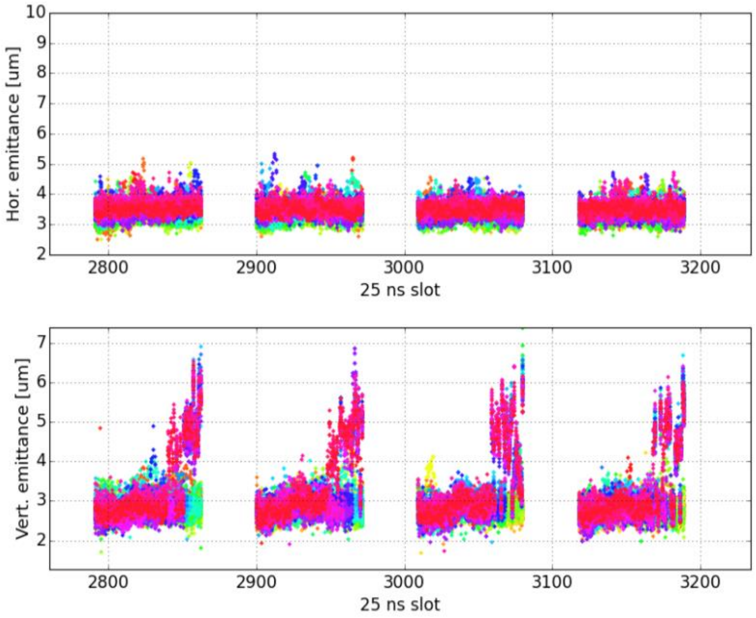


- No coherent instabilities observed in most of the fills
  - Some vertical instabilities in **stable beams** at beginning of 2016
  - Sporadic instabilities in **adjust**, after switching to low transverse emittances
- Usually only few bunches affected and no large impact on luminosity

- Coherent instabilities in stable beams
  - Always in the vertical plane and affecting the last bunches of long trains
  - Resulting in emittance growth but no beam loss





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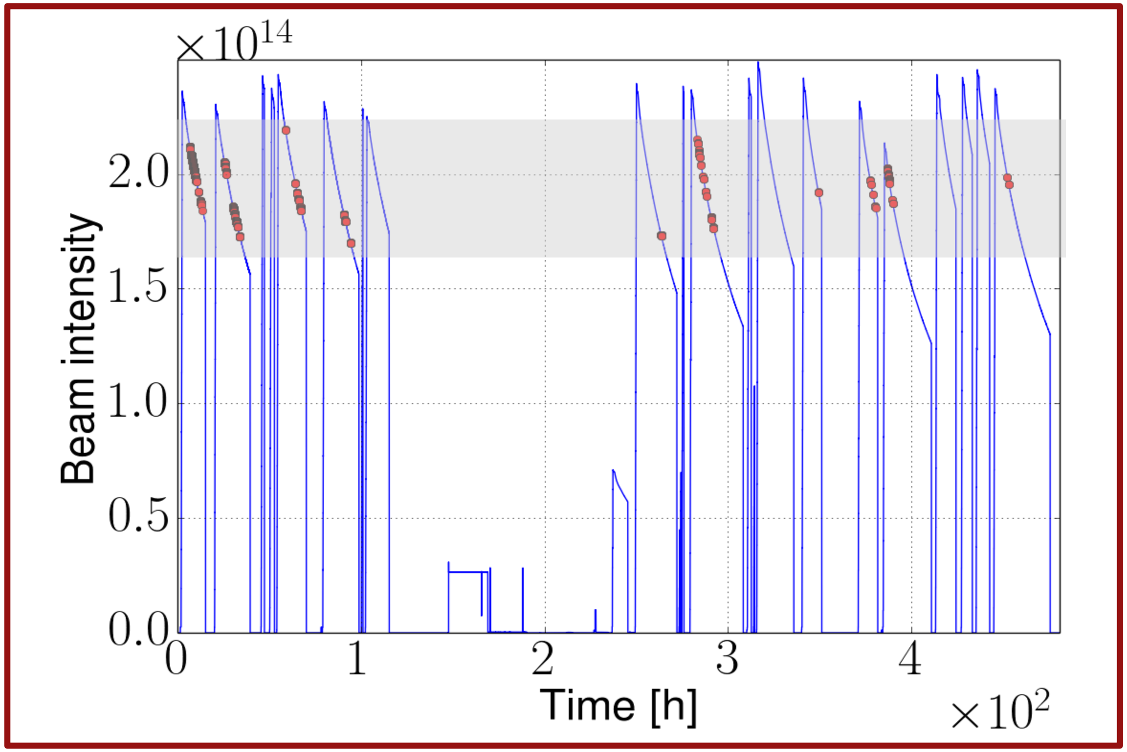

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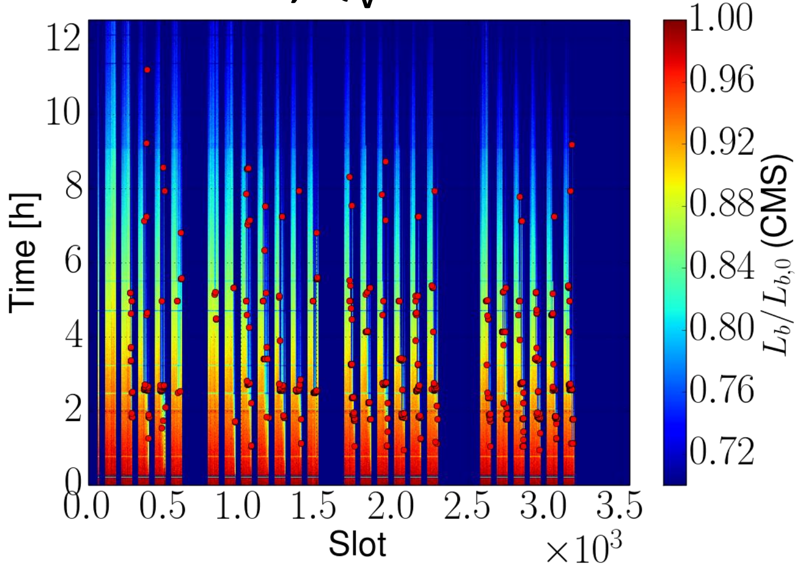
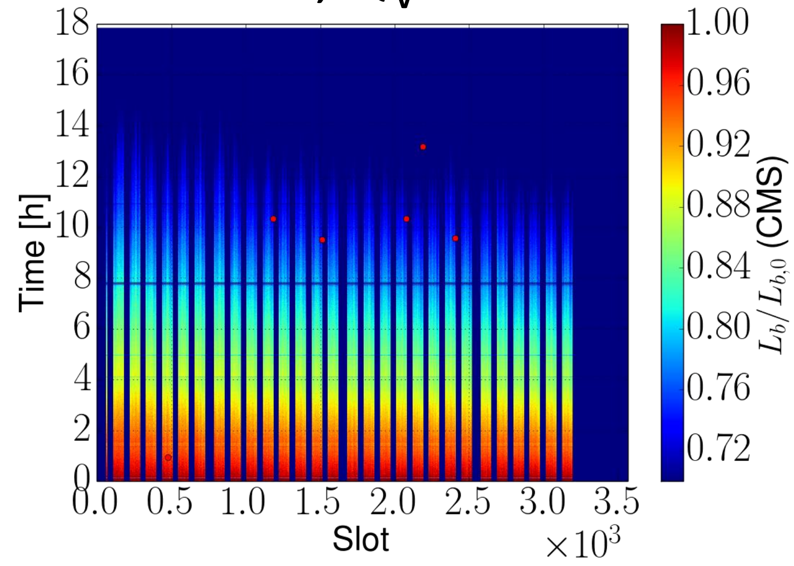
  - Data analysis showed that most of instabilities occurred for bunch intensities between 0.7e11 and 1.1e11
- Vertical chromaticity increased from 15 to 22 units after going in collision
  - Blow-up mitigated, instability still sporadically detected on the bunch-by-bunch luminosity data
  - Clear improvement on the number of unstable bunches

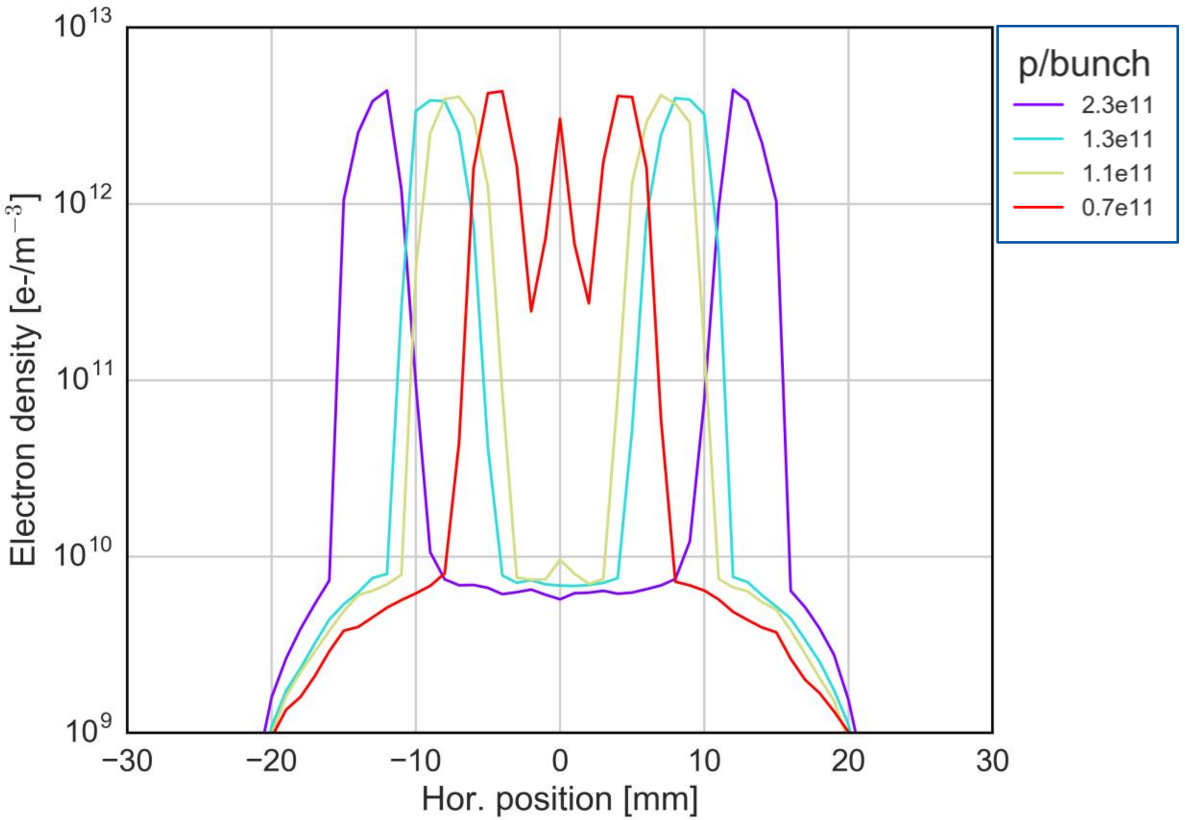
Fill 4964, Q'_v = 15



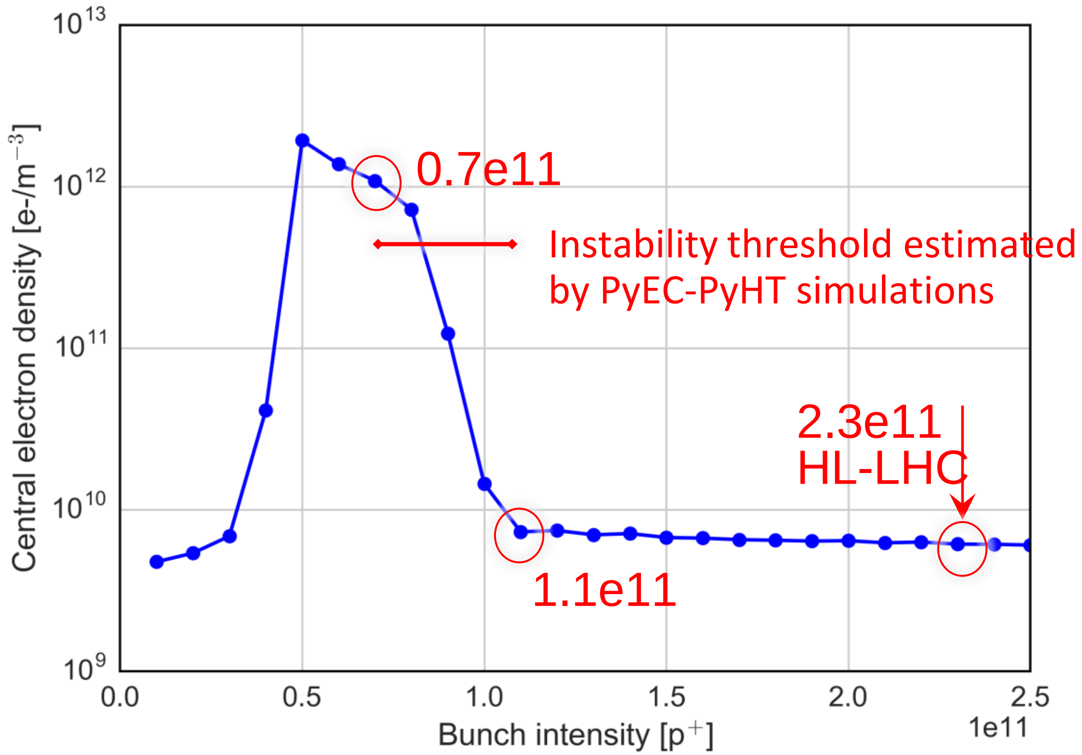
Fill 4988, Q'_v = 22



- Coherent instabilities in stable beams → Simulations
  - Electron cloud in the dipoles tends to form a central stripe for lower bunch intensities

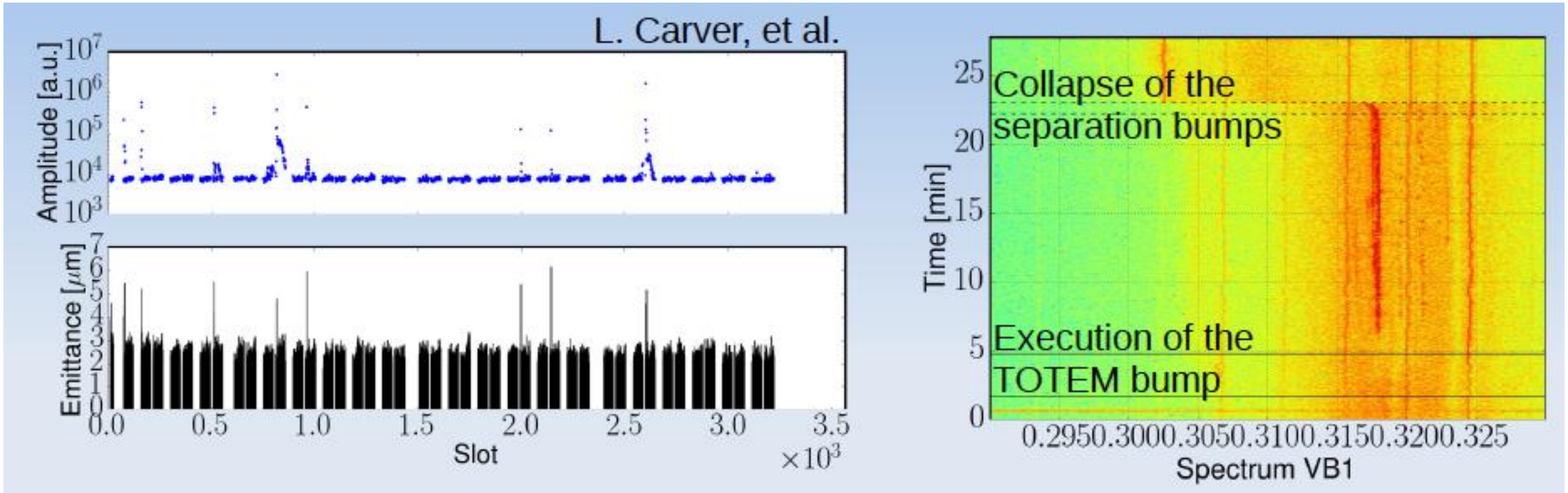


- Coherent instabilities in stable beams → Simulations
  - Electron cloud in the dipoles tends to form a central stripe for lower bunch intensities
  - The central density threshold (5e11 m^{-3}) is crossed when the bunch intensity decreases with Q'=15
  - The threshold becomes much higher for Q'>20
- Explanation also consistent with the disappearance of this phenomenon (due to scrubbing)



- Coherent instabilities in Adjust mode
  - Mainly affecting bunches at the head and tail of trains
  - Coherent signal seems to appear in correlation with the TOTEM bump
  - No observations in single beam

- Still under study!



Summary

- Beam instabilities have been observed at the different LHC beam processes. Some lesson learnt:
  - Narrow range of machine settings to keep beam stable along the cycle
  - Instabilities occur if coupling exceeds a certain threshold (at different stages)
  - Chromaticity settings are crucial along the cycle and can't be relaxed
  - Octupoles settings have to be adapted according to beam emittance
  - Transverse damper indispensable to preserve beam stability all along the cycle
- Sources of instability
  - Electron cloud (with 25 ns beams) → tends to become better with scrubbing
  - Machine impedance and loss of Landau damping
- Main question is to gain confidence in the scaling with bunch intensity (both of electron cloud and instability thresholds based on the models)

- See you in Benevento on 18-22 September!