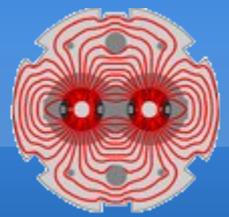




# LHC Beam Operation Workshop 2019 - Evian



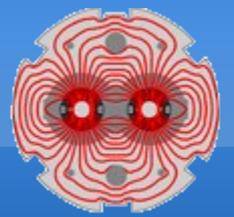
## Transverse instabilities during run II

X. Buffat, G. Arduini, D. Amorim, S. Antipov, N. Biancacci, L. Carver,  
S.V. Furuseh, G. Iadarola, K. Li, L. Mether, E. Métral, N. Mounet, A. Oeftiger,  
T. Pieloni\*, A. Romano, G. Rumolo, B. Salvant, M. Schenk, C. Tambasco\*

Many thanks to LHC OP, injectors OP, H. Bartosik, R. Bruce,  
R. De Maria, S. Fartoukh, W. Hofle, G. Kotzian, T. Levens, E. Maclean,  
A. Mereghetti, D. Mirarchi, T. Persson, M. Soderen, R. Tomas and  
D. Valuch for their important contributions



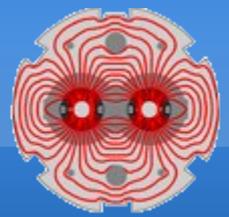
# Content



- Instabilities at injection
- Instabilities at top energy
  - Run I – II overview
  - Modelling : State of the art and future plans
  - Expectation for run III
- Diagnostics
  - Run I vs run II
- Summary



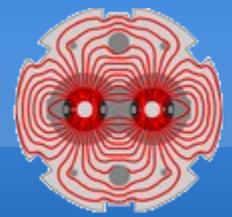
# Instabilities at injection



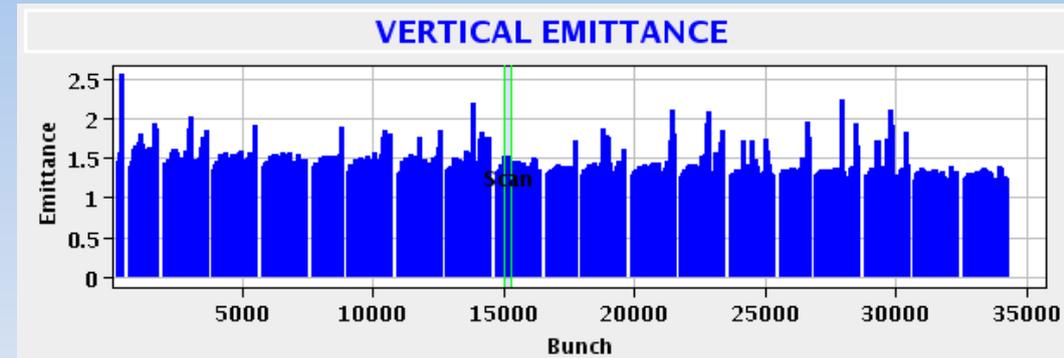
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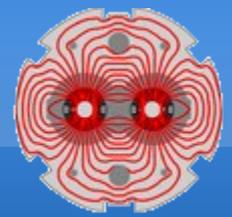


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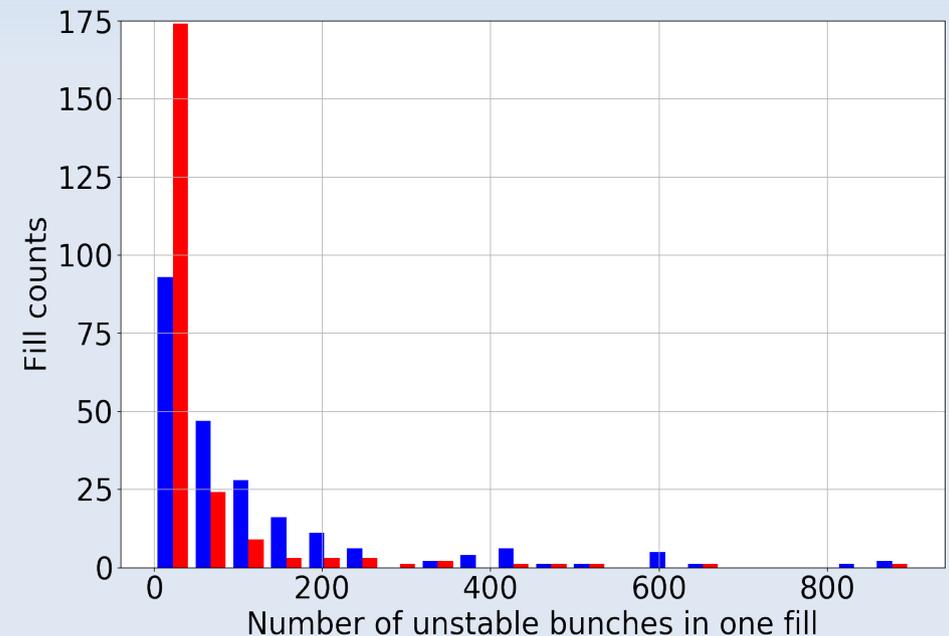
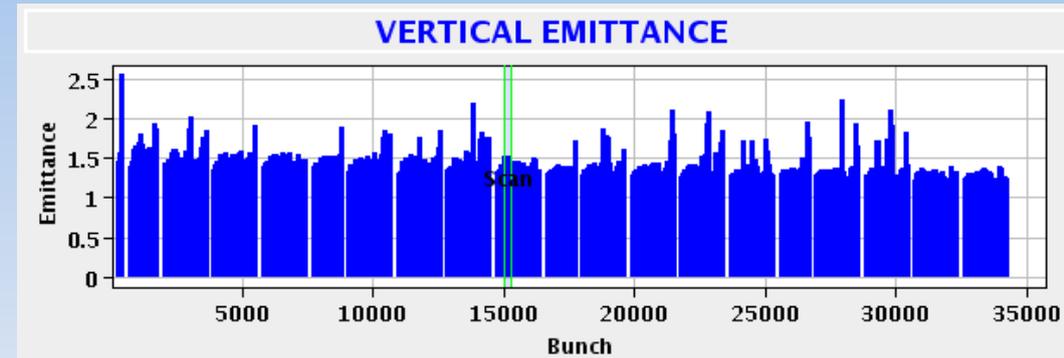




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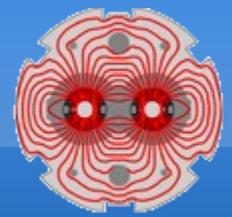


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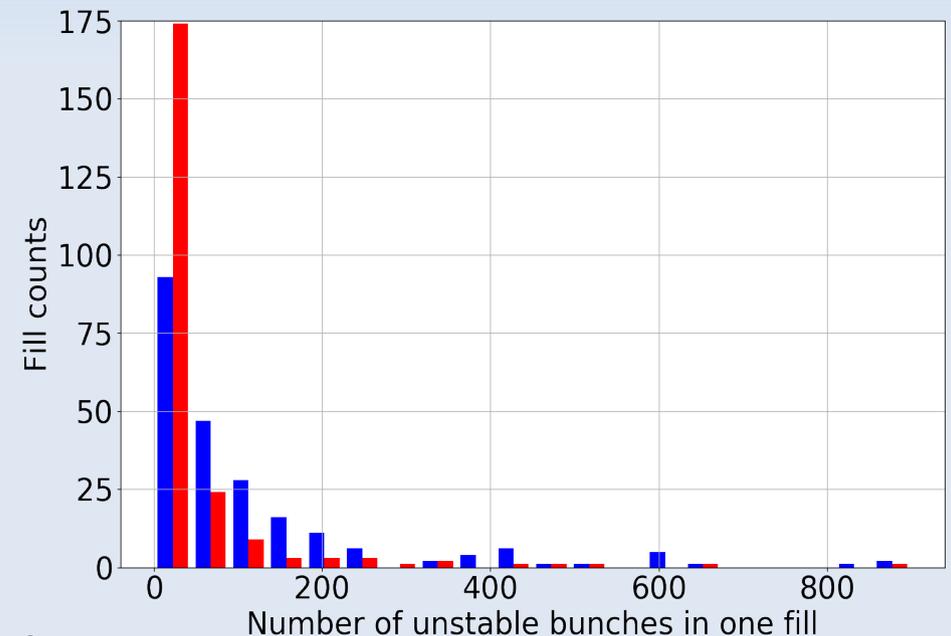
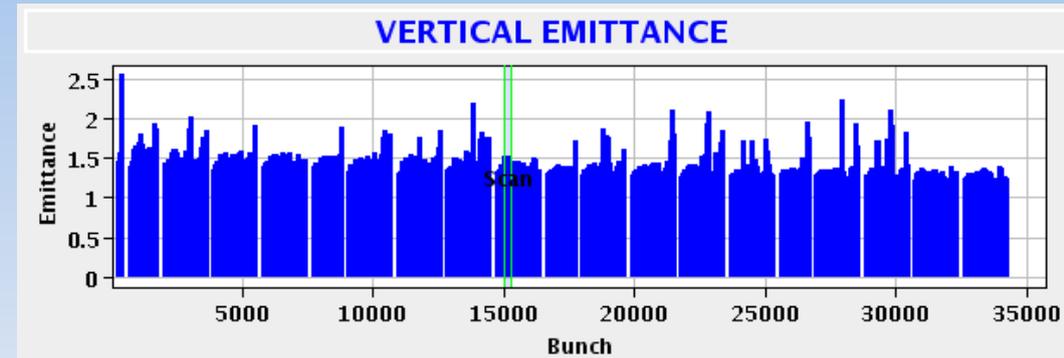




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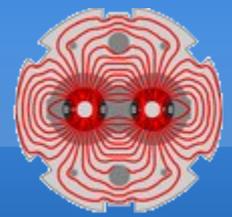
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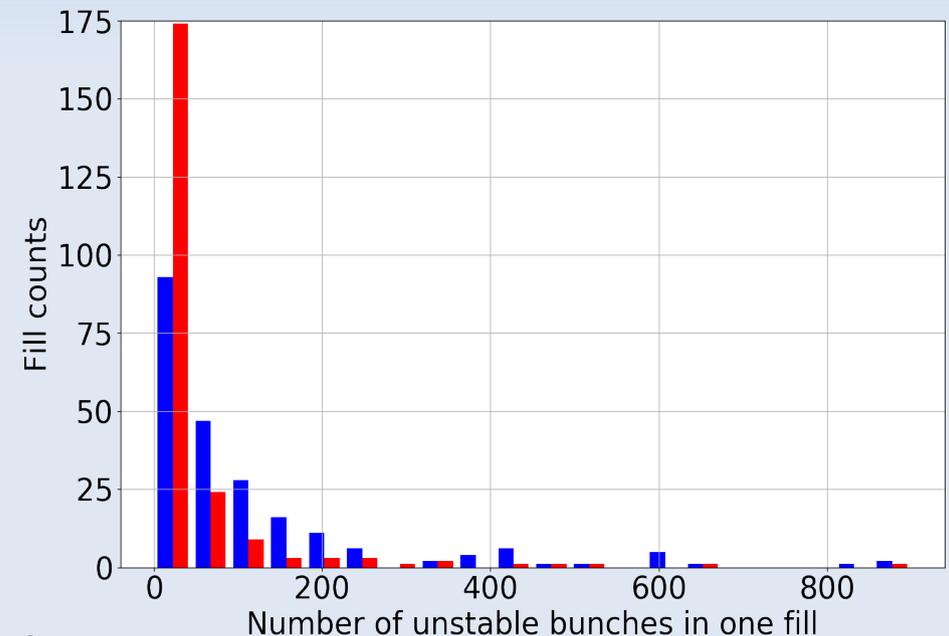
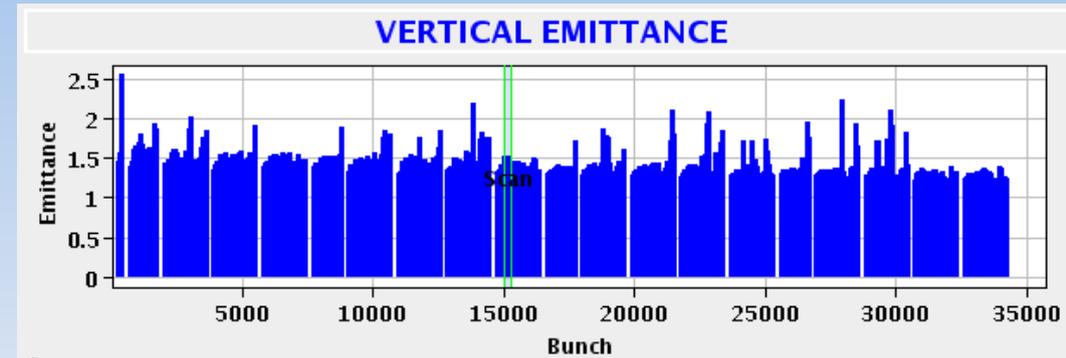
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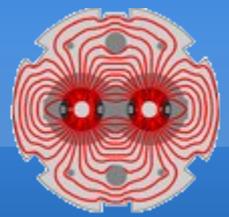


- After scrubbing the instabilities at injection were well contained with a high chromaticity (15-20) and octupole current (~50A)
- In 2018, a weak instability was observed almost systematically, its impact on the beam quality is hidden by the blowup in the ramp
  - It couldn't be fully cured within the range of chromaticity, gain and octupole current tested
  - Linear coupling correction and Laslett tune shift compensation are needed
  - It can be triggered by external excitations (leakage injection cleaning)
  - The reduction of RF voltage didn't have a significant impact
  - The description of this 'slow' e-cloud instability is computationally demanding
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  - Fast scanning BSRT (since 2017)
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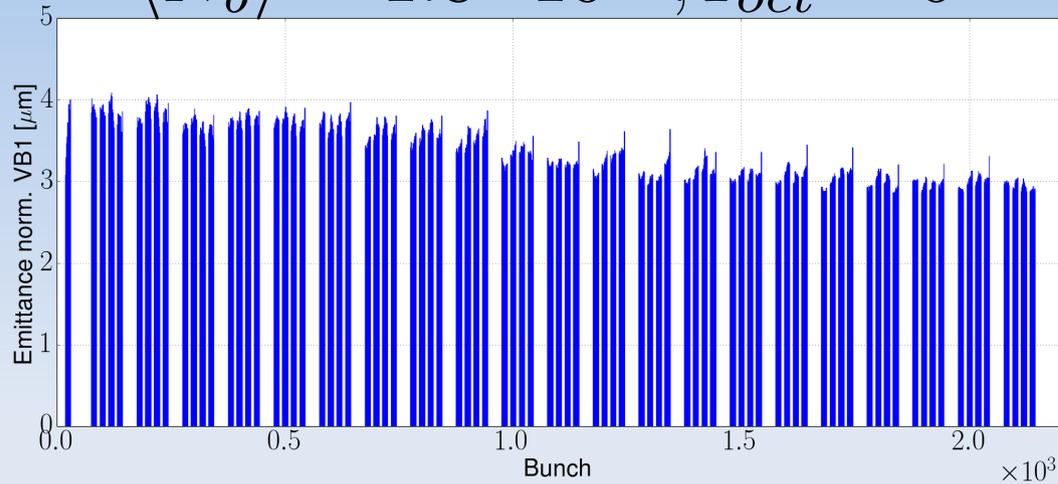




# Intensity scaling



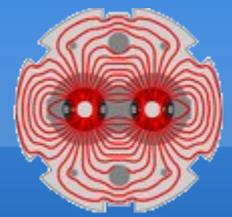
$$\langle N_b \rangle \approx 1.8 \cdot 10^{11}, I_{oct} = 0$$



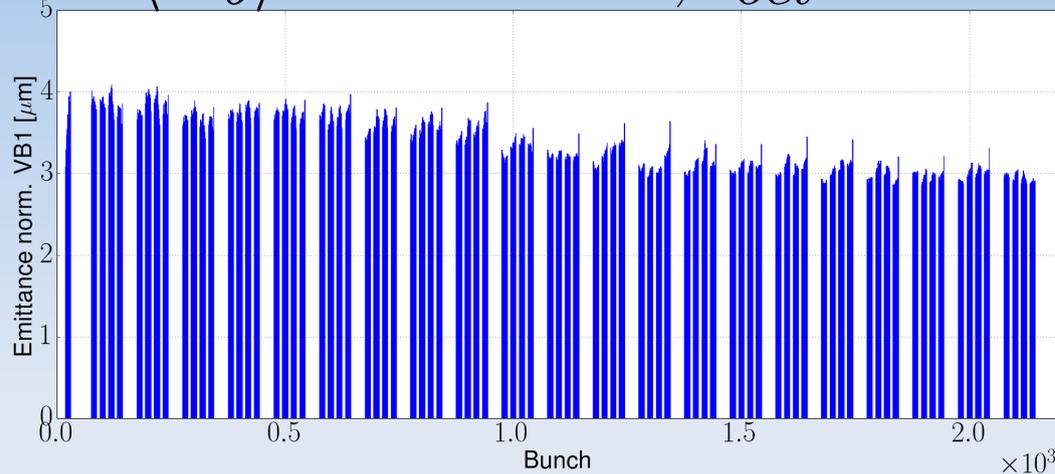
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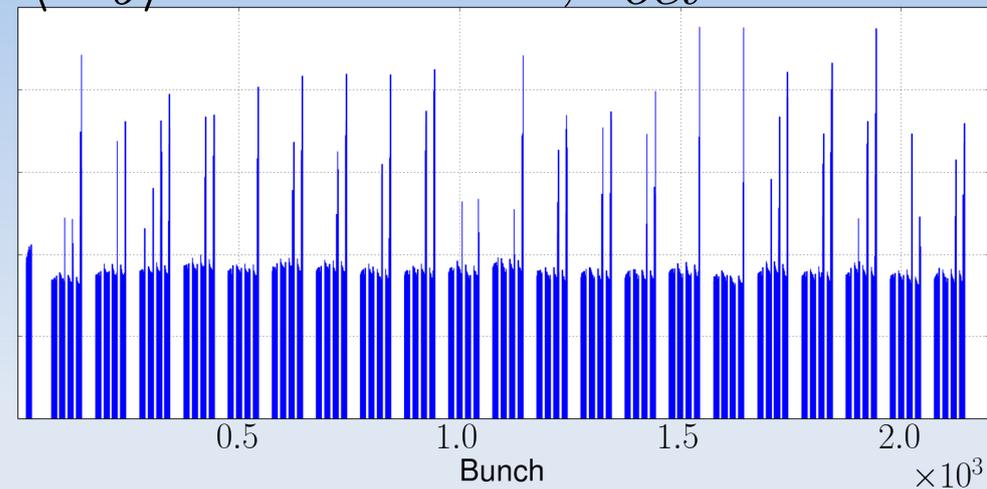
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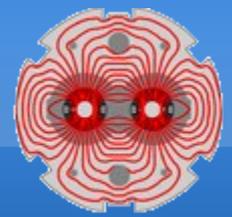
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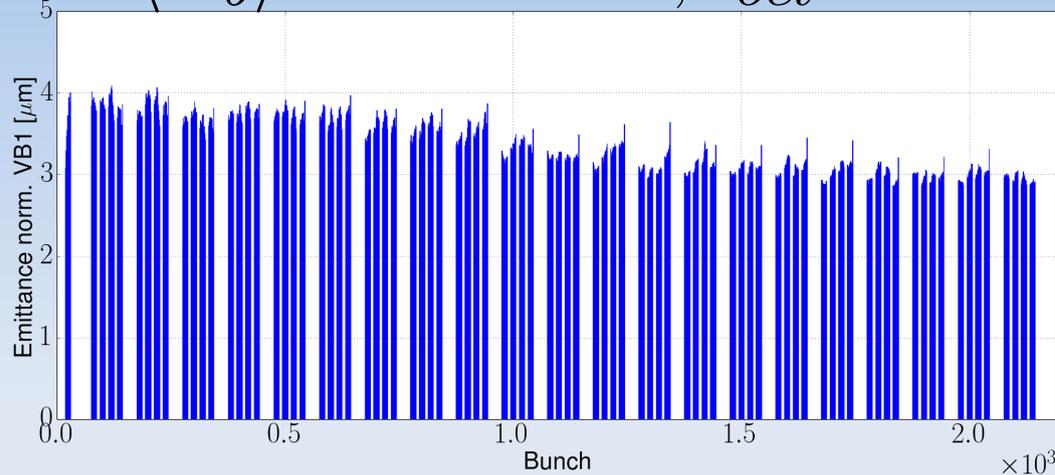
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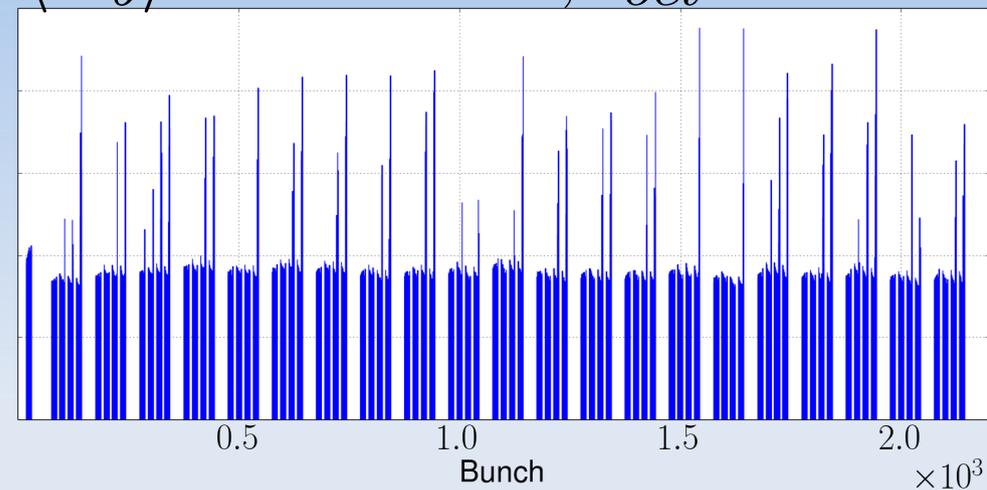
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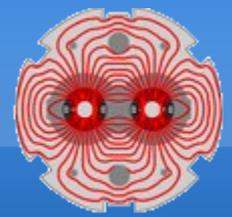
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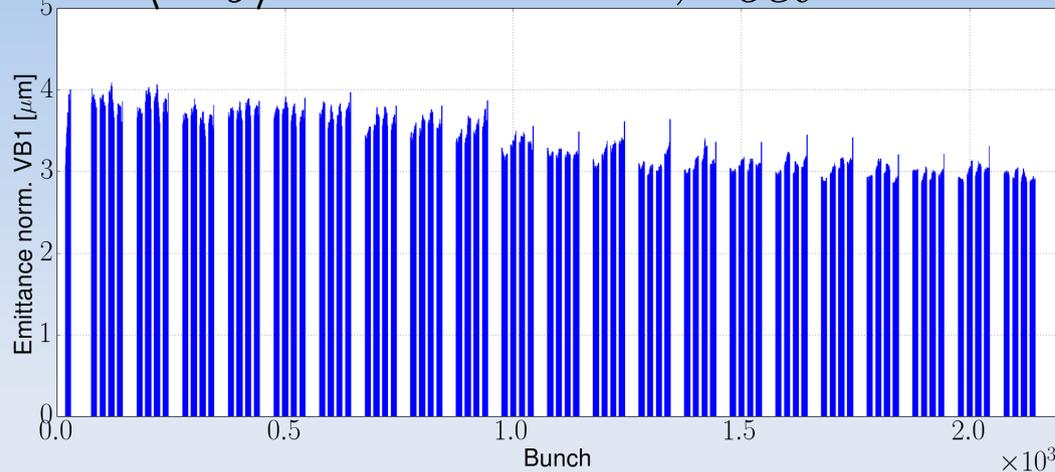
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[G. Iadarola, et al., Digesting the LIU high brightness beam: is this an issue for HL-LHC?, Chamonix 2018]



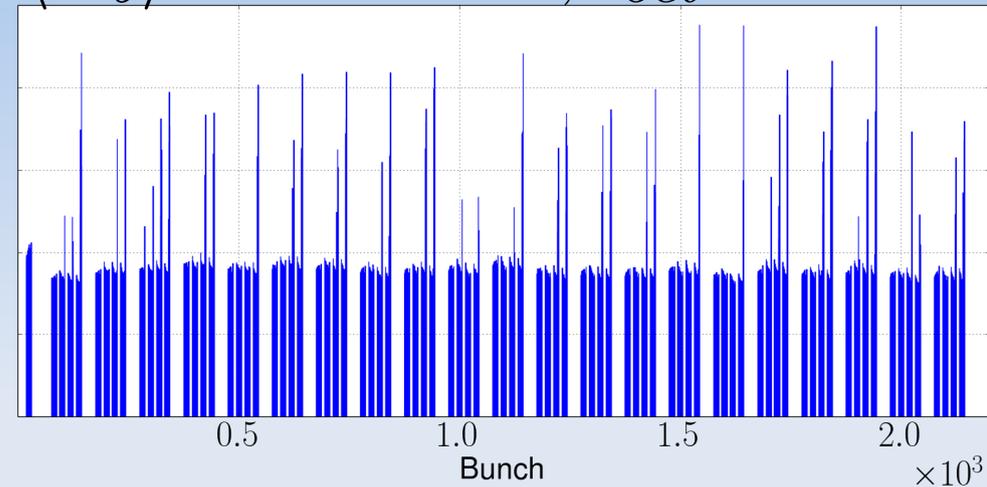
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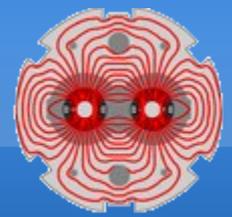


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- No other measures are foreseen for run III or HL-LHC

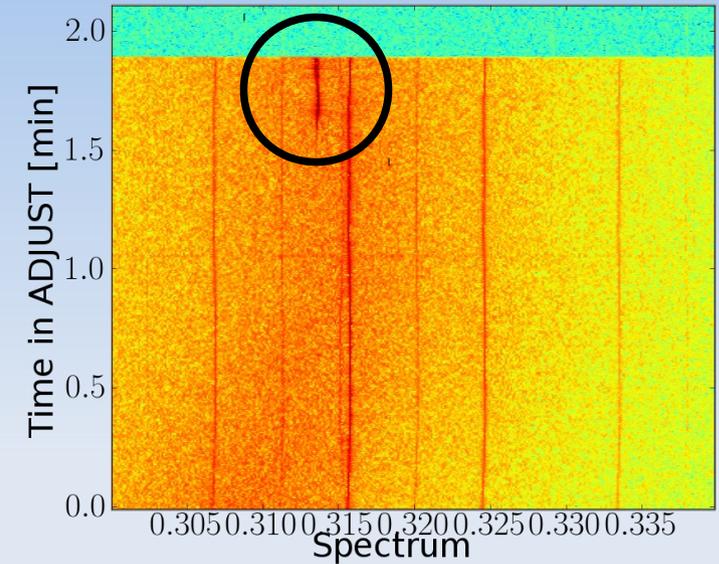


# Instabilities at top energy

## Reminder : Main issues in run I



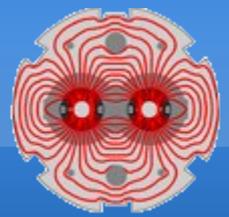
- Sporadic dumps in adjust with a strong impact on integrated luminosity



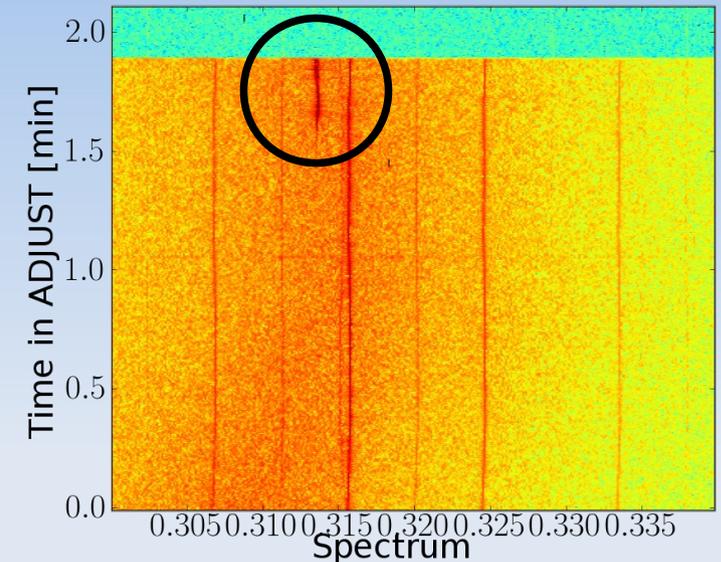


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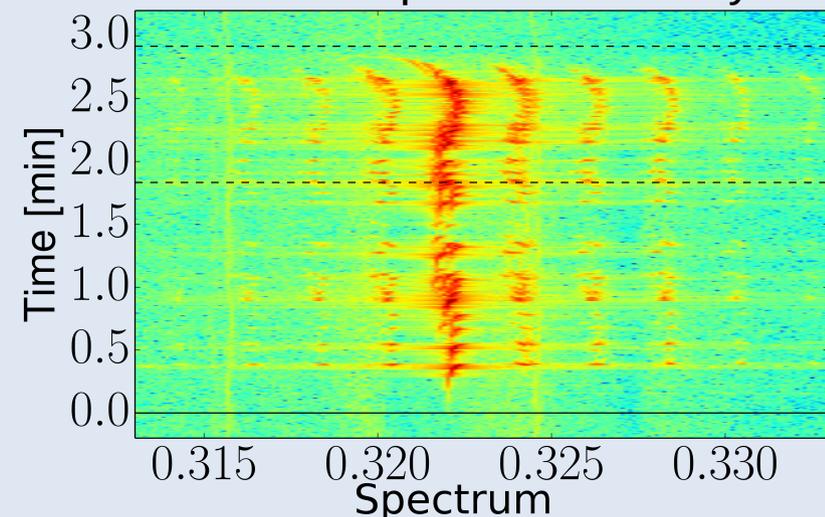
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End of squeeze instability



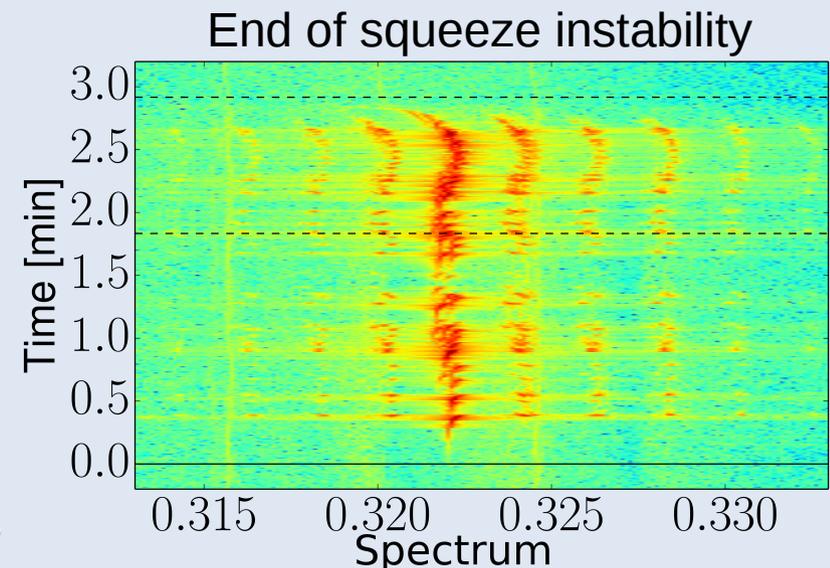
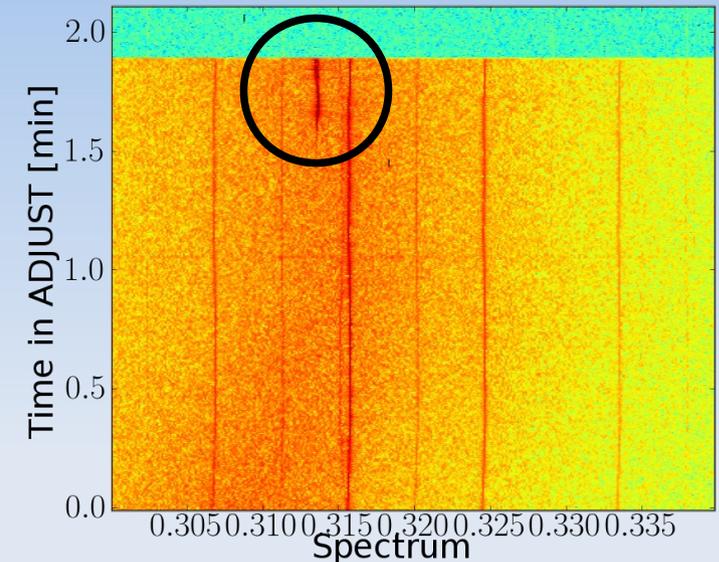


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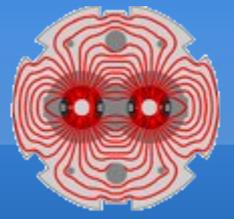


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  - Change of octupole polarity (favourable interplay beam-beam and octupole) and increasing the chromaticity to 15 units
  - New instability with 'acceptable' impact on the beam quality, but couldn't be cured
- Looking back with present knowledge :
  - Instability threshold with  $Q' \sim 0$  are consistently much higher than the model predicts
    - Most likely cause of dumps
  - Uncontrolled linear coupling may explain large fill to fill variations
  - Lack of diagnostics prevents fully conclusive statements on the nature of the instability



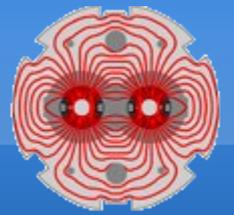


# Understanding of the LHC today





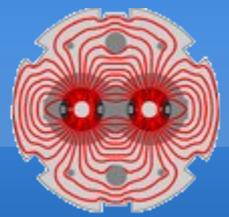
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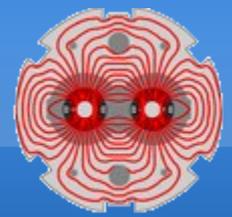
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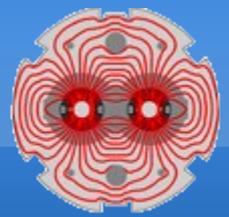
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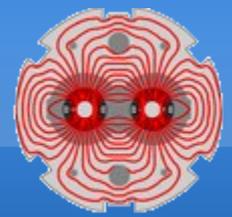
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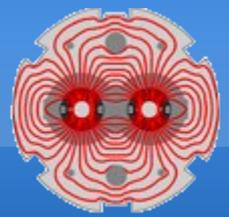
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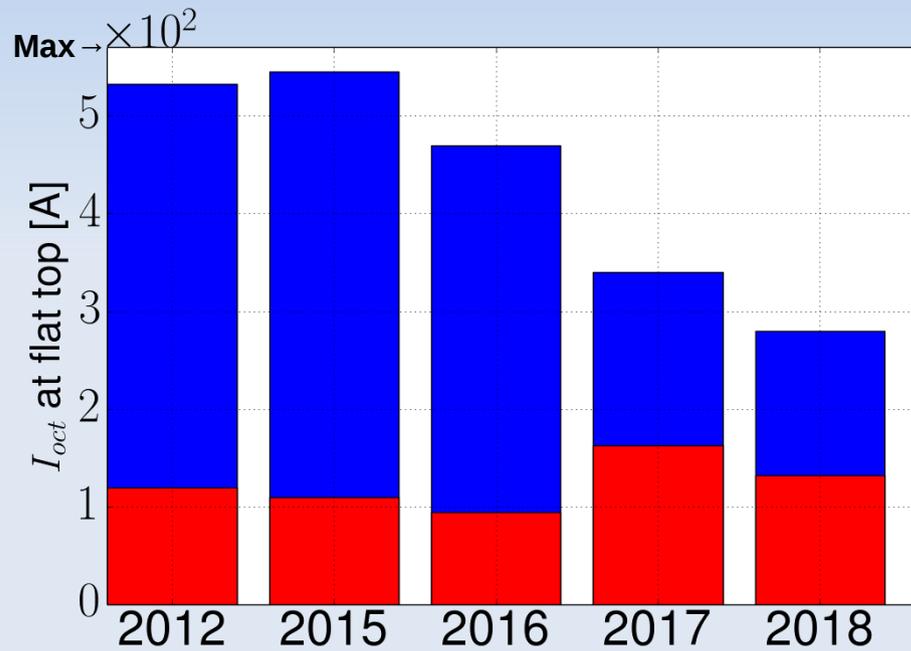
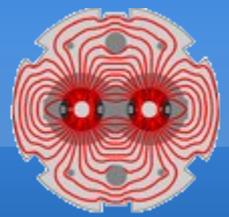
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- Instability latency, due to an external **noise source**
- Instability due to high central stripe electron cloud density with low bunch intensities (**Pop-corn**)

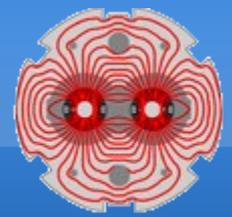


# Running closer to the limit

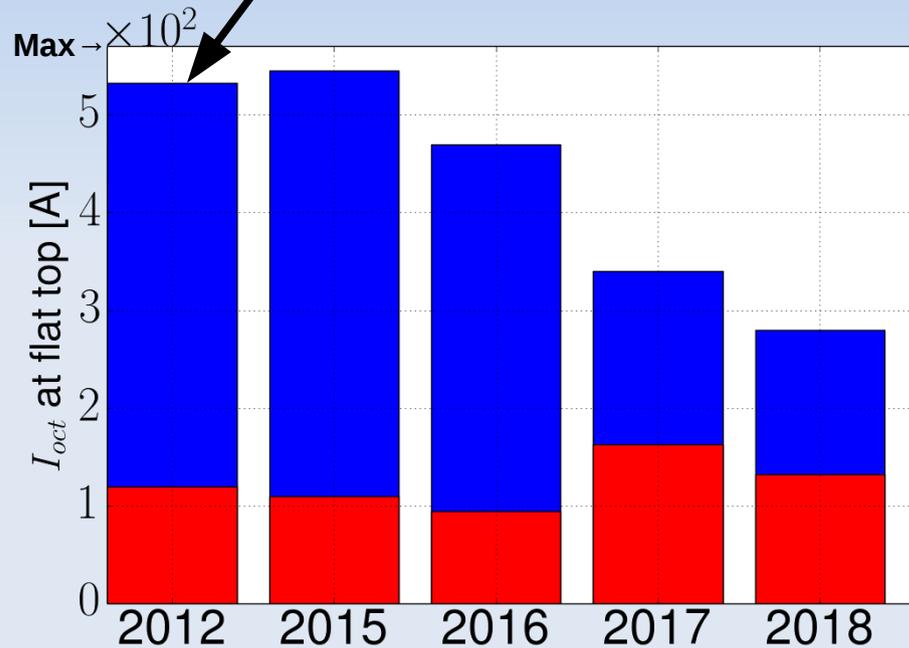




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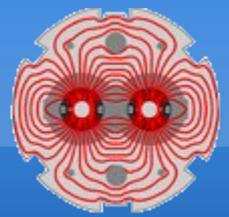


2012 : Limited by the end of squeeze instability



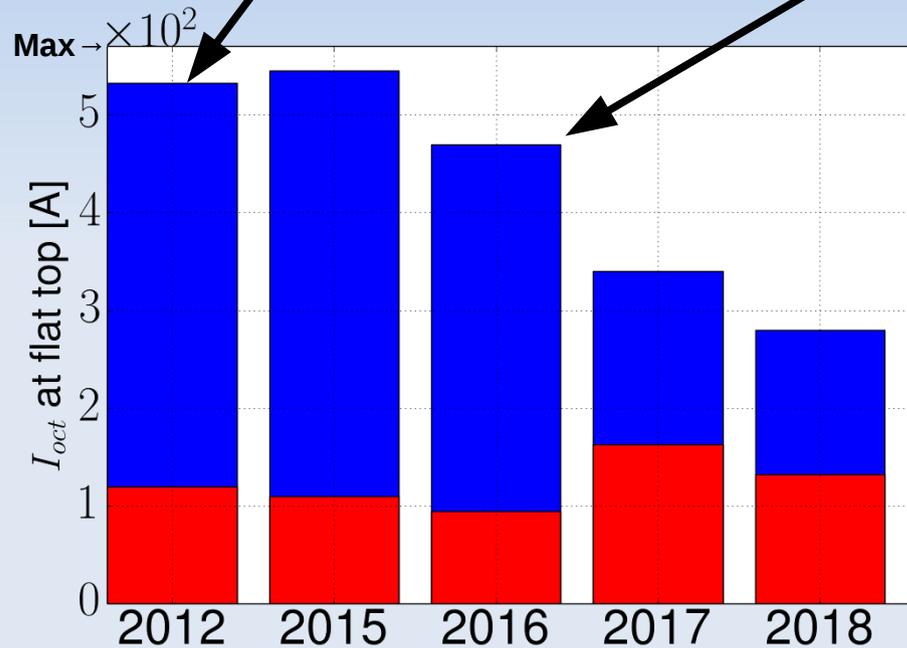


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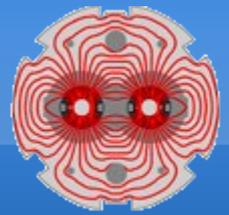
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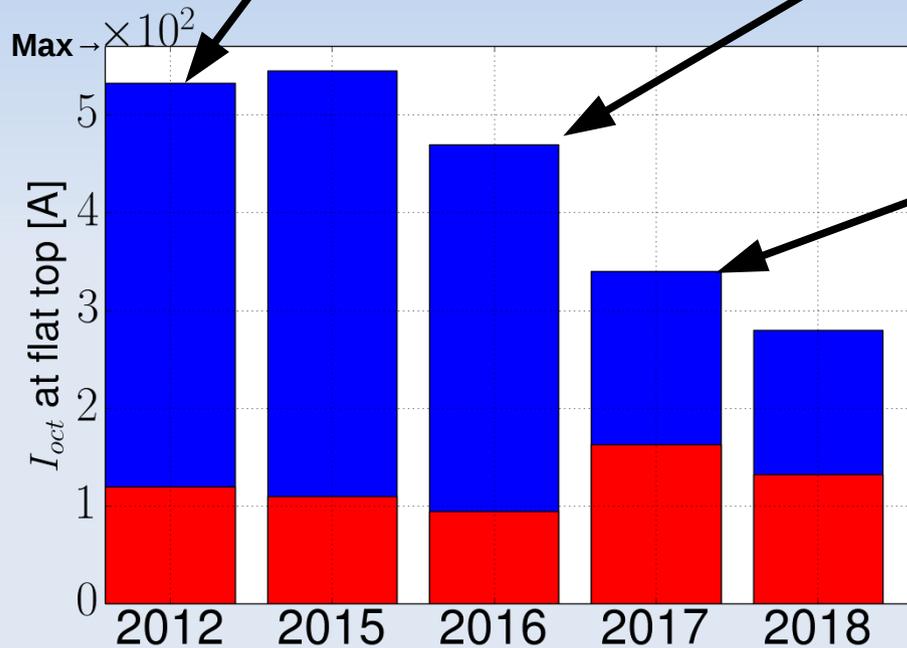
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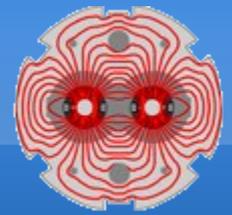
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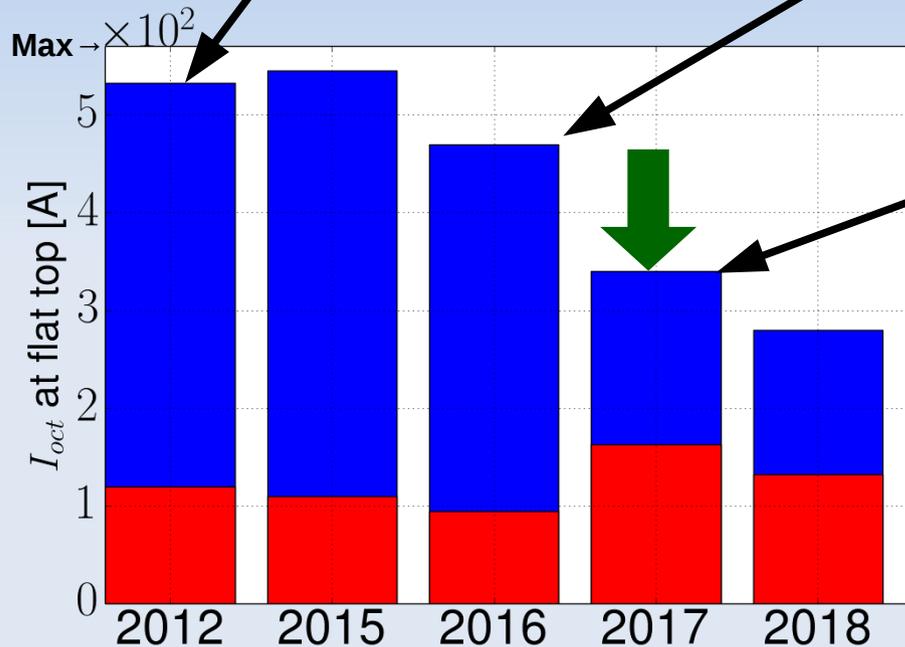
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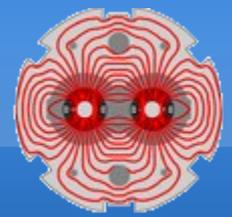
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- Single bunch linear coupling measurement based on ADT-AC dipole
- Non-linear optics correction during commissioning



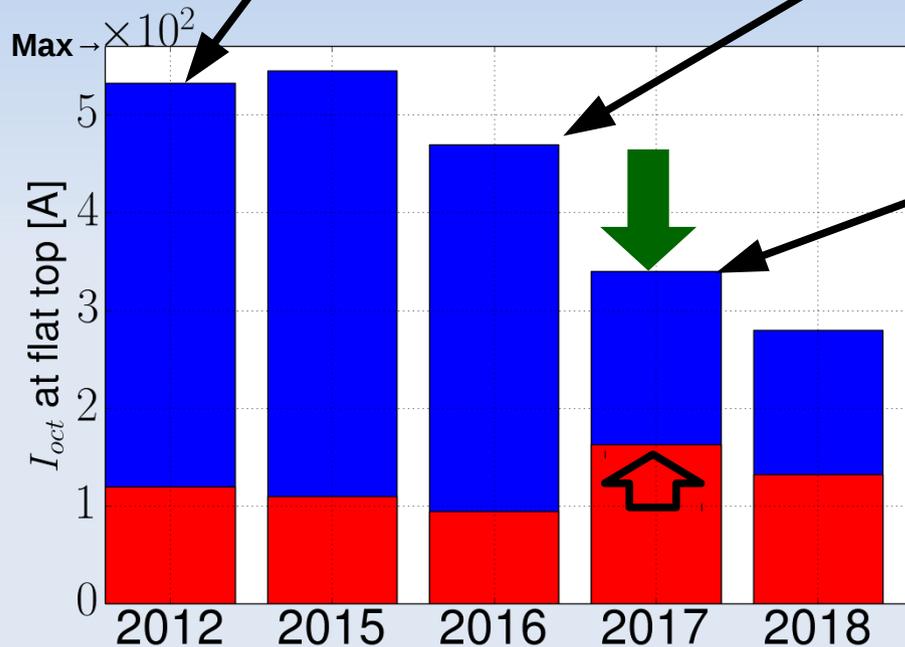
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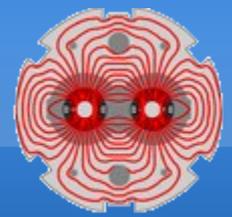
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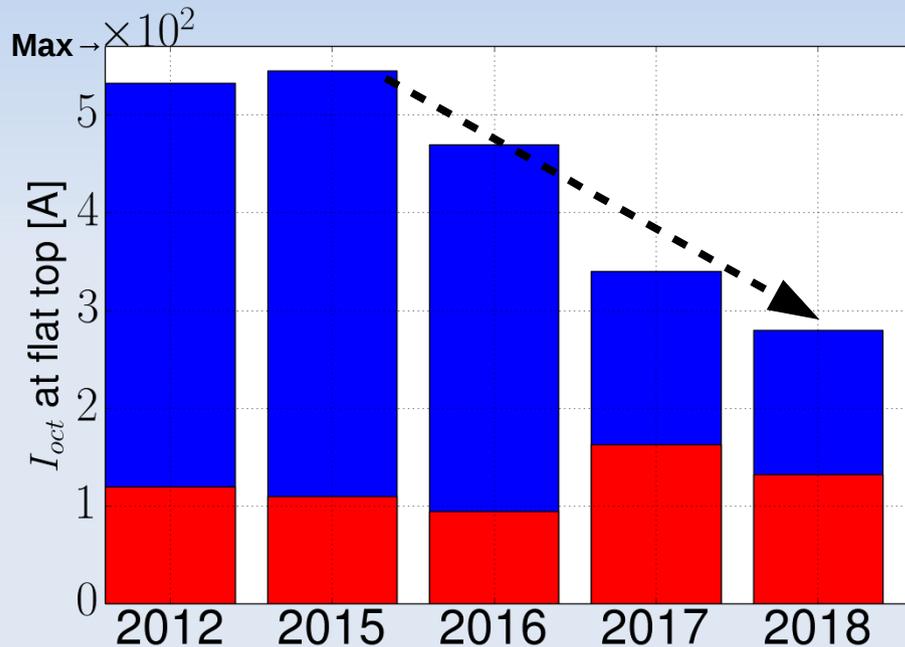
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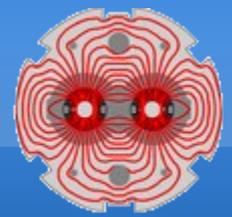


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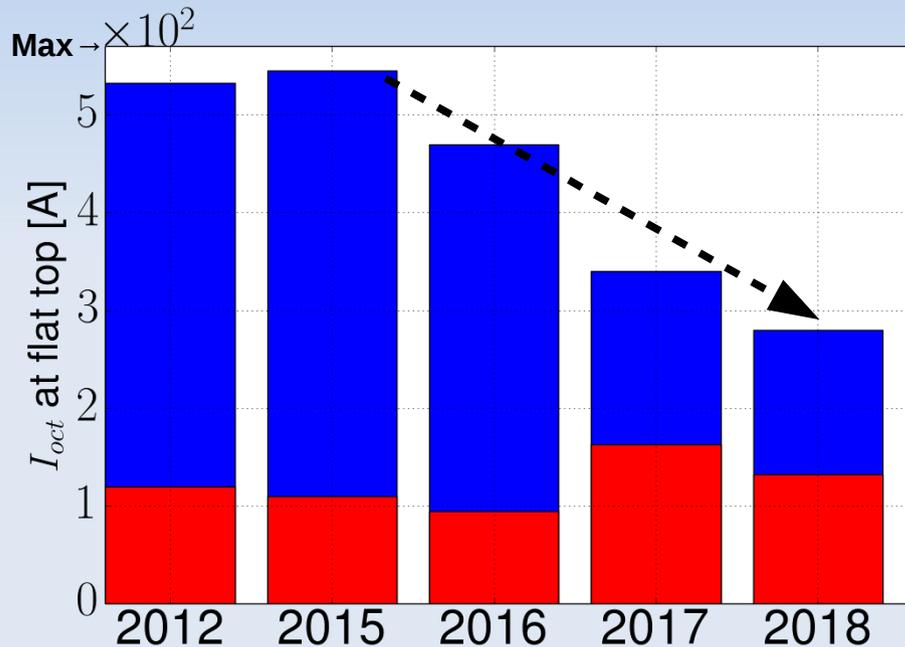
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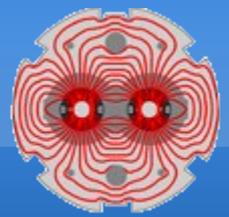
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- Important milestone in 2018 : operating routinely with a factor 2 margin in octupole current, thus becoming compatible with the future increase of brightness
- Main lessons for the operation of the machine :
  - Control over **linear coupling, Q, Q'** and **non-linear optics** becomes crucial with reduced margins



# Running closer to the limit

## Instability monitoring

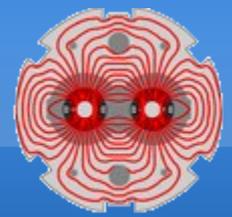


- Mitigation of the risk associated with the reduced margin by establishing an instability monitoring team :
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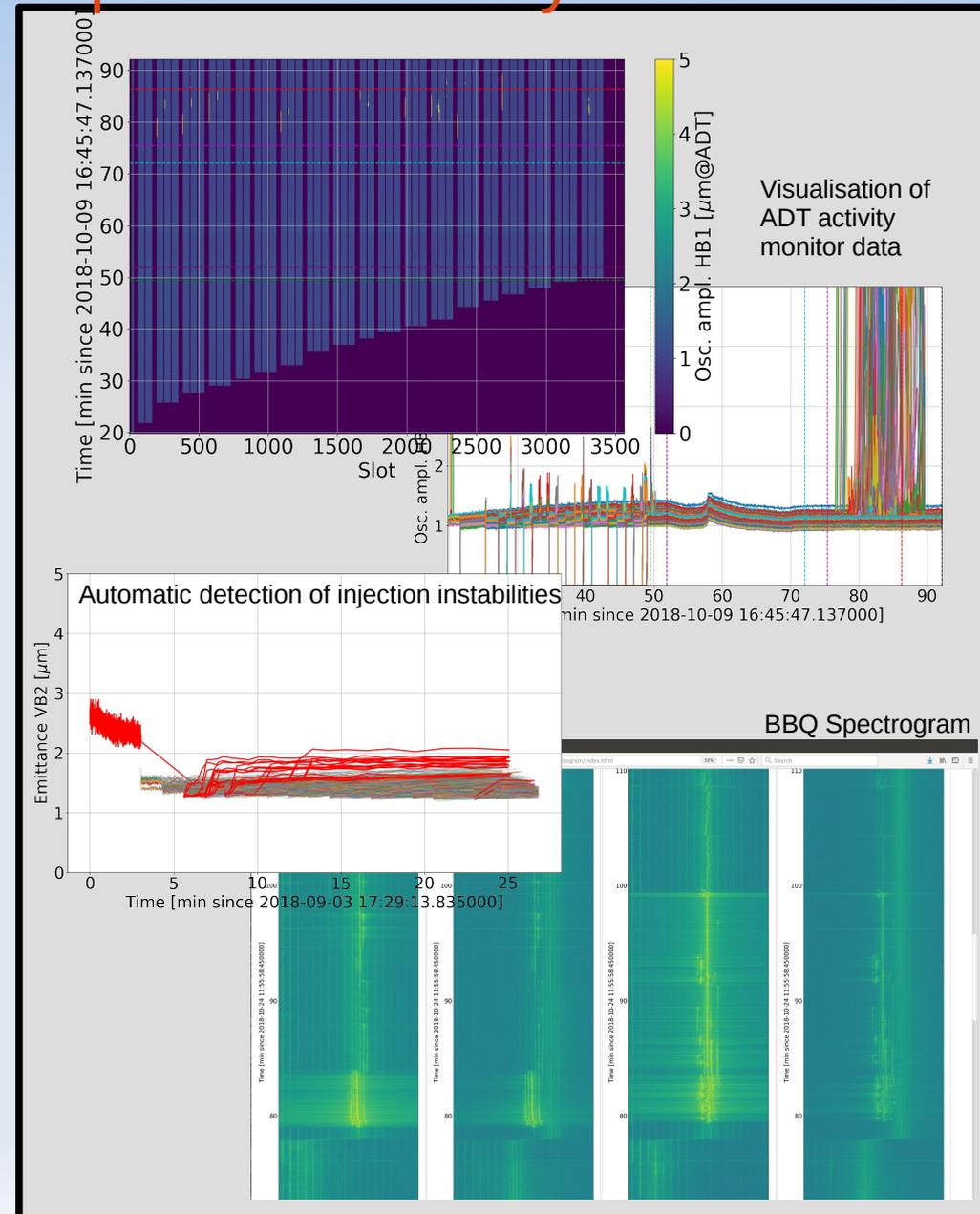
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  - Monitor the availability of instability diagnostics
  - Ease access to expert information and analysis

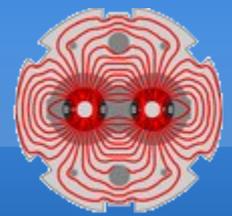
<http://lhcinstantiability.web.cern.ch/>





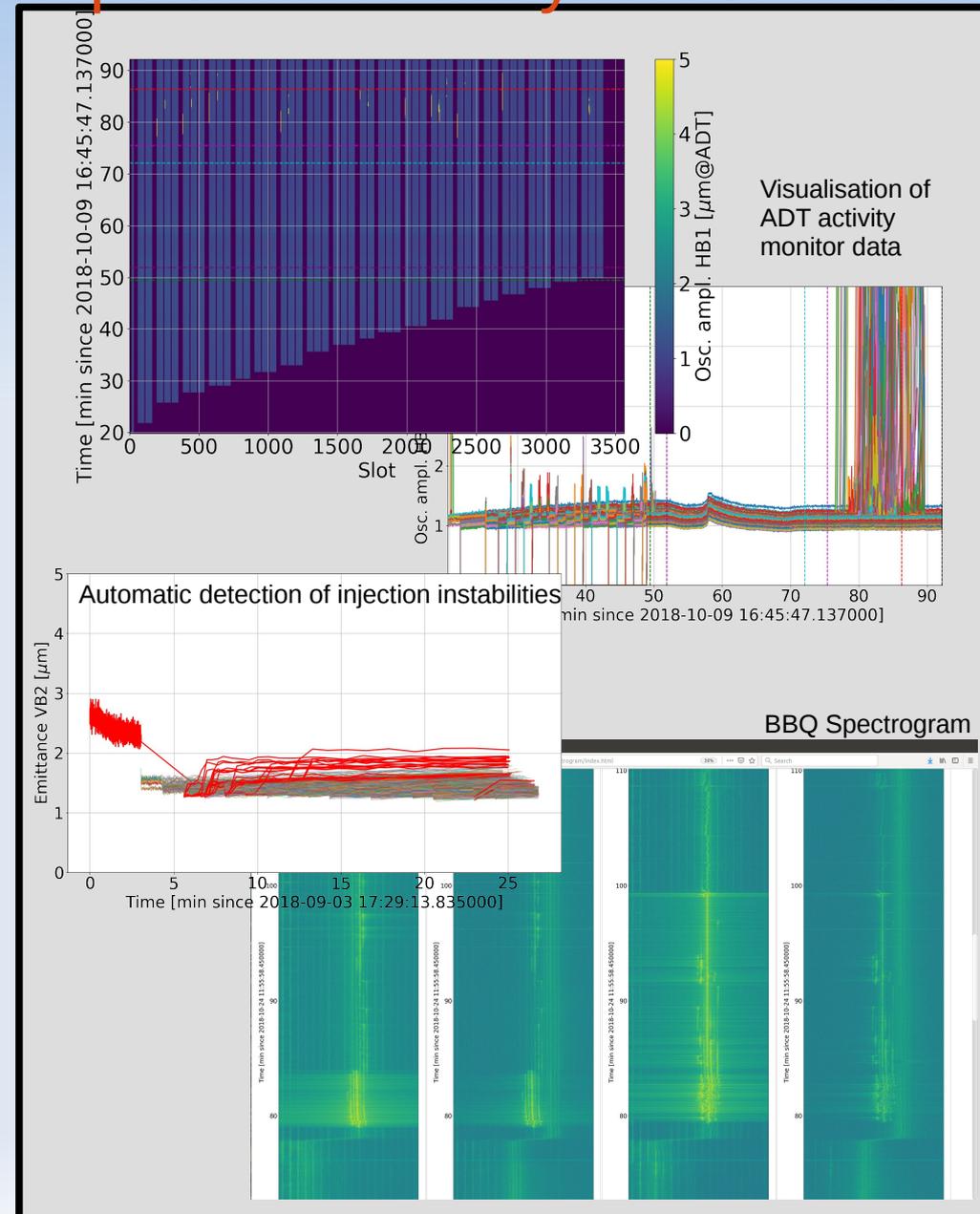
# Running closer to the limit

## Instability monitoring



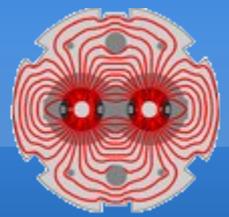
- Mitigation of the risk associated with the reduced margin by establishing an instability monitoring team :
  - Daily analysis of expert diagnostics and recommendation to coordinators in case of instabilities (Trying to avoid the usual “*increase  $I_{oct}$ ,  $Q'$ ,  $G_{ADT}$* ” runaway)
  - Monitor the availability of instability diagnostics
  - Ease access to expert information and analysis
  - Obtain a detailed overview of instabilities in physics, special runs and MDs to be compared with models

<http://lhcinstantiability.web.cern.ch/>

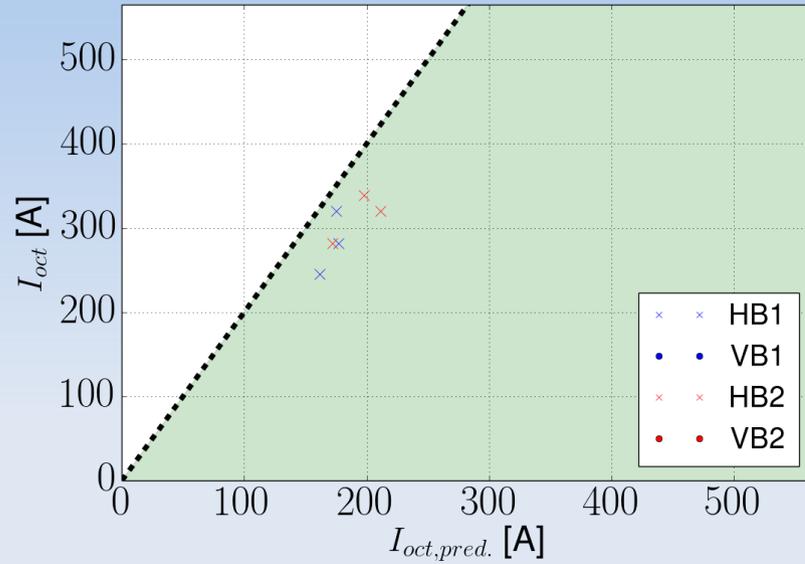


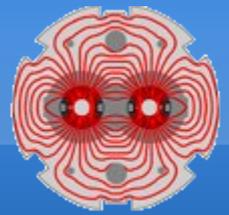


# 2018 - Summary

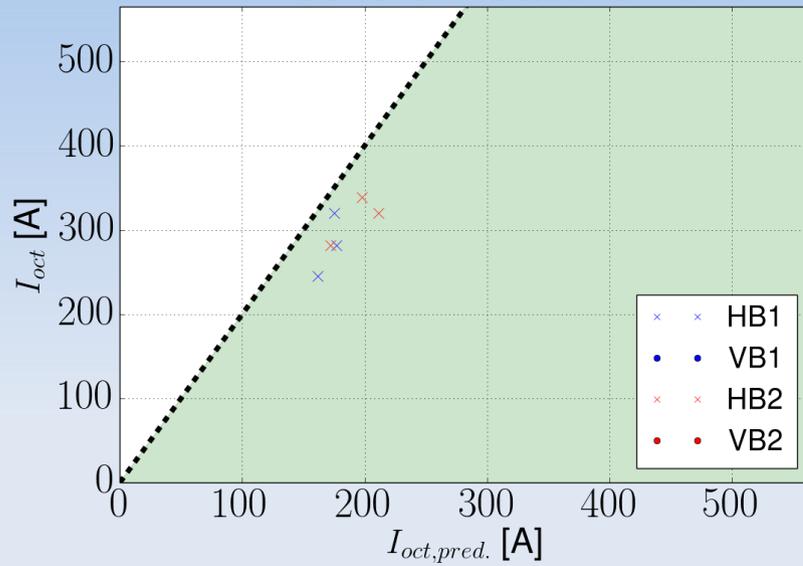


Threshold measurement

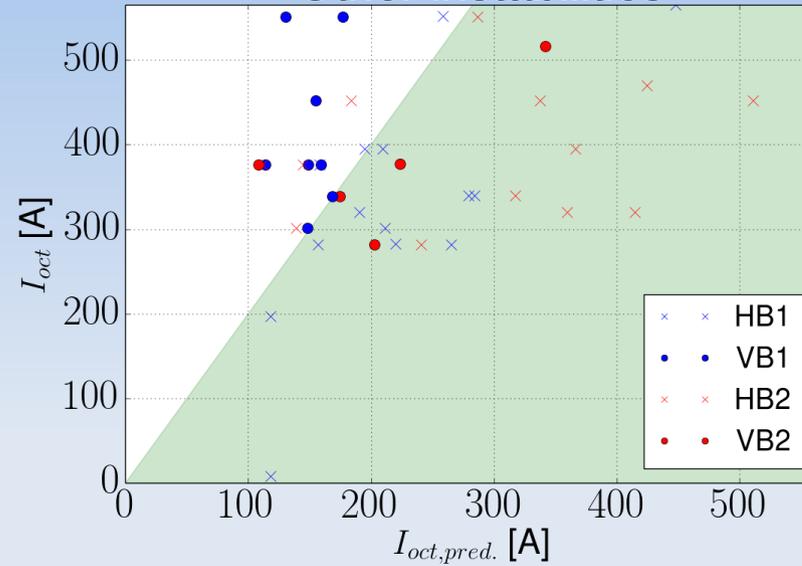


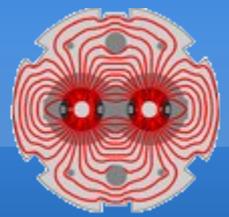


### Threshold measurement

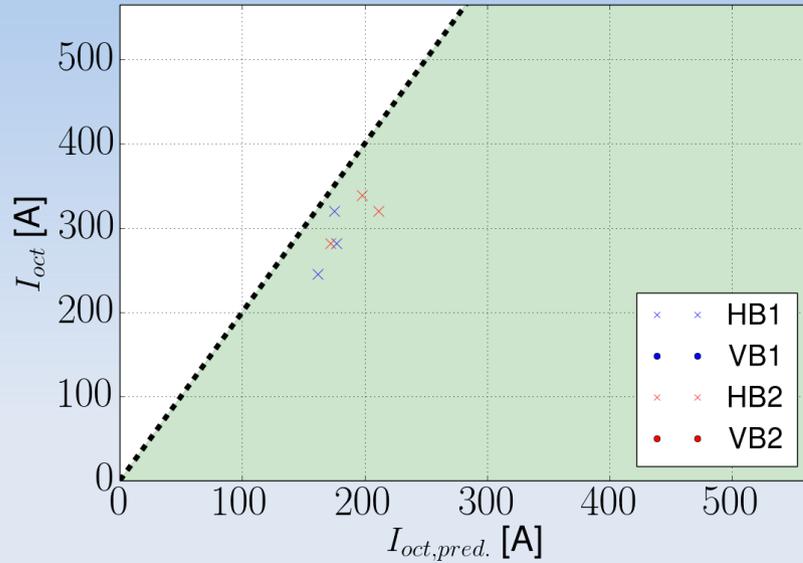


### Other instabilities

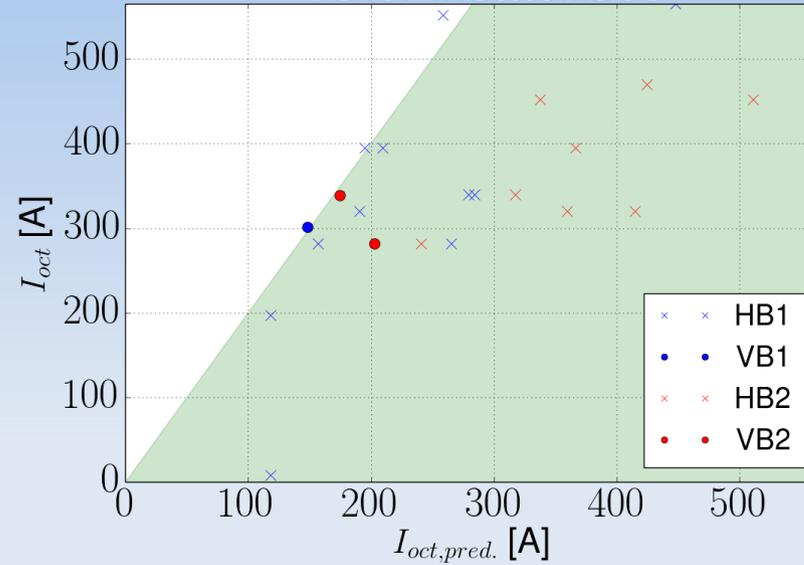




### Threshold measurement

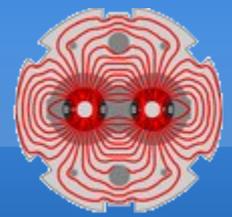


### Other instabilities

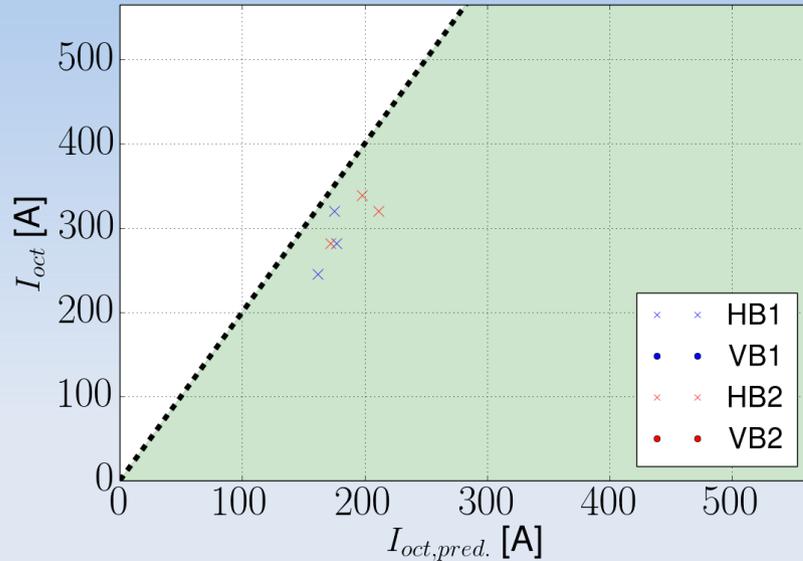


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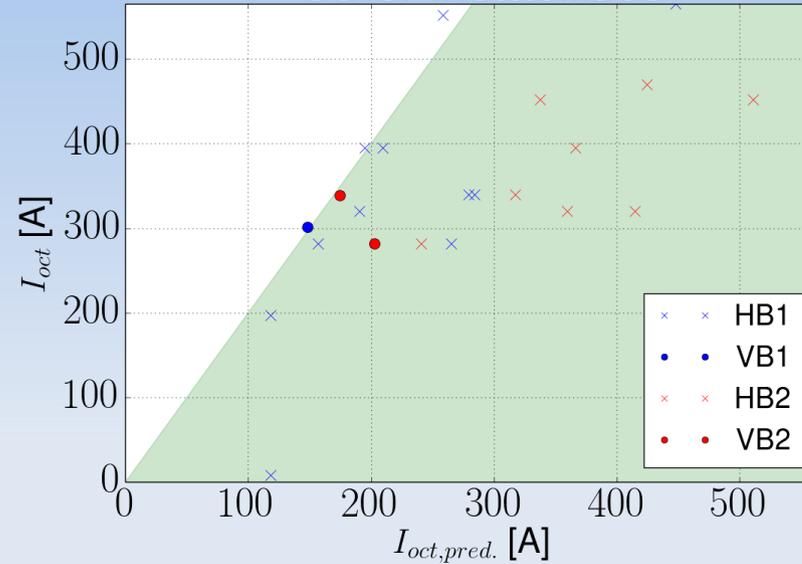
- Linear coupling
- Offset beams
- Reduced ADT gain
- Pop corn



### Threshold measurement



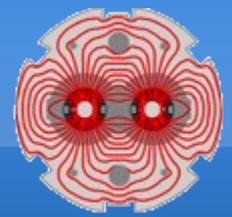
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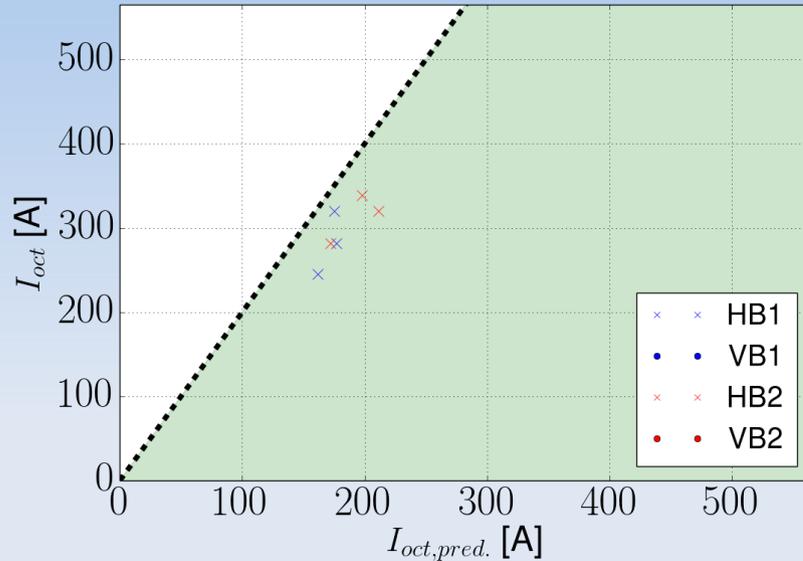
Filtered :

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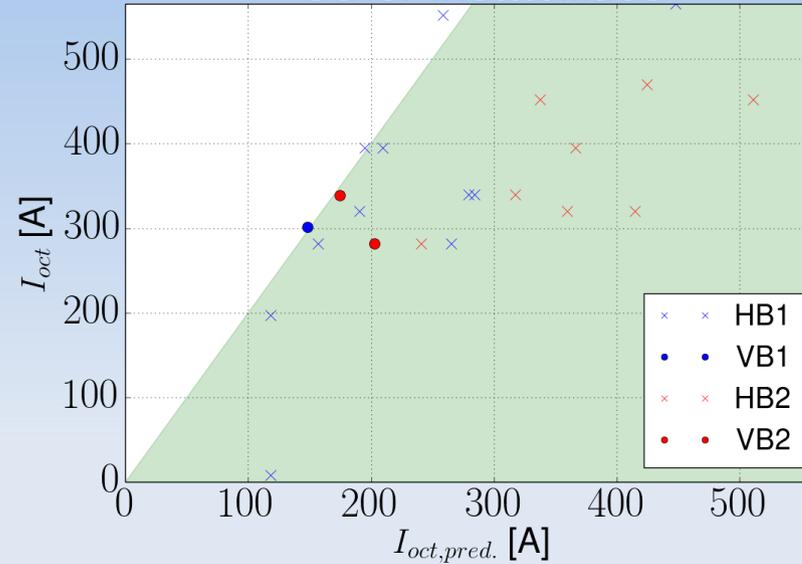
- All instabilities below the recommended margin occurred during MDs or intensity ramp up
  - Unexpectedly bright beams
  - Lack of preparation / oversight
  - Unclear recommendation
    - Take the time to consult the instability team for your MD



### Threshold measurement



### Other instabilities



Filtered :

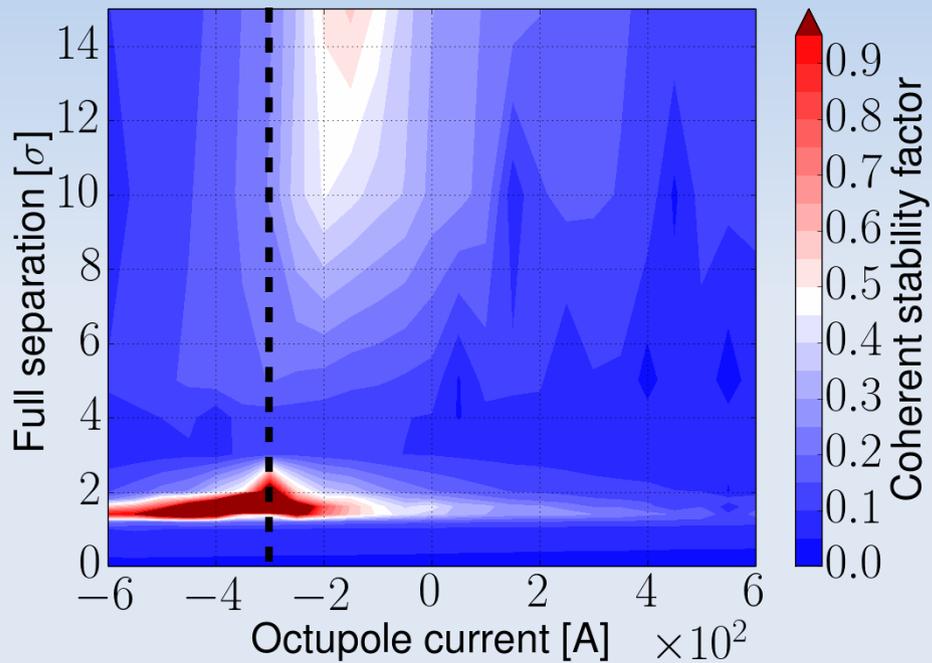
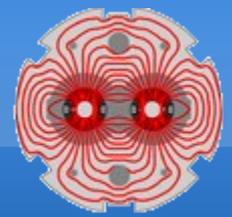
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- Pop corn

- All instabilities below the recommended margin occurred during MDs or intensity ramp up
  - Unexpectedly bright beams
  - Lack of preparation / oversight
  - Unclear recommendation
    - Take the time to consult the instability team for your MD
- Reproducibility issue:
  - Several fills reached brightnesses above the recommended margins, yet were stable (e.g. BSRT calib.)



# Offset beams

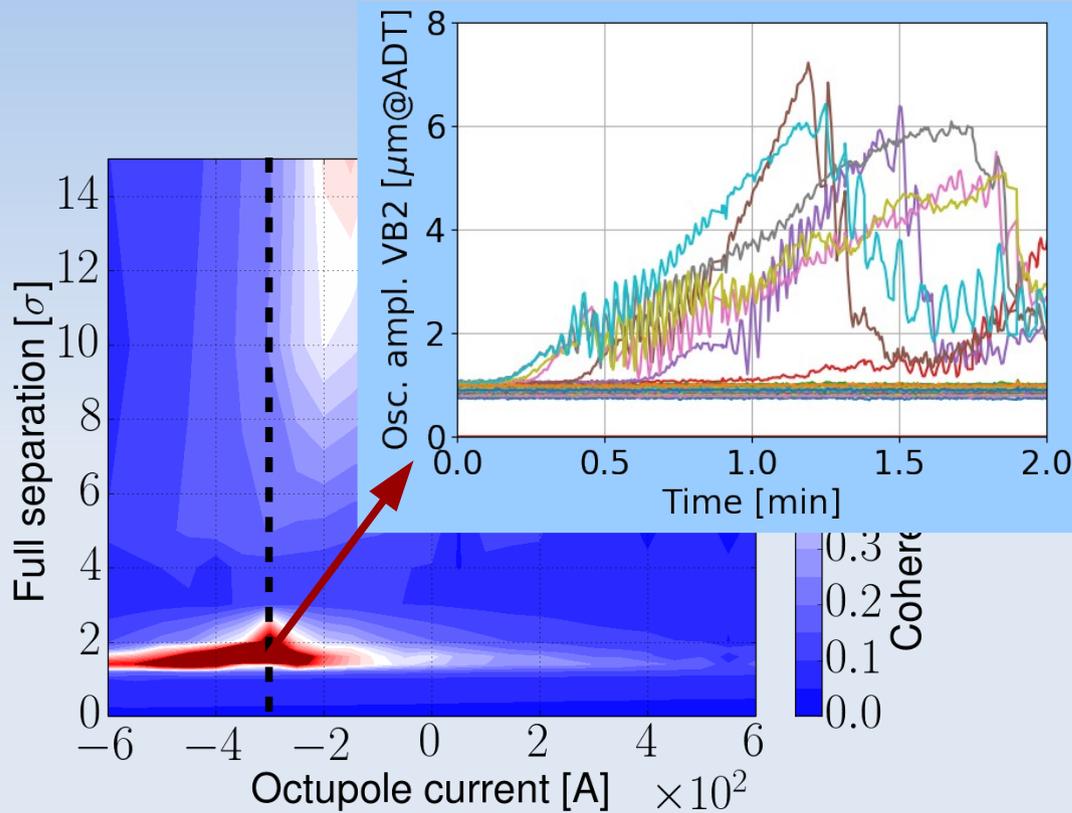
## Separation levelling, VdMs





# Offset beams

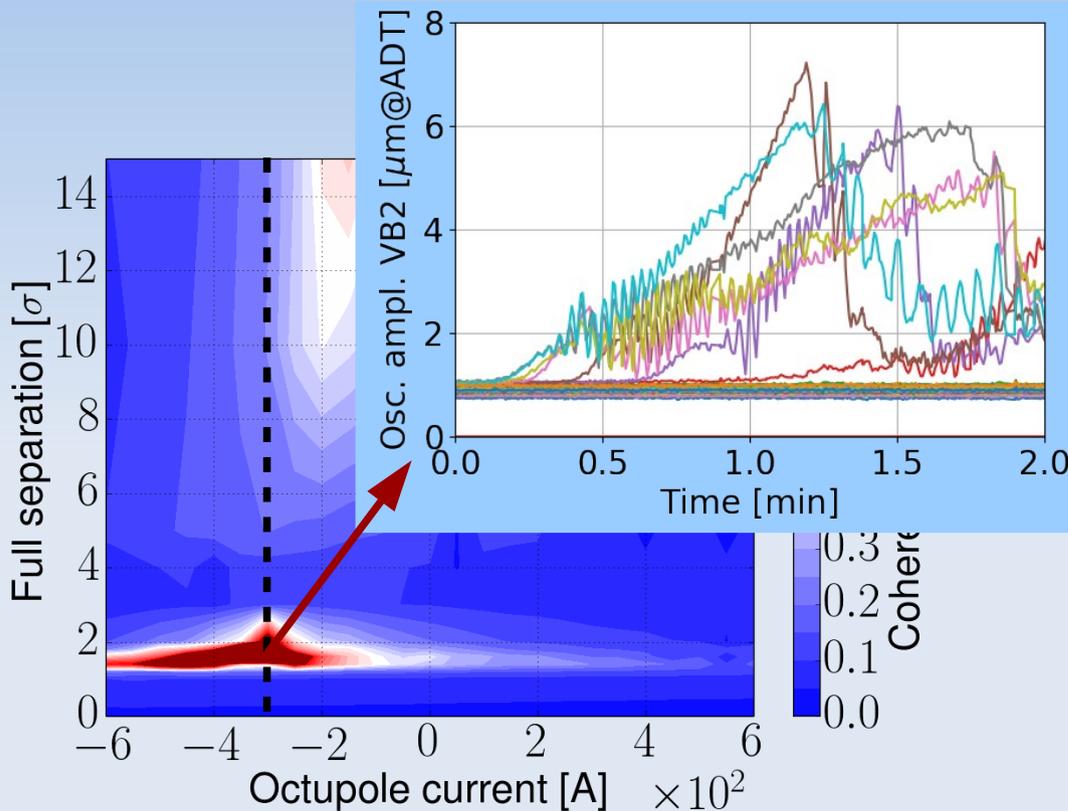
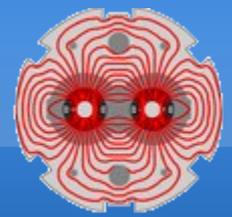
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# Offset beams

## Separation levelling, VdMs

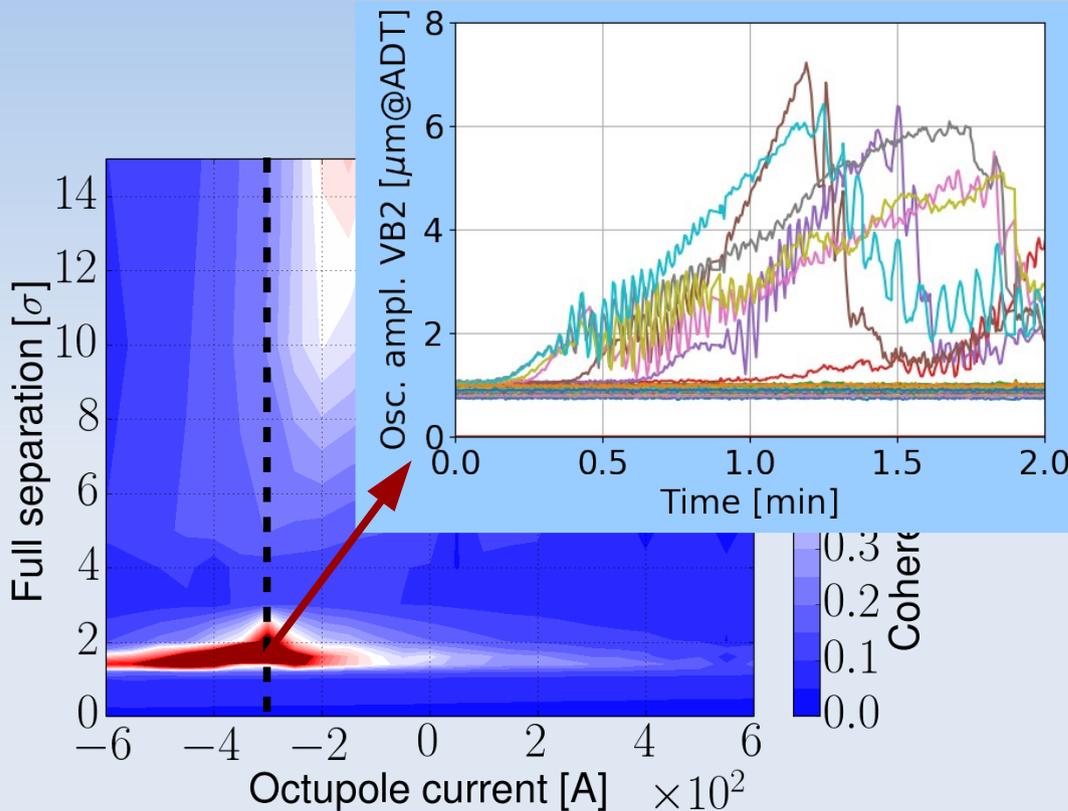
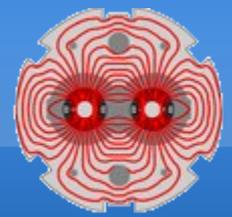


- The instability expected with offset beams could be well reproduced in controlled conditions with the negative polarity (and  $Q' \sim 15$ )
  - No beam dumps à la 2012, even with 733b, rather a slow instability, **slow enough not to occur when collapsing the separation in one go**



# Offset beams

## Separation levelling, VdMs

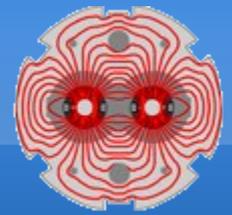


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  - No beam dumps à la 2012, even with 733b, rather a slow instability, **slow enough not to occur when collapsing the separation in one go**

- The positive polarity does not fully suppress the instability with offset beams, depending mainly on  $\beta^*$  and Xing angle (Snowflakes in 2012, VdMs in 2017)
  - The most robust option for VdMs or low- $\mu$  tests remains to ensure head-on collision in at least one IP at all time for all bunches



# Ongoing investigations



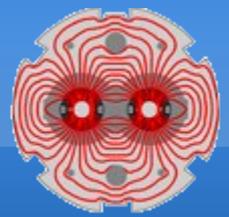
MOST  
**WANTED**

UNDERSTANDING - MITIGATION FOR

**- NEED FOR FACTOR 2 MARGIN  
AND CORRESPONDING LACK OF REPRODUCIBILITY**



# Ongoing investigations

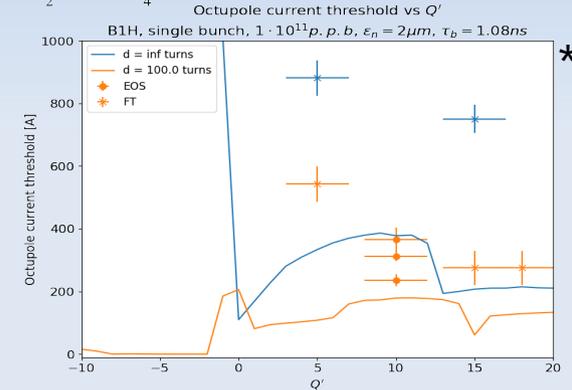
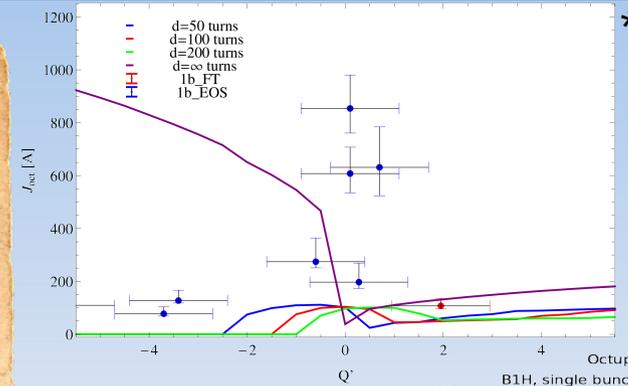


MOST  
**WANTED**

UNDERSTANDING - MITIGATION FOR

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- LARGE DISCREPANCIES AT  
 $G_{ADT} \sim 0$  OR  $Q' \sim 0$





# Ongoing investigations



MOST  
**WANTED**

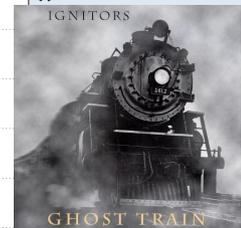
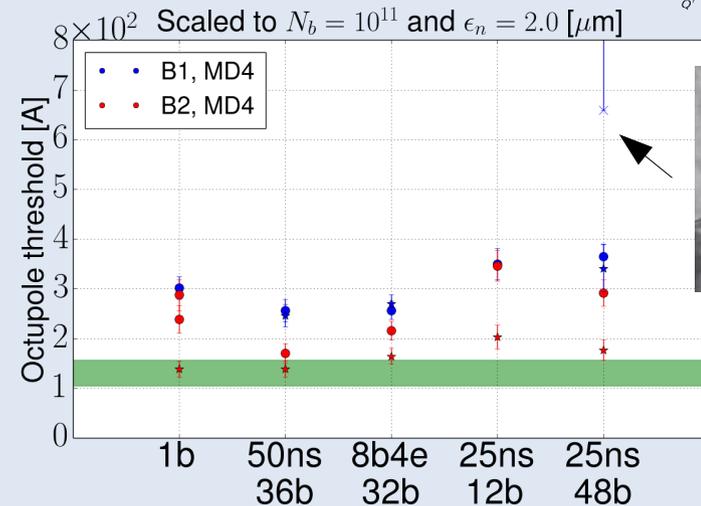
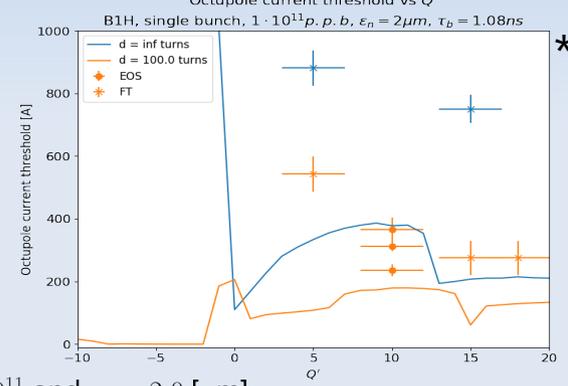
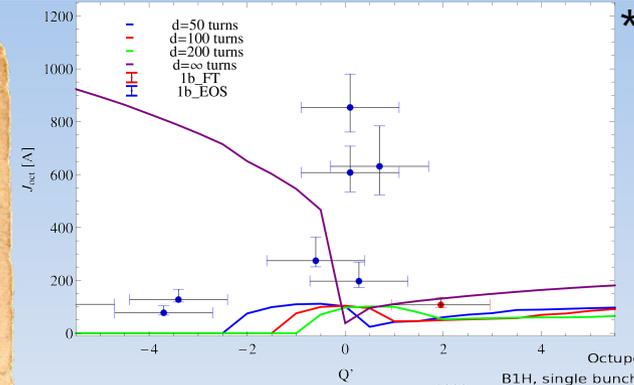
UNDERSTANDING - MITIGATION FOR

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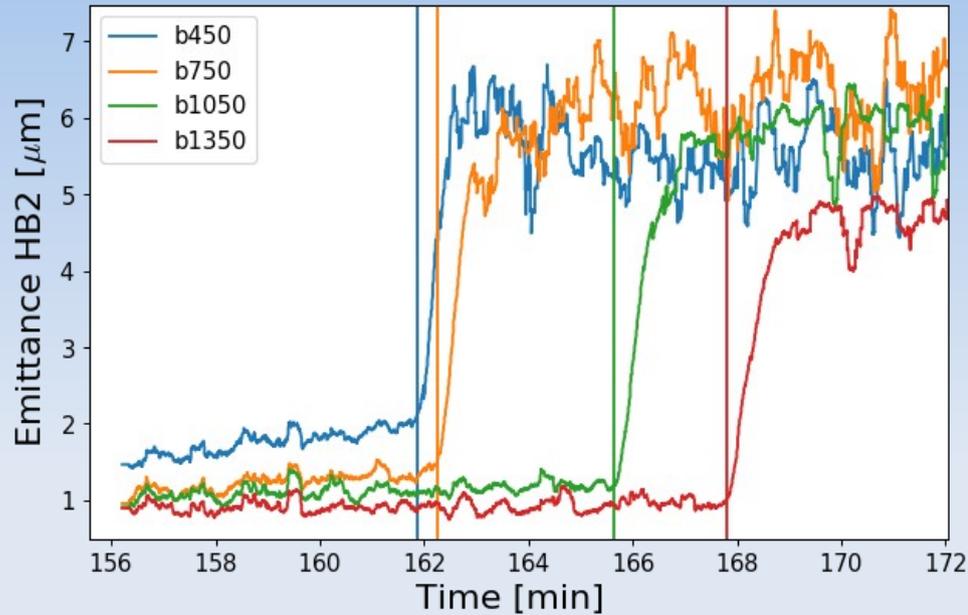
- GHOST TRAIN INSTABILITY (HB1)



\*L. Carver, et al., Evian 2015, 2016 & X. Buffat, et al., Evian 2017



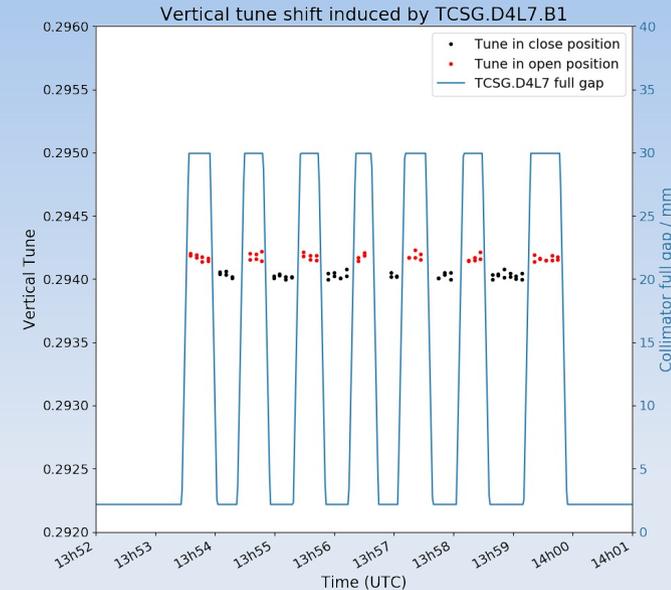
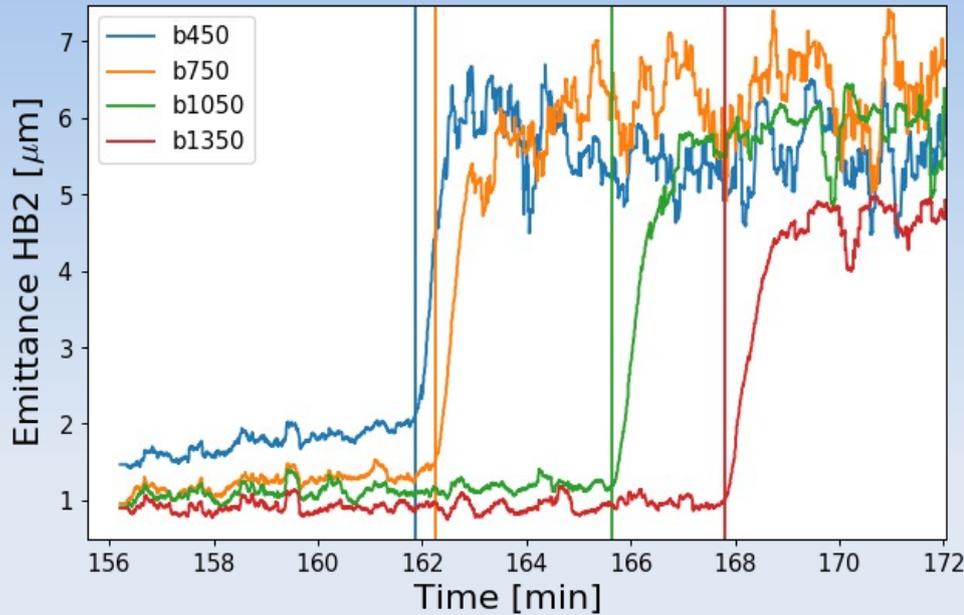
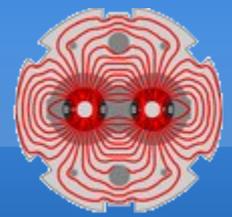
# Ongoing investigations



- Diffusion models
  - Effect of noise spectrum (e.g. 50 Hz noise lines)
  - Optimal damper settings (gain, bandwidth) and machine/beam parameters



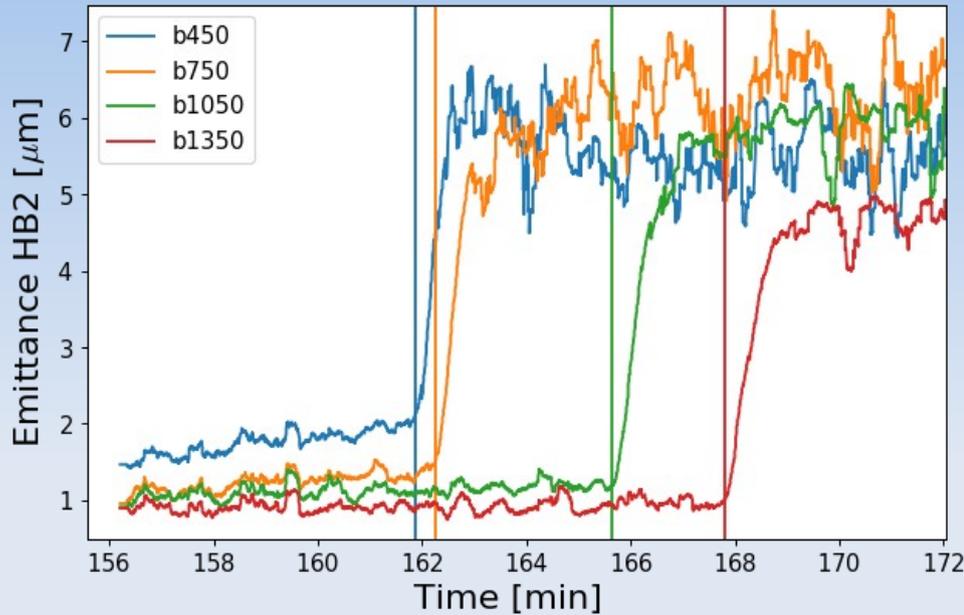
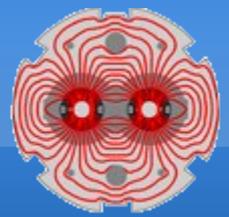
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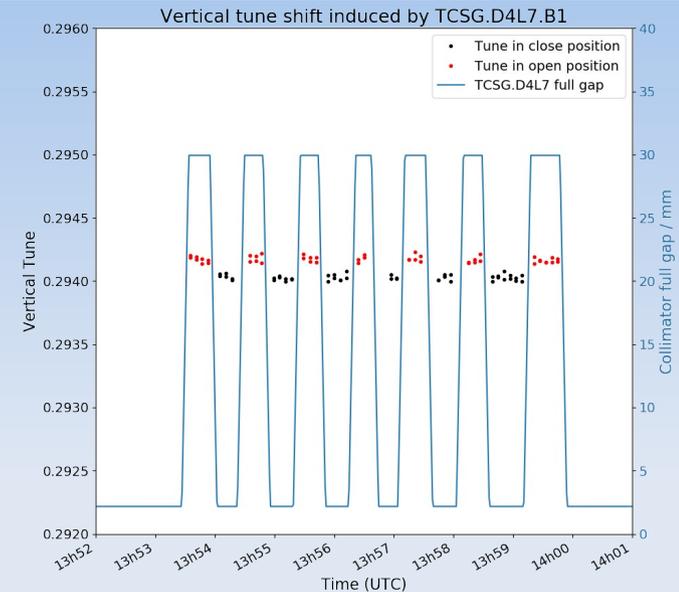
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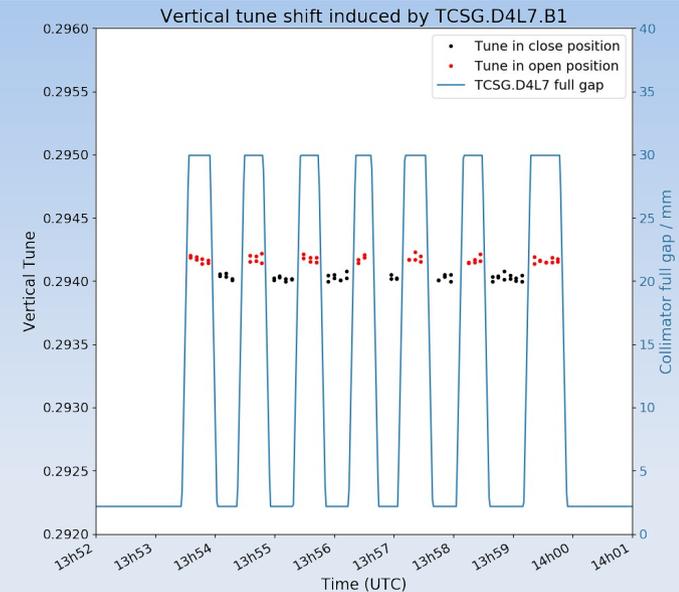
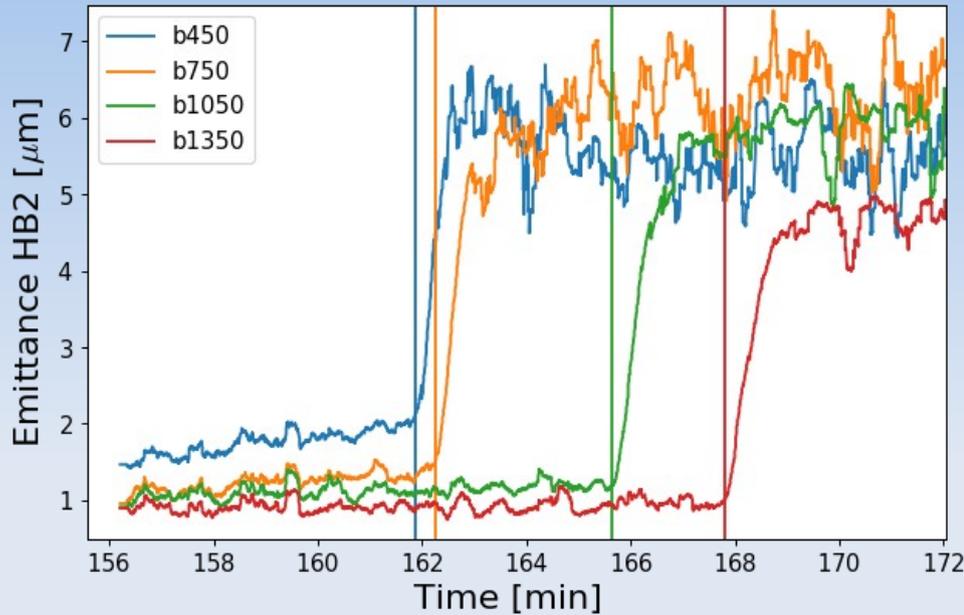
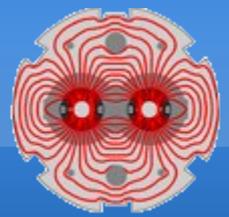
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- *Dark impedance searches*
  - Strongly constrained by measurements of
    - Single collimator tune shifts
    - Instability threshold
    - Head-tail signals
    - Rise time vs. chromaticity



# Ongoing investigations

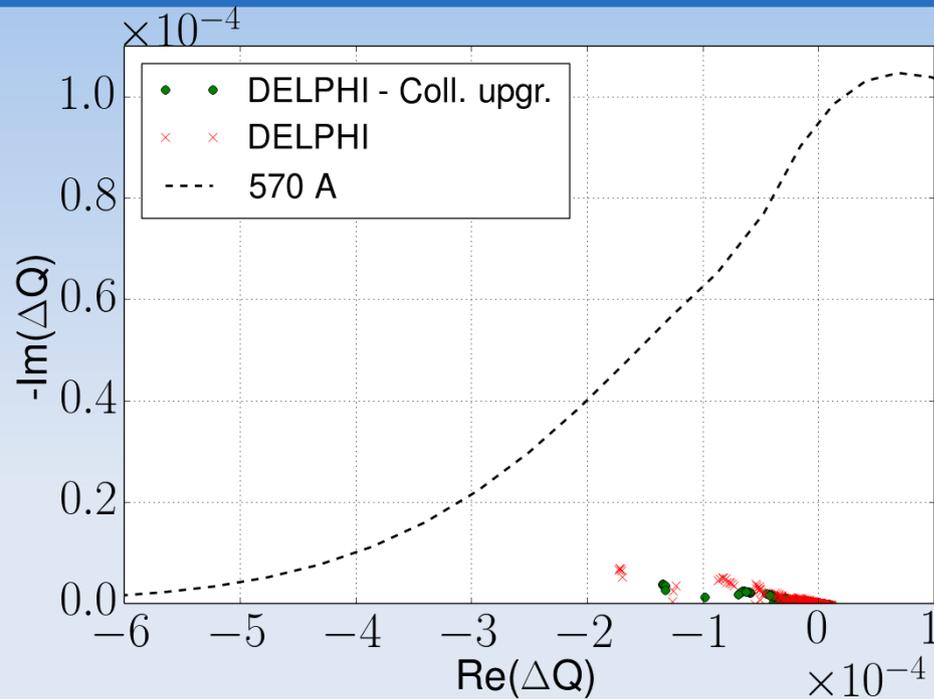
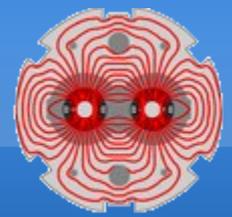


- Diffusion models
  - Effect of noise spectrum (e.g. 50 Hz noise lines)
  - Optimal damper settings (gain, bandwidth) and machine/beam parameters
- Interplay between the ADT and Landau damping (validity of the uncoupled-mode approximation)
- Weak electron cloud instabilities
- *Dark impedance searches*
  - Strongly constrained by measurements of
    - Single collimator tune shifts
    - Instability threshold
    - Head-tail signals
    - Rise time vs. chromaticity



# Stability limit

## In view of run III

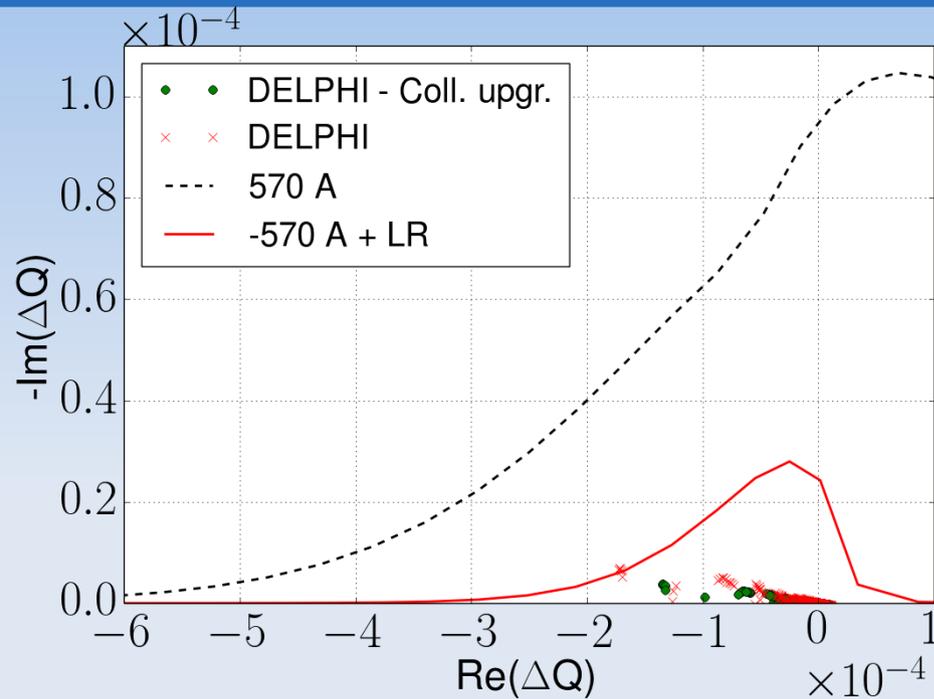
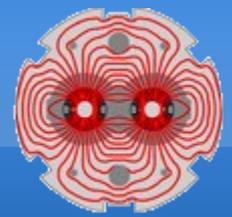


- The current optics with positive polarity offers enough margin for  $1.8 \cdot 10^{11}$  in  $1.8 \mu\text{m}$ 
  - Single bunches of even larger brightness as well as high intensity 12b trains were put into collision



# Stability limit

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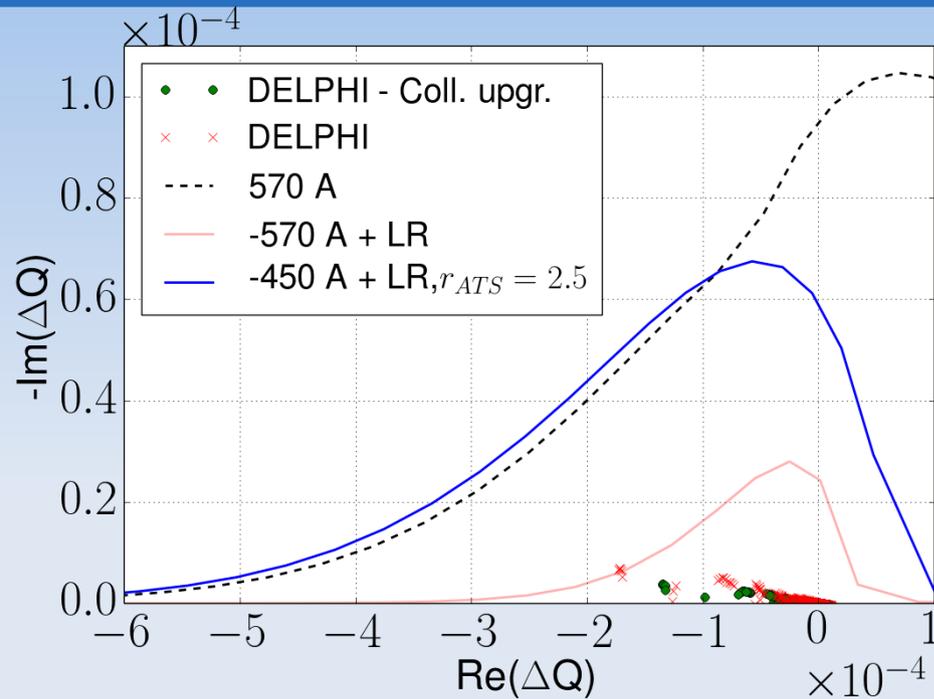
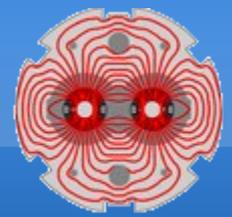


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- To enable the potential of beam-beam compensation with the octupole (negative polarity), a tele-index is required to maintain the tune spread
  - The capability of choosing the polarity could also become useful in case of limitations in IR NL correctors



# Stability limit

## In view of run III

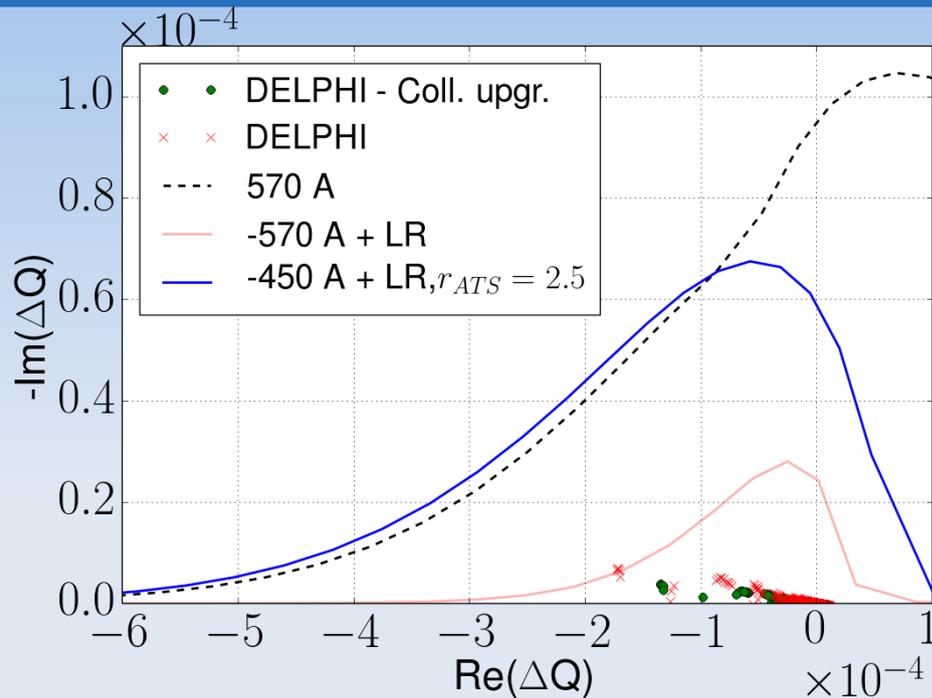
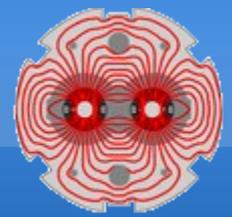


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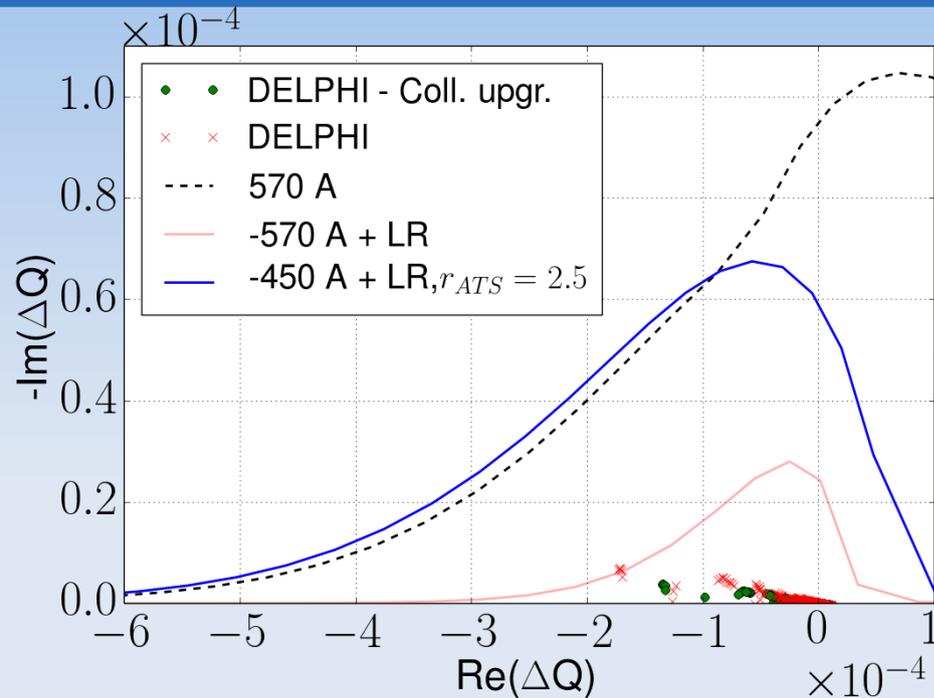
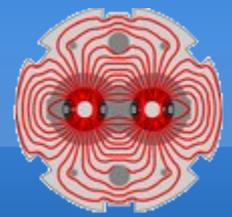
→ Develop a (anti-)telescopic ramp, featuring enough margins for both polarities (see N. Karastathis)

- $r_{ATS}$  or  $1/r_{ATS} \sim 2.5$  would be sufficient for  $1.8 \cdot 10^{11}$  in  $1.8 \mu\text{m}$ .  $r_{ATS} = 3.1$  was tested during ATS MDs with BCMS bunch trains (both polarities)



# Stability limit

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- Drawback with  $I_{oct} < 0$ : The stability with offset collisions is more critical
  - Head-on collision in at least one IP for special tests
  - Offset levelling range for physics (i.e. both IP1 and IP5) limited to  $1\sigma$  ( $L/L_0 \sim 20\%$ )
  - Polarity reversal in stable beam could be envisaged if the quality of non-colliding bunches is not a concern (tested in 2018)



# Diagnostics

## Run I



BI, RF

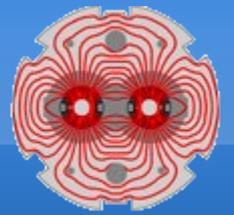
ABP

Bunch-by-bunch  
everything



# Diagnostics

## Run II



- Fast scanning BSRT
- ADT Activity Monitor

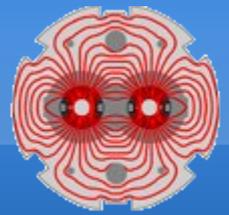


Detection, timing (i.e. correlation with other events) and bunch selection



# Diagnostics

## Run II

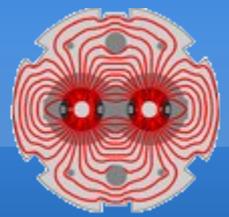


- Fast scanning BSRT → Detection, timing (i.e. correlation with other events) and bunch selection
- ADT Activity Monitor → Detection, timing (i.e. correlation with other events) and bunch selection
- ADT ObsBox
- Instability trigger network → Identification of the instability type (coupled bunch, head-tail, electron cloud, 16L2, ...)
  - Critical for the head-tail monitor acquisition



# Diagnostics

## Run II



- Fast scanning BSRT
- ADT Activity Monitor
- ADT ObsBox
- Instability trigger network
  - Critical for the head-tail monitor acquisition

Detection, timing (i.e. correlation with other events) and bunch selection

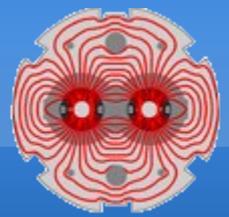
Identification of the instability type (coupled bunch, head-tail, electron cloud, 16L2, ...)

Understanding  
→ possibly a cure



# Diagnostics

## Run II



- Fast scanning BSRT
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- ADT ObsBox
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  - Critical for the head-tail monitor acquisition

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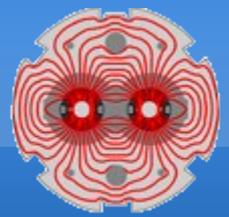
Probing the models (predicted mode type, complex tune shift, Landau damping)

Understanding → possibly a cure



# Diagnostics

## Run II



- Fast scanning BSRT →
- ADT Activity Monitor →
- ADT ObsBox
- Instability trigger network
  - Critical for the head-tail monitor acquisition
- Single bunch kick capability
  - Single bunch tune for impedance measurement →
  - Single bunch beam transfer function measurement →

Detection, timing (i.e. correlation with other events) and bunch selection

Identification of the instability type (coupled bunch, head-tail, electron cloud, 16L2, ...)

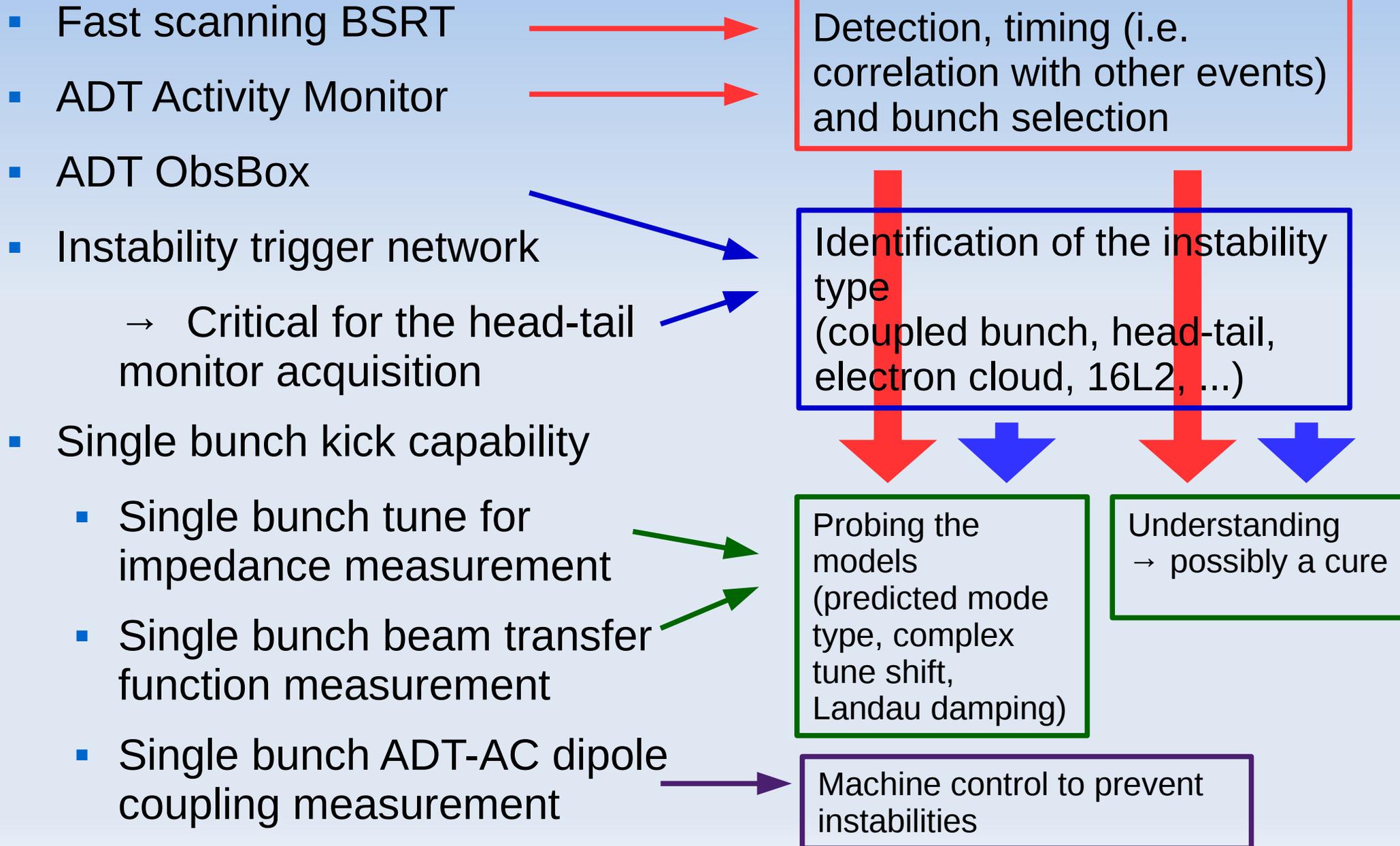
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Understanding → possibly a cure



# Diagnostics

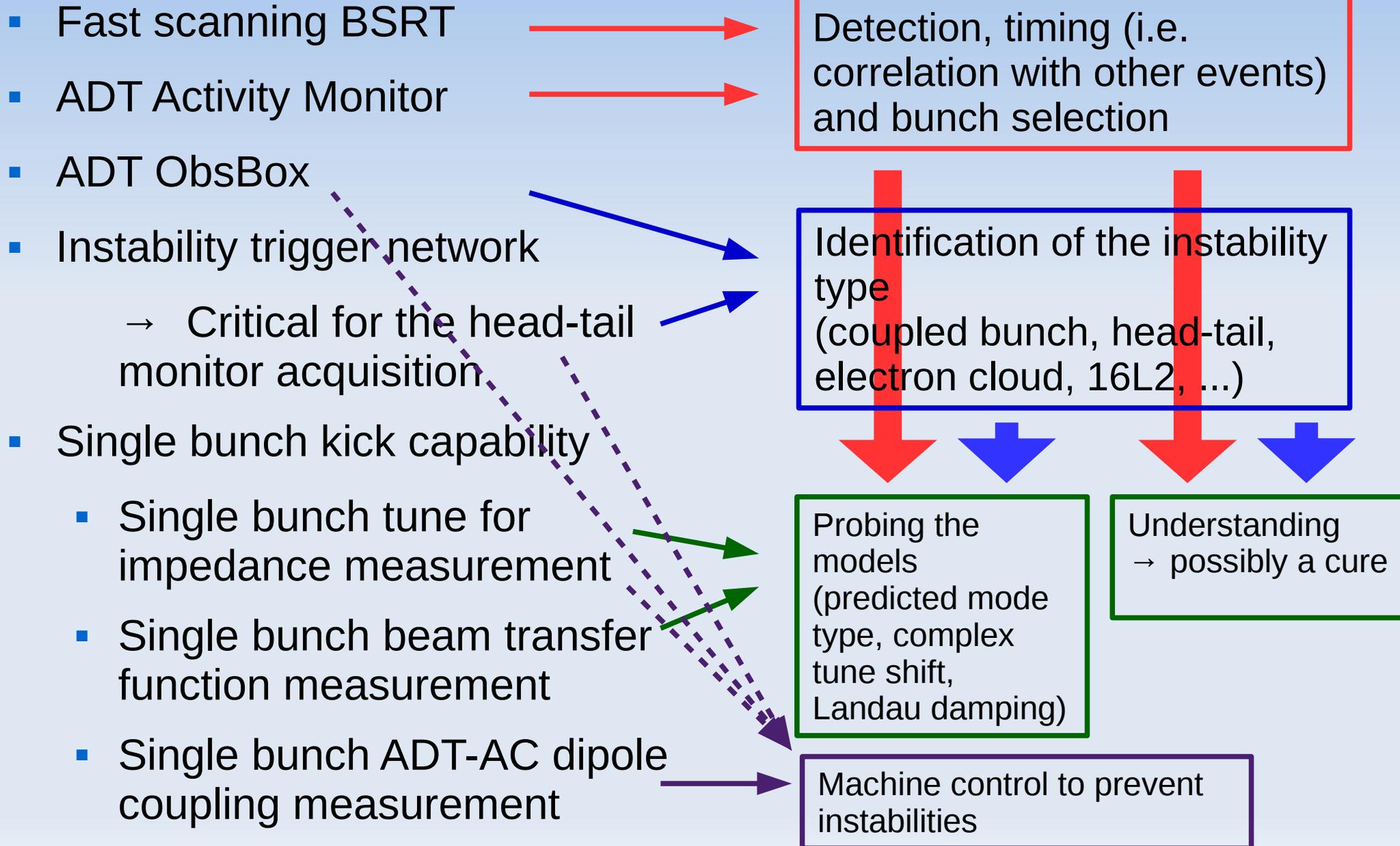
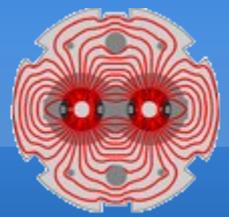
## Run II





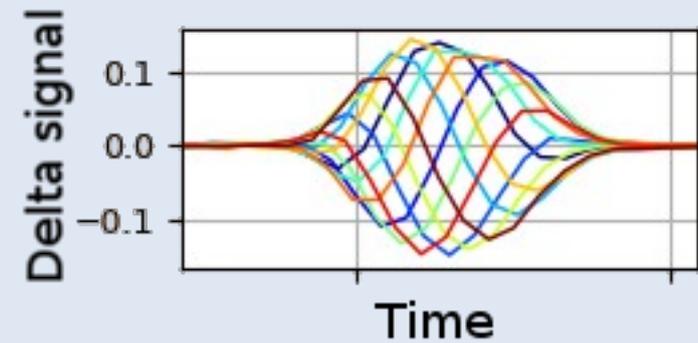
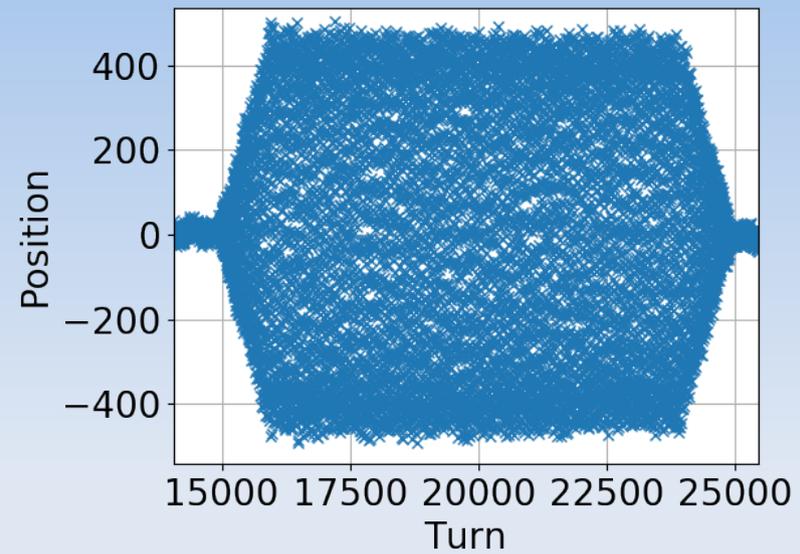
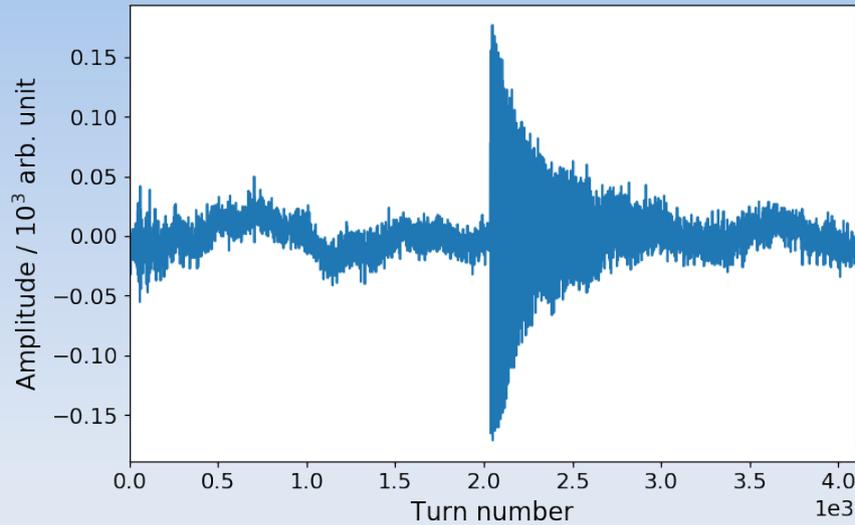
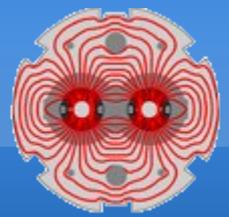
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## Run II



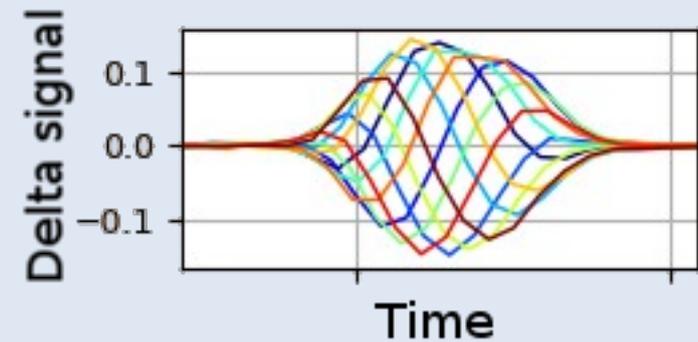
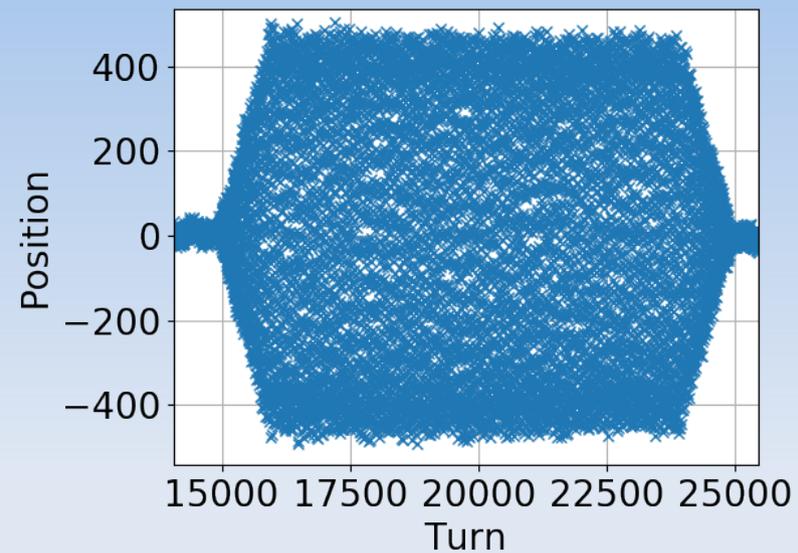
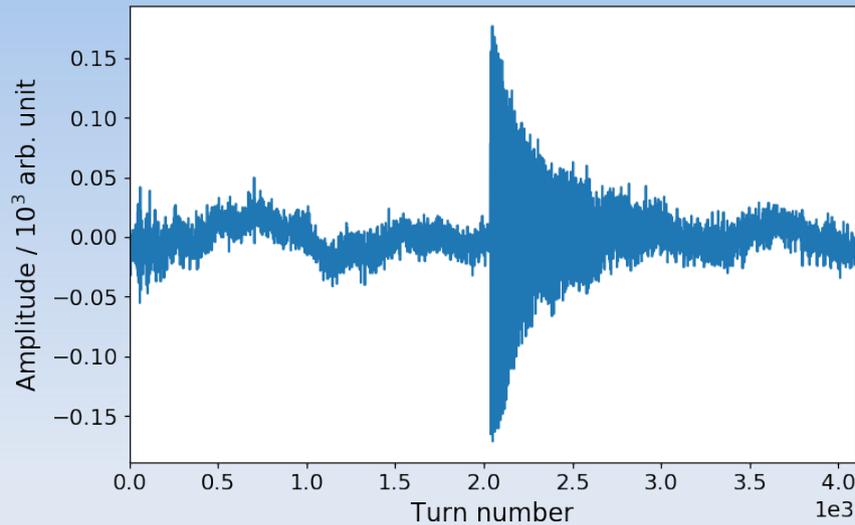
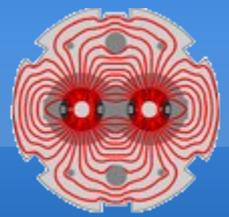


# Bunch-by-bunch EVERYTHING





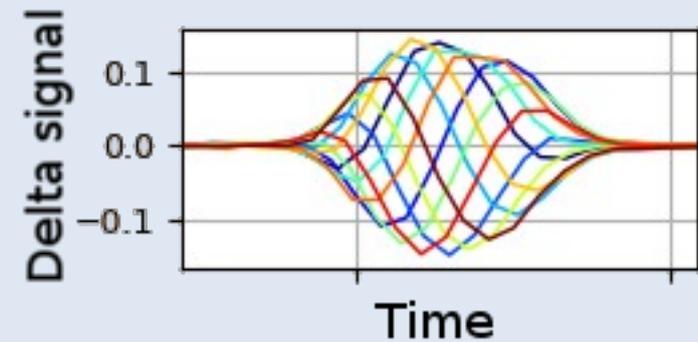
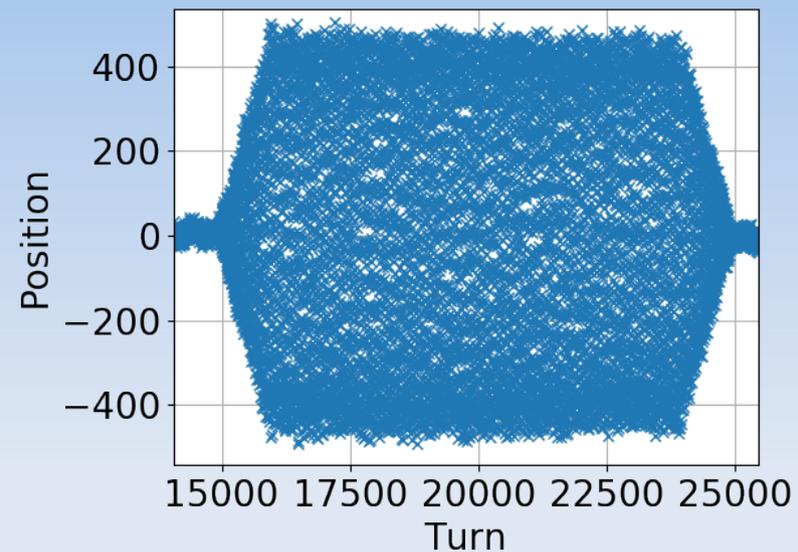
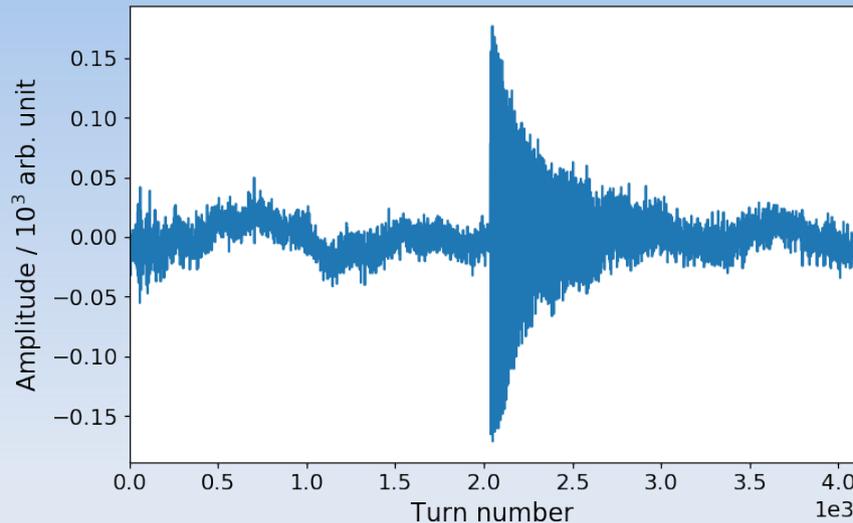
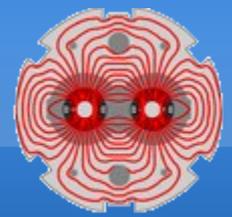
# Bunch-by-bunch EVERYTHING



- An application capable of
    - Controlling the gain on a single bunch (ADT mask)
    - Enable single bunch kick
    - Enable single bunch ADT-AC dipole
    - Trigger and read turn-by-turn BPM, Head-tail monitor and ADT ObsBox acquisitions
- could enable accurate  $Q$ ,  $Q'$ ,  $|C|$  measurement (including PACMAN effects)



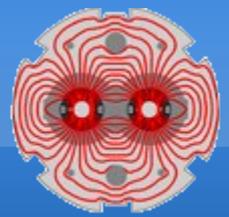
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    - Trigger and read turn-by-turn BPM, Head-tail monitor and ADT ObsBox acquisitions
- could enable accurate  $Q$ ,  $Q'$ ,  $|C|$  measurement (including PACMAN effects)
- Improved operation (i.e. relax need for special run when an instability occurs due to drifts)
  - High potential for parasitic tests and MDs



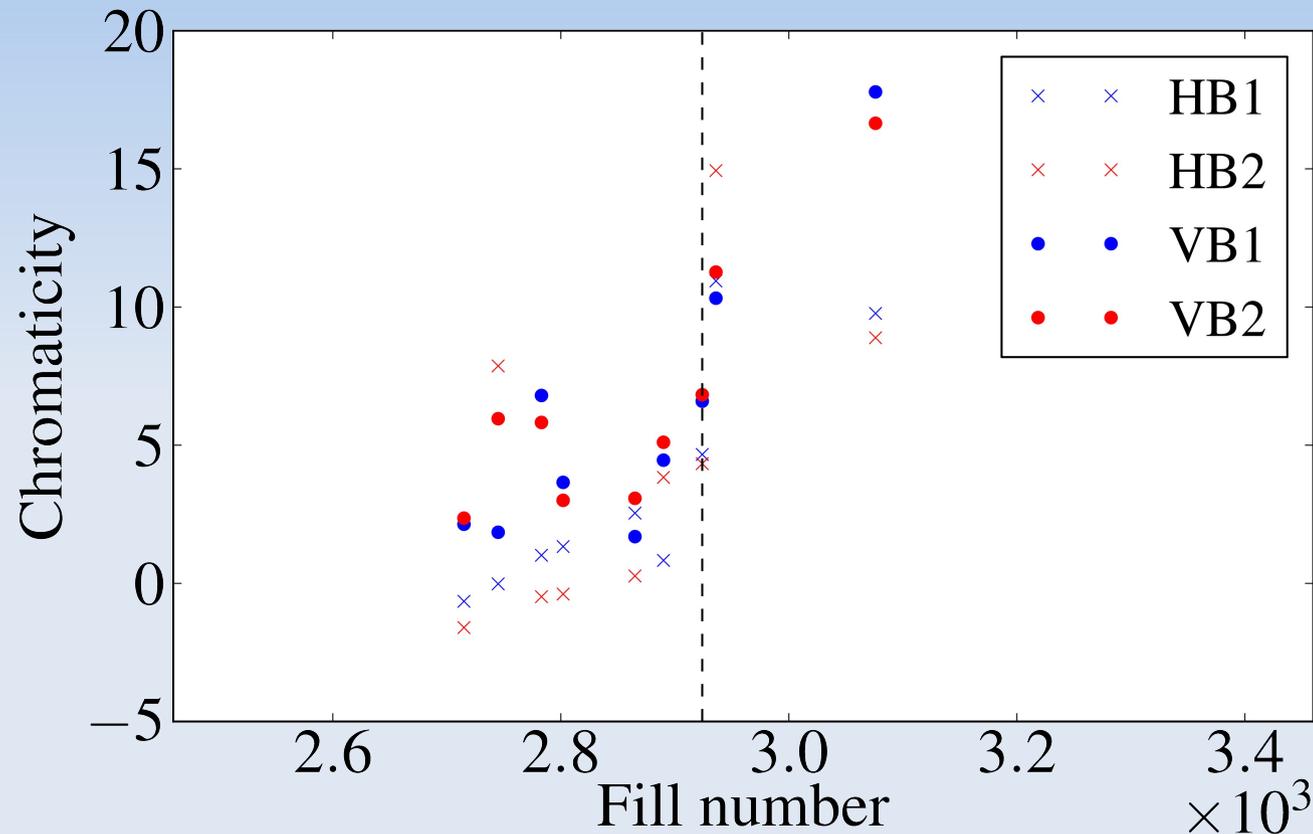
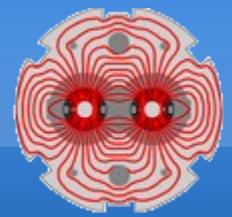
# Summary



- The development of **instability models, diagnostics and control tools** (coupling, non-linear optics) were needed to ensure the beam stability with margins compatible with run III beams
  - Large improvement w.r.t. run I, **many thanks** to OP, BI, RF and OMC !
  - Any ease in the **control of Q, Q' and |C|** (including drifts) will be beneficial for the robustness of operation
  - Both octupole polarities are possible for run III given a (anti-)telescopic squeeze during the ramp, allowing for performance (DA) optimisation
- We have to keep in mind LHC's yearly *menu surprise* of instabilities
  - The need for instability diagnostics remains for future runs
- Several features are not understood but are under study
  - The effect of **external noise** was demonstrated in MDs, but should be better quantified in realistic configurations (e.g. noise spectrum)
  - Search for **dark impedances** will take place thanks to the data acquired in MDs (thresholds, rise times, tune shifts, head-tail signals)



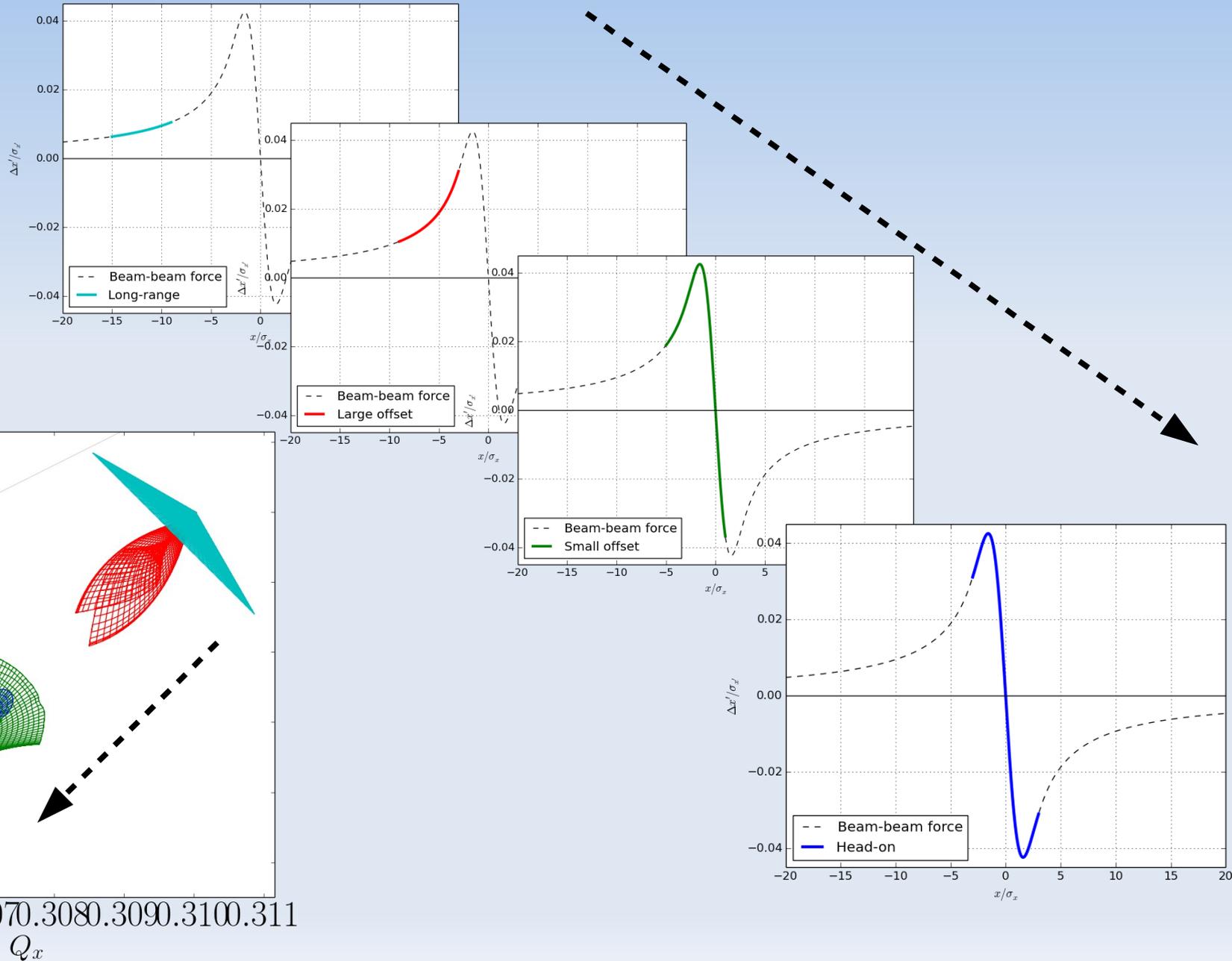
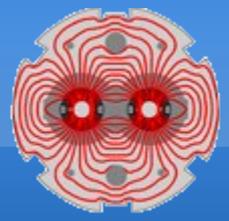
# Chromaticity in run I



- Before the configuration change, the chromaticity varied in the range where the octupole current is systematically measured higher than expected, i.e. close to 0

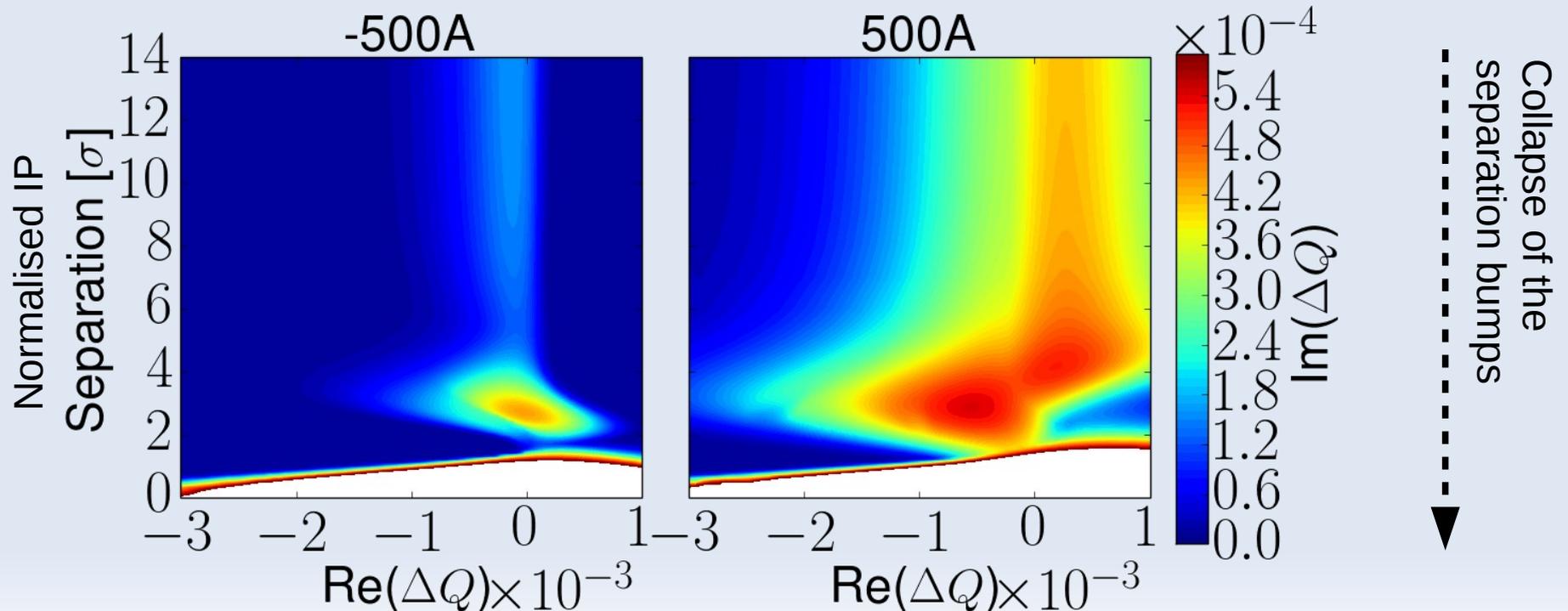
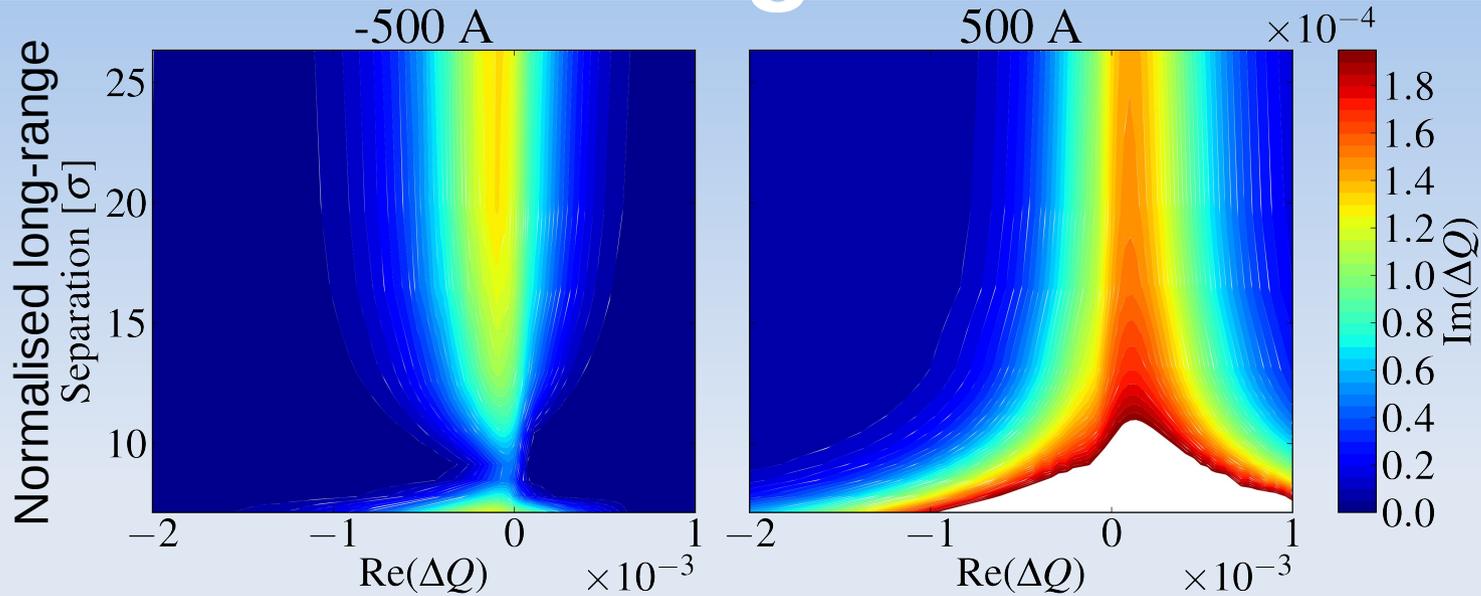
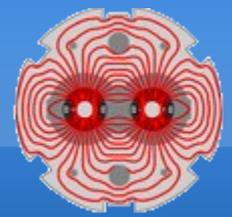


# Tune footprints of colliding beams



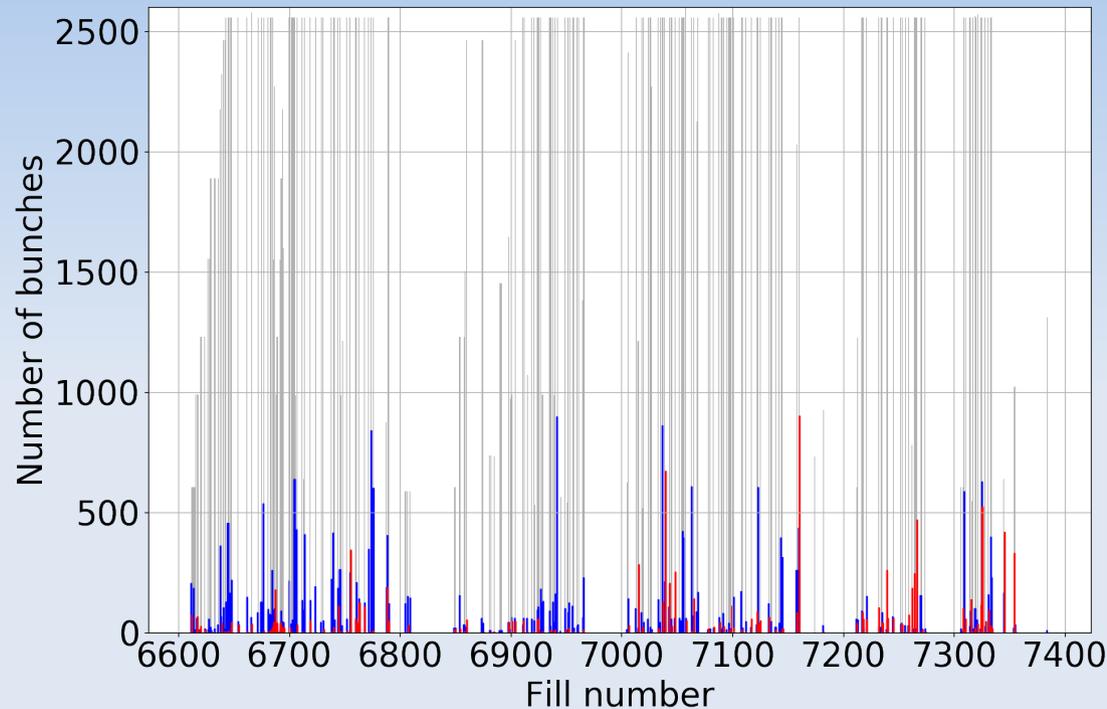
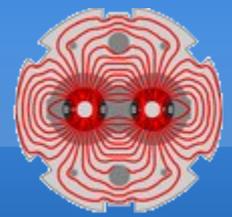


# Stability diagrams of colliding beams





# Injection instability



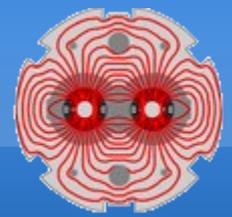
Total number of bunches  
Unstable bunches in B1  
Unstable bunches in B2

- No statistically significant difference can be observed through the year
  - A slight degradation is observed for B2 since fill 7031, during which the injection energy match was corrected (mainly in B2), indicating a possible dependence on the longitudinal emittance

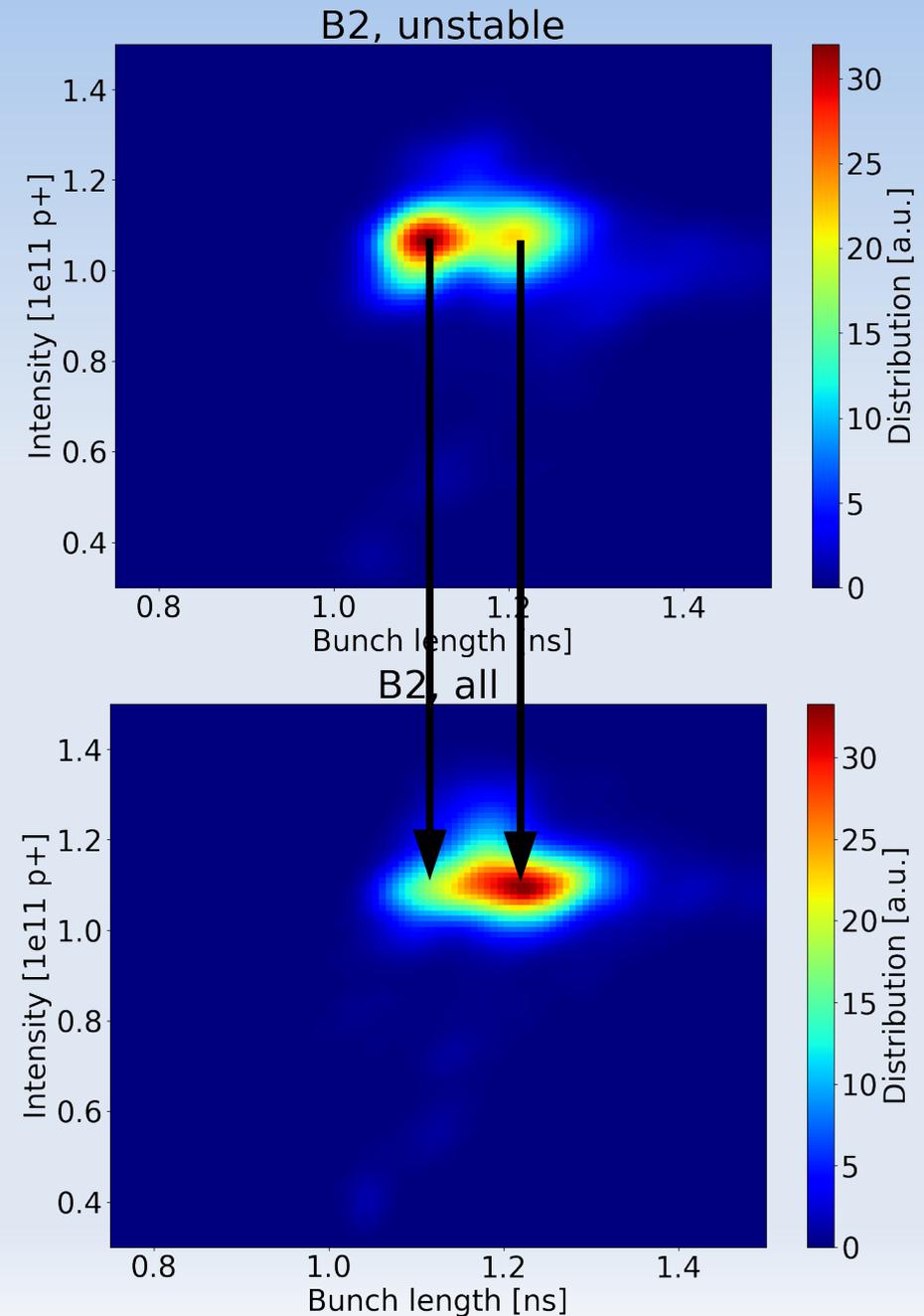


# Injection instability

## bunch length

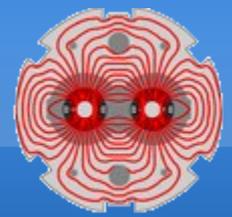


- In proportion shorter bunches seem more affected by the weak e-cloud instability
  - This effect is not visible in B1
  - Electron cloud build up depends on the bunch length of leading bunches, which is not taken into account here

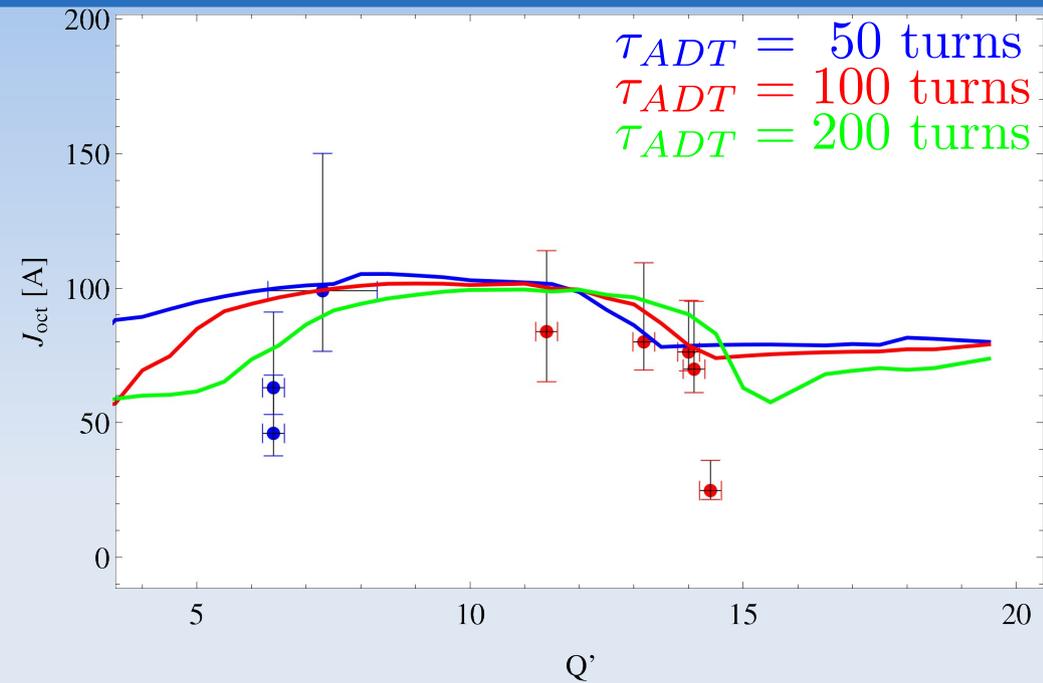


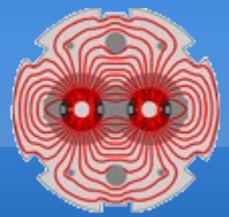


# 2015 - 2016

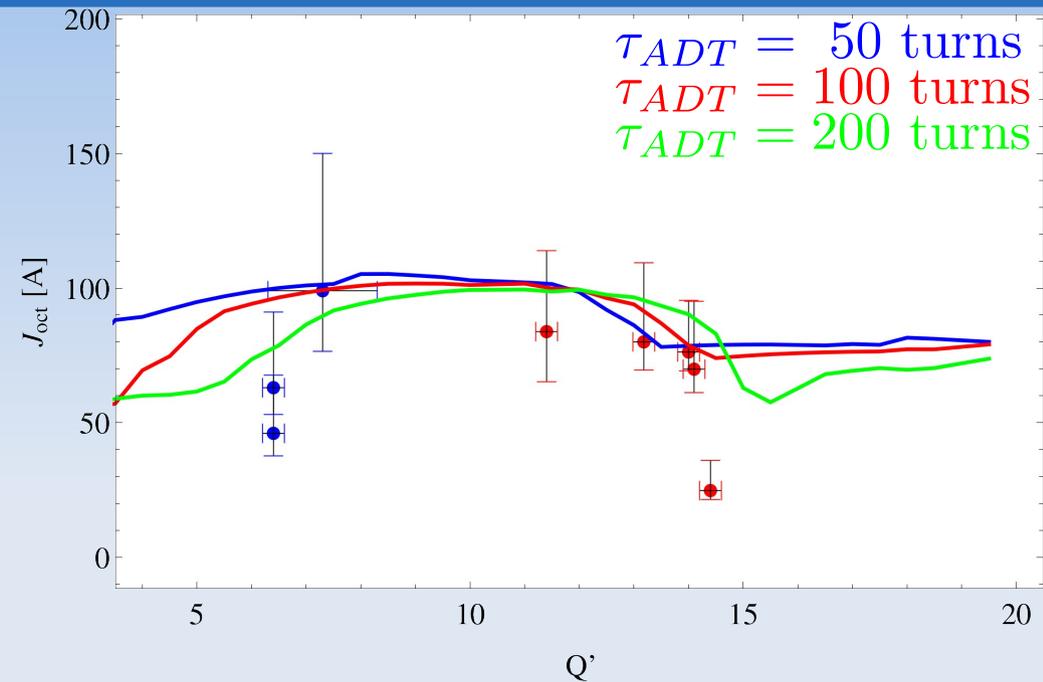


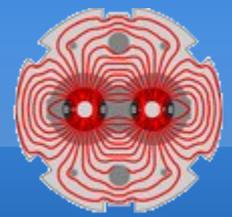
- Dedicated experiments (fast octupole current scan) show a good agreement with model in the 'operational configuration'



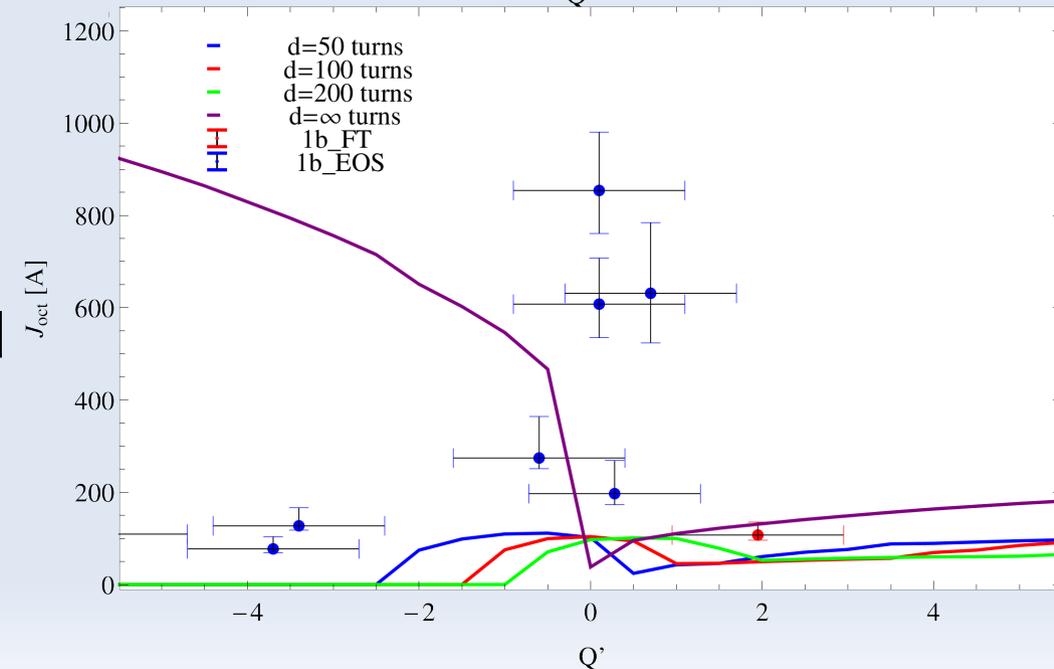
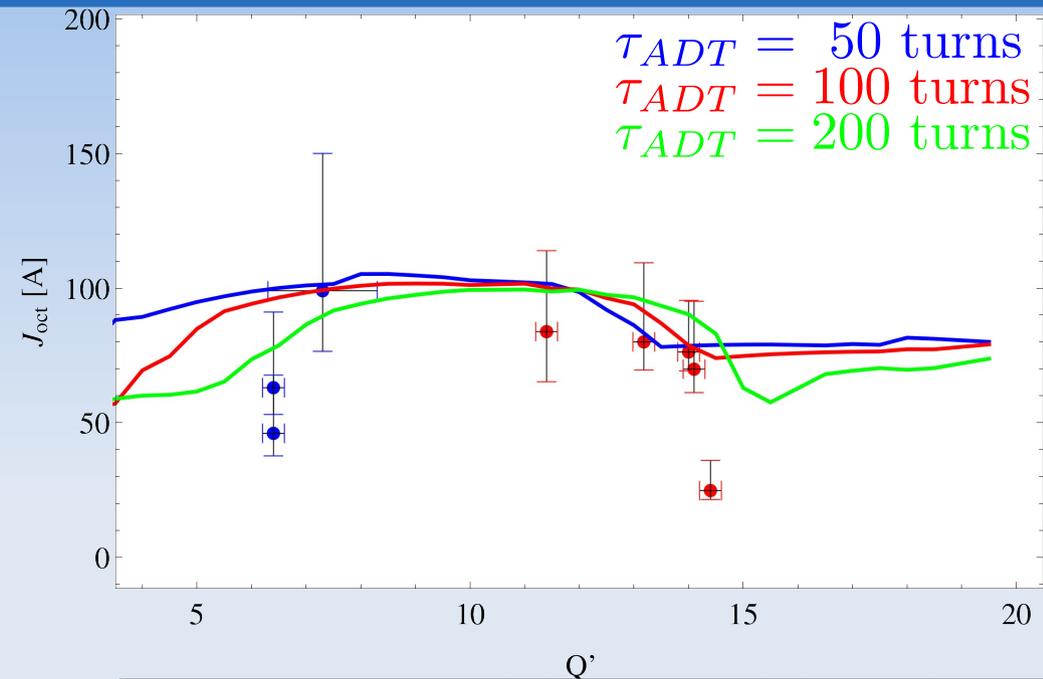


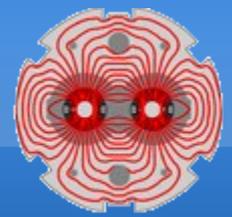
- Dedicated experiments (fast octupole current scan) show a good agreement with model in the 'operational configuration'
  - Yet, in physics fills, much larger currents were needed
    - (Non-)linear optics during ADJUST
    - External noise



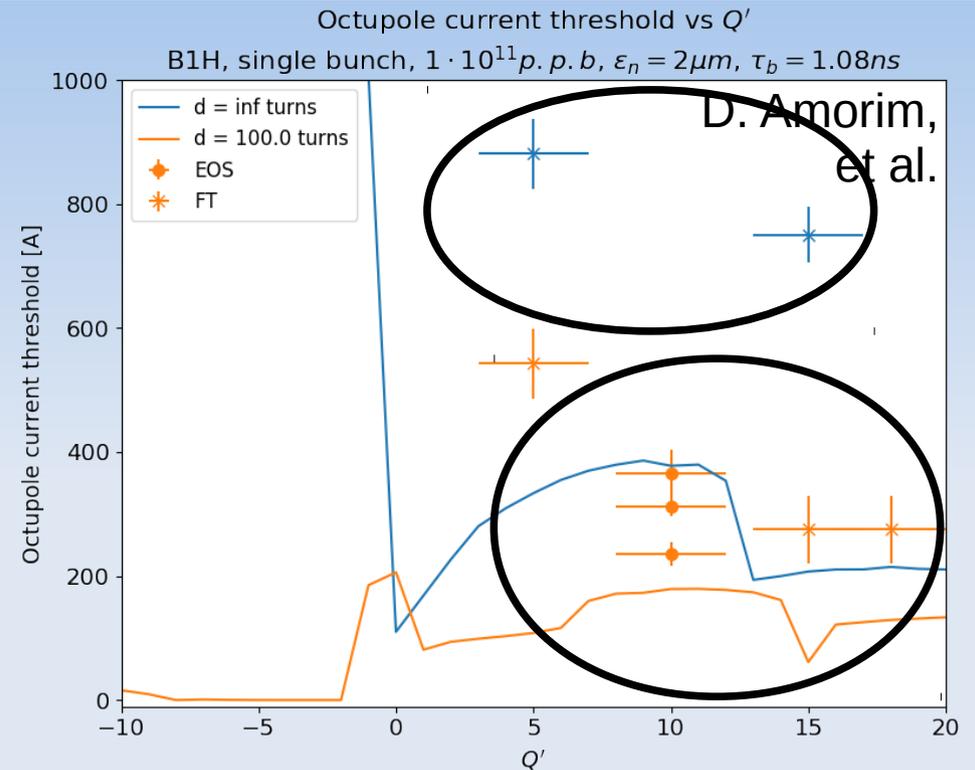


- Dedicated experiments (fast octupole current scan) show a good agreement with model in the 'operational configuration'
  - Yet, in physics fills, much larger currents were needed
    - (Non-)linear optics during ADJUST
    - External noise
- At very low and negative chromaticities, the threshold is consistently higher than expected
  - Consistent with the dumps in ADJUST of run I
  - The cause is not understood

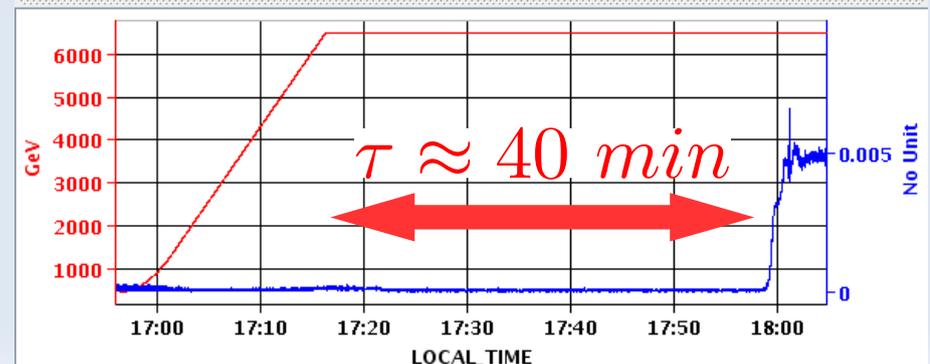
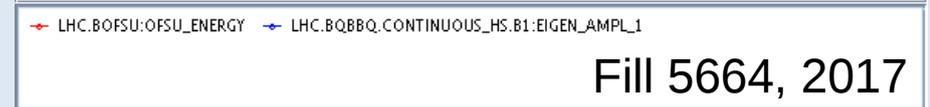




- With slow octupole current scans, allowing for **instability latency**, the factor 2 was also observed in MD
  - Agreement between MD and operation
  - Very long instability latencies were observed
- Without ADT, the beam stability is also significantly worse than expected

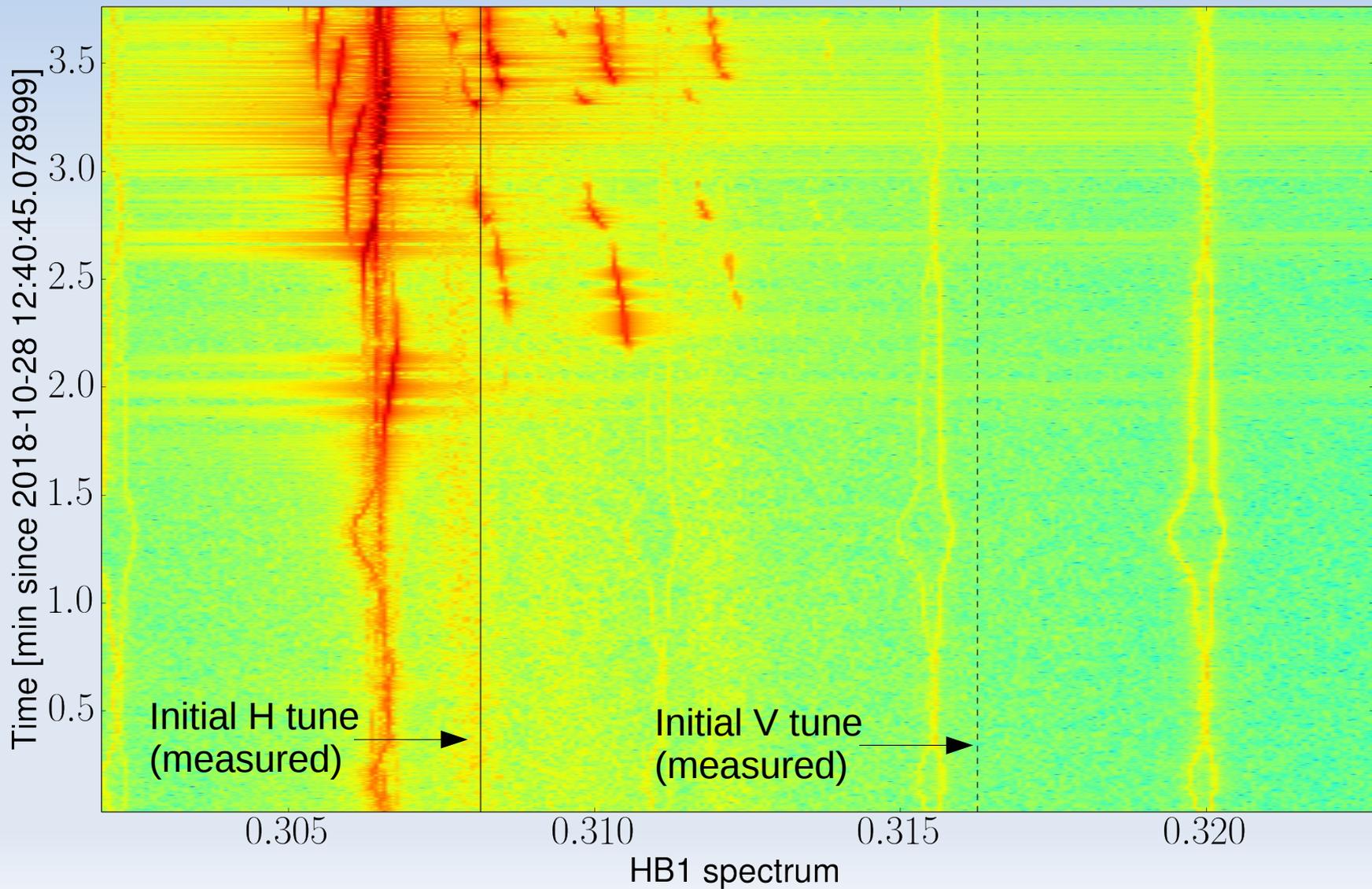
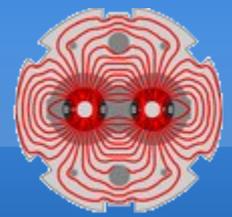


Timeseries Chart between 2017-05-16 16:55:55.149 and 2017-05-16 18:28:16.797



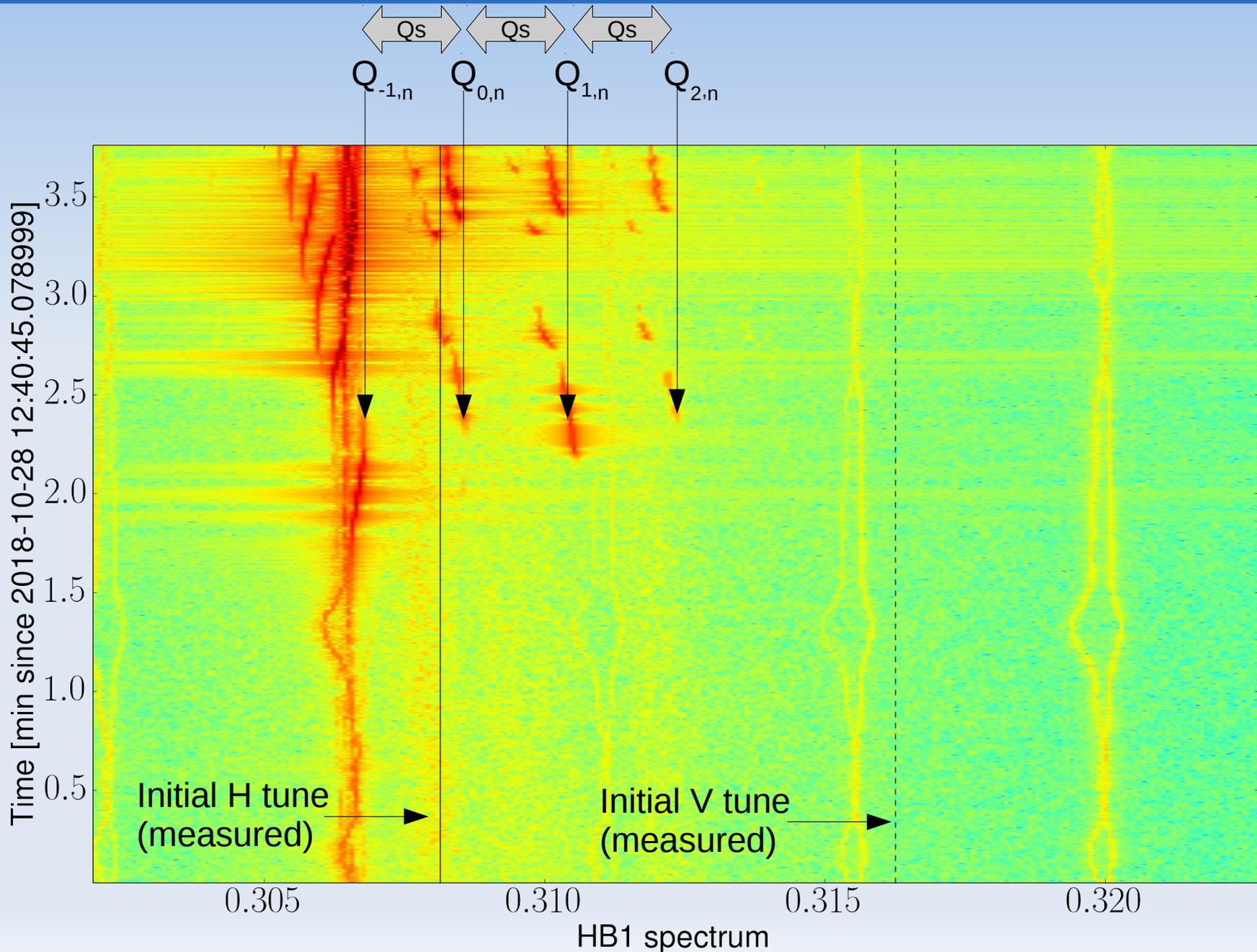
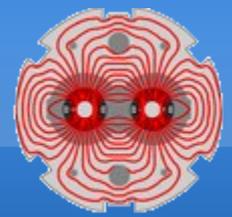


# Impact of noise line on the beam stability



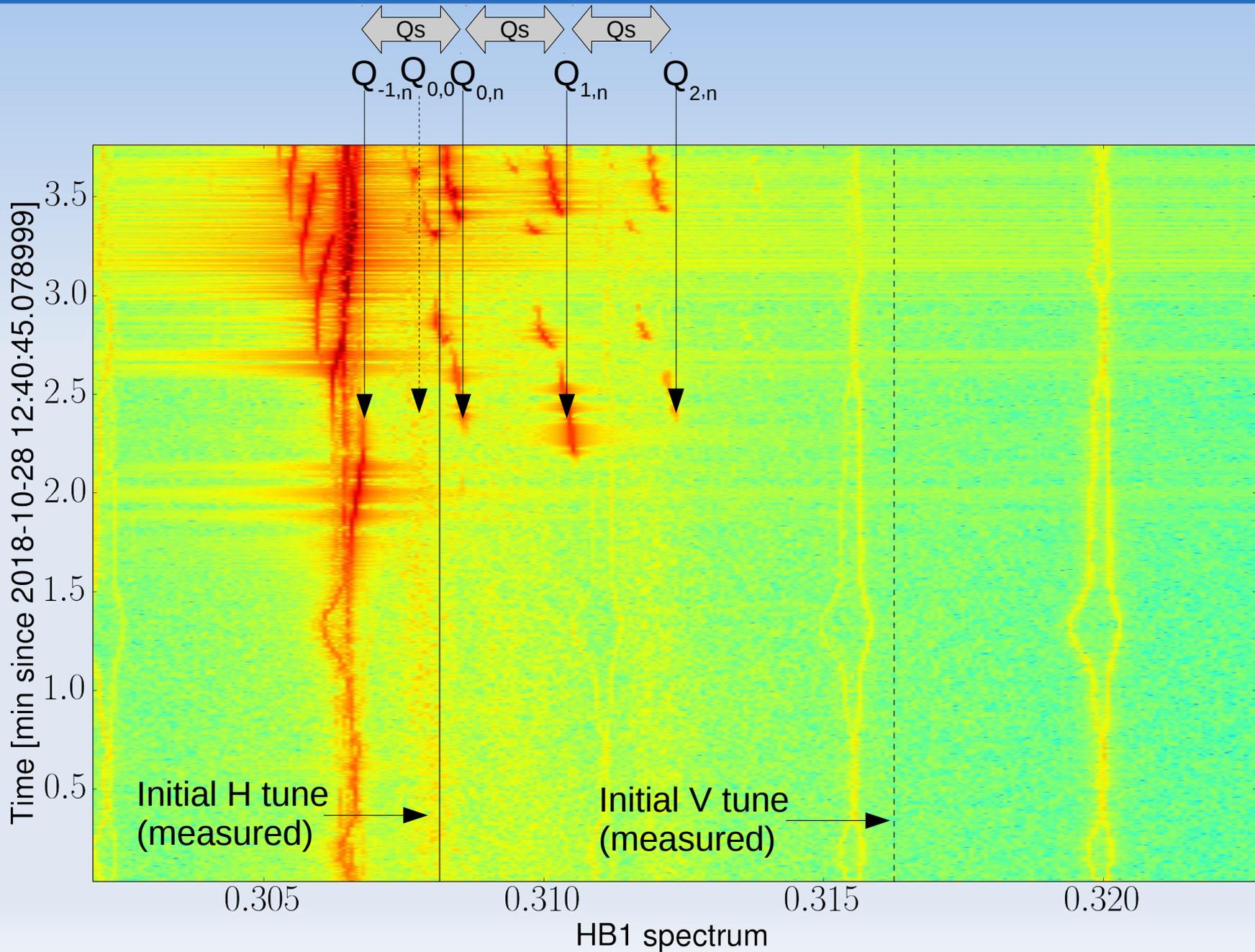
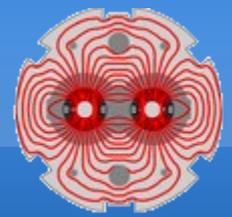


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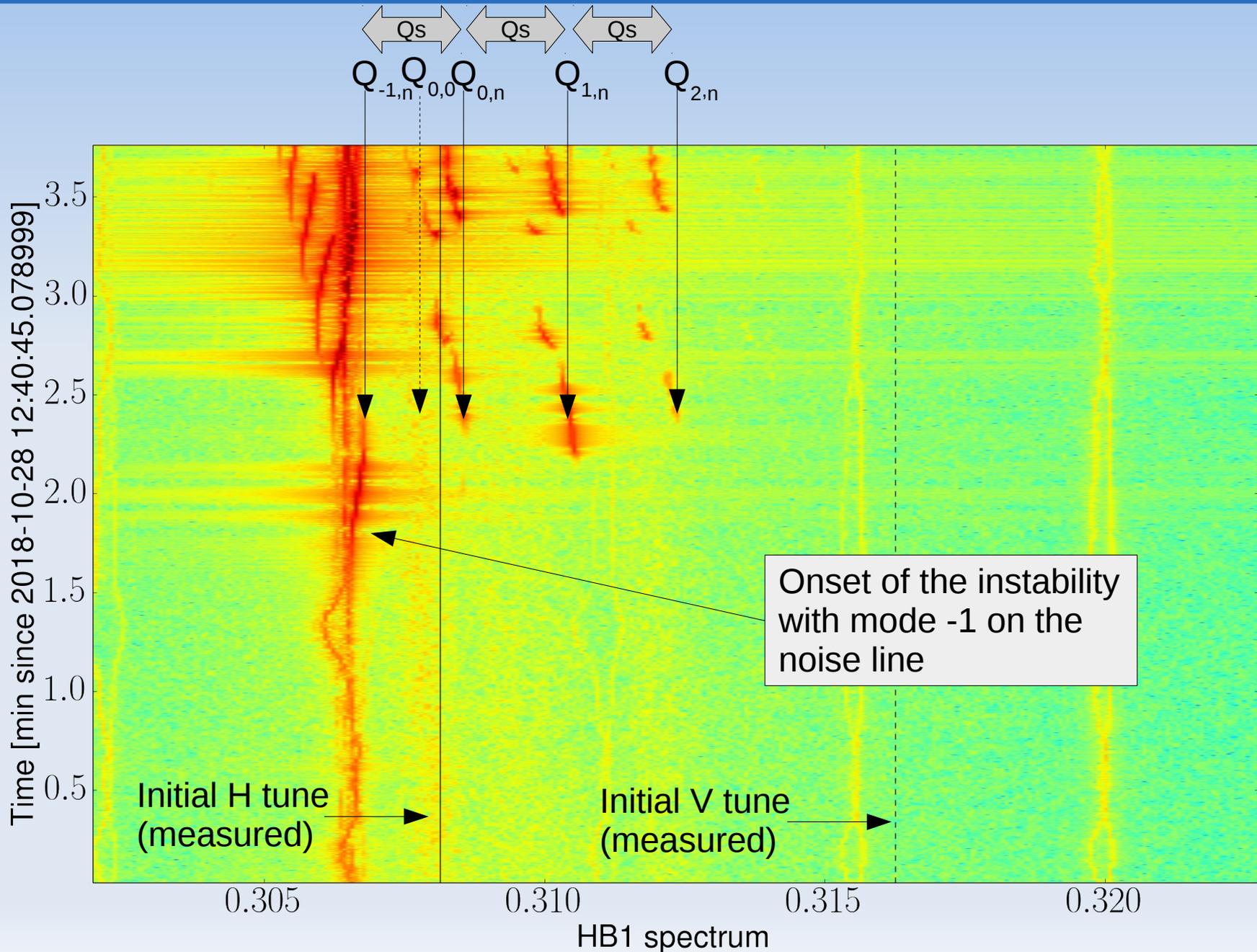
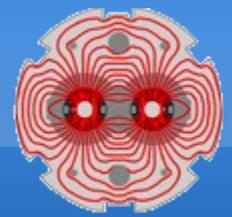


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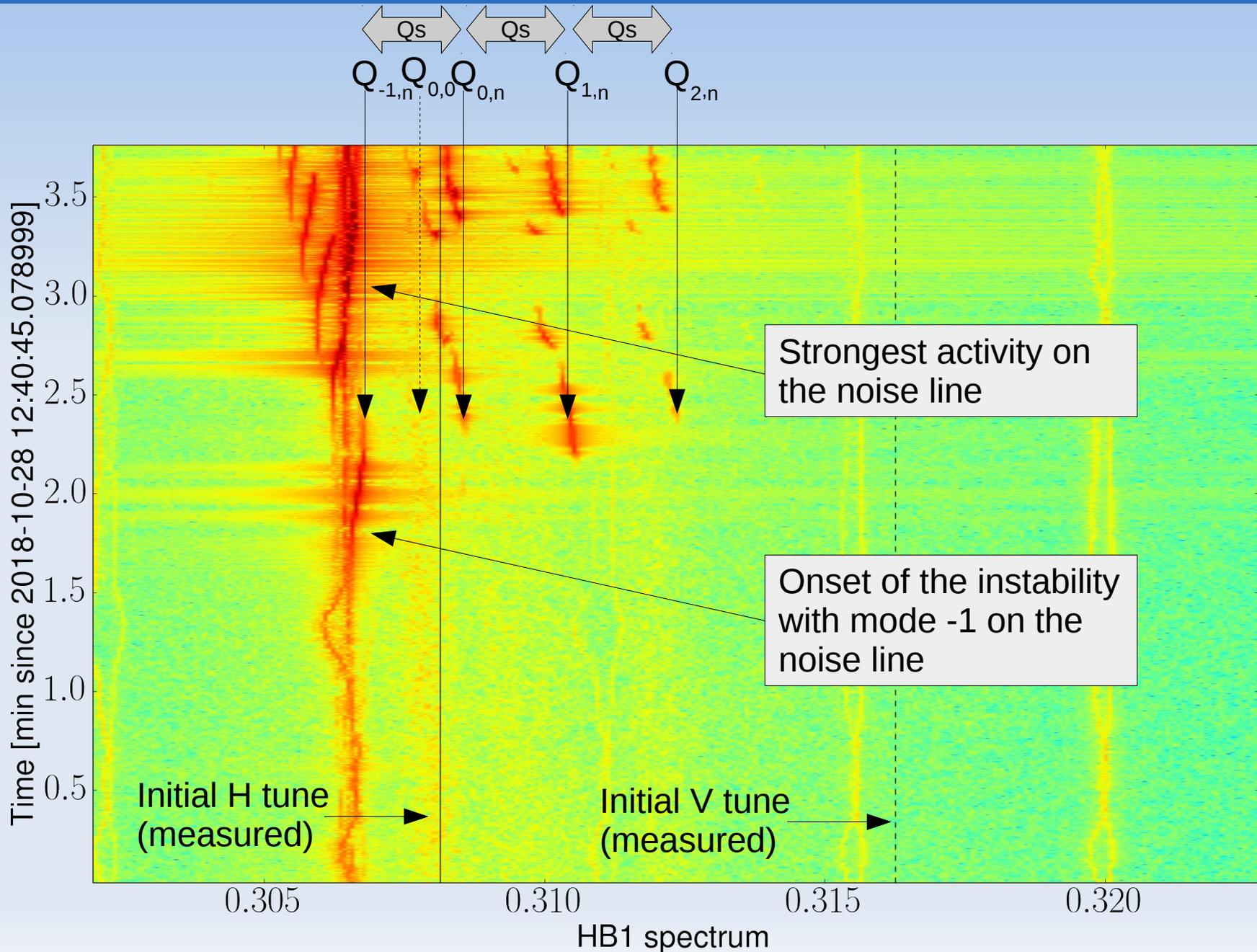
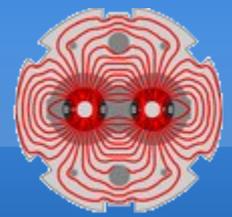


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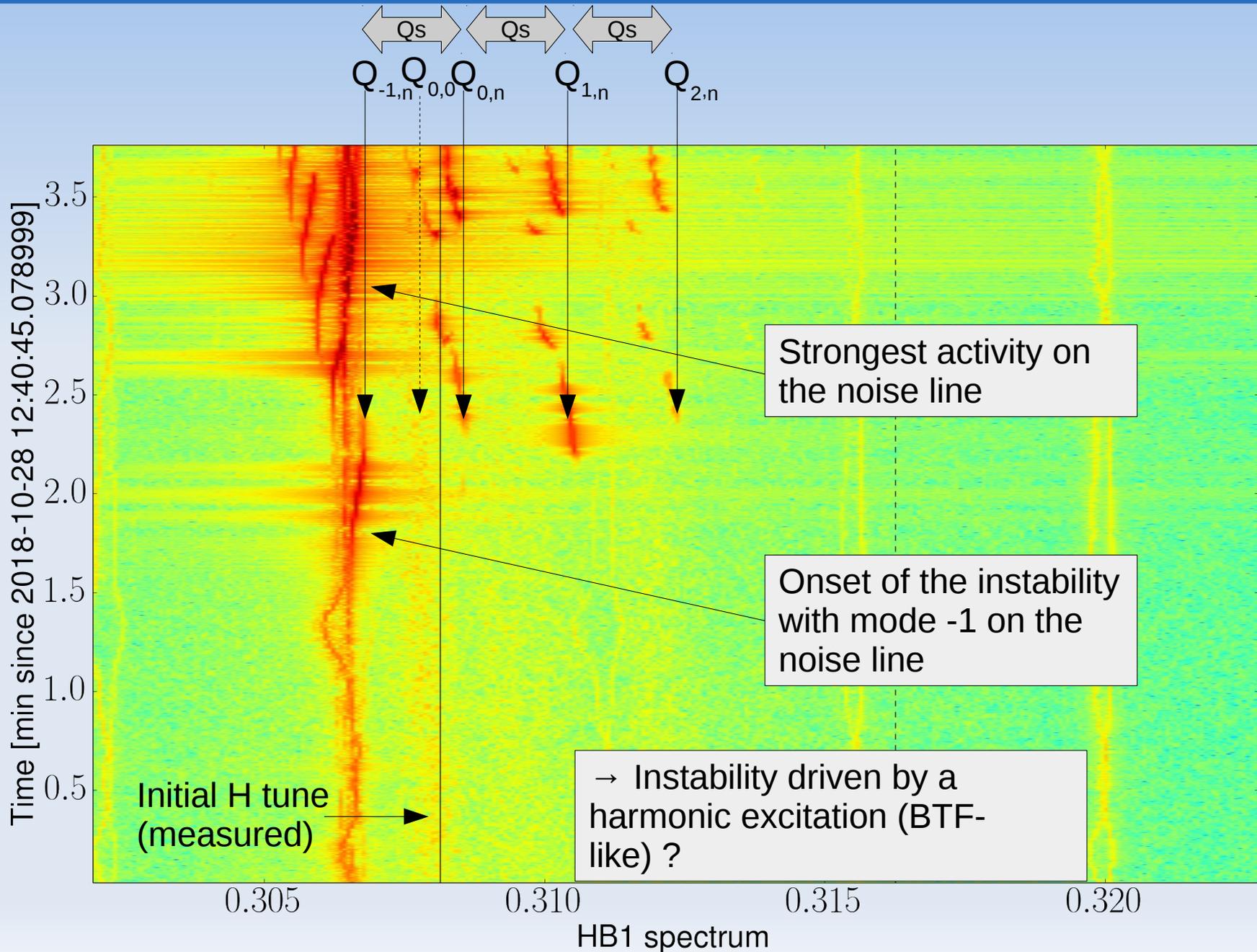
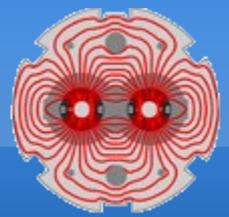


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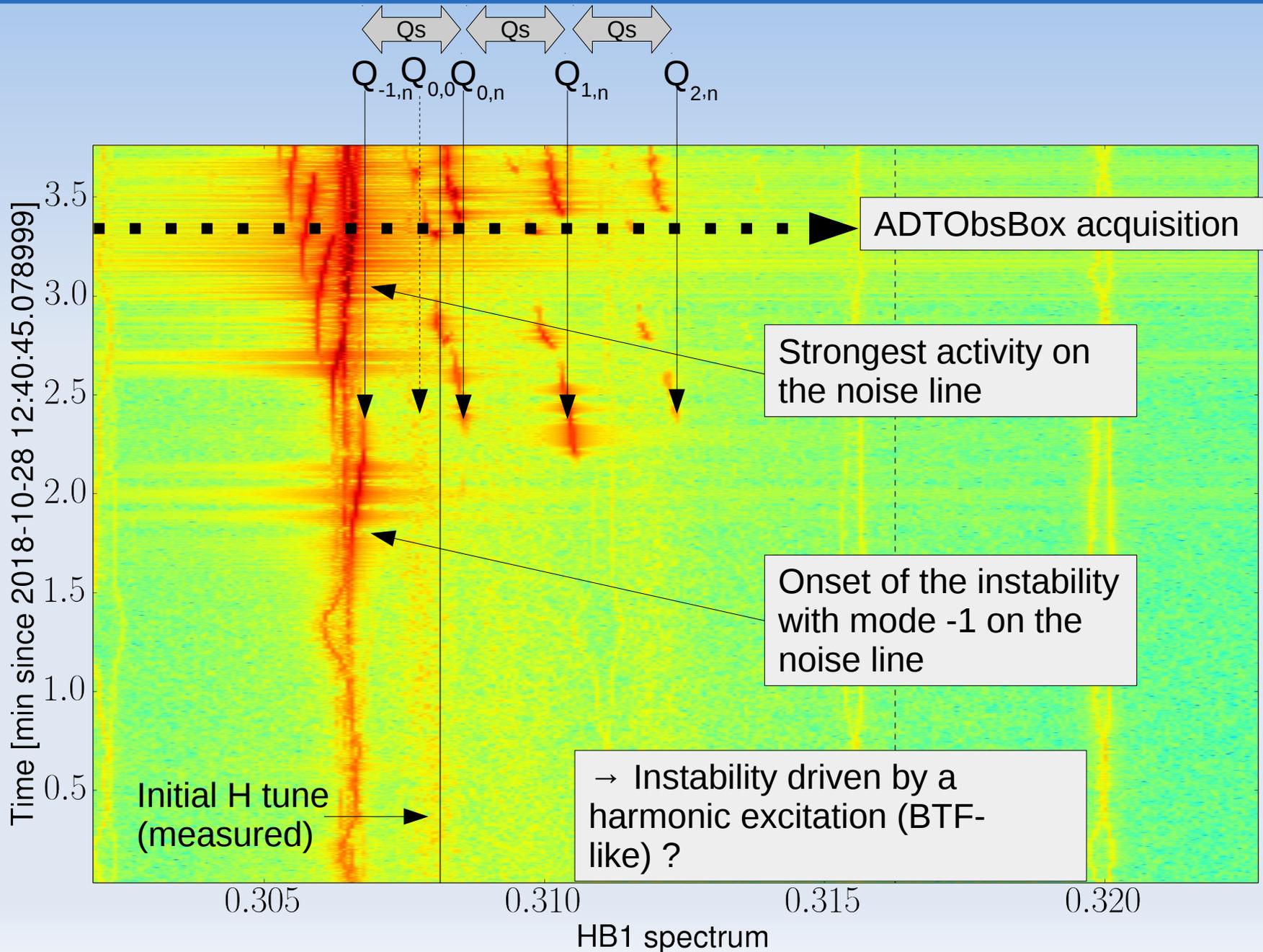
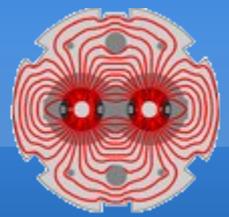


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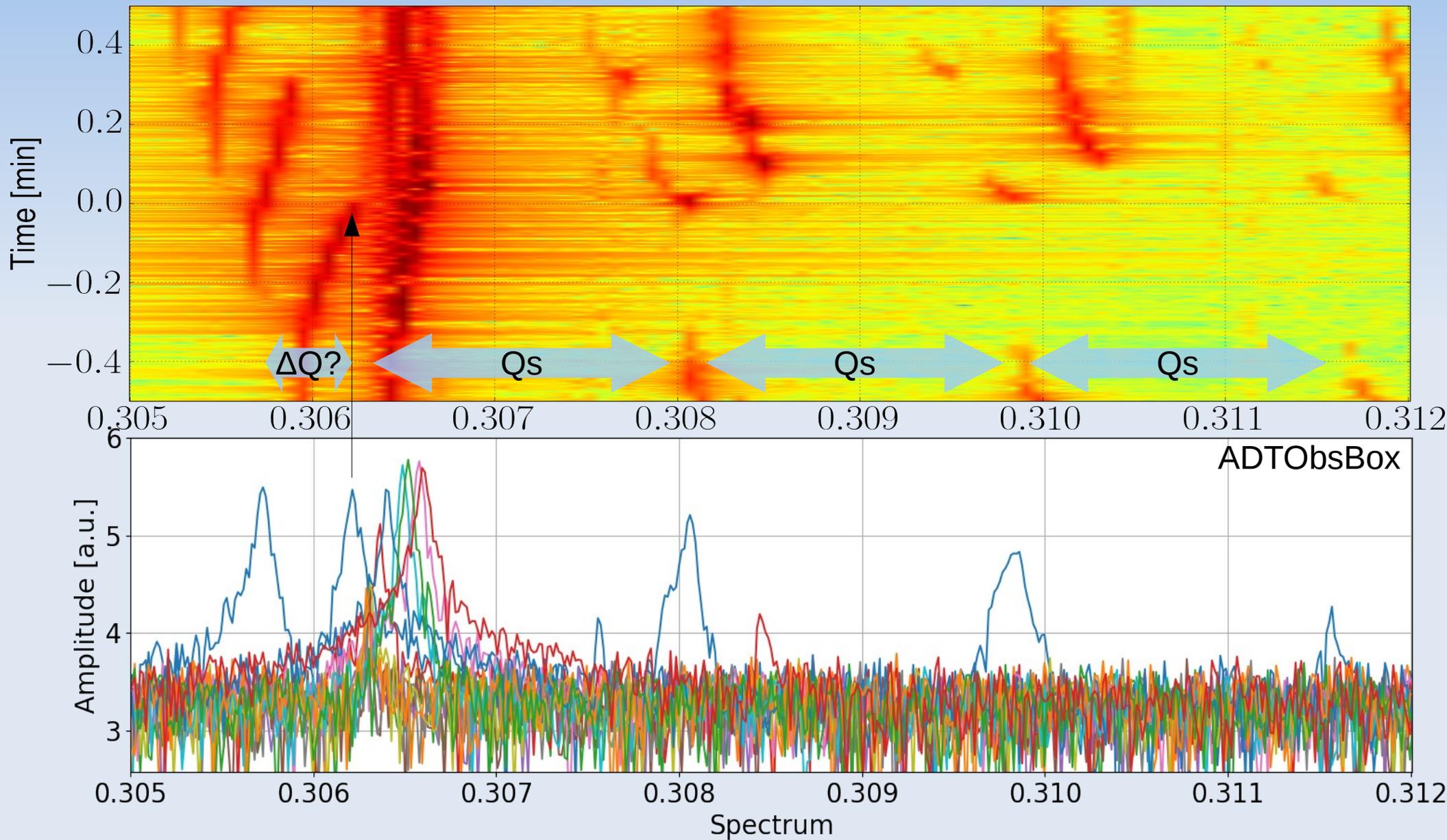
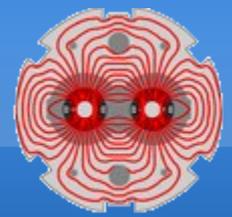


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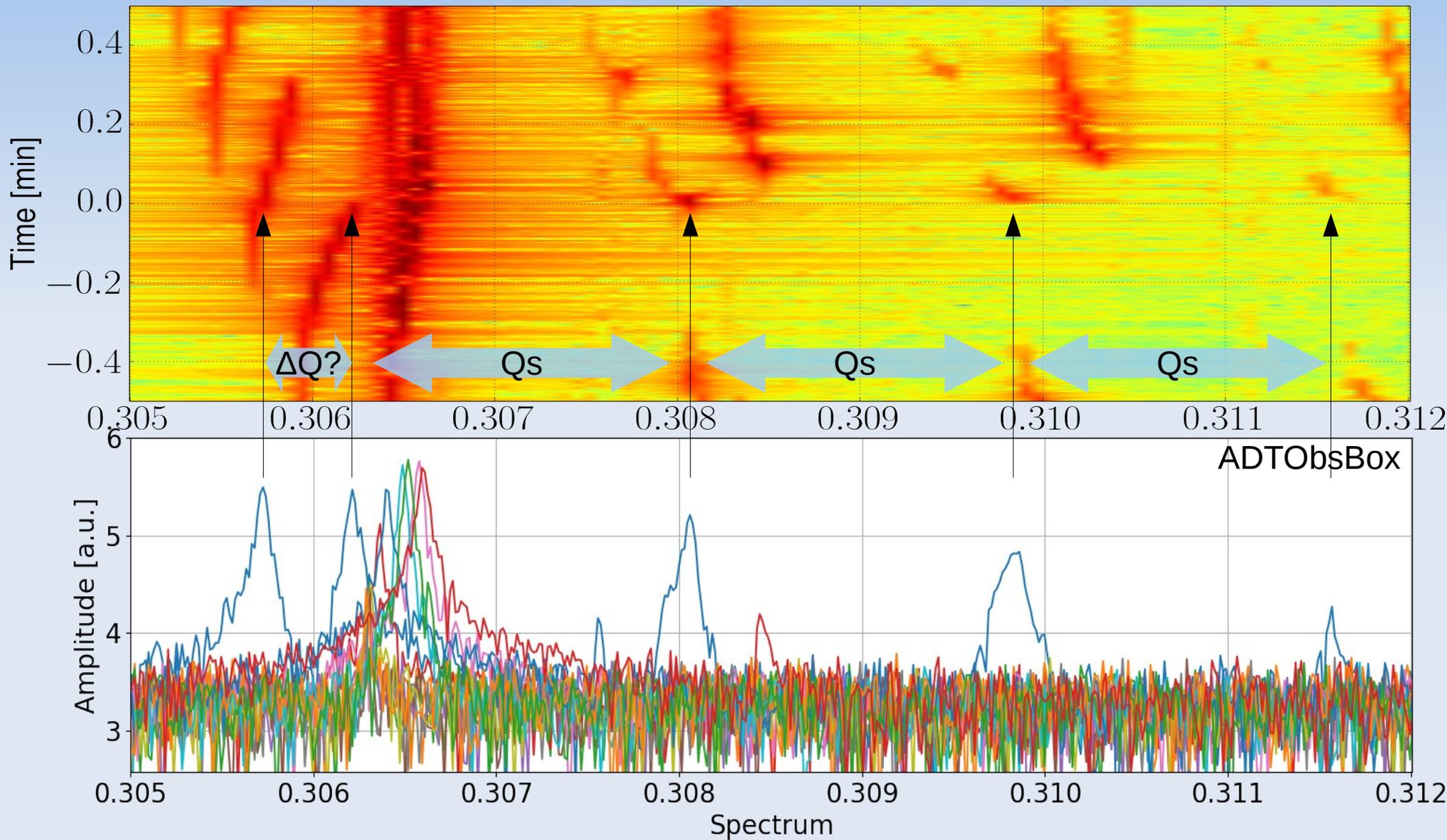


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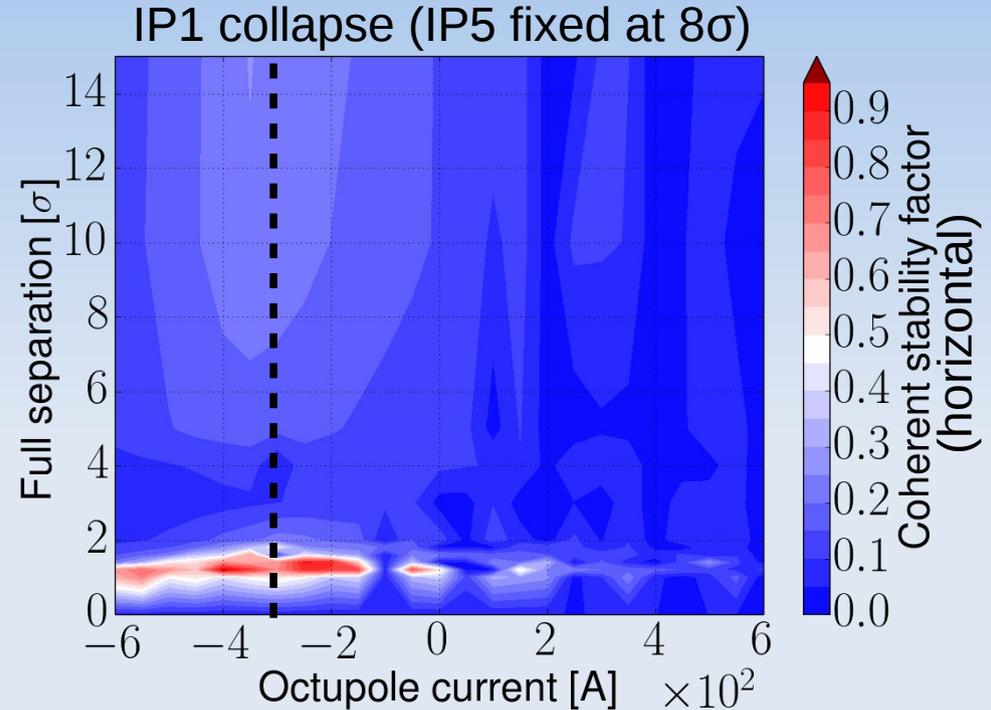
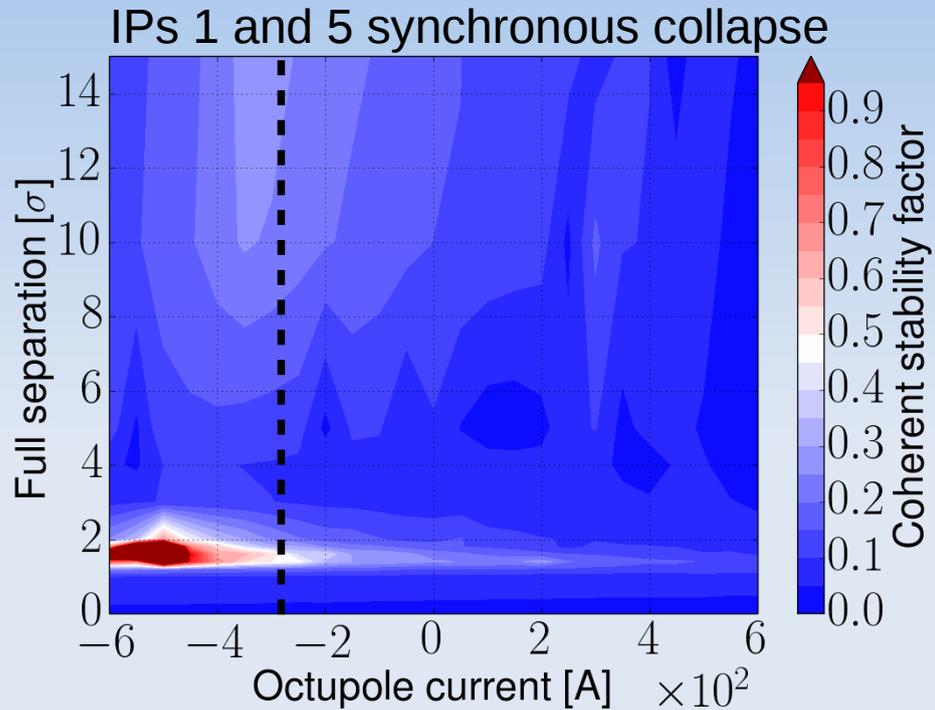
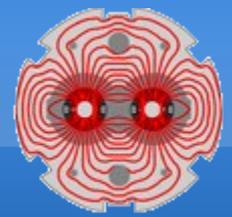


# Impact of noise line on the beam stability





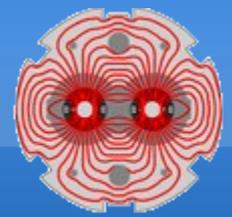
# Asynchronous collapse of the separation



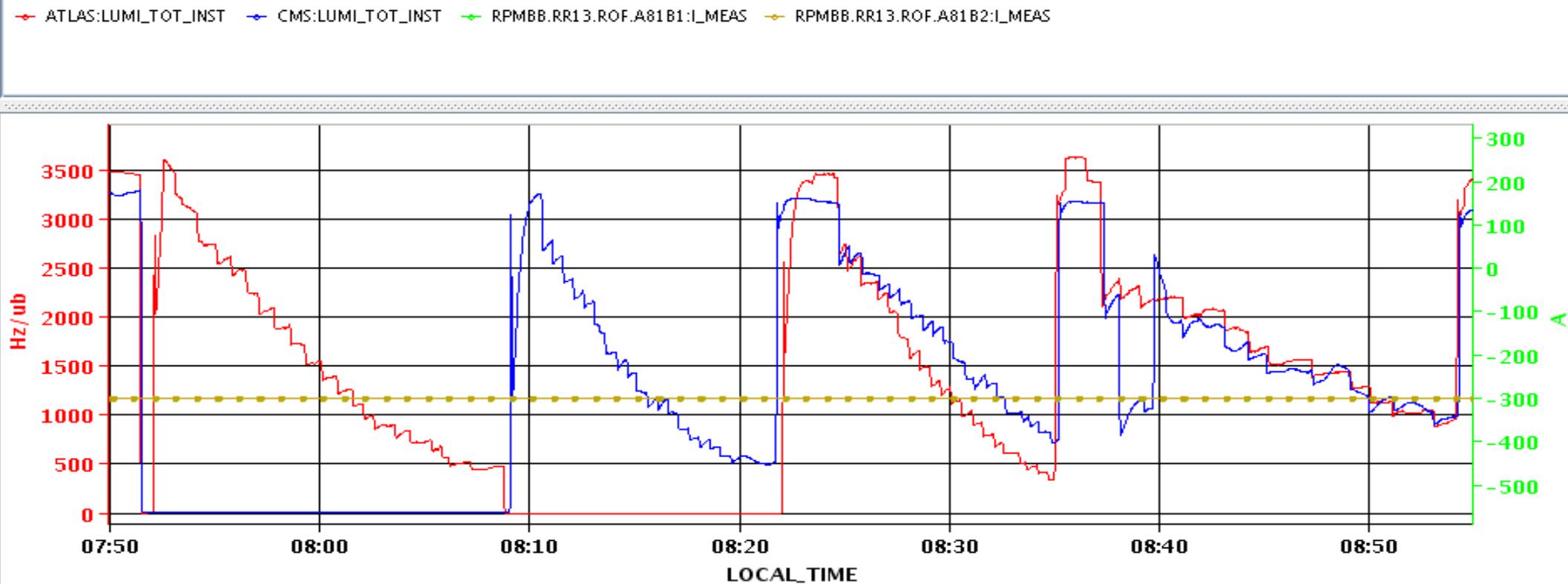
- With the negative polarity, the minimum of stability with offset beams remains below 1



# Asynchronous/symmetric collapse of the separation bumps

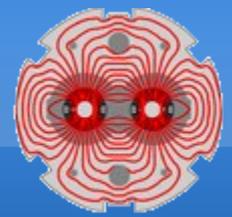


Timeseries Chart between 2018-09-15 07:13:01.208 and 2018-09-15 09:42:36.303 (LOCAL\_TIME)

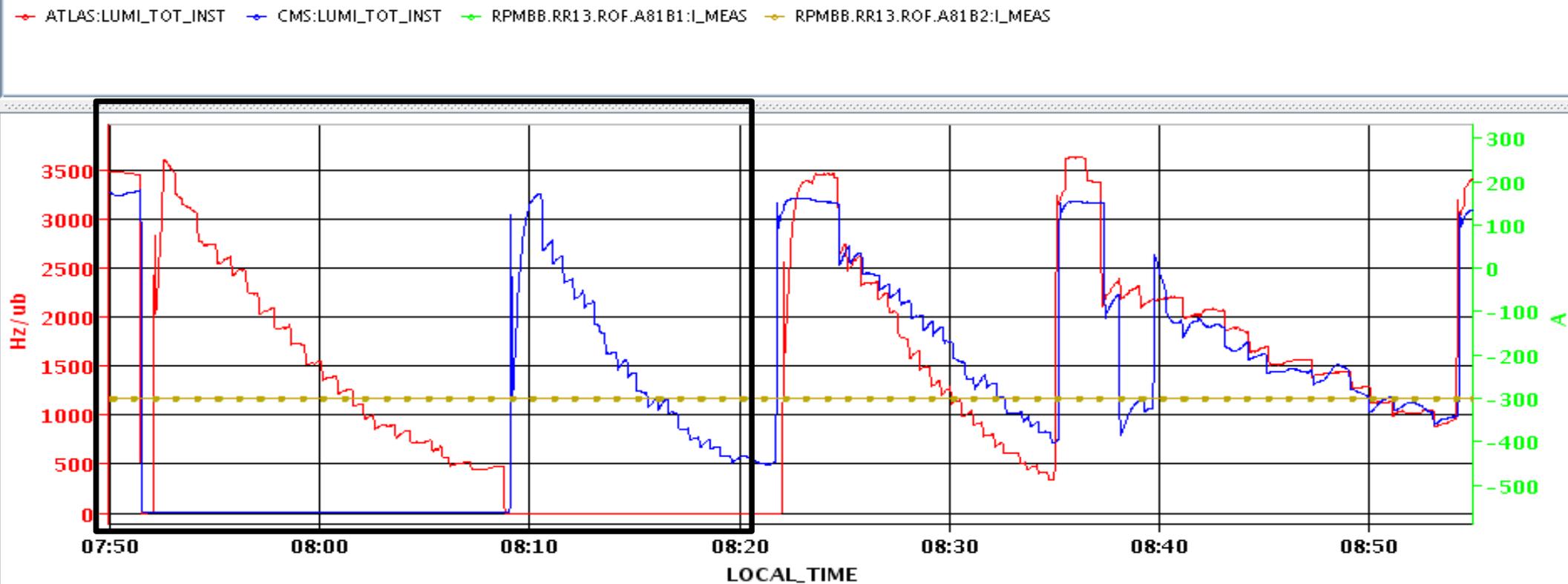




# Asynchronous/symmetric collapse of the separation bumps



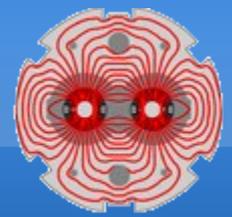
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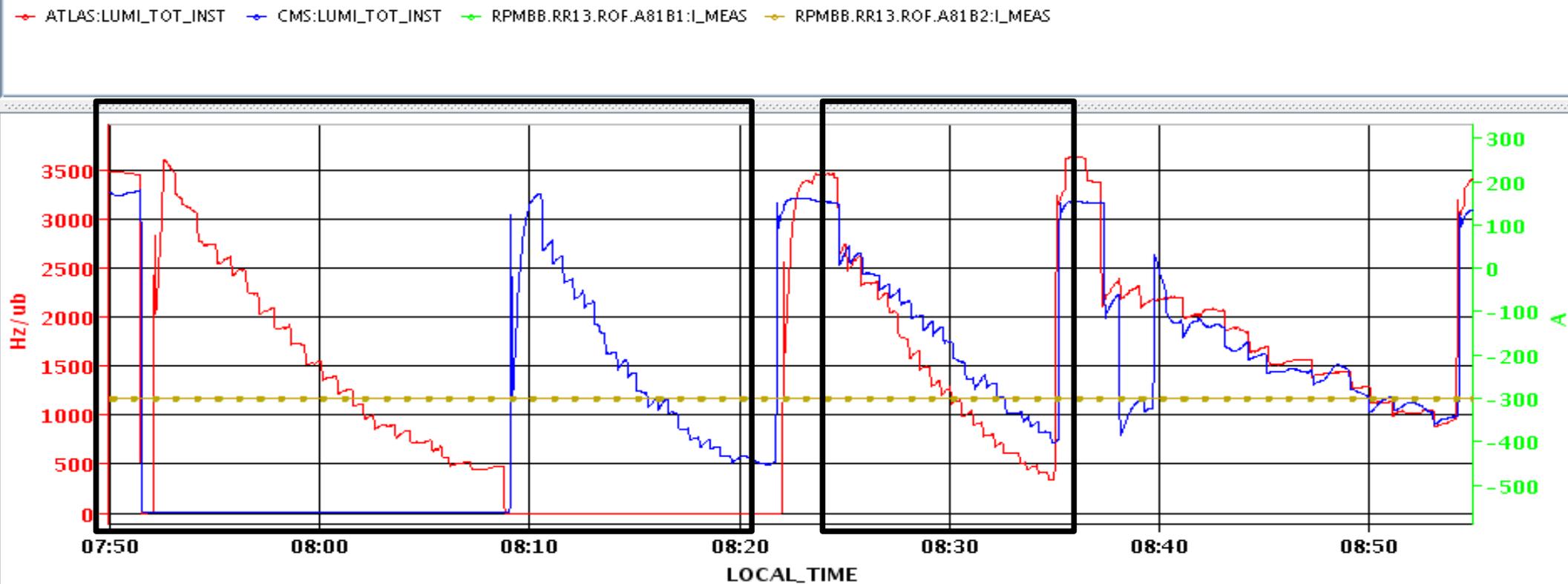
- Slow separation scans in IPs 1 and 5 asynchronously (the other IP is fixed at  $8\sigma$ )  
→ No instability



# Asynchronous/symmetric collapse of the separation bumps



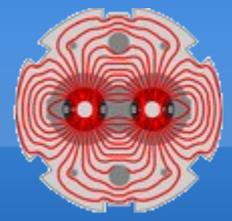
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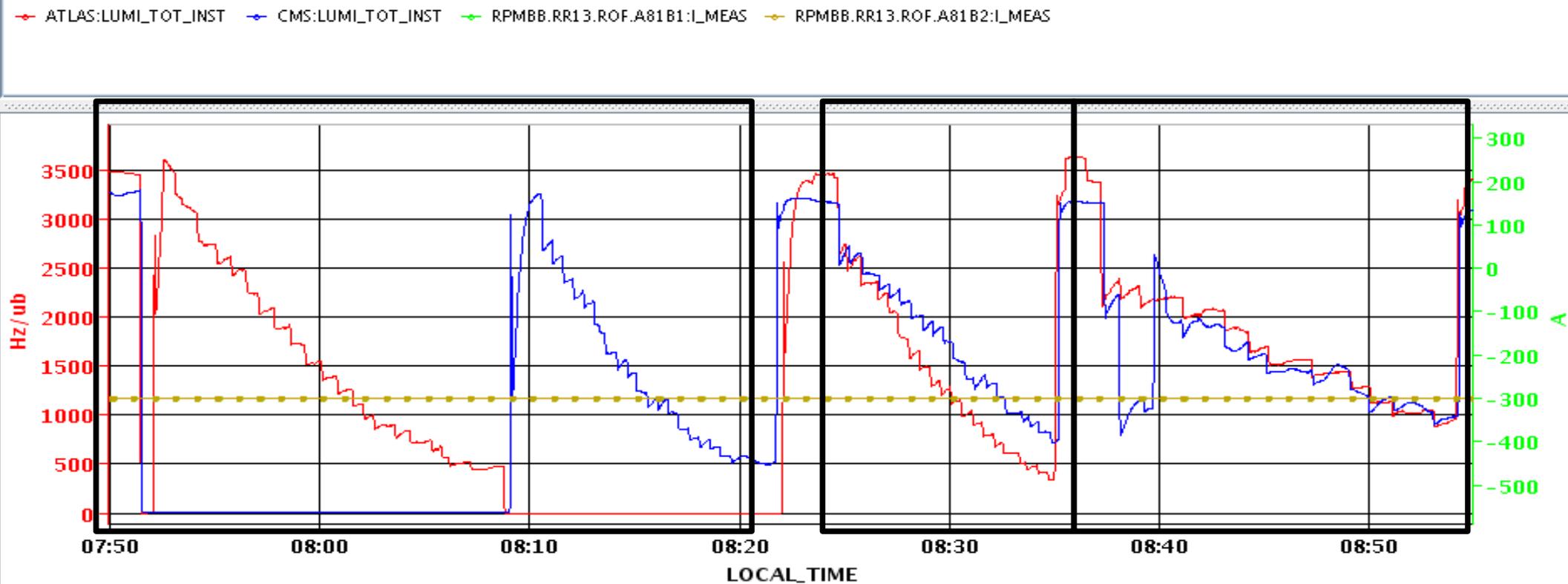
- Slow separation scans in IPs 1 and 5 asynchronously (the other IP is fixed at  $8\sigma$ )
  - No instability
- Slow separation scan with scans in the horizontal plane in both IP 1 and 5 (i.e. symmetrically)
  - No instability



# Asynchronous/symmetric collapse of the separation bumps



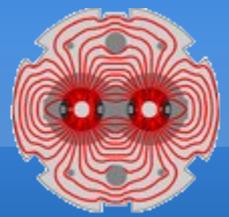
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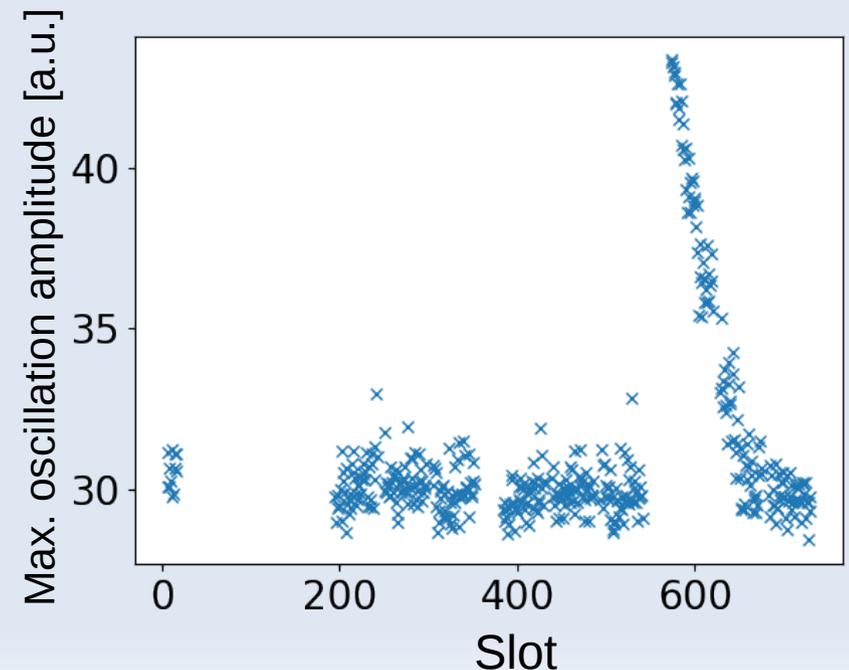
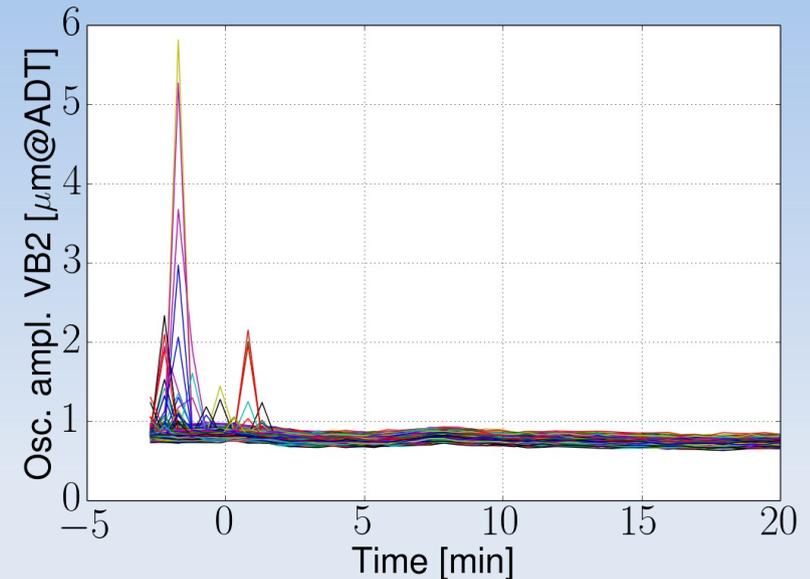
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  - No instability
- Slow separation scan with scans in the horizontal plane in both IP 1 and 5 (i.e. symmetrically)
  - No instability
- Synchronous and asymmetric (the usual way) slow separation scan
  - Instability at  $1.6\sigma$  (as in previous test)



# 'Ramp' instability

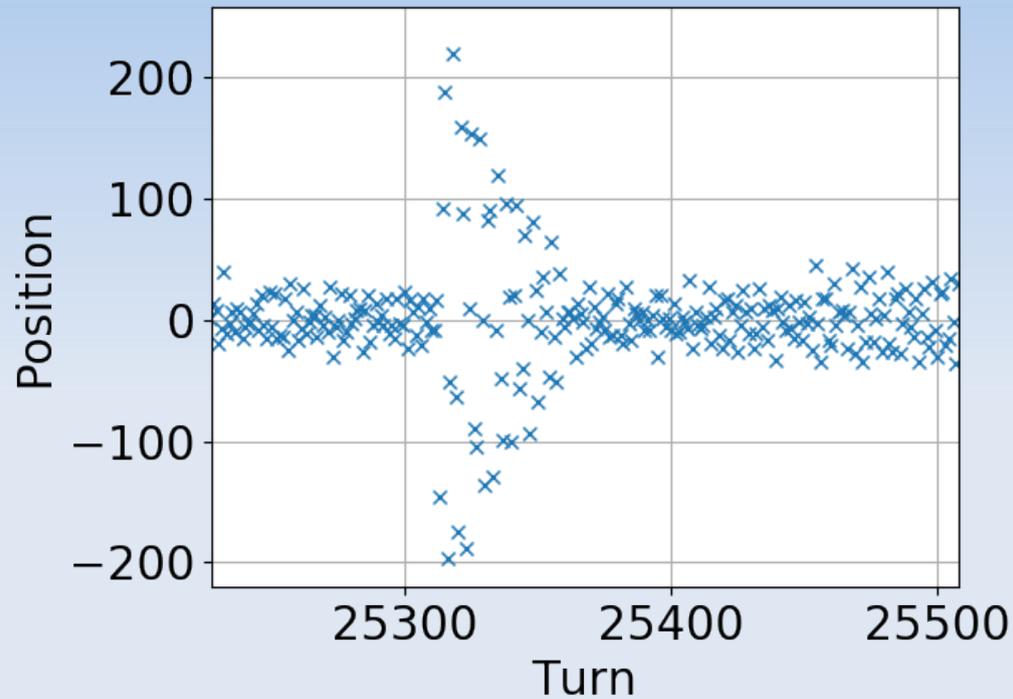
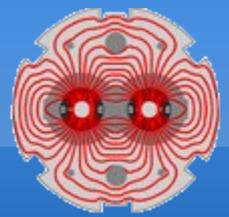


- The ADT activity monitor revealed vertical oscillations after the end of the injection up to the first minutes of the ramp (not seen in 2017 with 8b4e)
- The ADT ObsBox captured it 3 times in VB2
- Common features:
  - Appear sporadically in both beams
  - Appear with bunch trains
  - ~20 to 50 consecutive bunches are affected
  - The peak amplitude is within the first bunches of a 48b train
  - The motion of the bunches is correlated (in-phase motion)

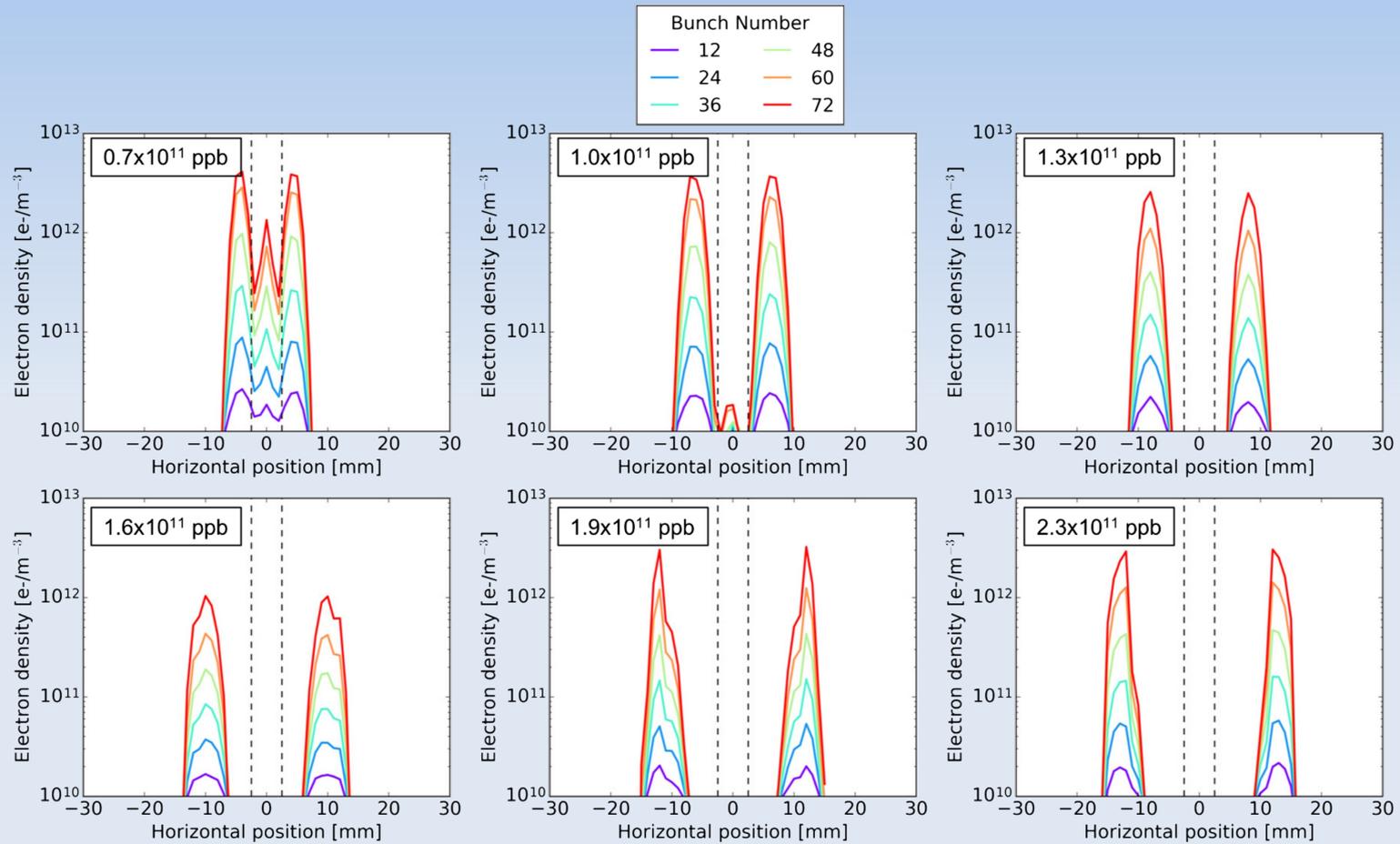
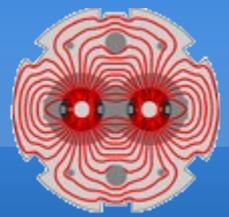




# 'Ramp' instability



- The time evolution of the oscillation indicates a single kick followed by damping, rather than a slow growth  
→ Investigations are ongoing by the ADT team

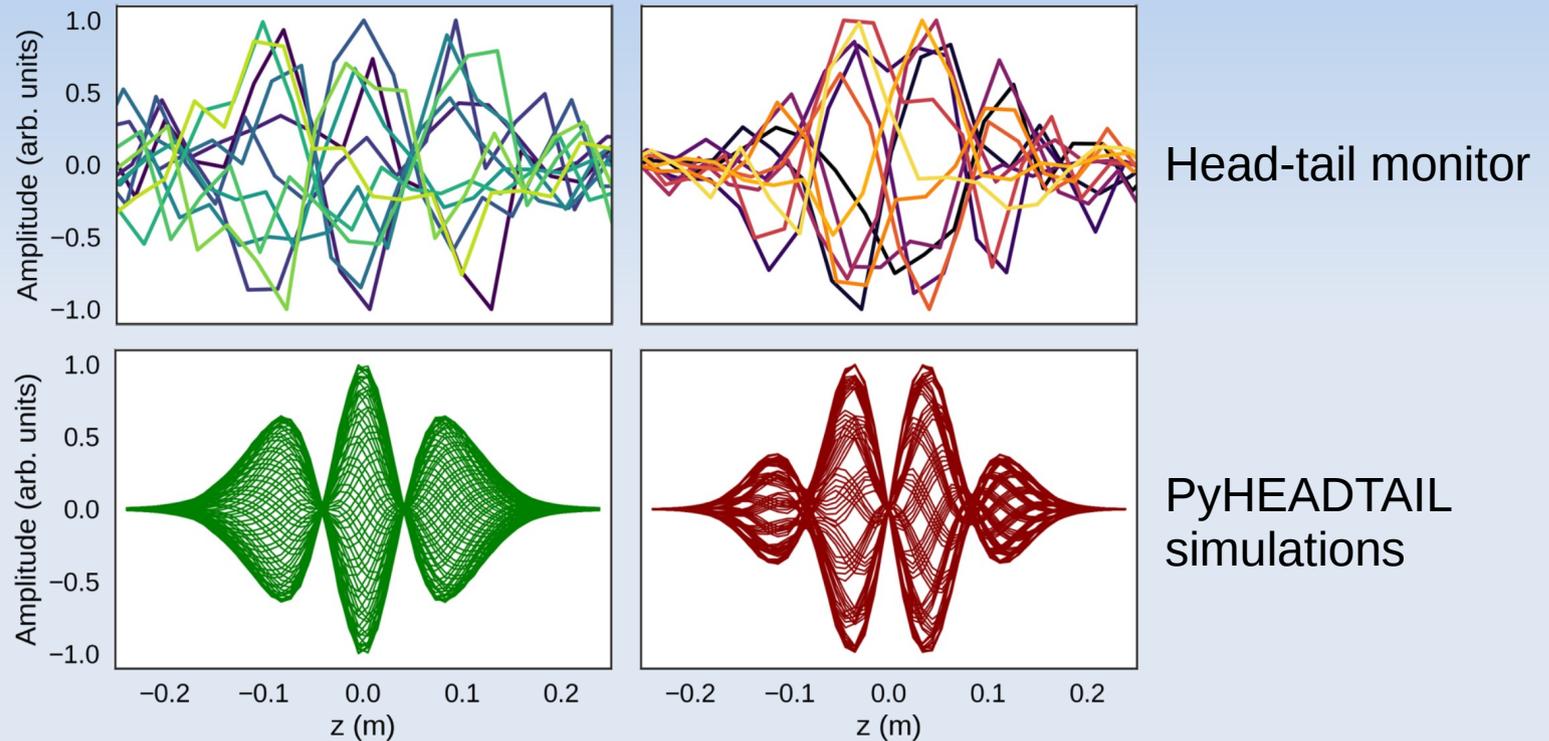
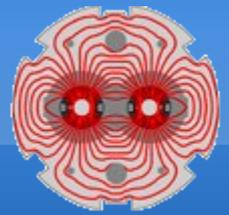


- Annalisa Romano, et al., Phys. Rev. Accel. Beams 21, 061002 (2018)



# Head-tail signal

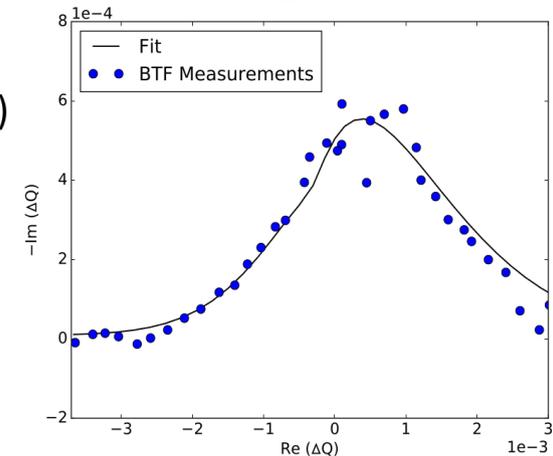
## Prediction vs measurement



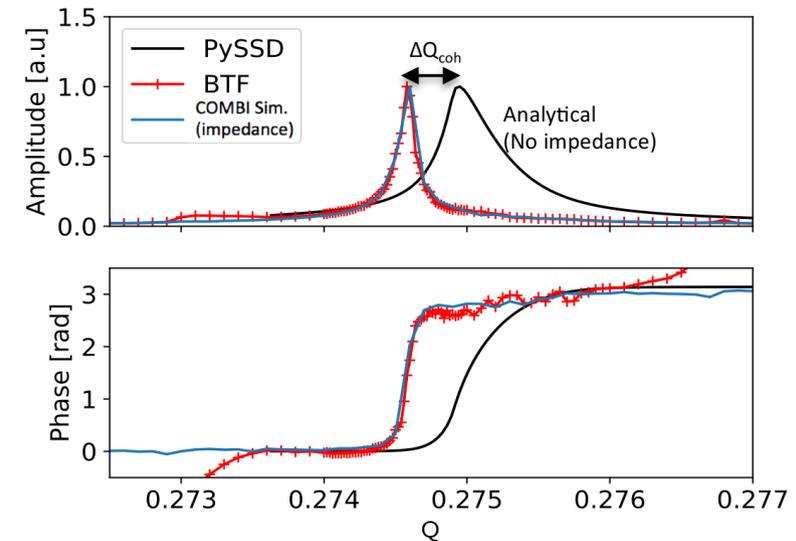
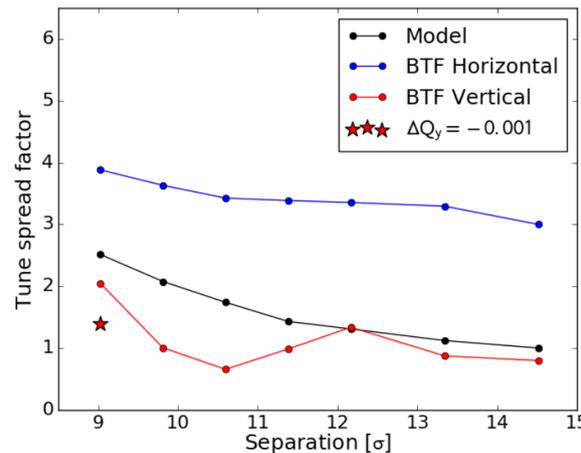
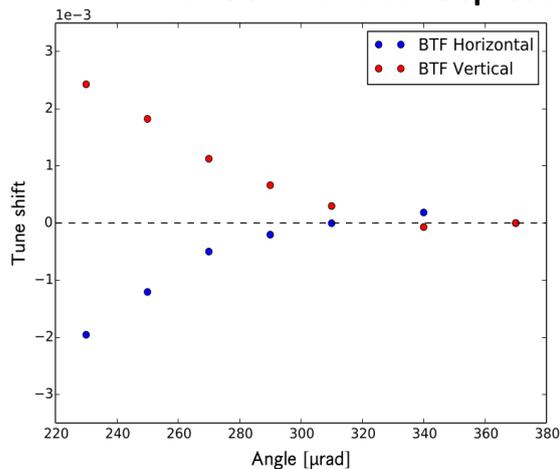
- M. Schenk, et al., Phys. Rev. Accel. Beams 21, 084401 (2018)

- **Good reconstruction of stability diagrams** at injection energy (fitting function and averaging method)
- **Measurements of Landau damping (Tune spread)** with linear coupling
- Good measurements of **tune shifts and tune spread** at top energy with **BB-LR** (2016)
- **External excitations reduce stability thresholds** (LBOC 2018)
- Impact of **impedance** on BTF: **tune shift corresponding to 1.5-2 stronger impedance** (compatible with other observations)
- **Measured coherent tune shifts**
- **Measured minimum of stability with colliding beams at 1.5  $\sigma$**   
**Still missing**
- **Modification of the stability diagram due diffusive mechanisms**
- **Reconstruction of SD at flat top due to strong impedance**

Stability Diagram at injection



Tune shift and tune spread with beam-beam long range



**Necessary BTF features were available only in 2018** (bunch by bunch): the gated BTF is fundamental to measure in various conditions and avoid instabilities. **The system** was not used operationally and **required expert support during every MD to maintain the functionalities**