LHC Beam Operation Workshop 2017 - Evian

Our understanding of transverse instabilities and mitigation tools/strategy

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Many thanks to OP, BI and RF for their important contributions

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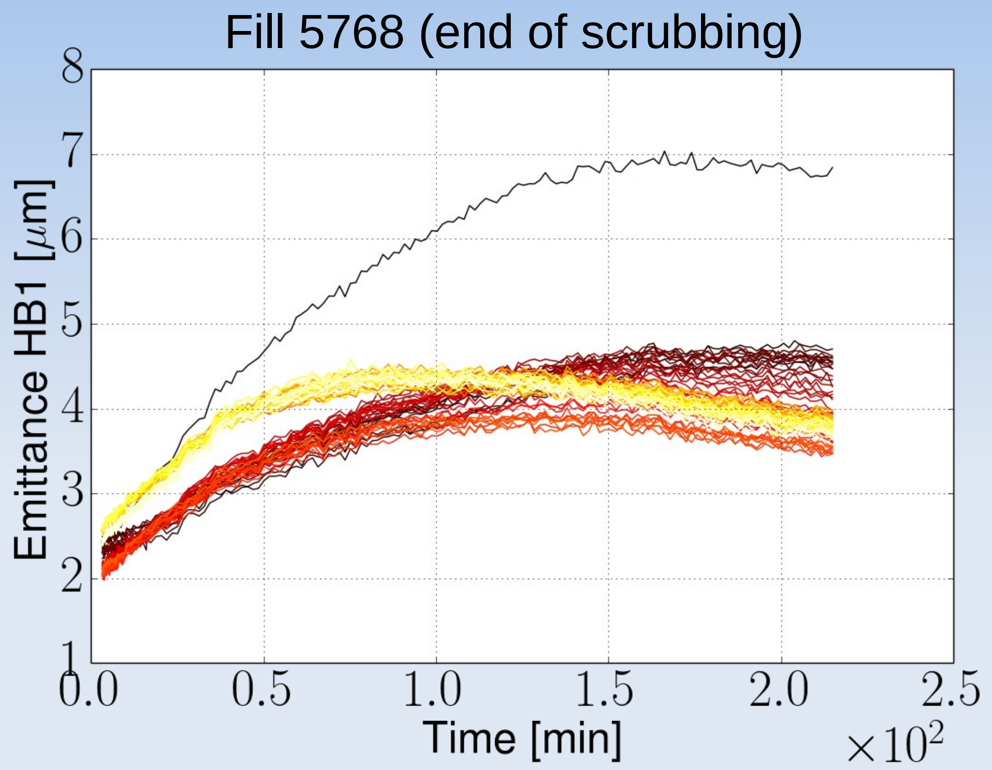
- Injection
- Ramp
- Flat top, squeeze and collision
  - Octupole threshold and impedance measurements
  - Observations of instabilities
- Mitigation strategies
  - Tools
- Conclusion

Injection

Beam quality preservation

- E-cloud driven instabilities require large ADT gain (τ~10 turns), chromaticities (Q'~15) and tune spread (I_{oct}~40 A) (see. K. Li, et al @ Chamonix 2017)
    - The octupole current needs to be adjusted with the injected beam emittance to maintain the tune spread



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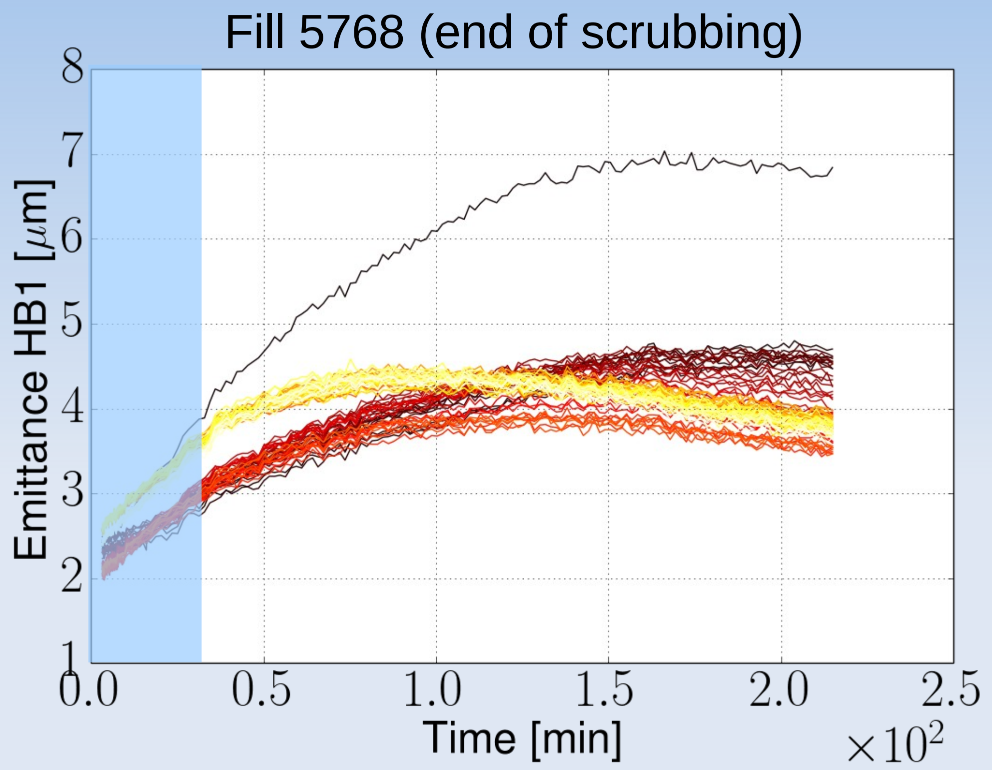

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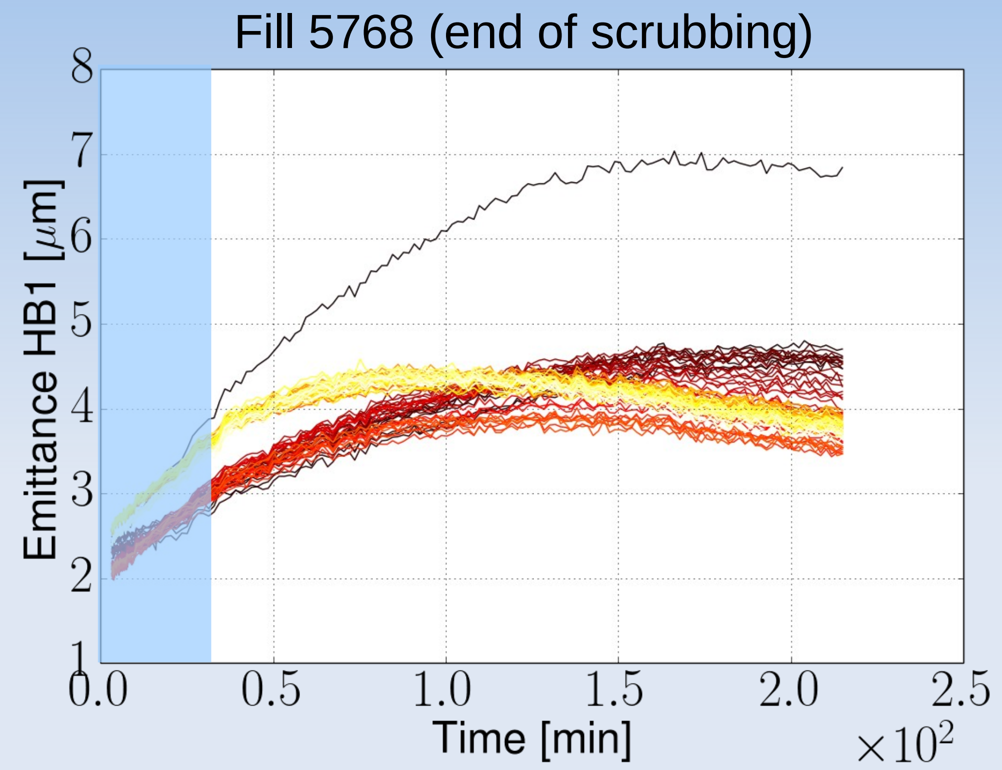
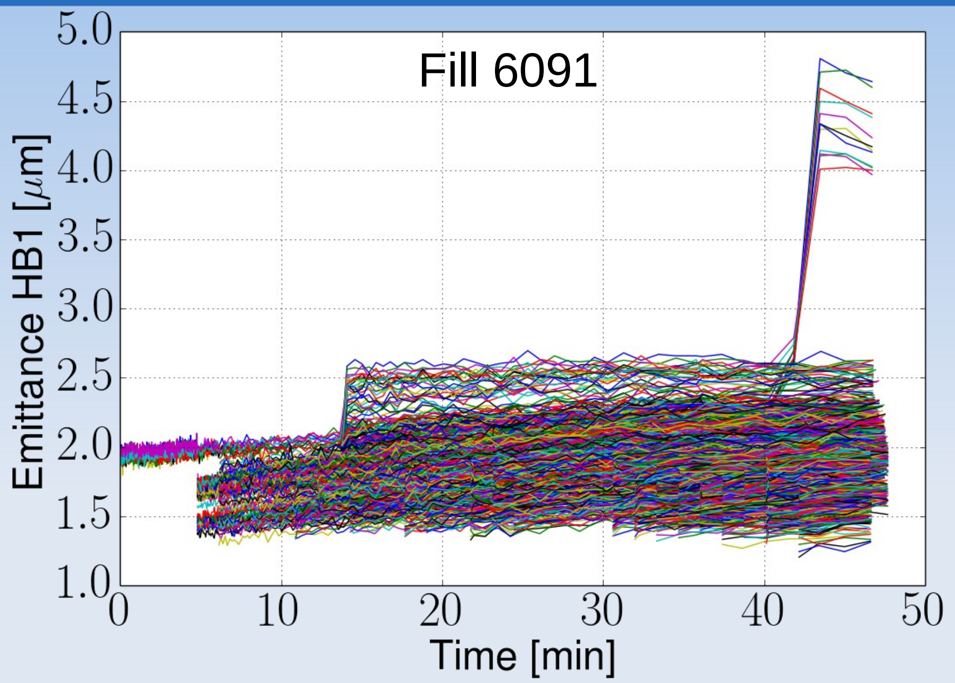


- The incoherent effects on the beam quality is significant for long injection plateau, but reasonable for typical injection times

- Empirical optimisation is needed to find the balance between coherent and incoherent effects
  - MDs investigating the possibility to use Q'' to improve the beam stability with reduced impact on the incoherent dynamic ongoing

Injection

Observations of coherent motion



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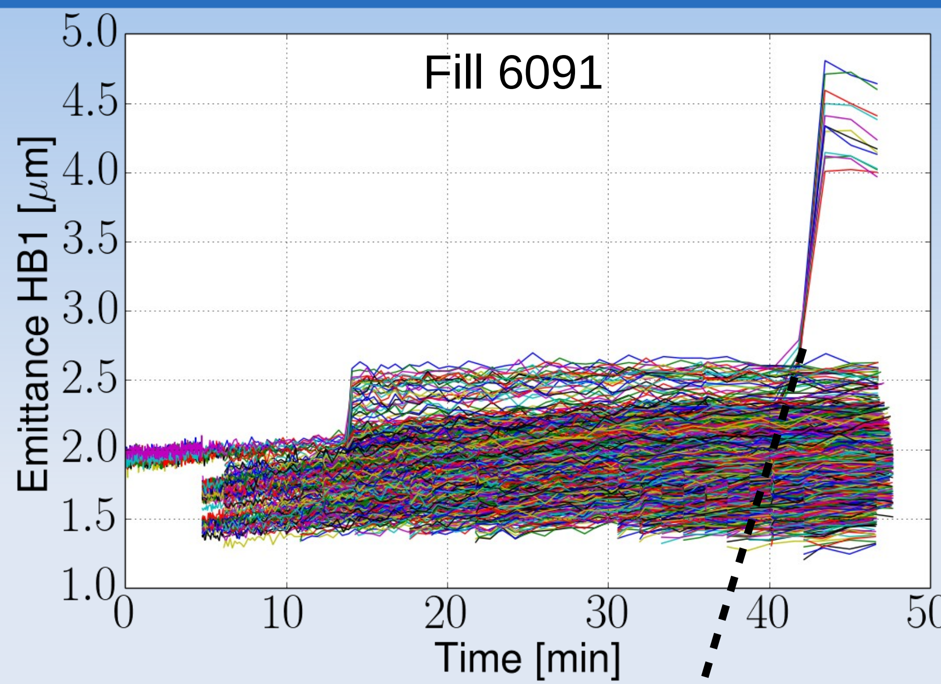
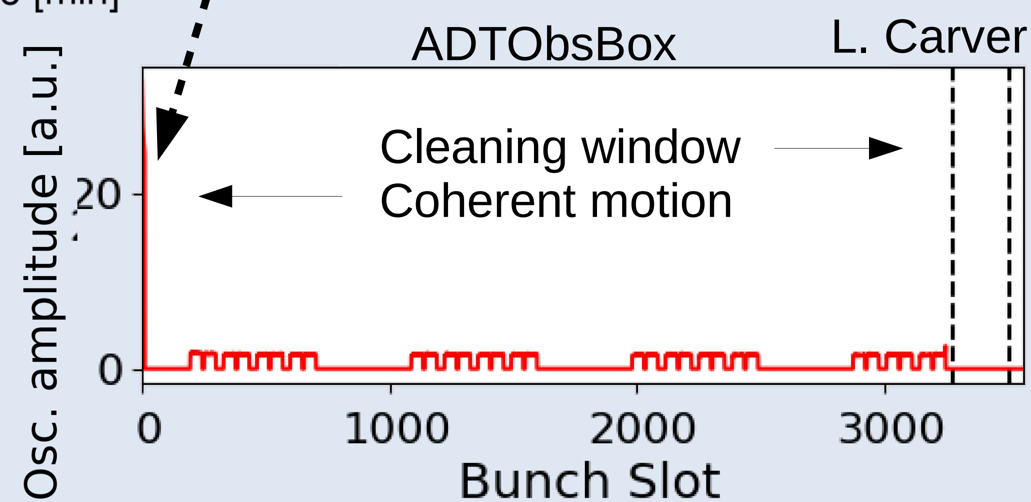
- The injection cleaning of the last train excites the first bunches
  - Reducing the cleaning on the last injection would increase the risk of dump





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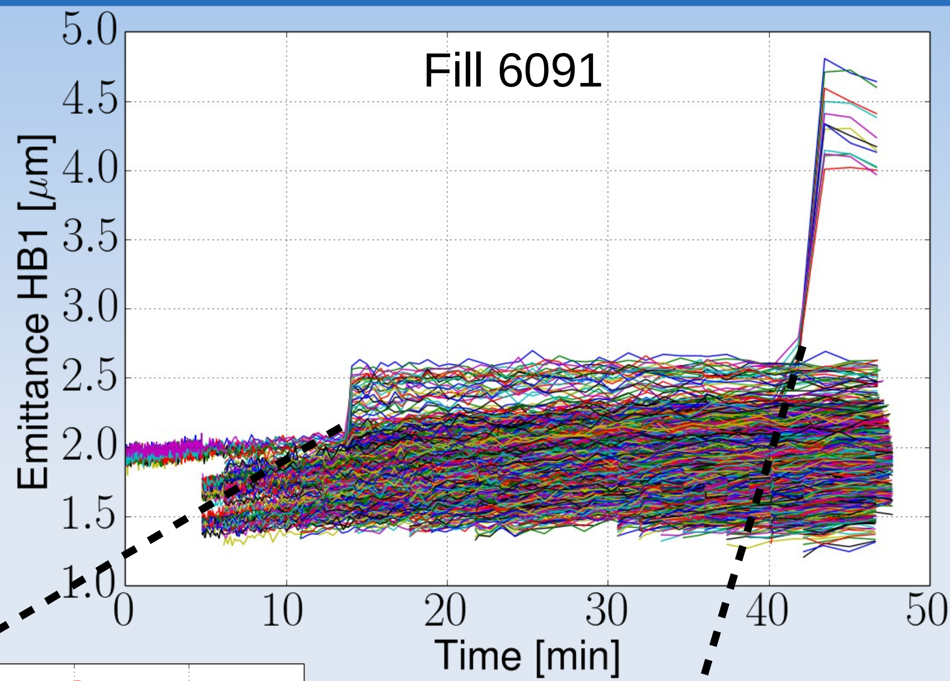
    - Reduced but still present with 8b4e



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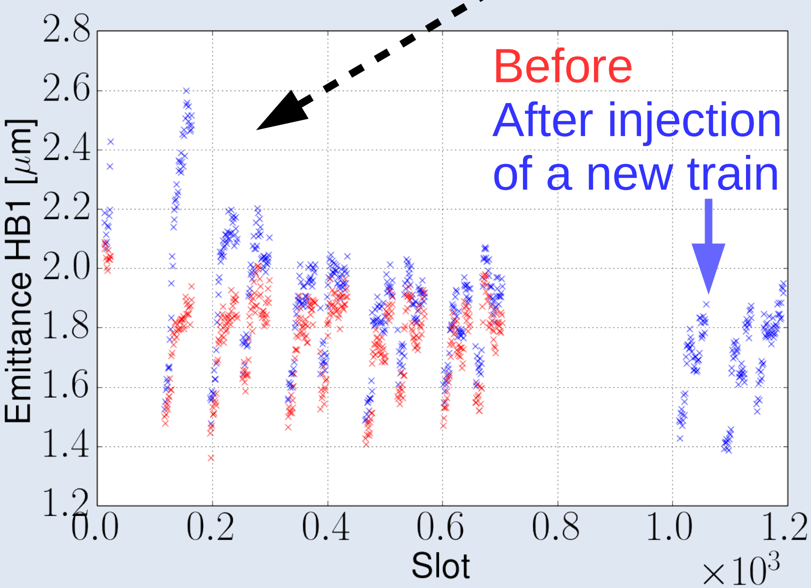

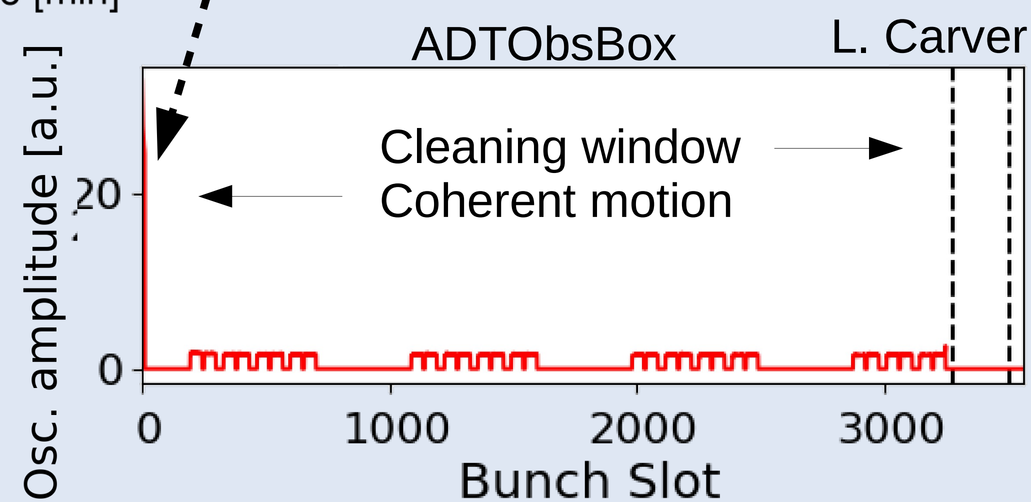

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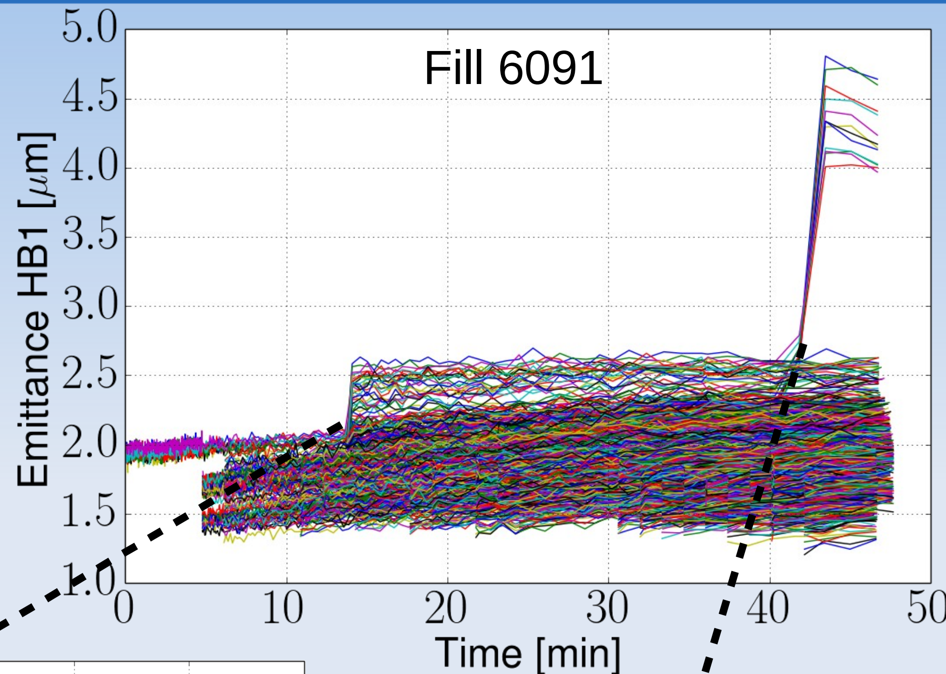

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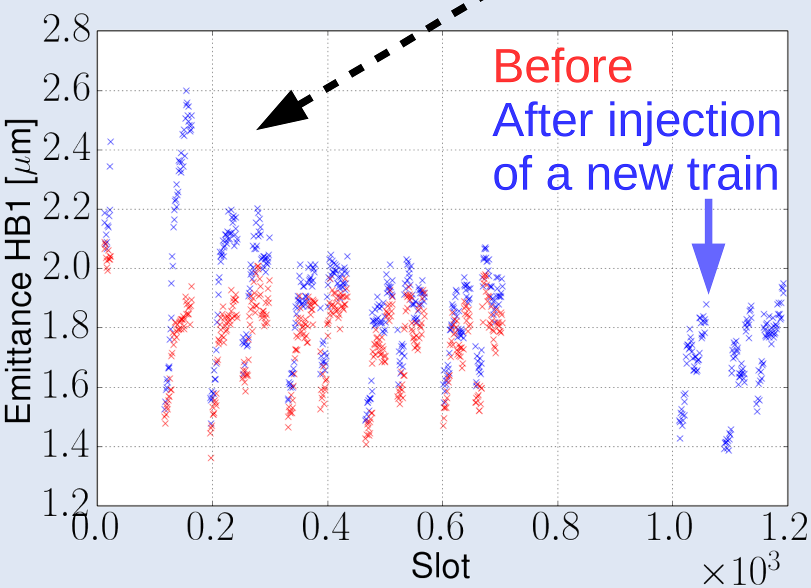
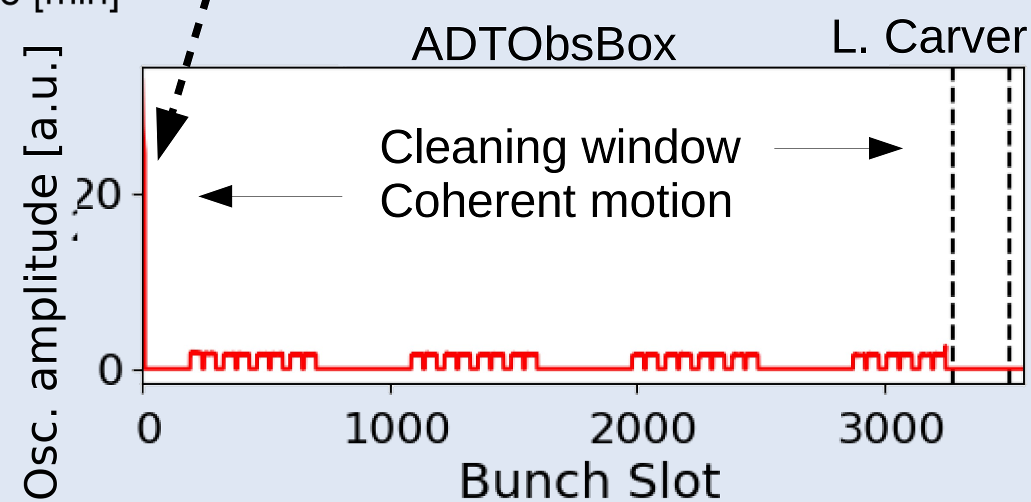
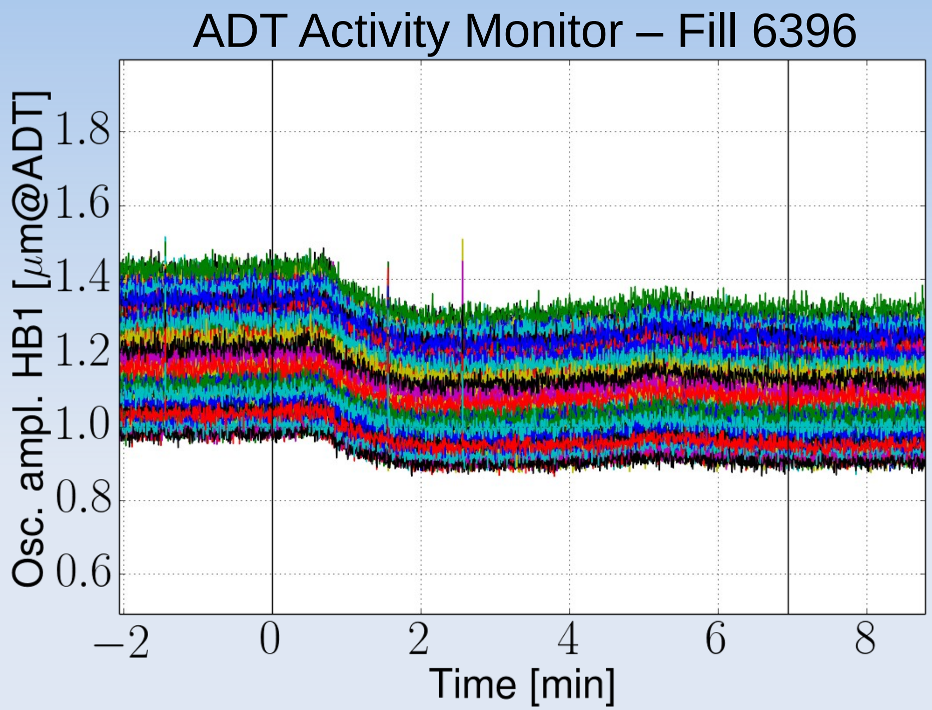




- Not covered here : MKI effect on last circulating bunches, transmission of beam-beam interaction through long-range beam-beam interactions

Ramp



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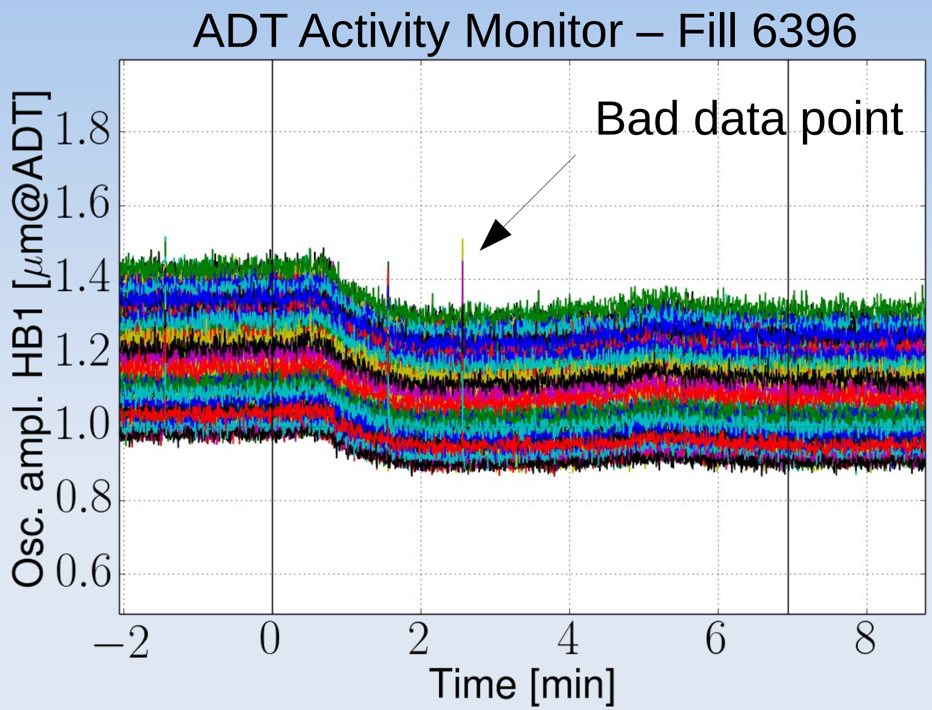

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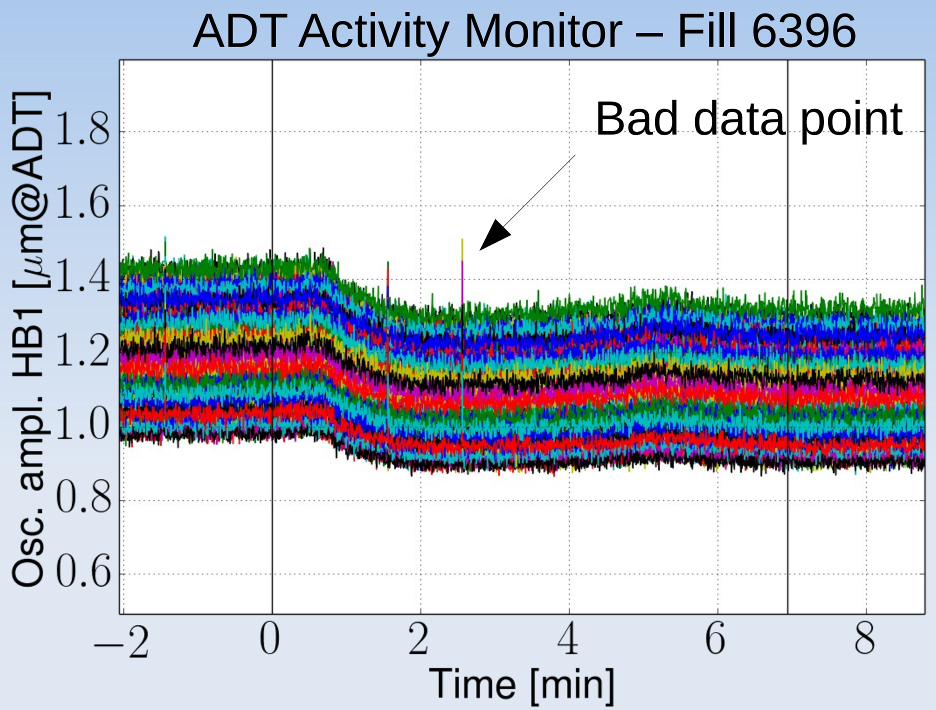

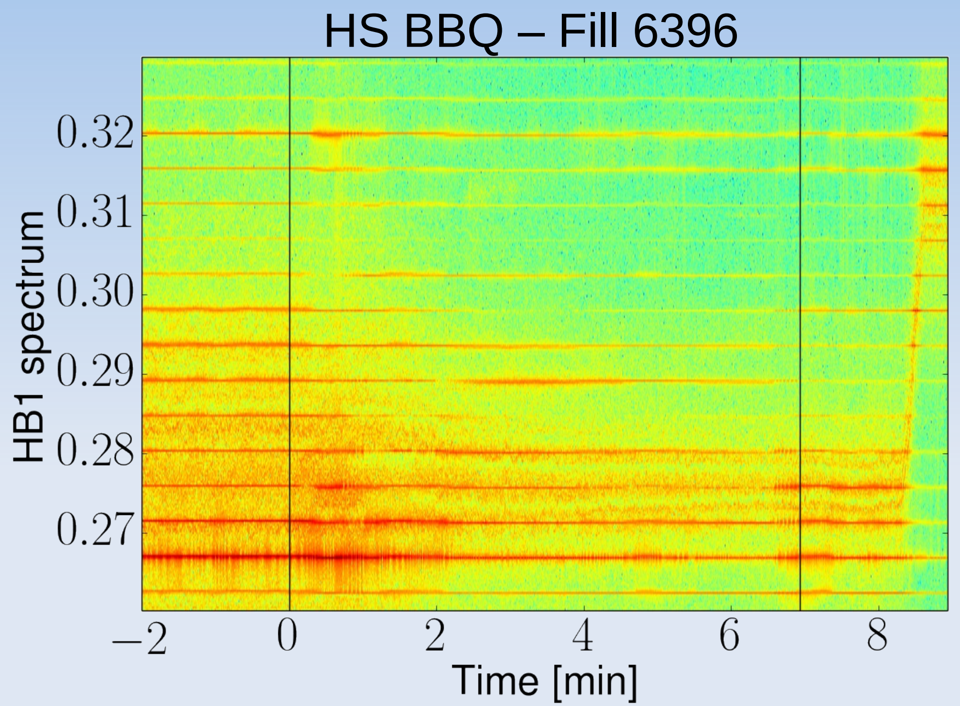

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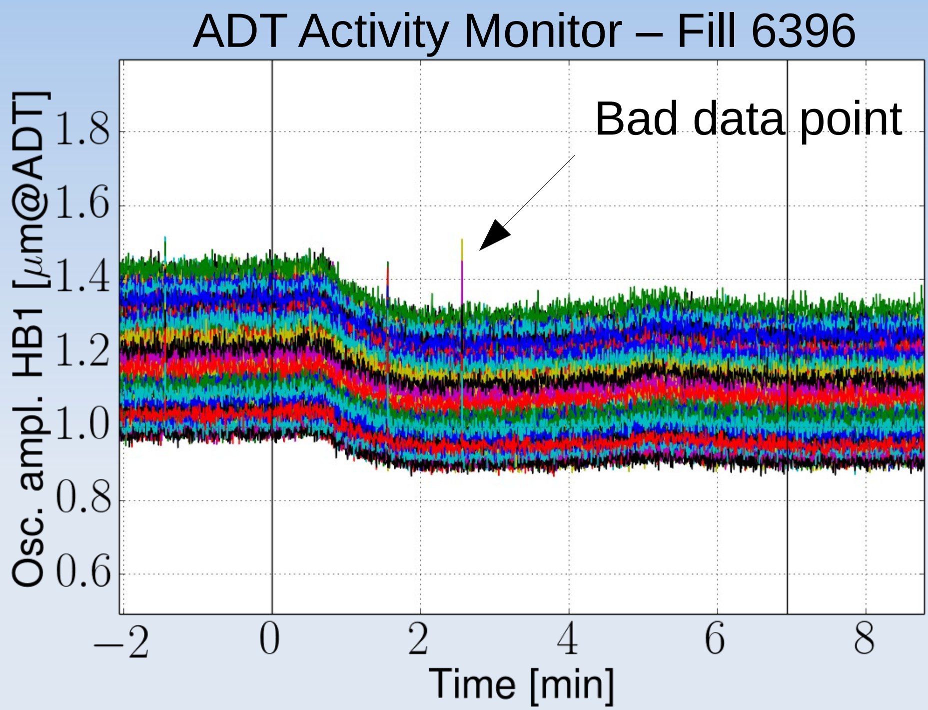

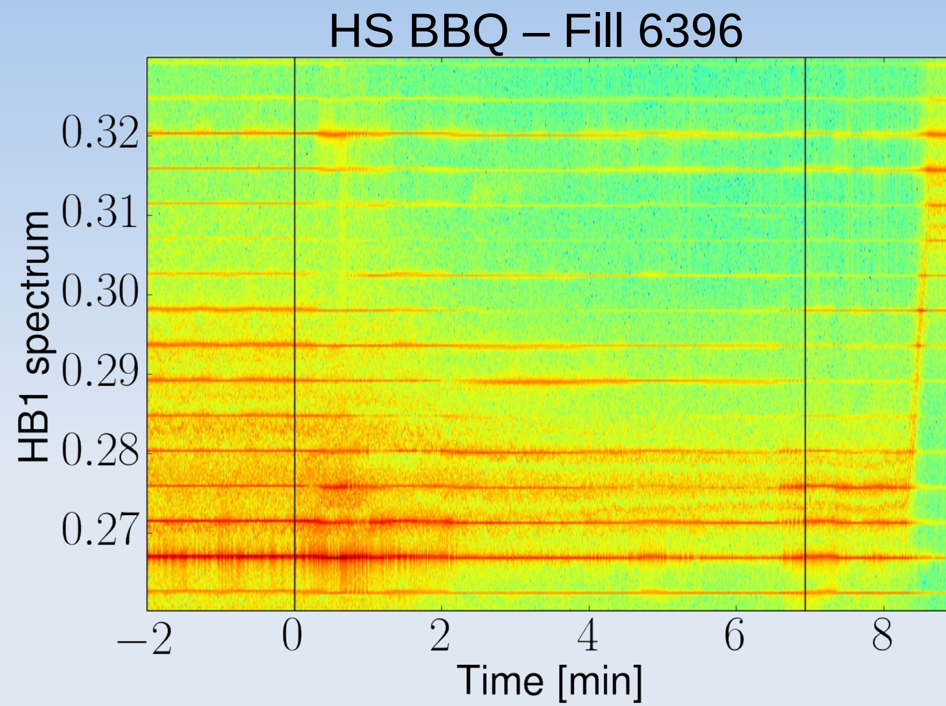

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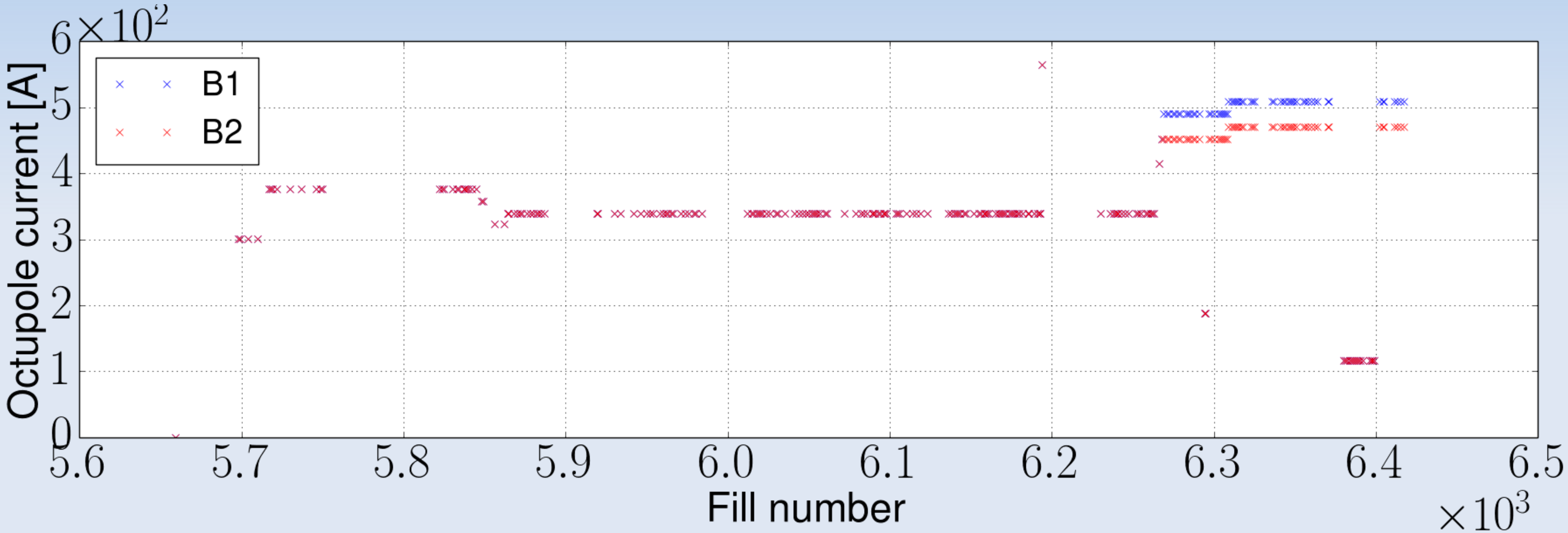
  → Effect on the emittance to be studied by varying slightly the tunes during the ramp
- No indications that the emittance blow up observed during the ramp is linked to coherent instabilities

Octupole current at top energy during physics fills



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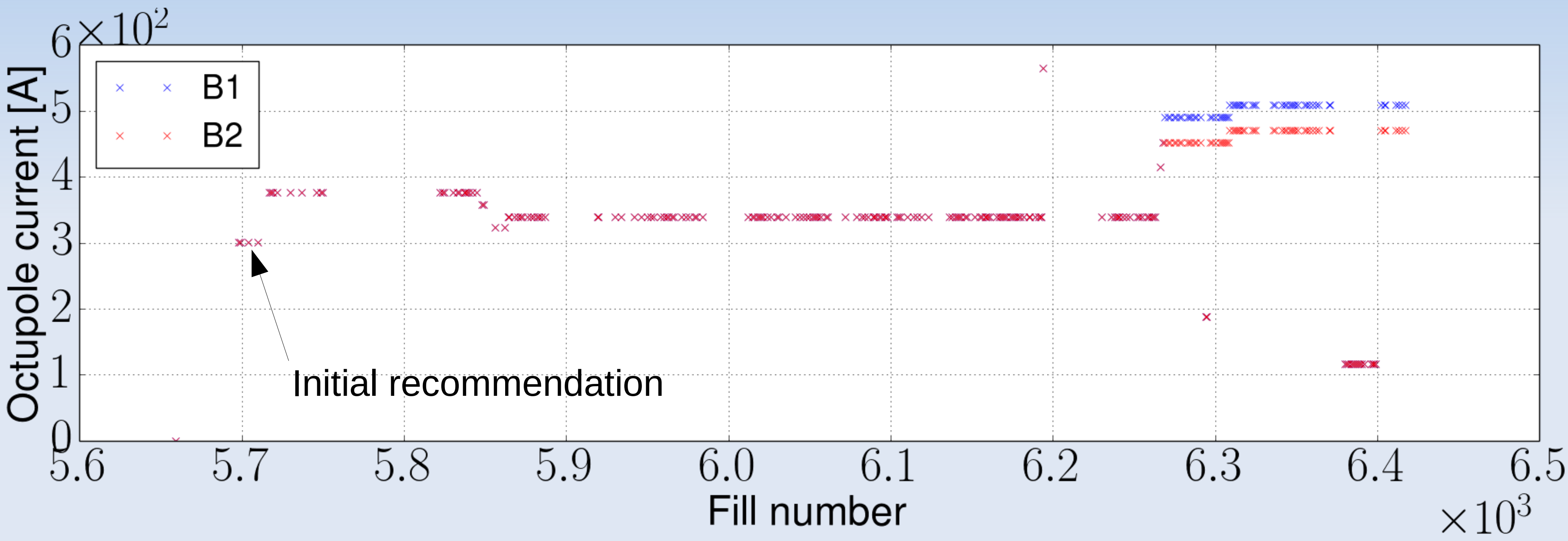

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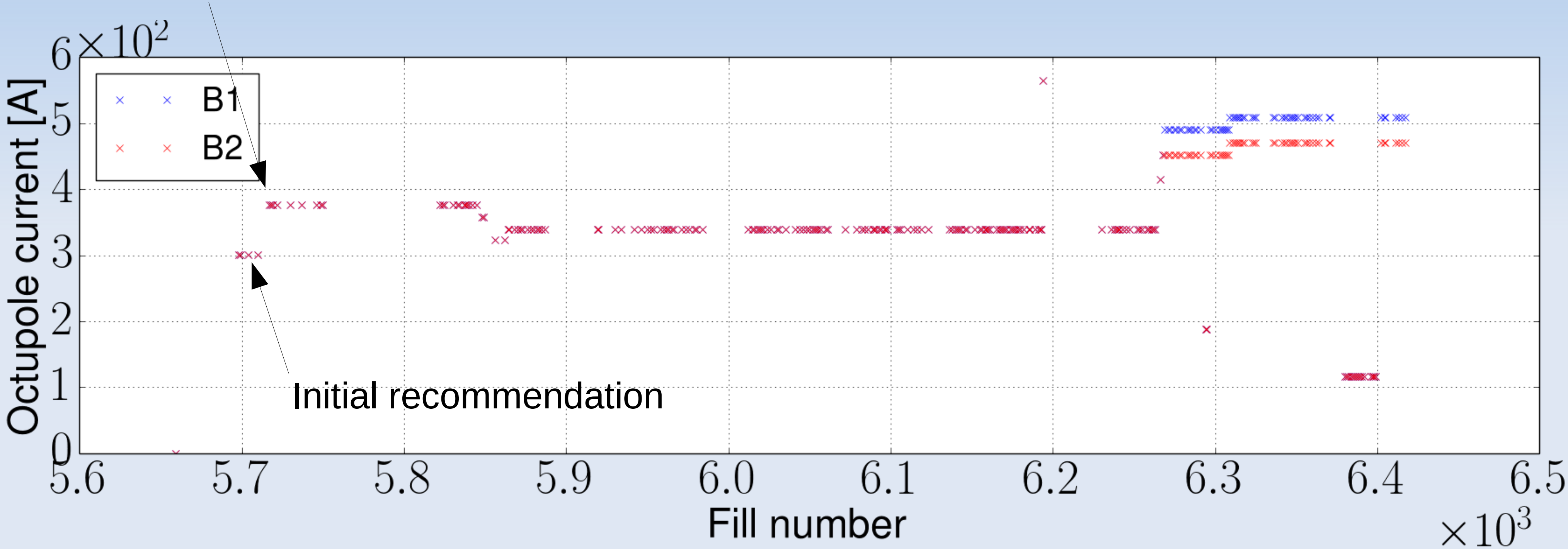
Instabilities of the witness bunches (low ADT gain, offset collision in IP2/8)



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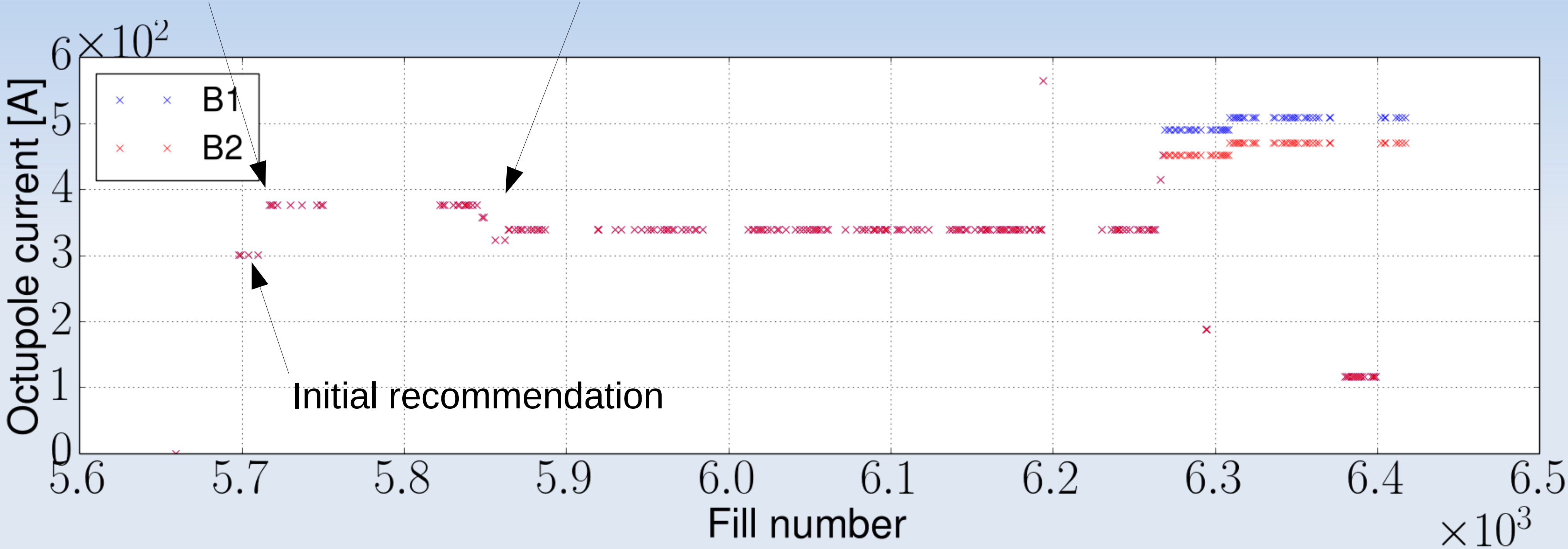

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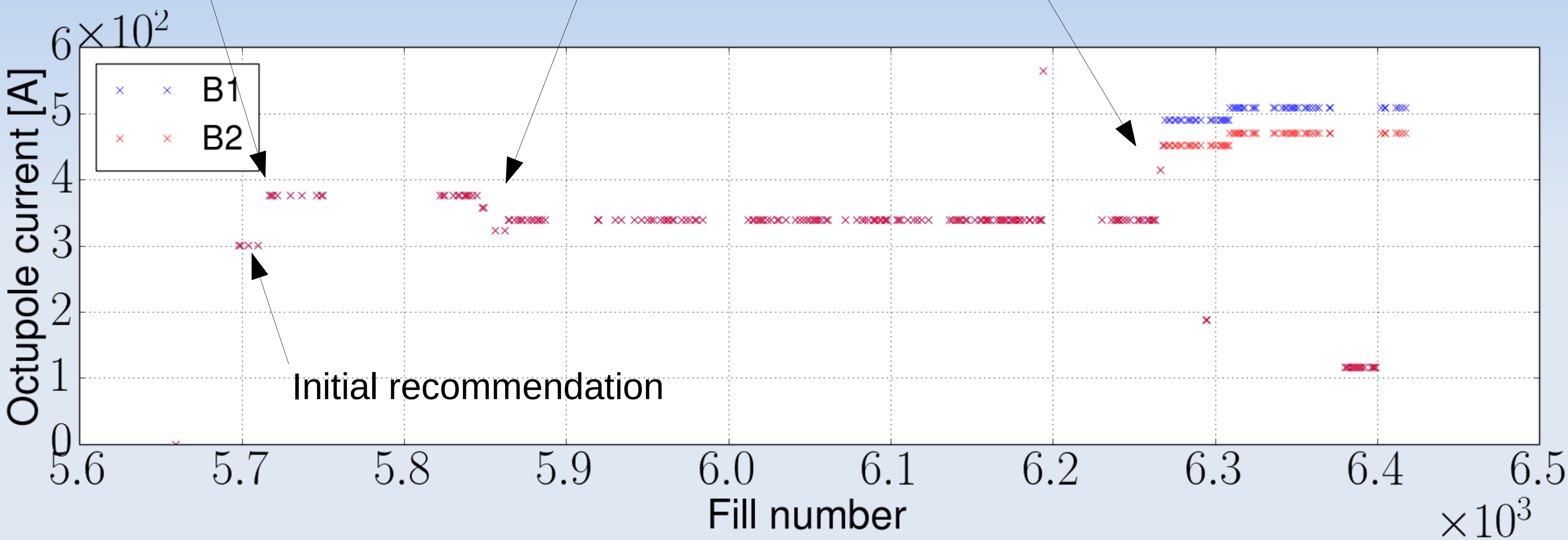
Change to BCS scheme (reduced emittance)



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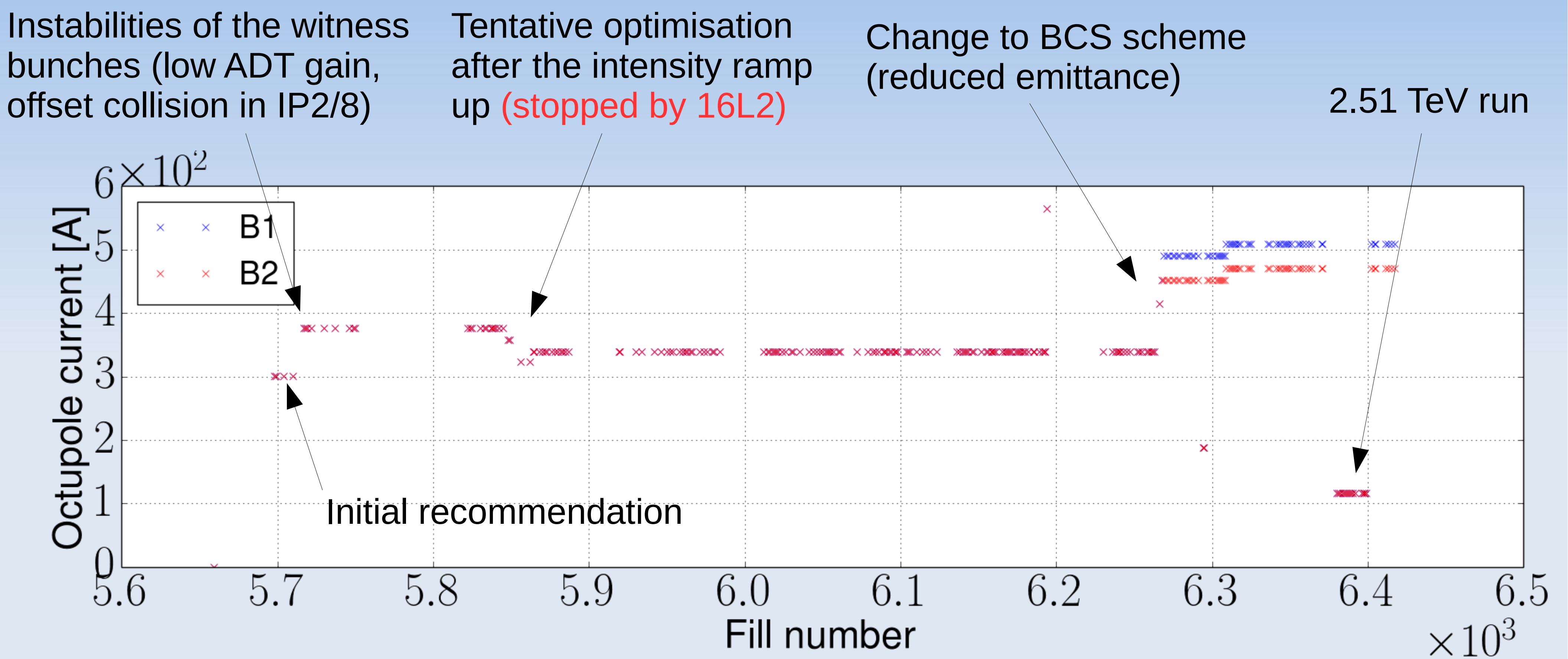

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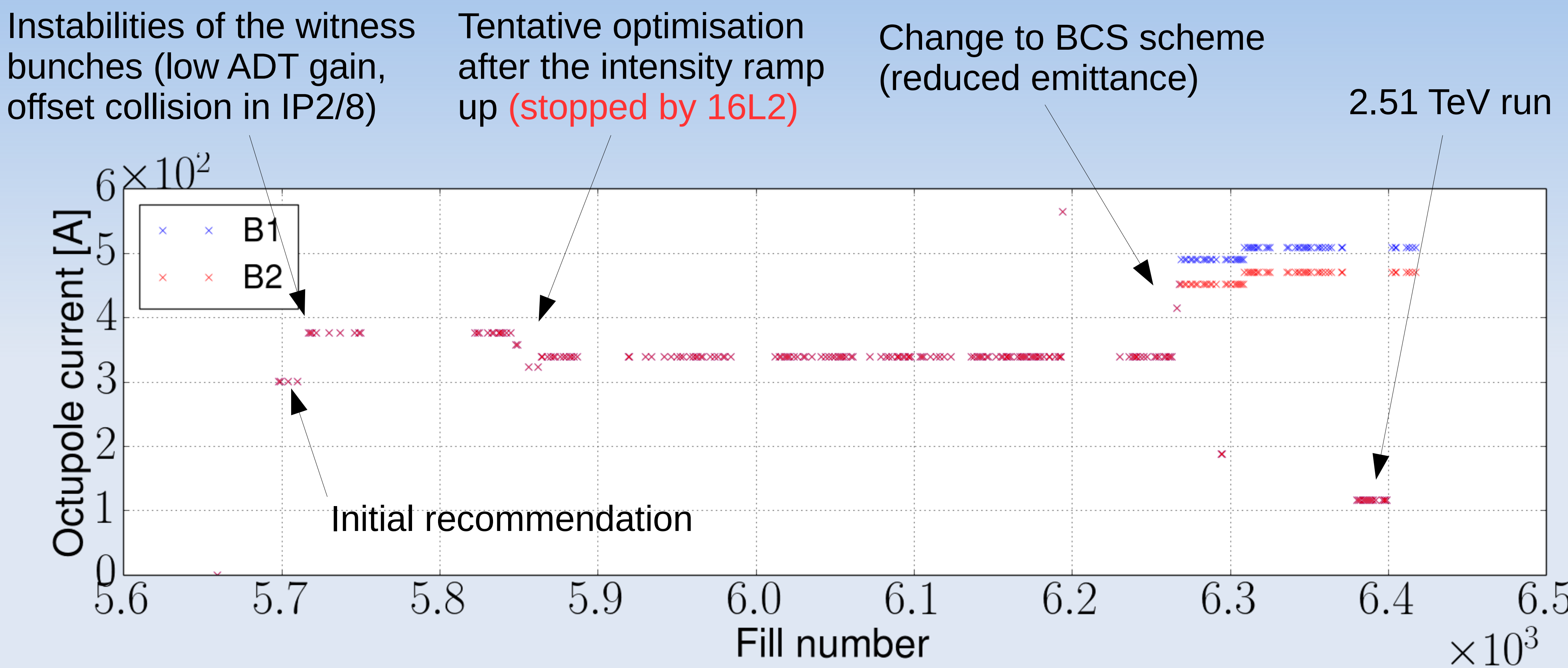

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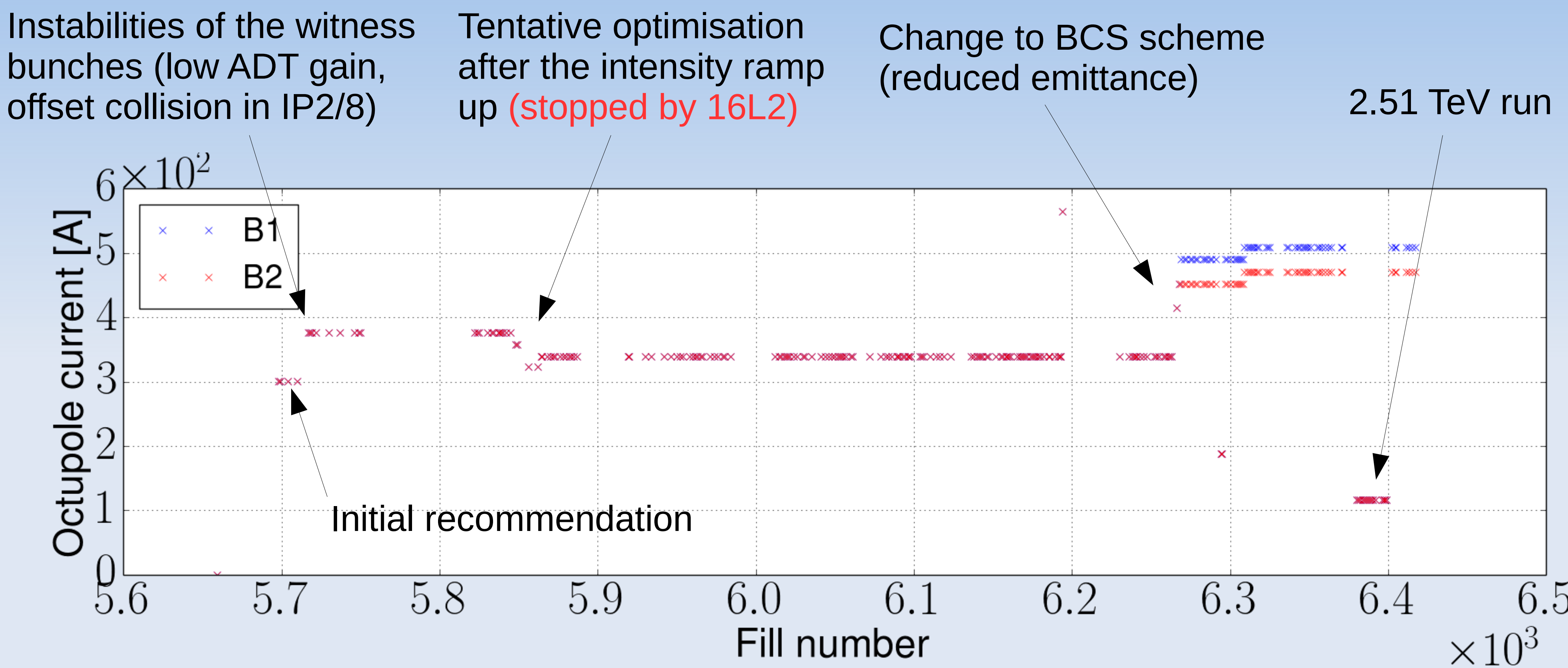
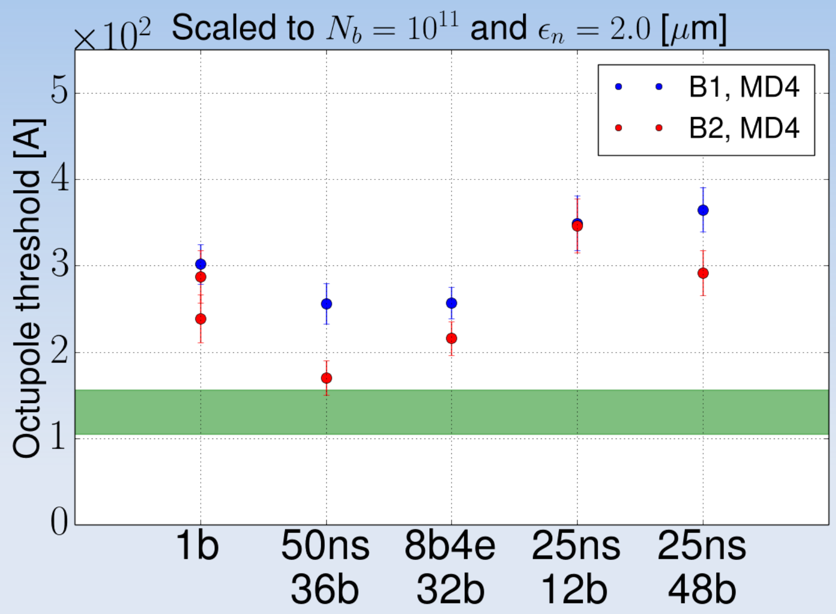


- We could operate close to the recommendation
  - The recommendation is based on a factor 2 with respect to the model
  - Single bunch octupole threshold measurement confirmed the need for such a margin in 2017, as opposed to 2015 and 2016

Instability threshold

- The stability of 25 ns trains is more critical than other schemes for both beams



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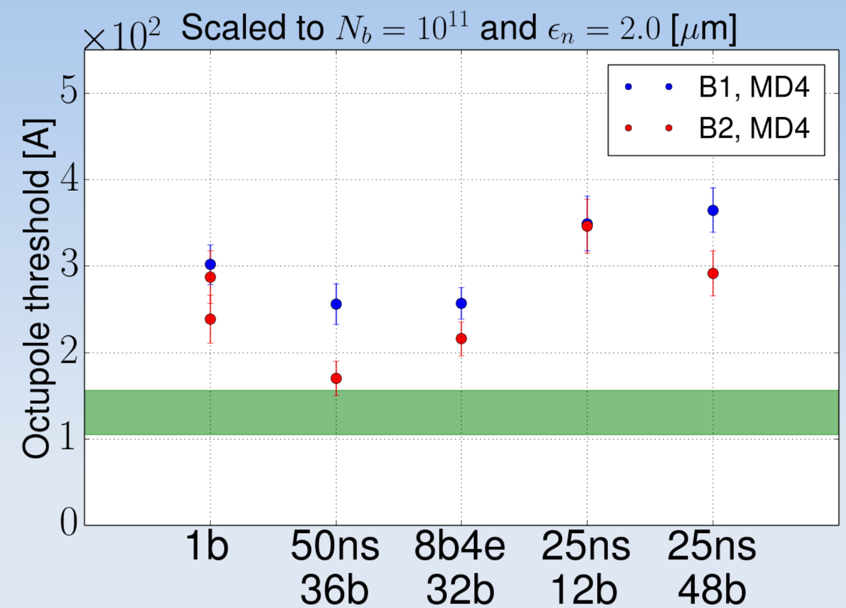

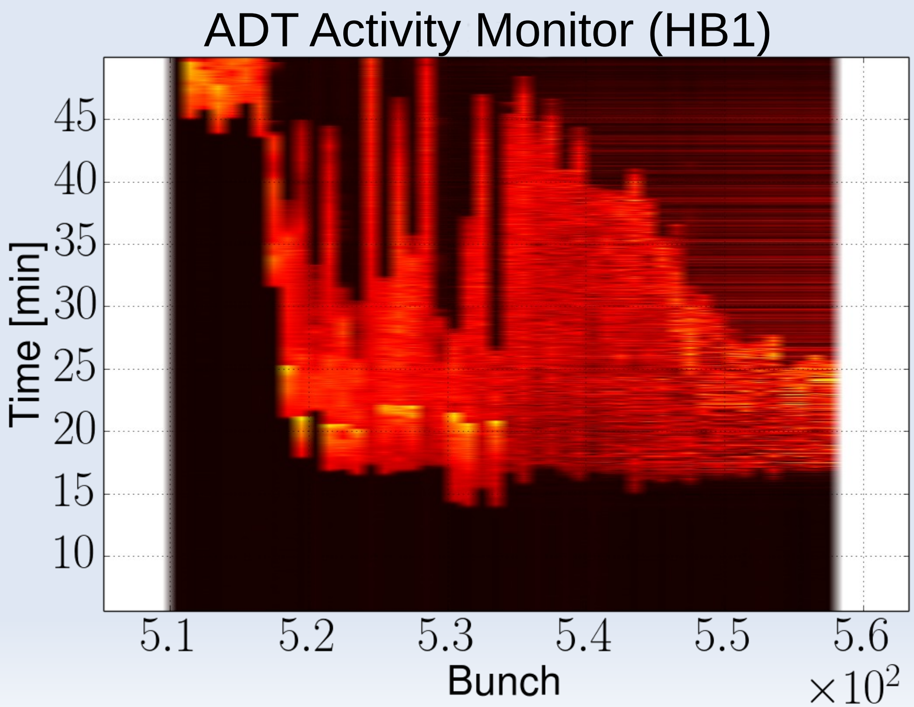

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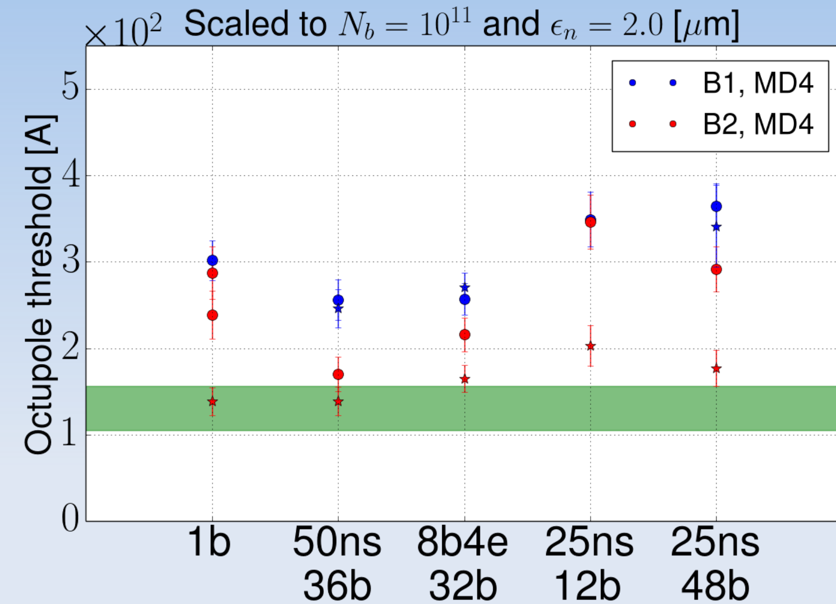

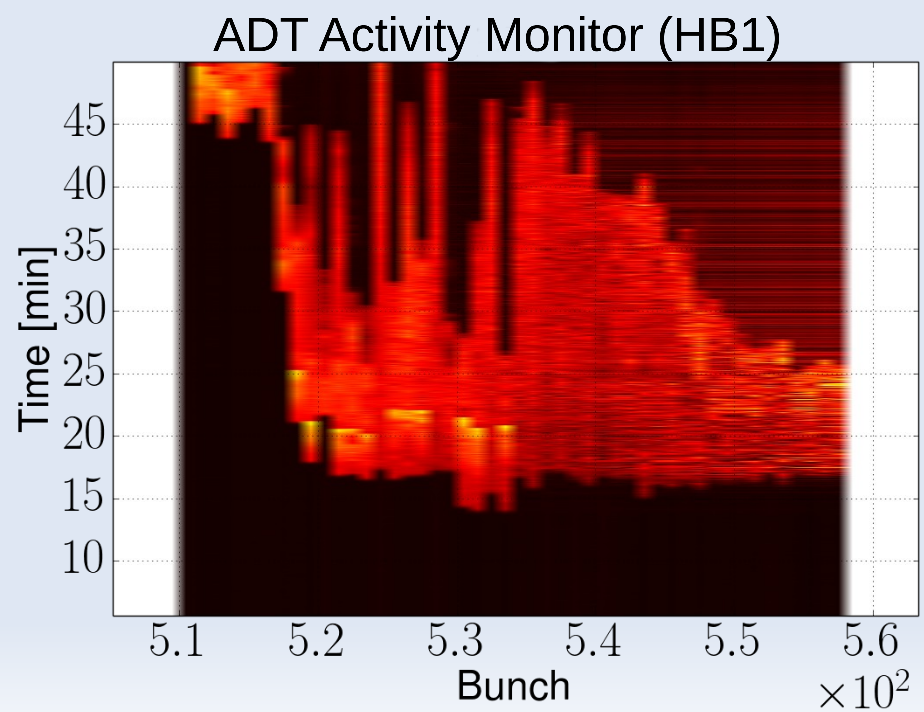

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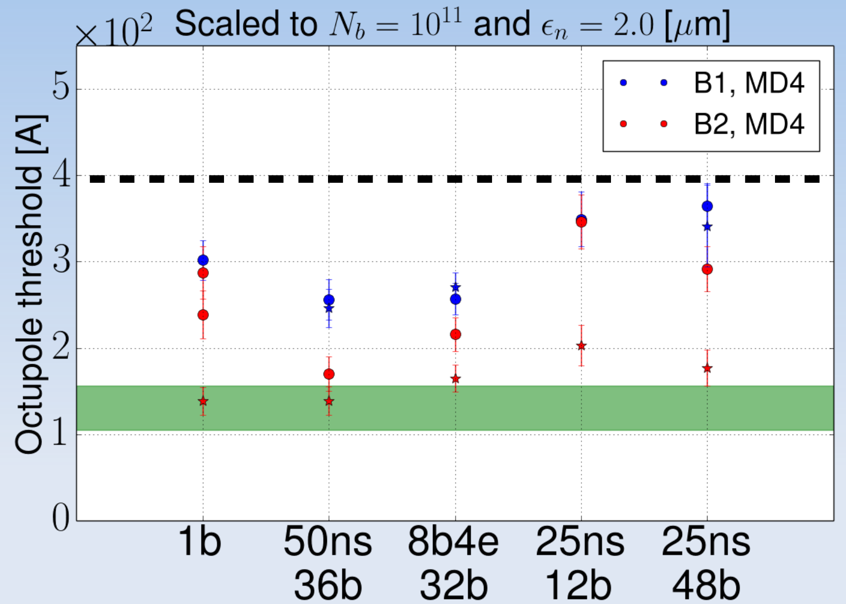
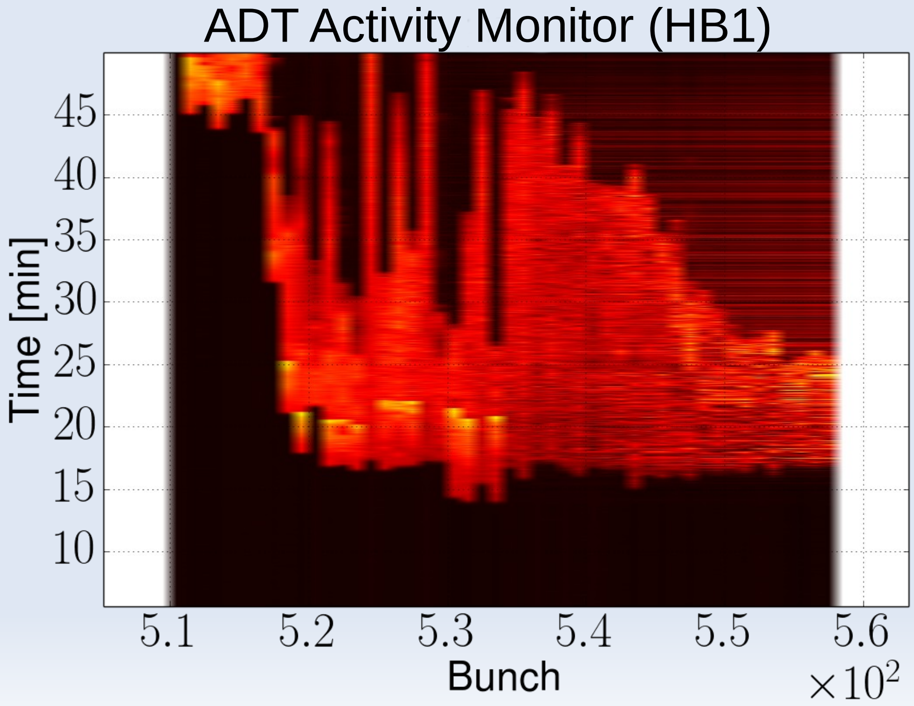
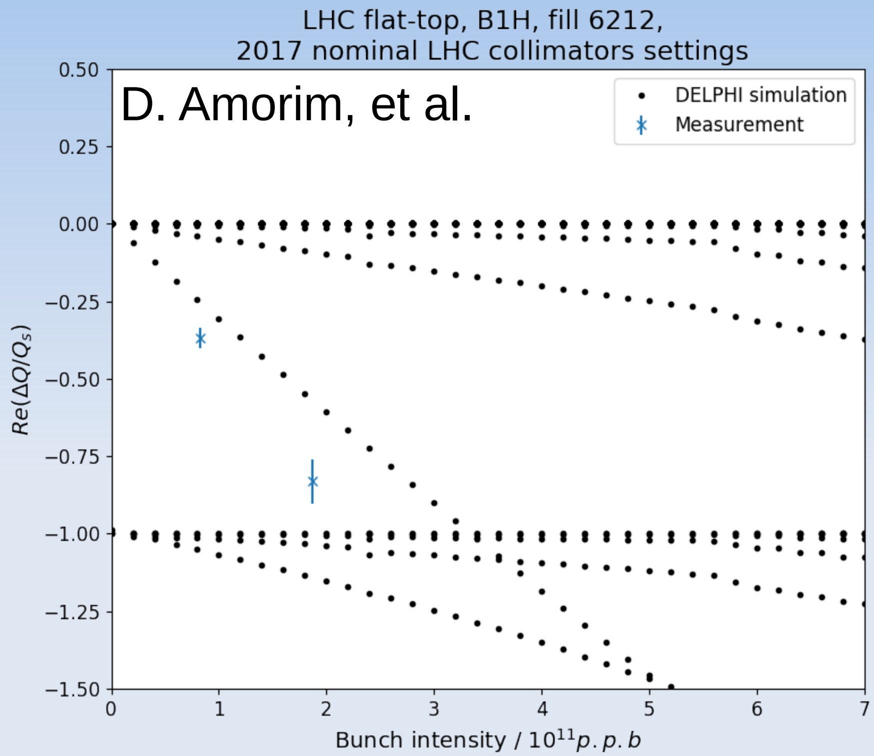
→ 400 A seems a good starting point (to be scaled with the bunch brightness)

  - Long-range beam-beam interaction added ~60 to 120 A equivalent spread with BCMS beams





Impedance measurements



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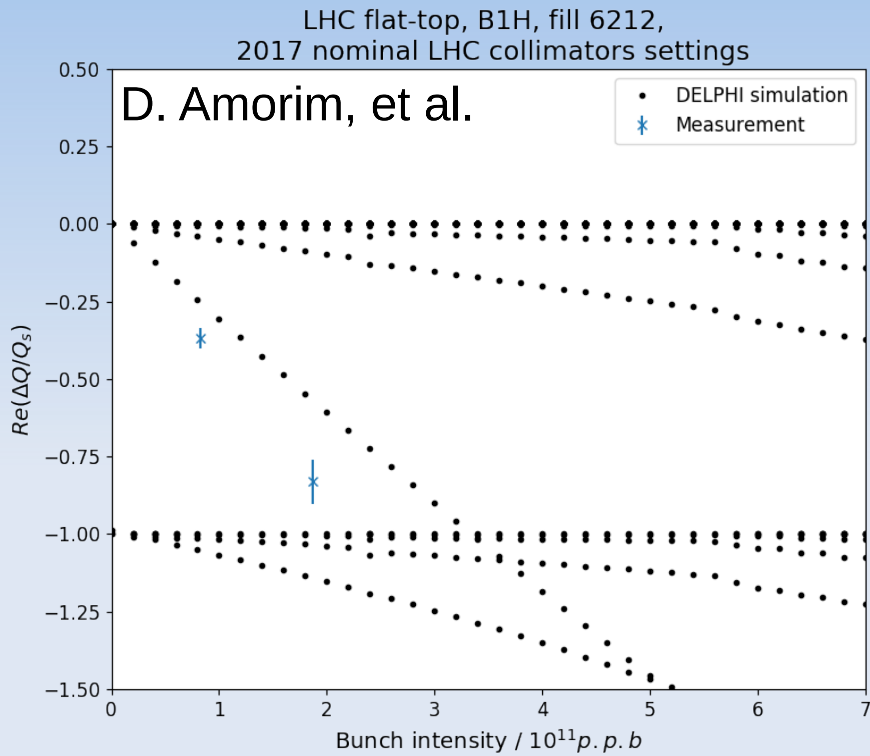

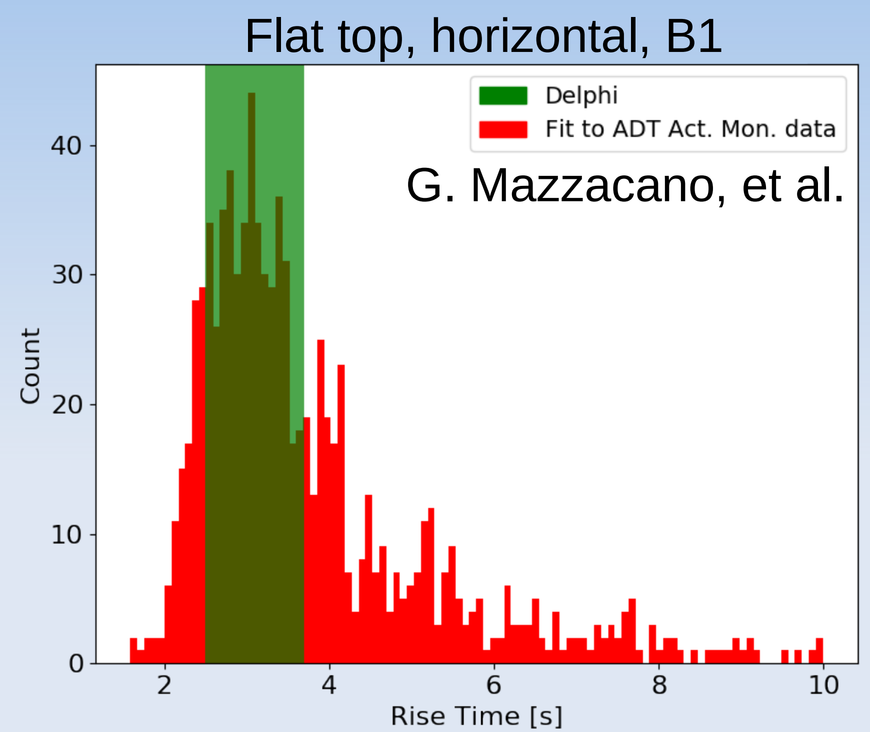

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- The single bunch rise time measured with the ADT Activity Monitor show that some instabilities are faster than the expectations (~50%)

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*** *Menu Surprise* ***

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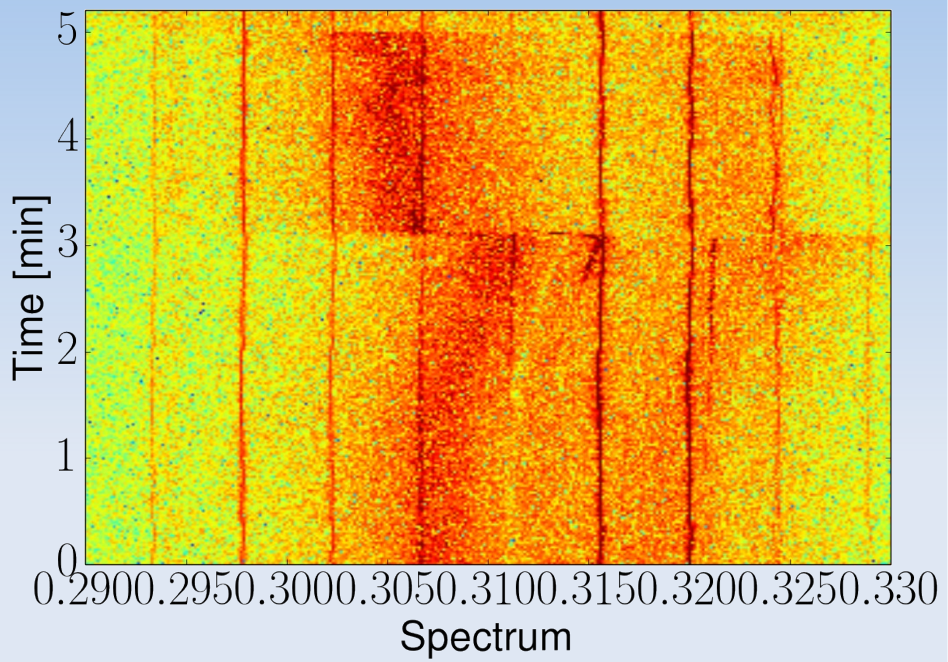
- High latency instability
  - Commissioning / setup fills and MDs
- Low impact on performance this year
  - Instabilities usually lead to blow up of some bunches, w/o beam losses or beam dump

→**Keep the same strategy (octupole, ADT gain, chromaticity), with fine tuning and understanding of the limits (towards HL-LHC)**

The impact of lattice imperfections

- Reducing the tune separation for lifetime optimisation or reduction of loss spikes should no longer be a concern thanks to online linear coupling corrections



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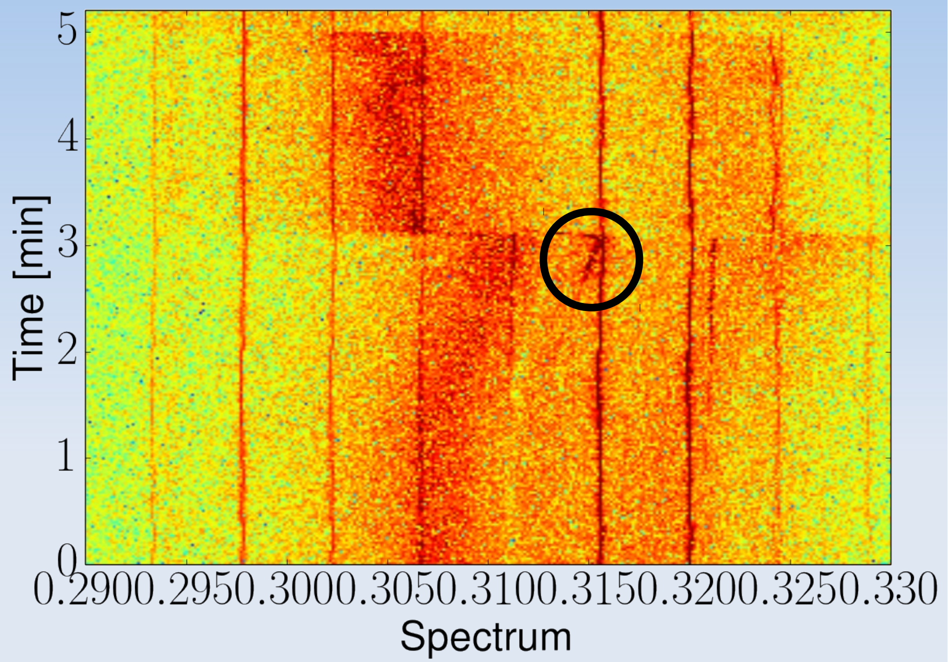

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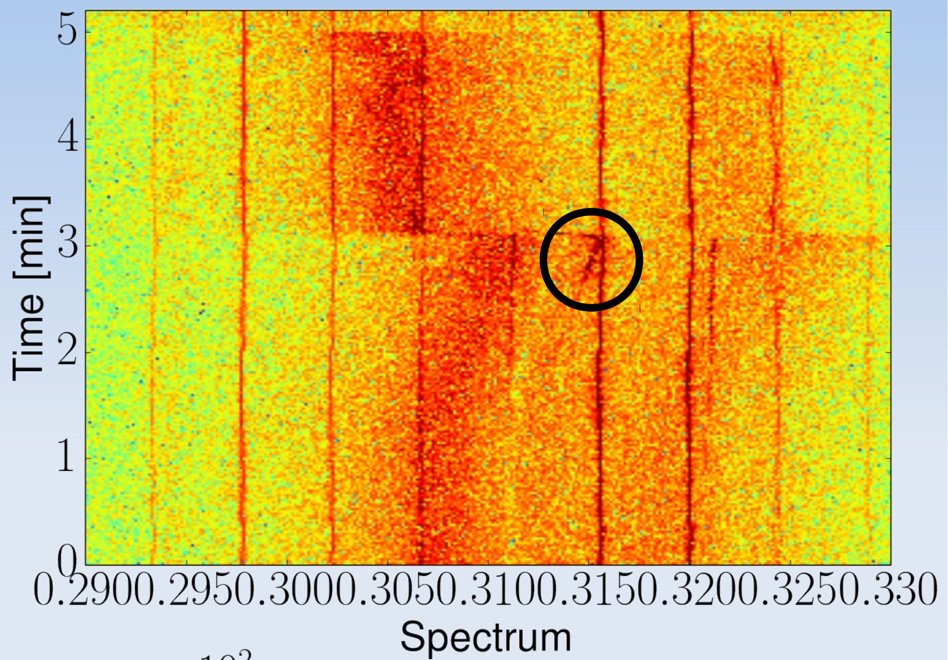

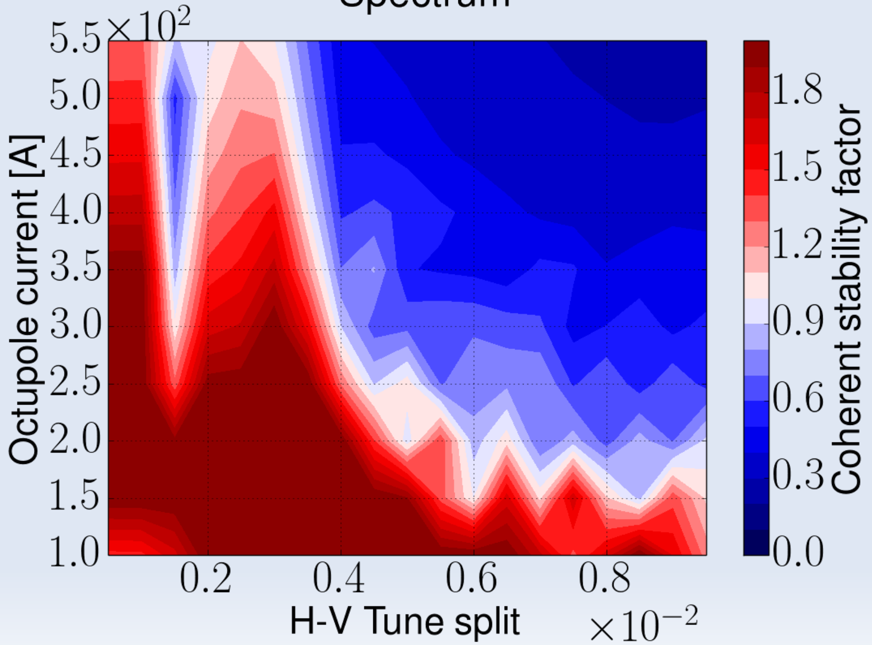

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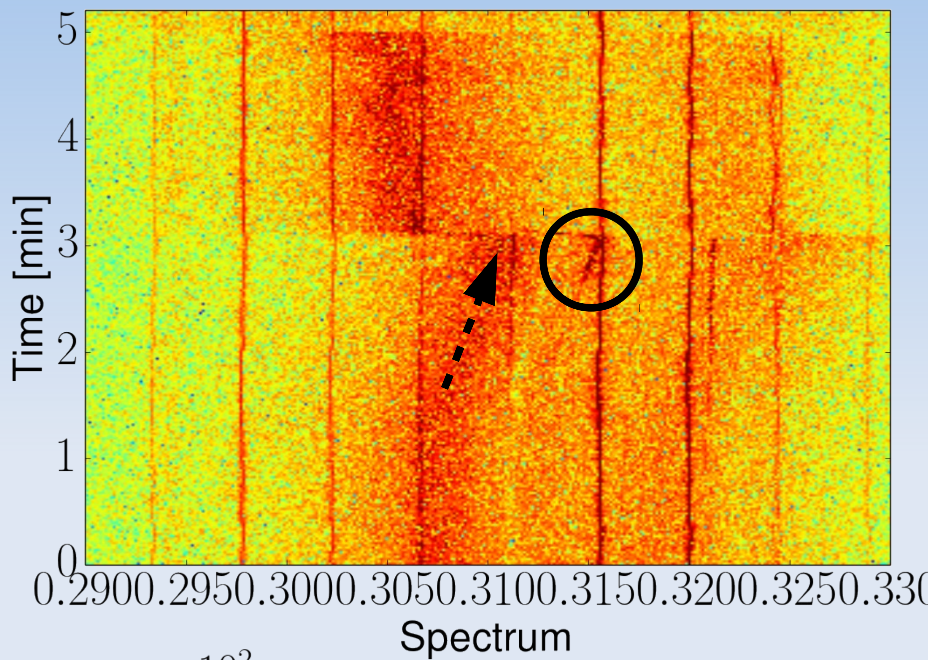

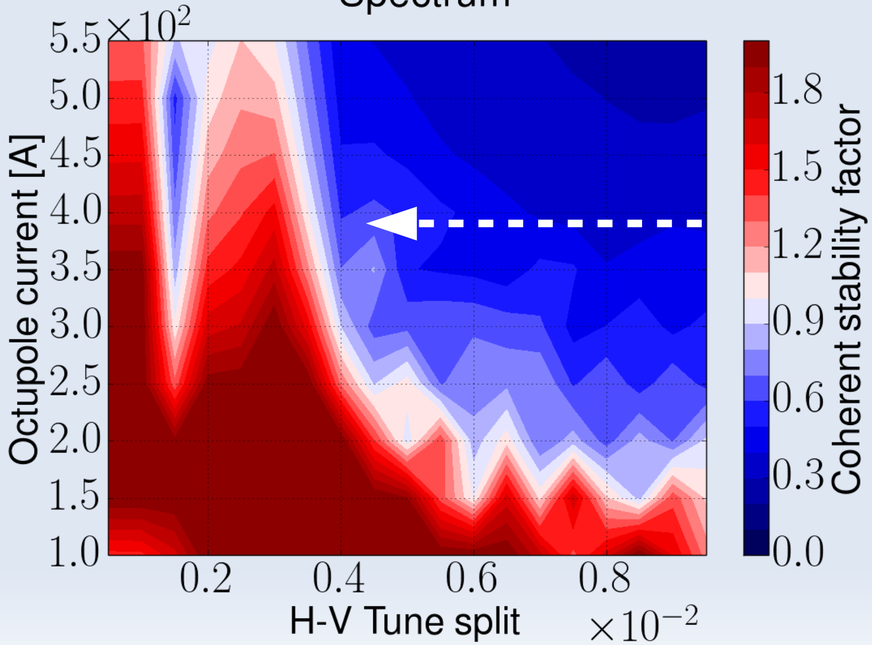

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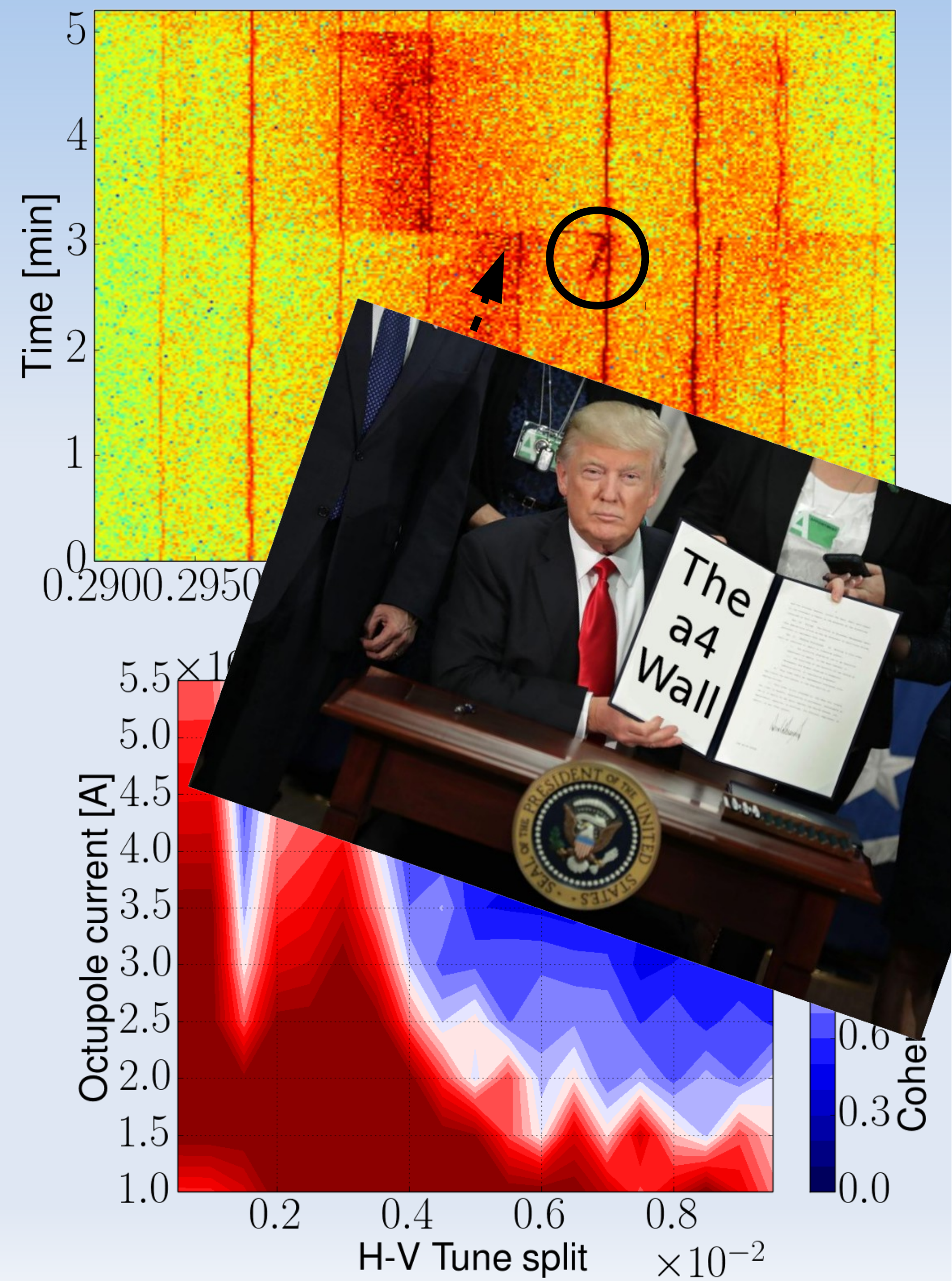

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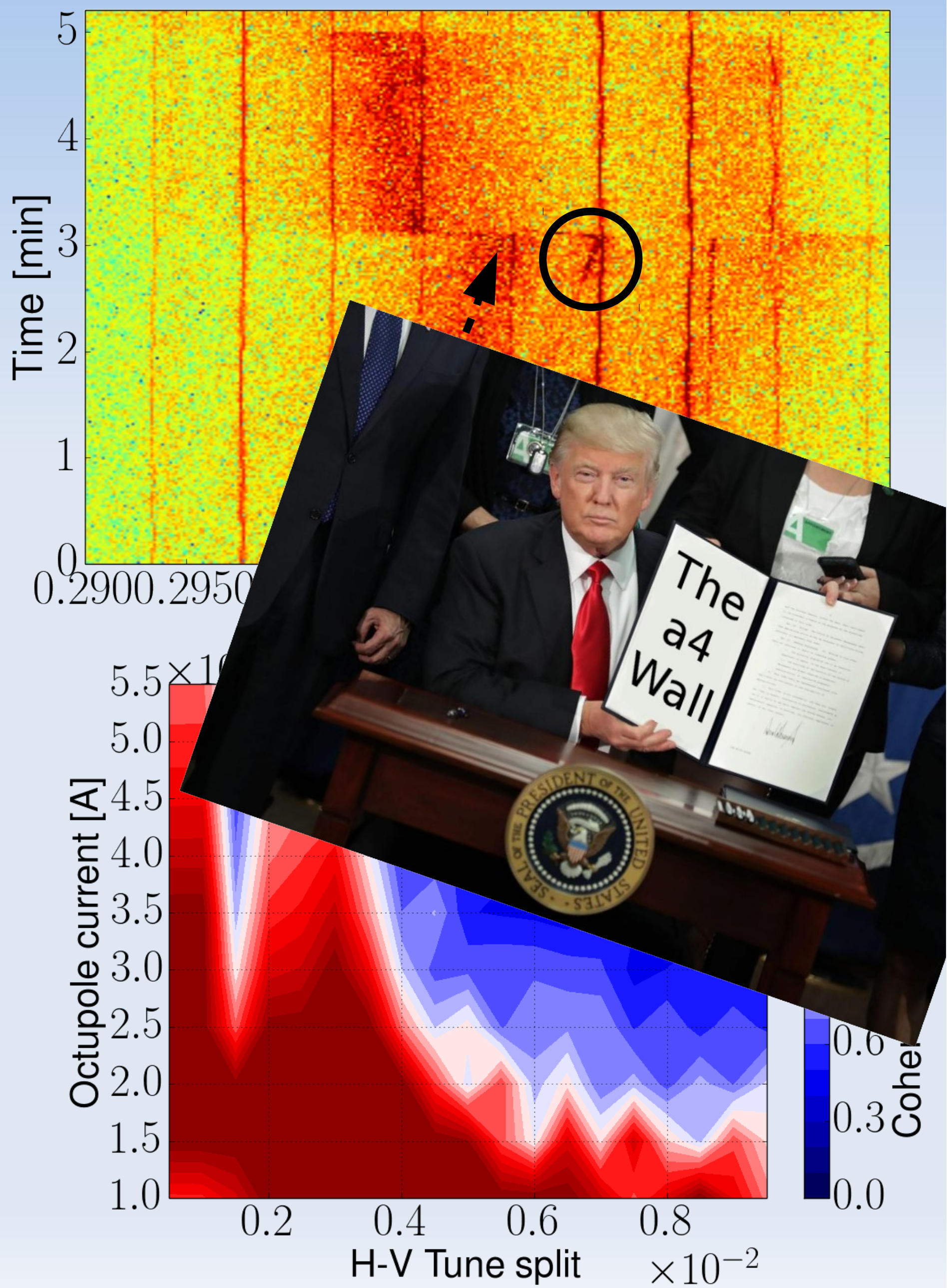

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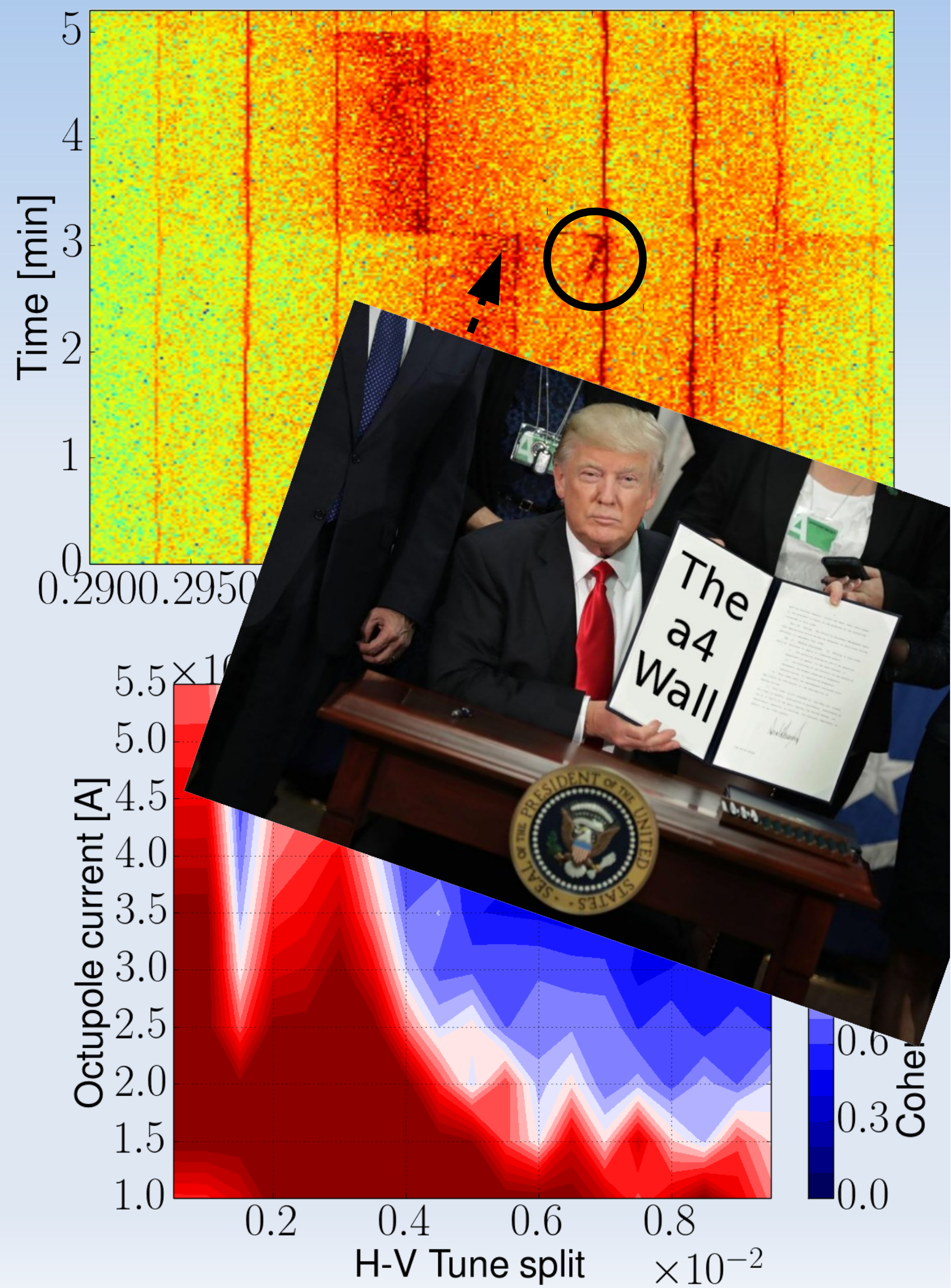
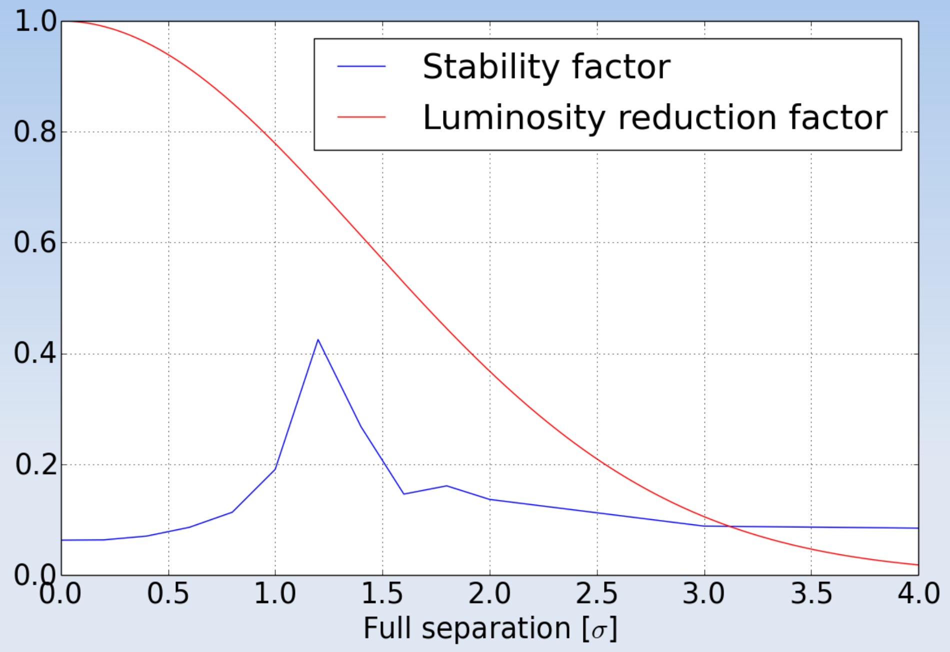
- The measured lattice non-linearities do not explain the discrepancy with the octupole threshold at flat top



VdM scans / offset levelling



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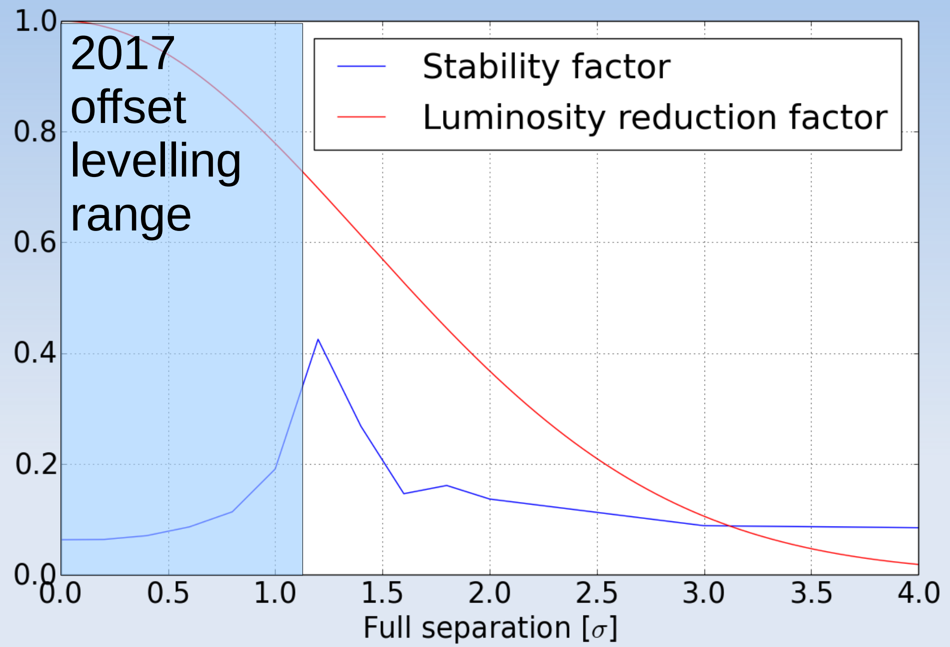
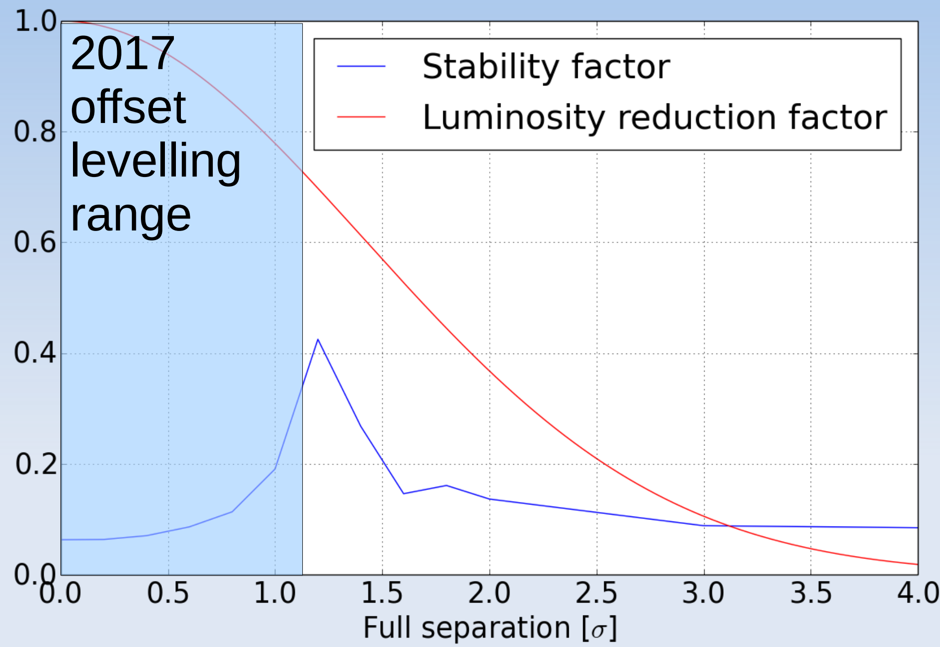
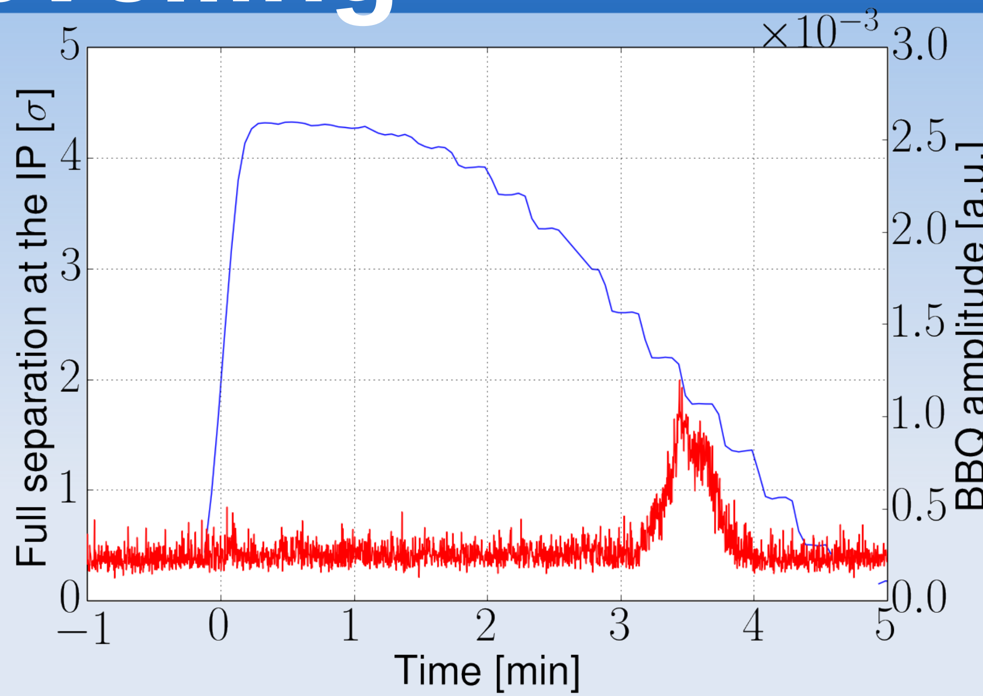


- No instabilities were observed due to offset levelling
  - The reduction of the stability diagram remained acceptable in this configuration with large octupole current
  - This would likely not have been possible without good control of coupling

VdM scans / offset levelling

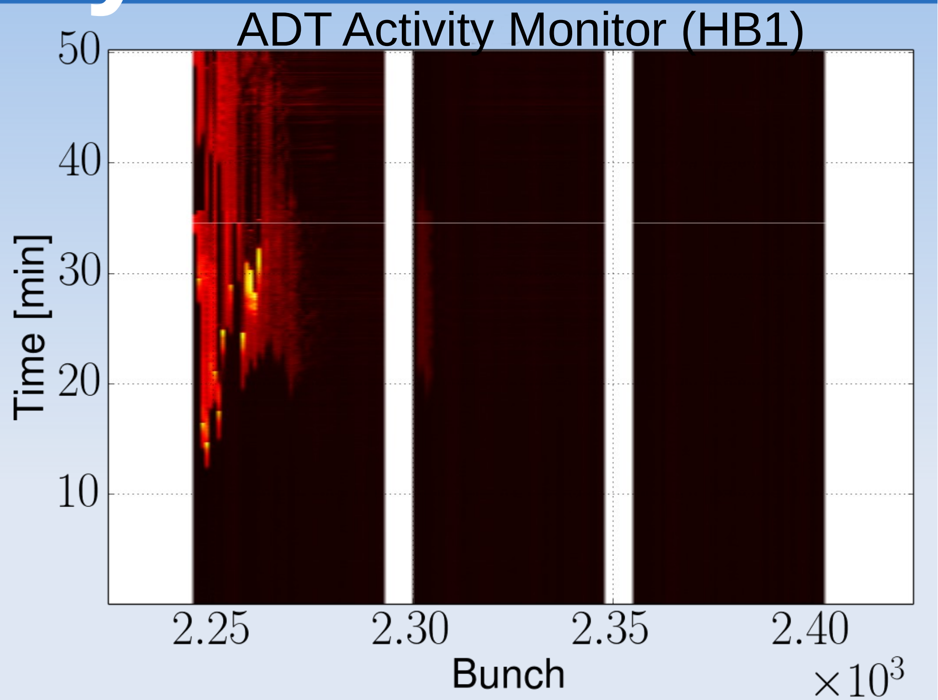




- No instabilities were observed due to offset levelling
  - The reduction of the stability diagram remained acceptable in this configuration with large octupole current
  - This would likely not have been possible without good control of coupling
- Instabilities were observed in VdM scans (Requirements : low octupole current, no other beam-beam interactions)
  - The best option that meets the requirement is relaxing the collimator settings

The Ghost Train instability

- Instabilities of the first bunches of the trains were observed in MDs during block 2 and 3 (BBLR and instability MD)



The Ghost Train instability

- Instabilities of the first bunches of the trains were observed in MDs during block 2 and 3 (BBLR and instability MD)
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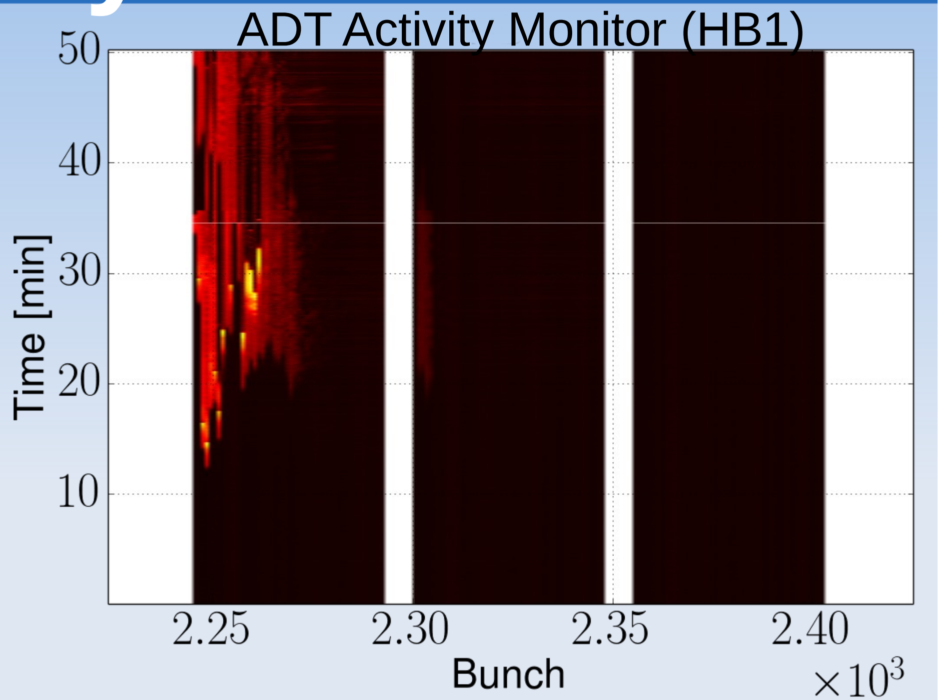

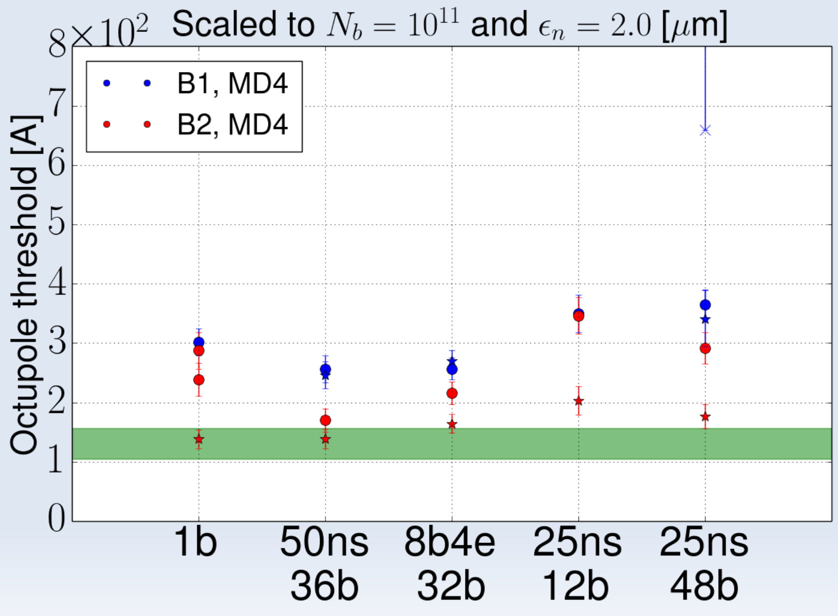

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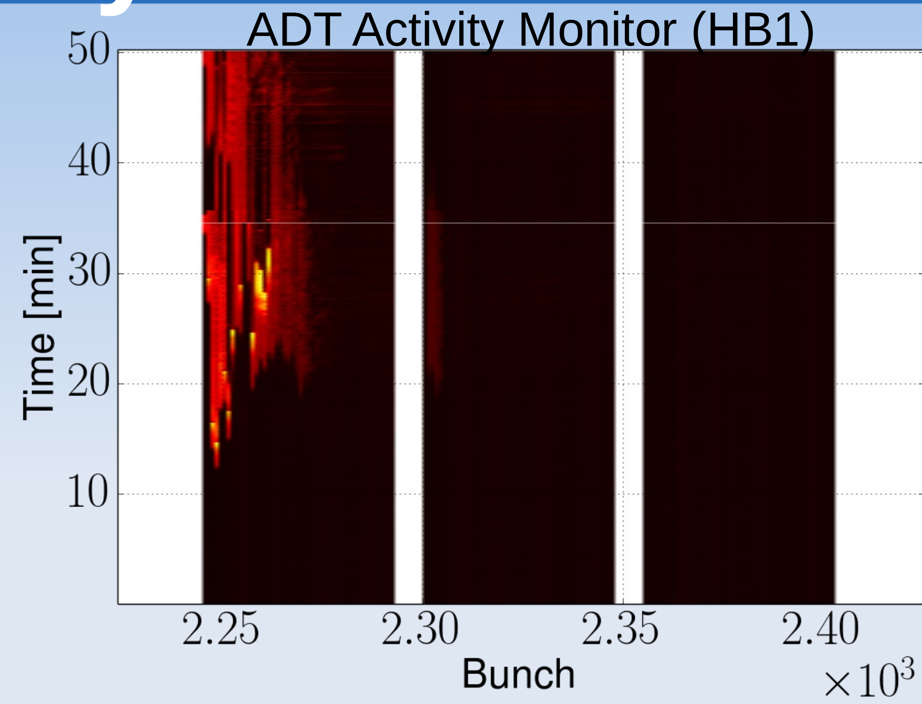

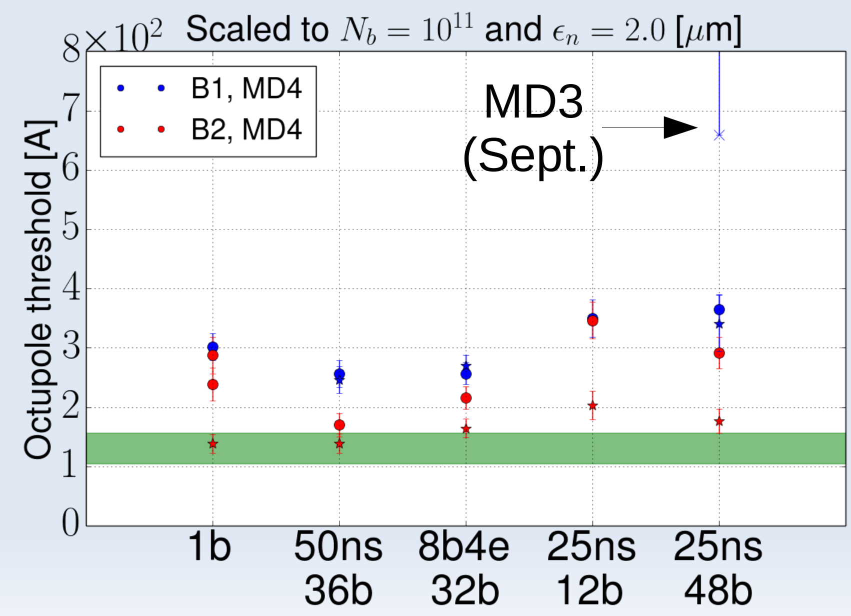

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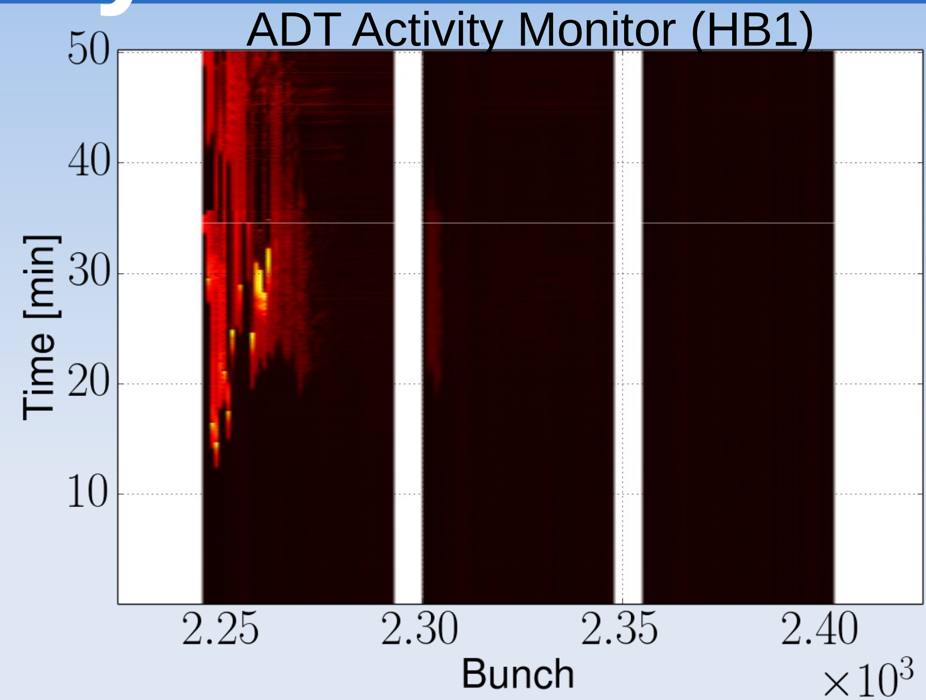

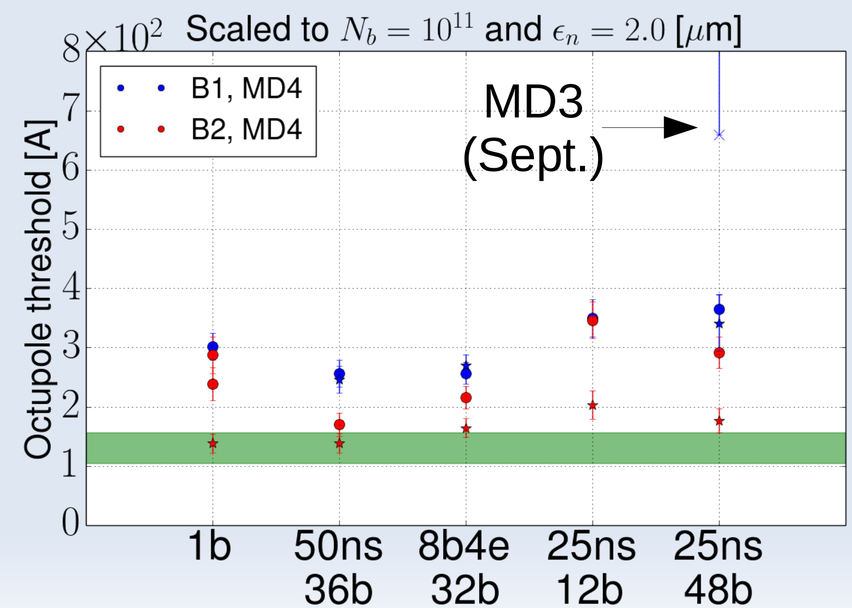

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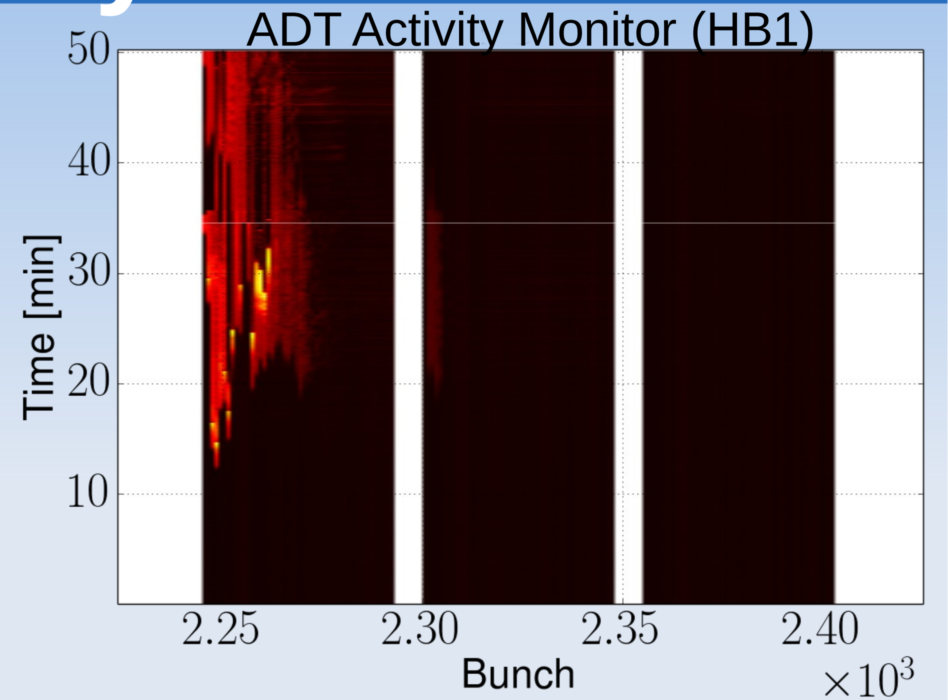

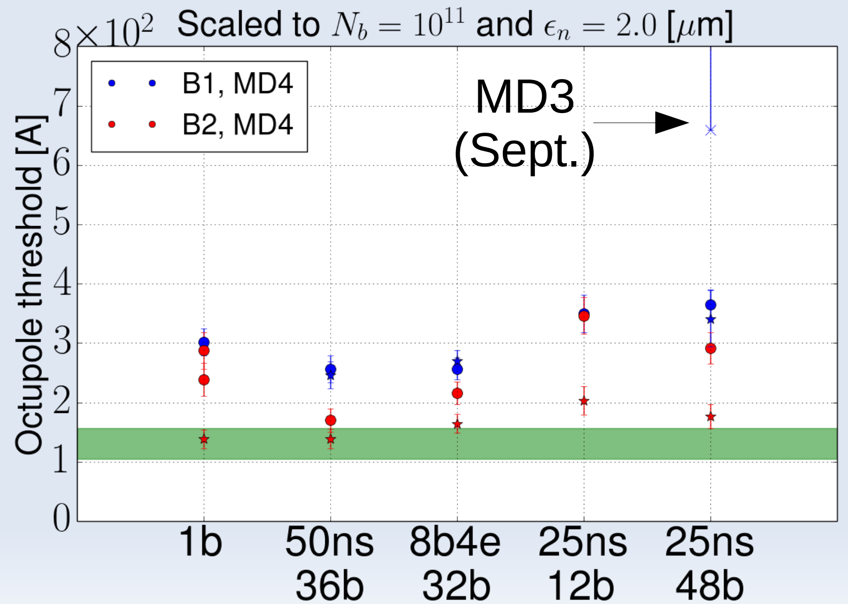

The Ghost Train instability

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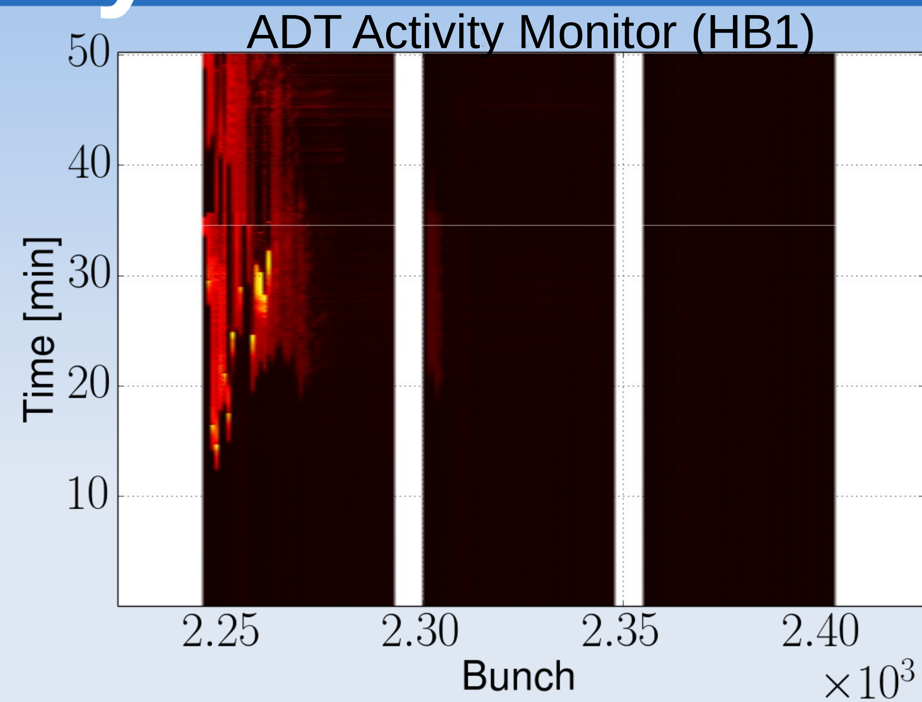
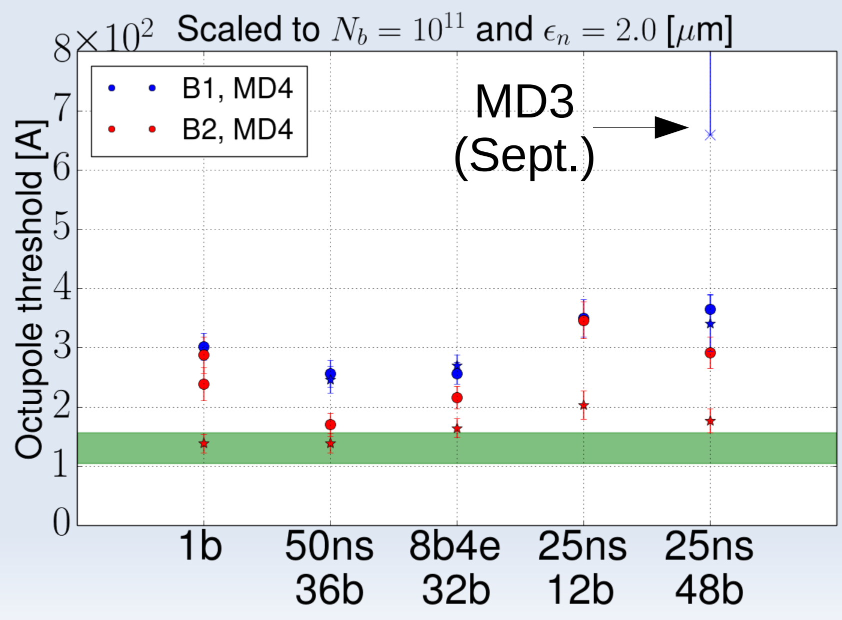
  - At the end of the squeeze B2 was stable w/o octupoles
  - Investigations in MDs allowed to rule out the effect *clearing* bunches/trains, of the full detuning scheme and of the low β*
- The effect was no longer observed in MD block 4 (BBLR and instability MD)
  - Conditioning ? Effect of the 16L2 solenoid?





- Instabilitie
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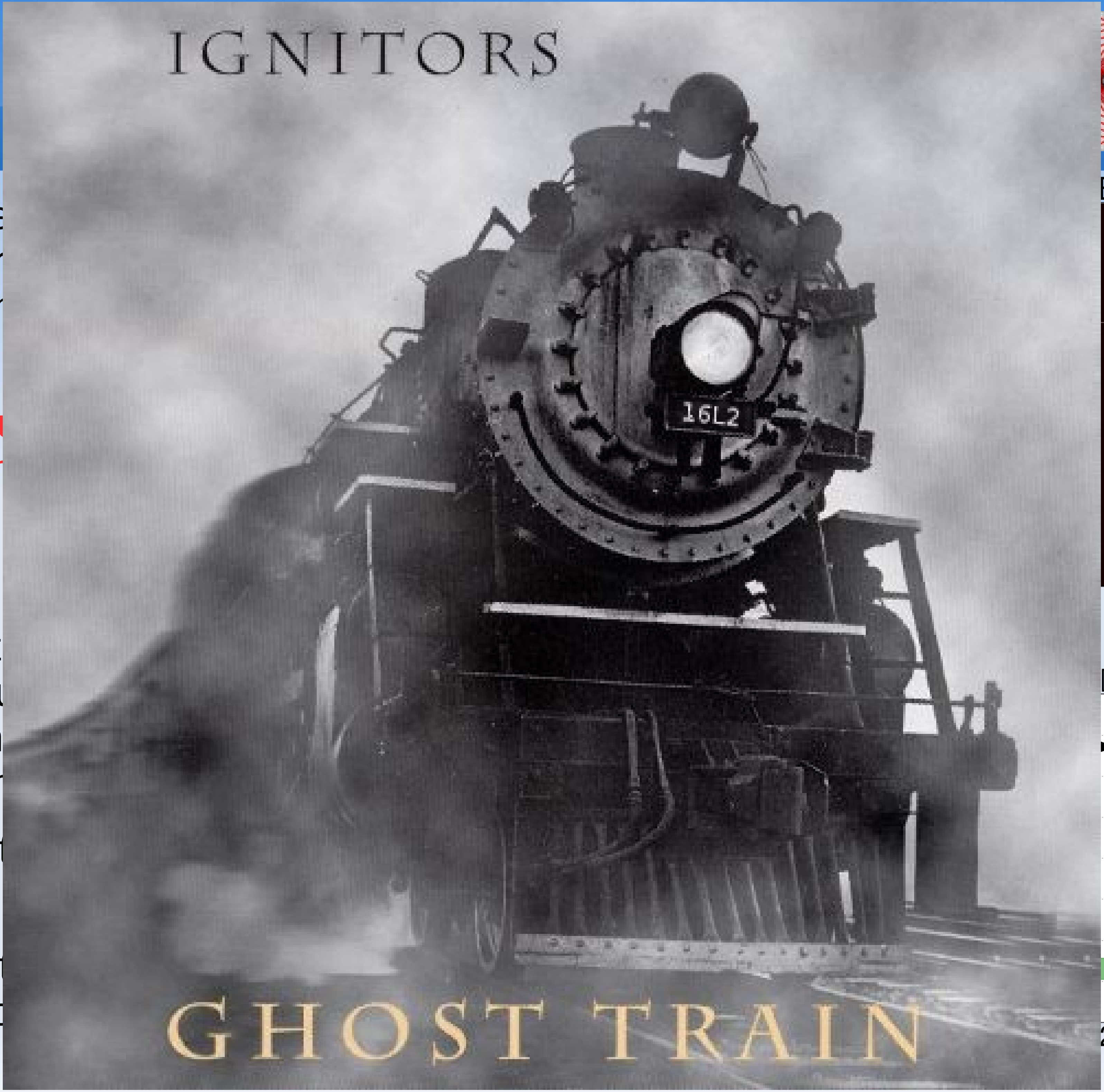
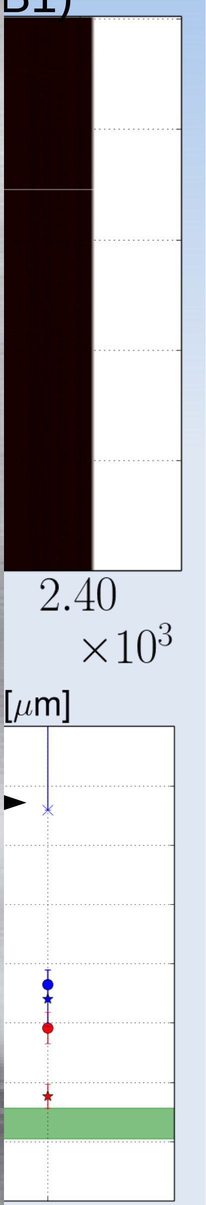




Strategy

Beam stability

Strategy

Beam stability

Understanding

Impedance
- Single bunch tune measurements
- Growth rate measurements

→ Beam based characterisation of individual contributors

E-cloud
- Good old recipe at injection (Q, Q', ADT, I_{oct})
- Investigate parameter space / instability mechanism
- Evolution of thresholds ((de-)conditioning)

Landau damping
- Octupole threshold measurement
- Beam transfer function
- AC dipole

→ Effect of beam-beam, e-cloud, lattice imperfections, tail distributions

Strategy

Beam stability

Understanding

Mitigation

Impedance
- Single bunch tune measurements
- Growth rate measurements

→ Beam based characterisation of individual contributors

Impedance reduction
- Collimator material
- Design of new elements

E-cloud
- Good old recipe at injection (Q, Q', ADT, I_{oct})
- Investigate parameter space / instability mechanism
- Evolution of thresholds ((de-)conditioning)

Machine control
- Online single bunch tune and coupling correction
- Non-linear optics correction
- Online detection and analysis

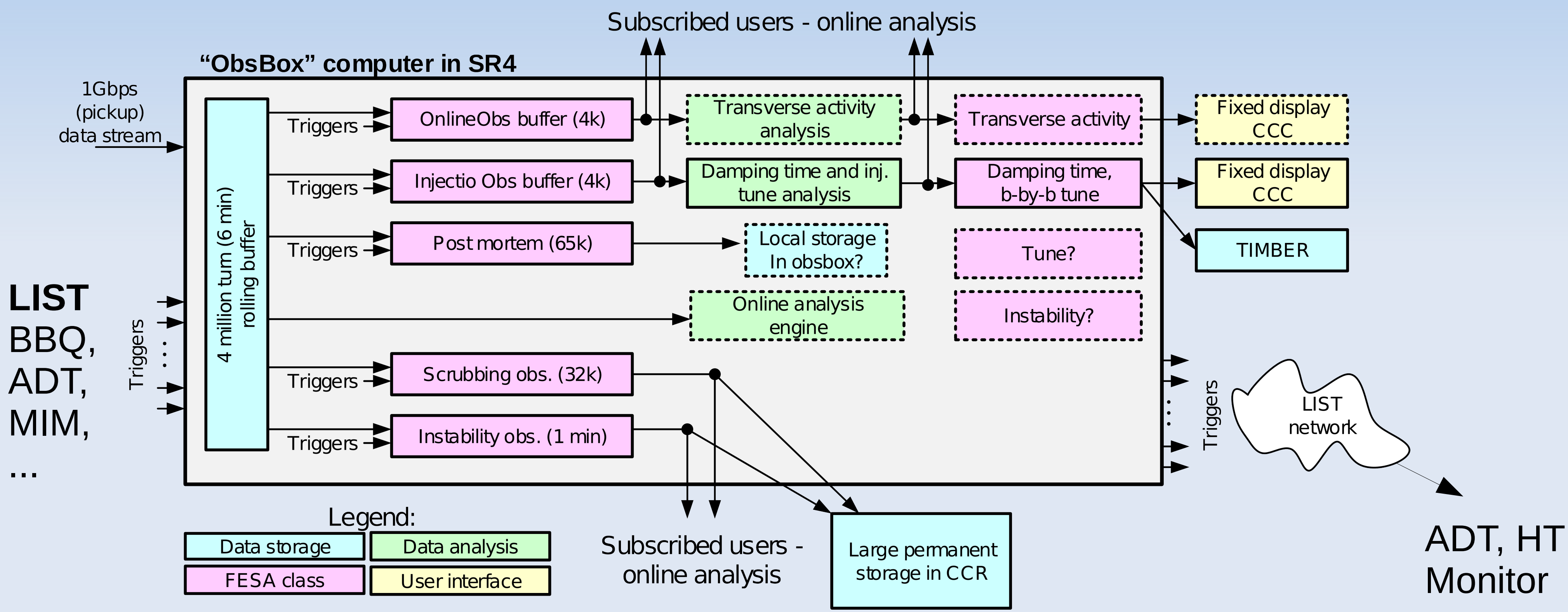
→ fast reaction to operational changes

Landau damping
- Octupole threshold measurement
- Beam transfer function
- AC dipole

→ Effect of beam-beam, e-cloud, lattice imperfections, tail distributions

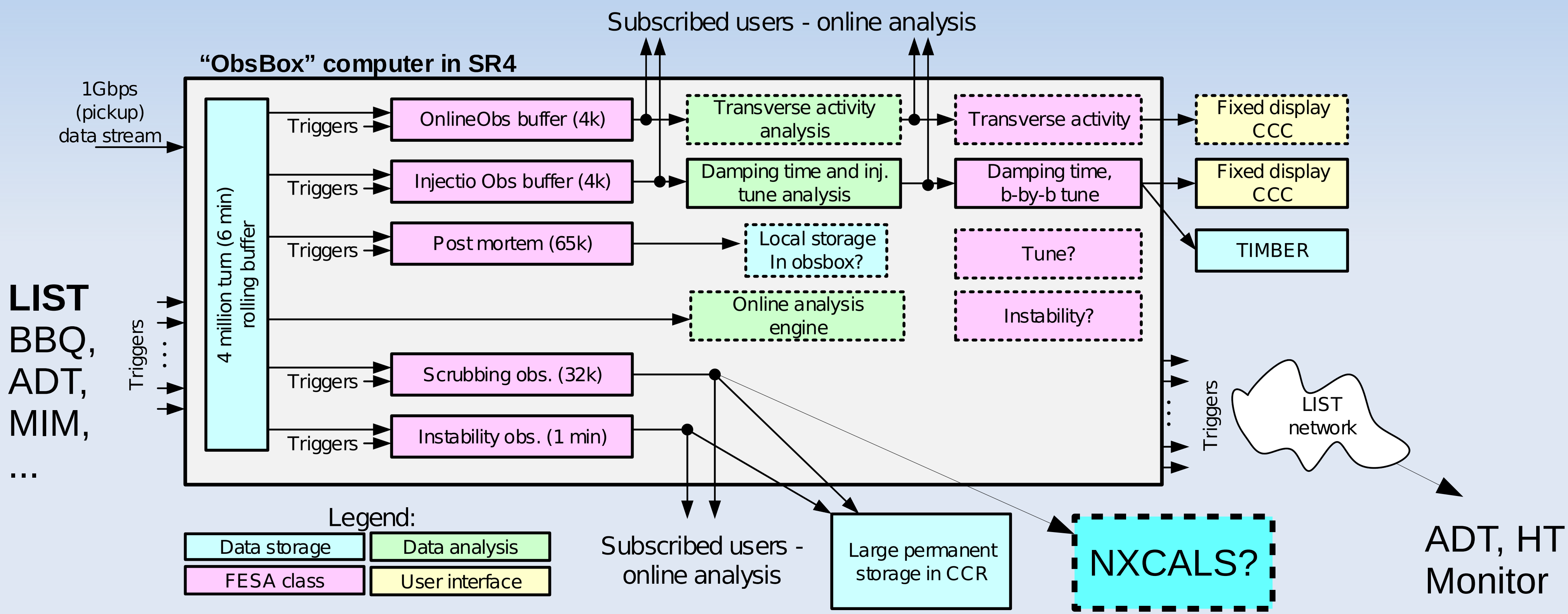
Operational procedures
- Ramp and ATS
- β* levelling
- Collimator mouvement in collision

ADTObsBox



Subscribed users - online analysis
"ObsBox" computer in SR4
1Gbps
(pickup)
data stream
4 million turn (6 min)
rolling buffer
Triggers
OnlineObs buffer (4k)
Injectio Obs buffer (4k)
Post mortem (65k)
Scrubbing obs. (32k)
Instability obs. (1 min)
Transverse activity
analysis
Damping time and inj.
tune analysis
Local storage
In obsbox?
Online analysis
engine
Transverse activity
Damping time,
b-by-b tune
Tune?
Instability?
Fixed display
CCC
Fixed display
CCC
TIMBER
LIST
BBQ,
ADT,
MIM,
...
Triggers
Triggers
LIST
network
ADT, HT
Monitor
Legend:
Data storage
Data analysis
FESA class
User interface
Subscribed users -
online analysis
Large permanent
storage in CCR

ADTObsBox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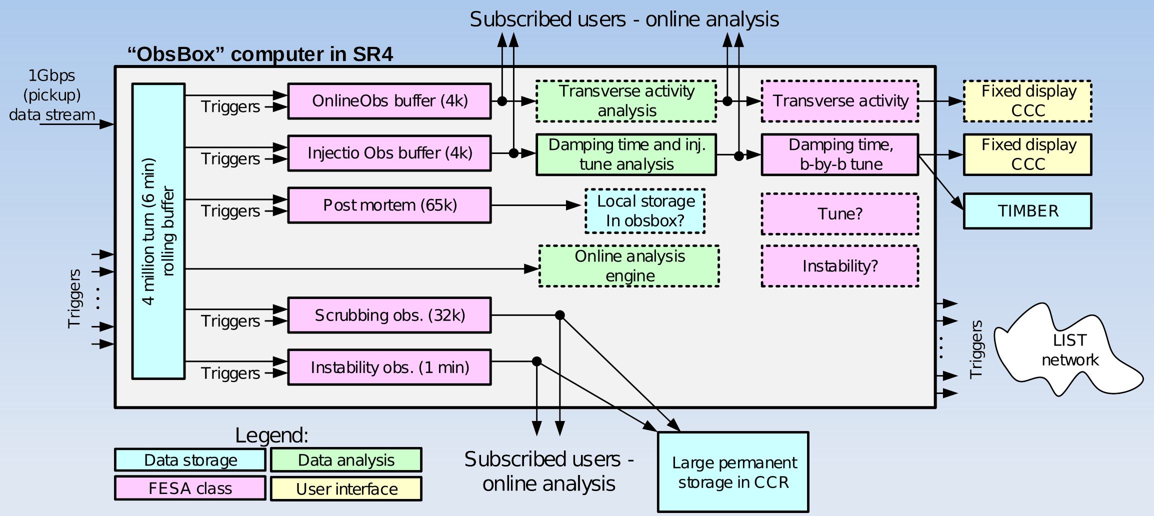
ADTObsBox



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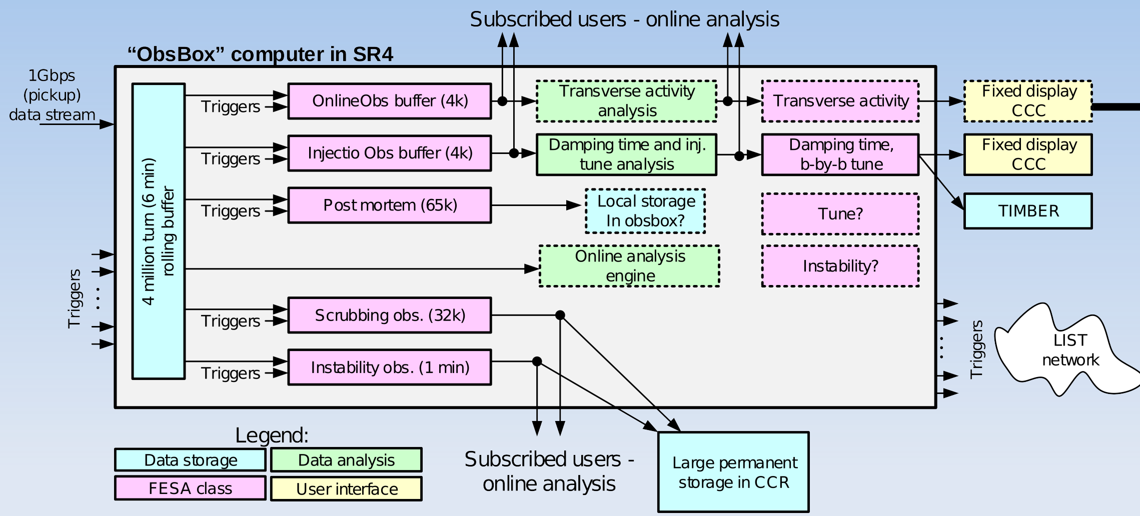
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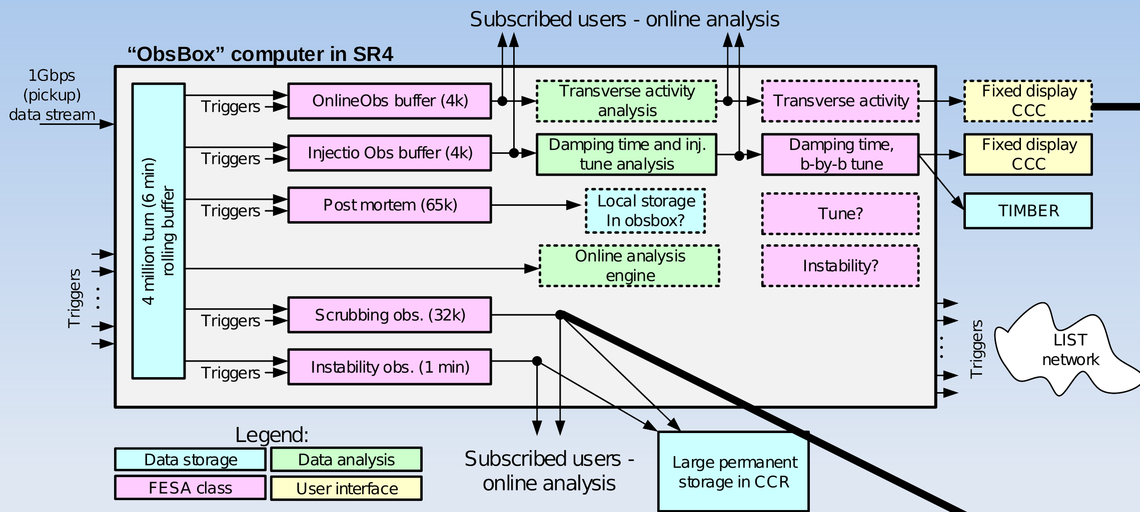
ADT Activity Monitor
Reset BbB Max
Reset History
Peak Activity
Activity by bunch
HO IP1/5
B1 new bunches
HO IP2 or 8
HO IP1/5
25 ns slot
Activity [A.U.]

ADTObsBox



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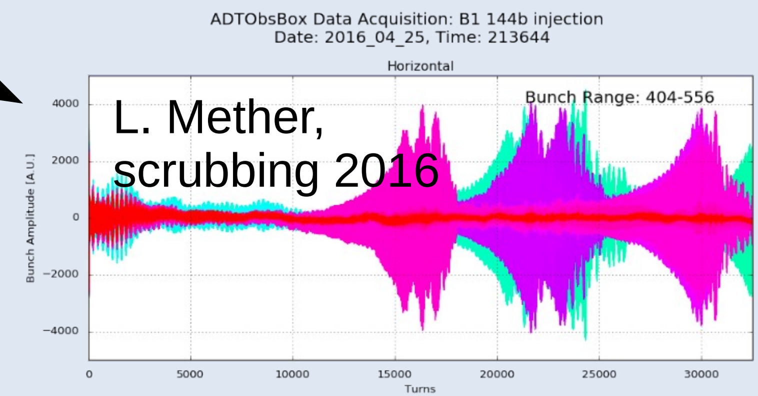

ADTObsBox Data Acquisition: B1 144b injection
Date: 2016_04_25, Time: 213644
Horizontal
Bunch Range: 404-556
L. Mether, scrubbing 2016
Bunch Amplitude [A.U.]
Turns

ADTObsBox

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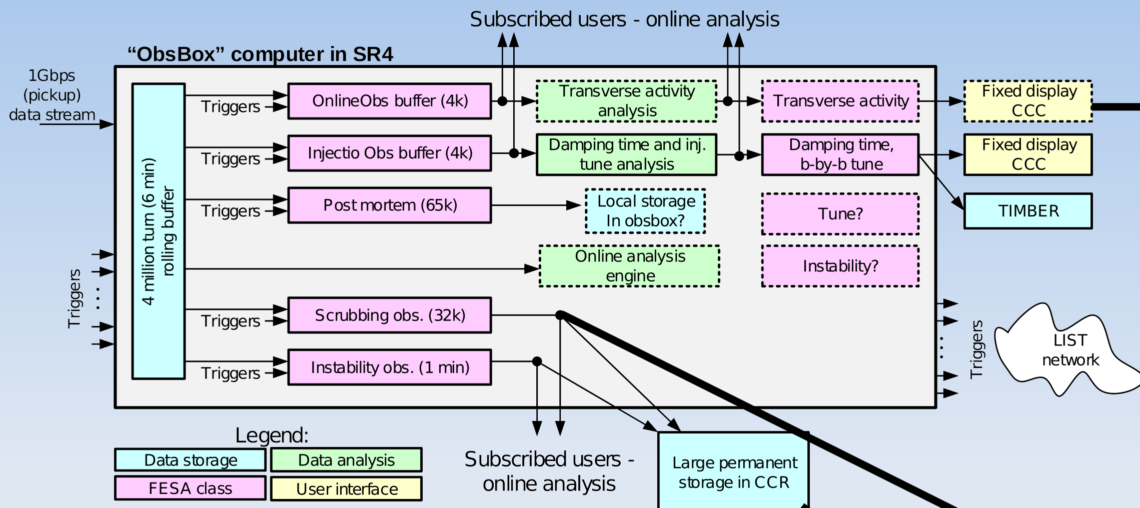
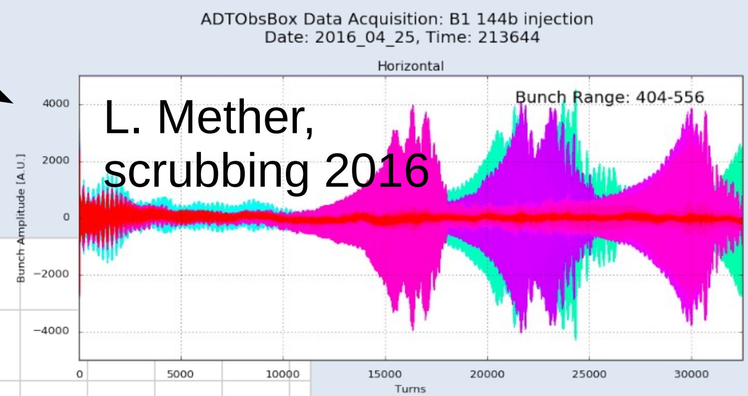
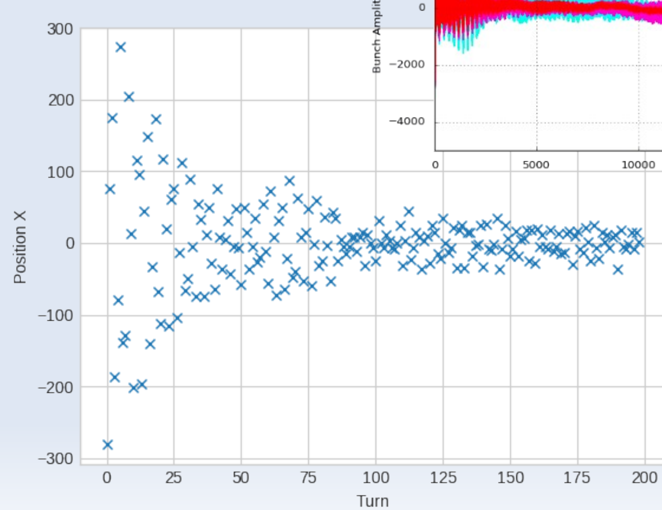
Turn

ADTObsBox







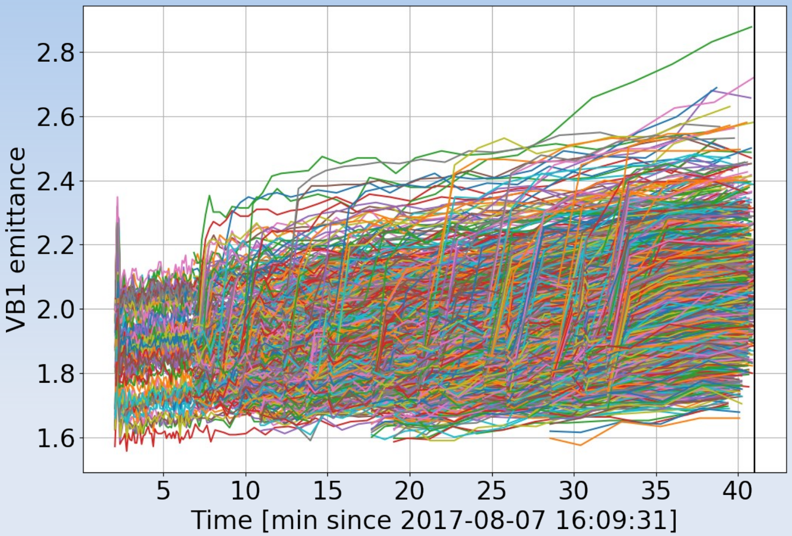
- Very versatile and useful device, its potential is not yet fully exploited
  - → Fine tuning of instability detection
  - → Improve data post processing and filtering
  - → Automatise now standard measurements
  - → New analysis adapting to *Menu Surprise* of next year

Conclusion

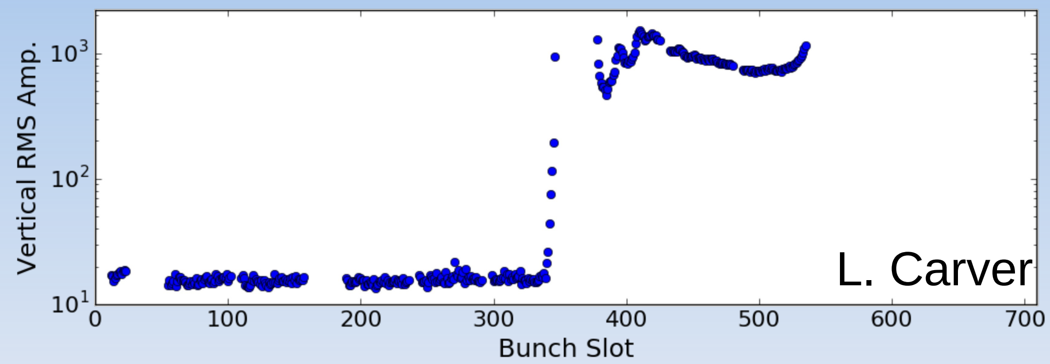
- **Collective effects (16L2 aside) were not a limitation for the LHC in 2017**
  - A balance between coherent and incoherent effects has to be found empirically at injection
  - Significant discrepancies with the beam stability model at flat top remains tolerable, but are not compatible with LIU beams
- **Tune and coupling measurement have improved the robustness of the LHC against loss of Landau damping**
  - Successfully operated with offset levelling, **with** strong octupoles
  - Non-linear corrections are needed to allow tune optimisation (ADJUST and stable beam)
- **New tools dedicated to instability studies have allowed significant progress in the follow up of instabilities during operation and in the understanding of the discrepancies with the models**
  - Fine tuning and software developments are still needed
  - Excitation capabilities are fundamental for several studies, the tools need to be automatised (single bunch kick, ADT-AC dipole)
- **We need to prepare (mainly with MDs) in order to cope with LIU beams in case the stability threshold cannot be reduced (RATS, β* levelling with collimator mouvements)**

BACKUP - Injection
Observations of coherent motion

Fill 6054



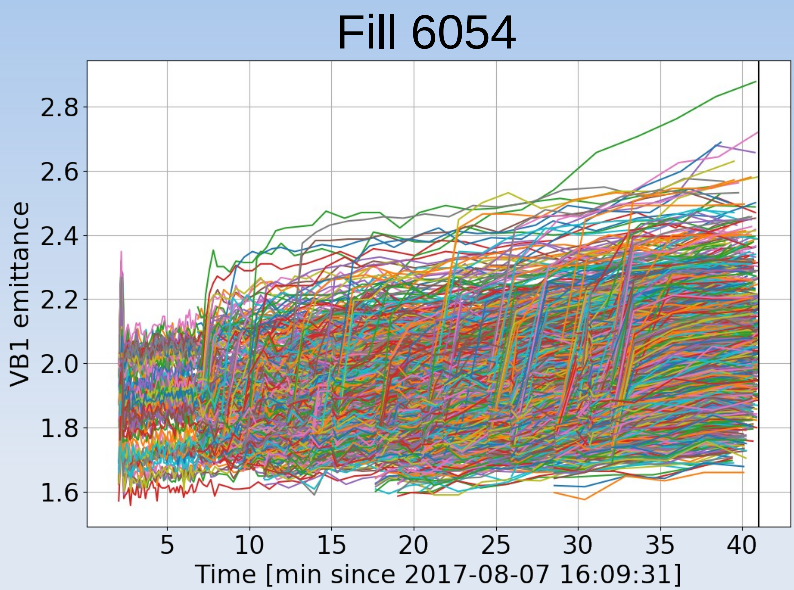
ADT ObsBox – Fill 6054

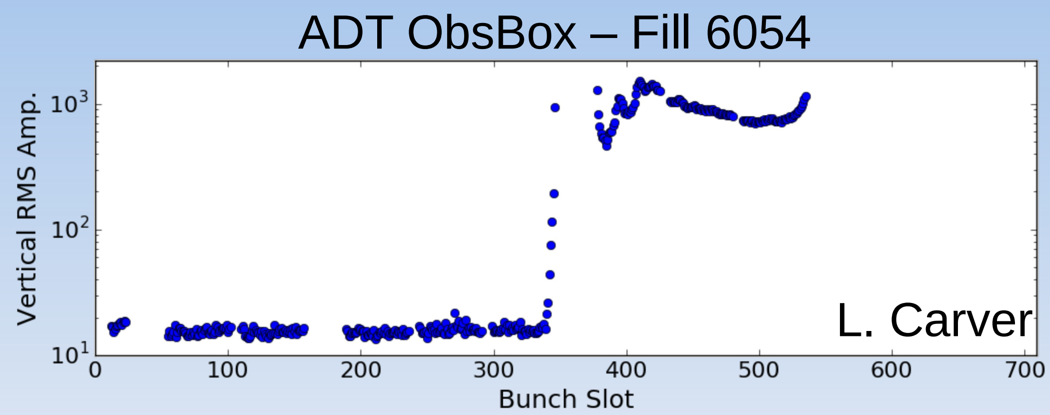


- The MKI kicks 2-3 last circulating bunches in the vertical plane resulting in emittance blowup
  - Allows the injection of more bunches

BACKUP - Injection

Observations of coherent motion





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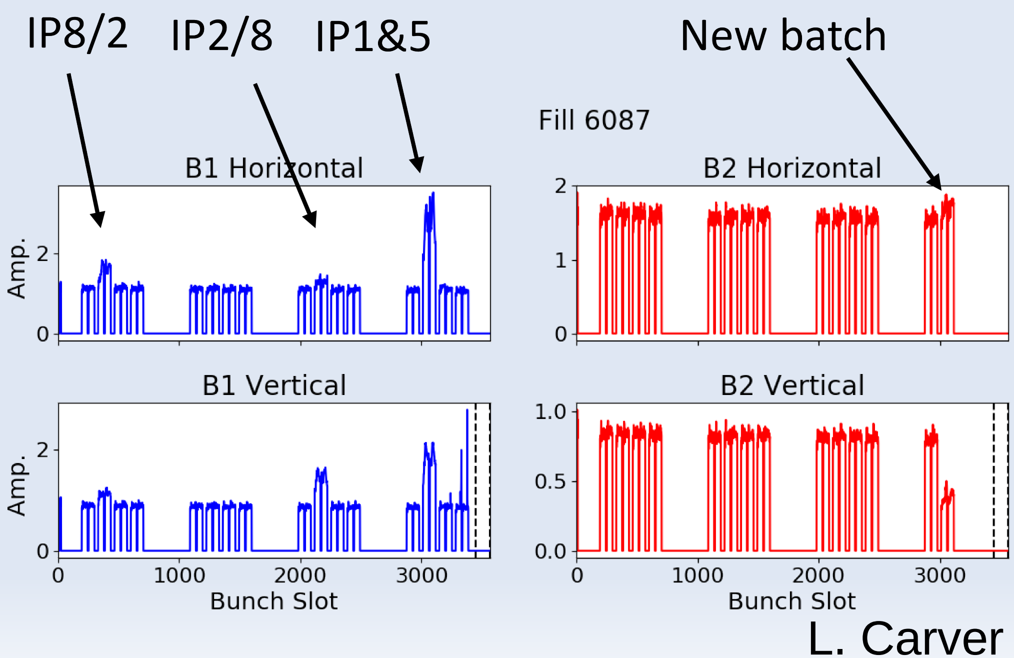
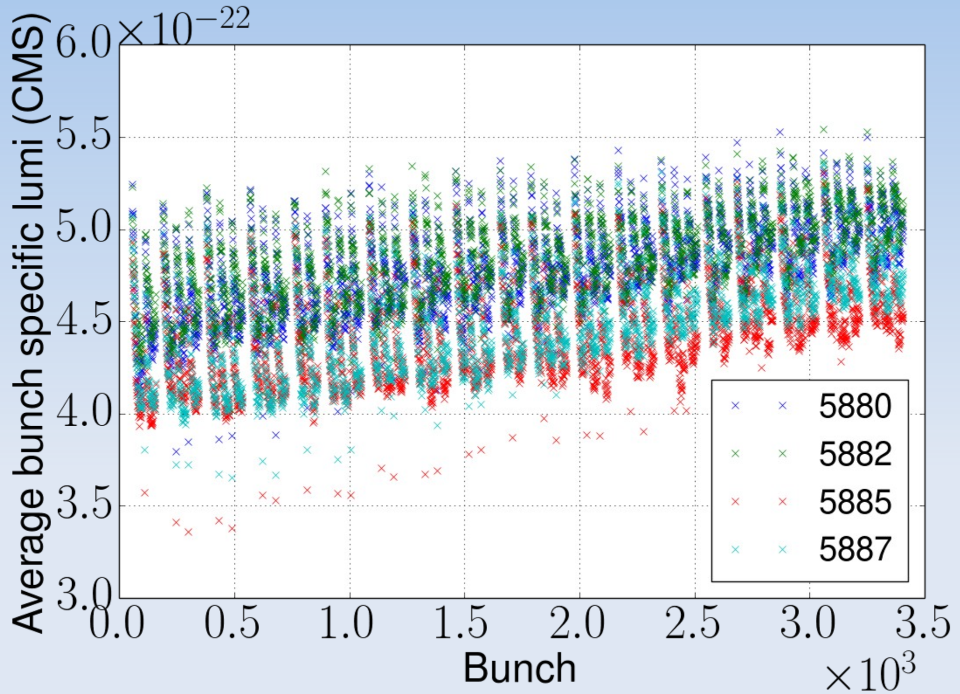
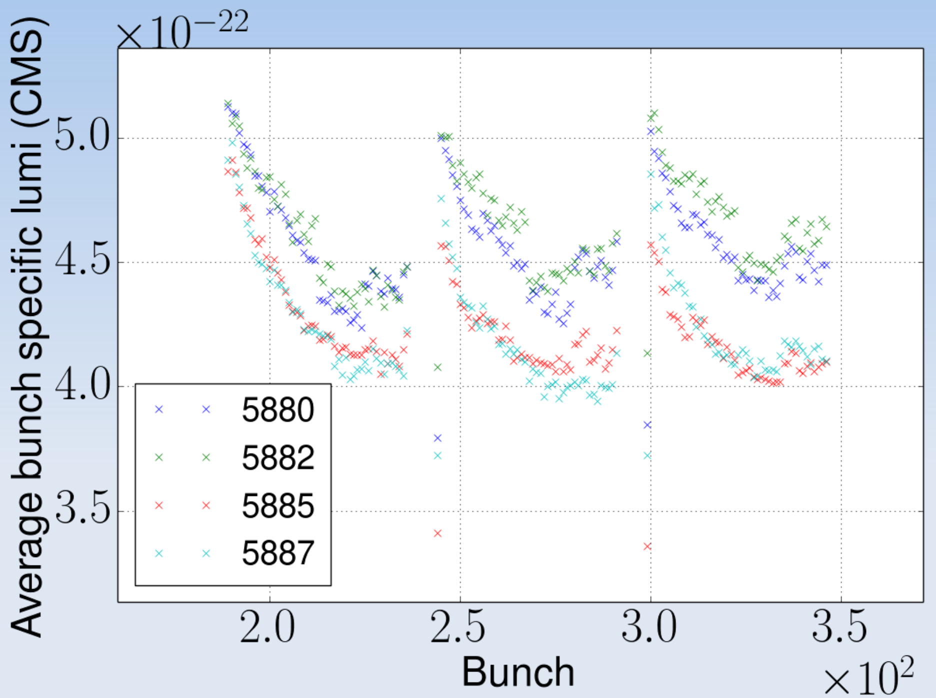


- The injection oscillations of one beam are seen as an excitation by the other through long-range beam-beam interactions
  - No evident impact on the emittance

Bunch by bunch specific luminosity at start of stable beam

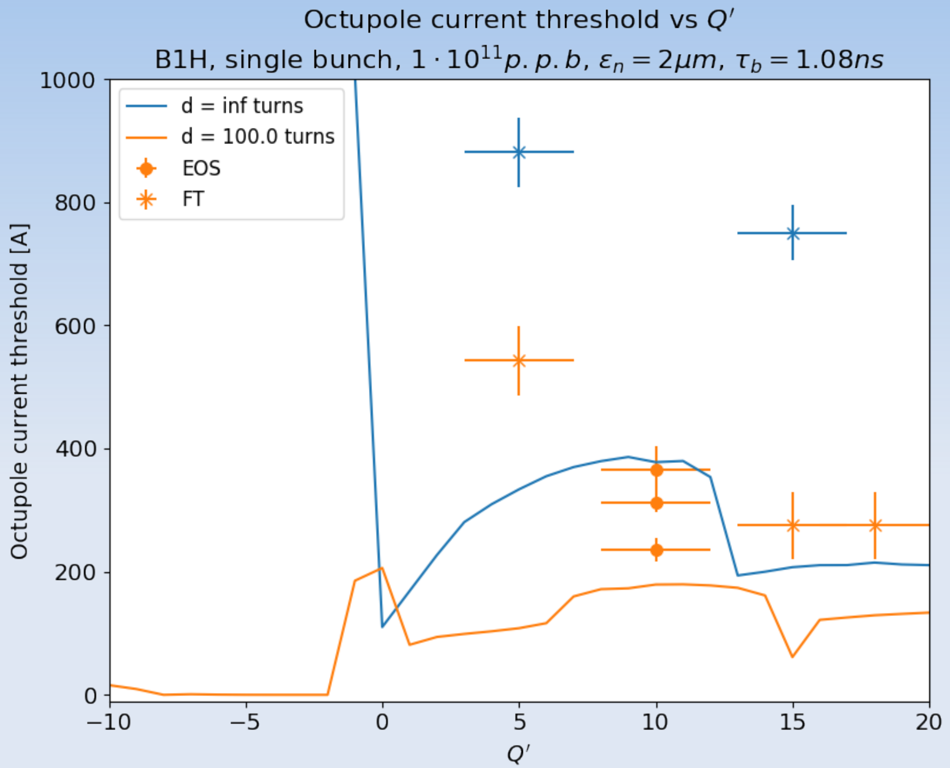


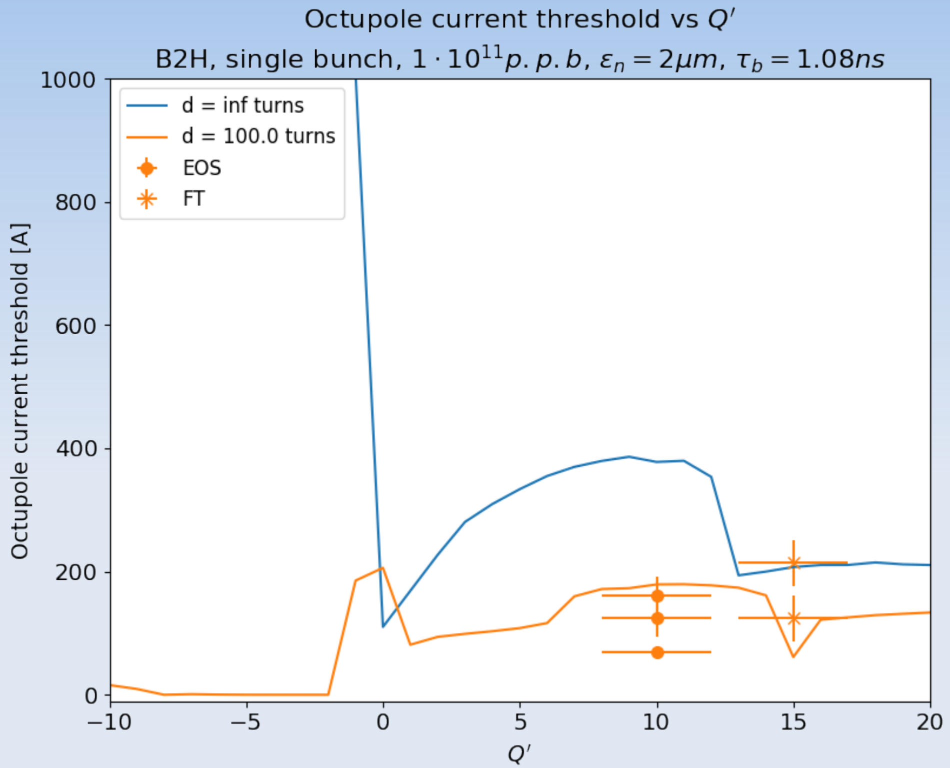


- The e-cloud pattern as well as the correlation with the time spent at injection is clear in the specific luminosity
  - The last two fills before TS1 with Q'=20 in B1 are slightly worse for all bunches
  - Coherent instabilities of few bunches were observed with Q'=10
- First bunch of all PS batch except for the first in the SPS train blow up significantly faster than others → anomalous bunches
- A potential gain of ~15% of the peak luminosity can be achieved if all bunches would behave as the best one

BACKUP

Single bunch octupole threshold

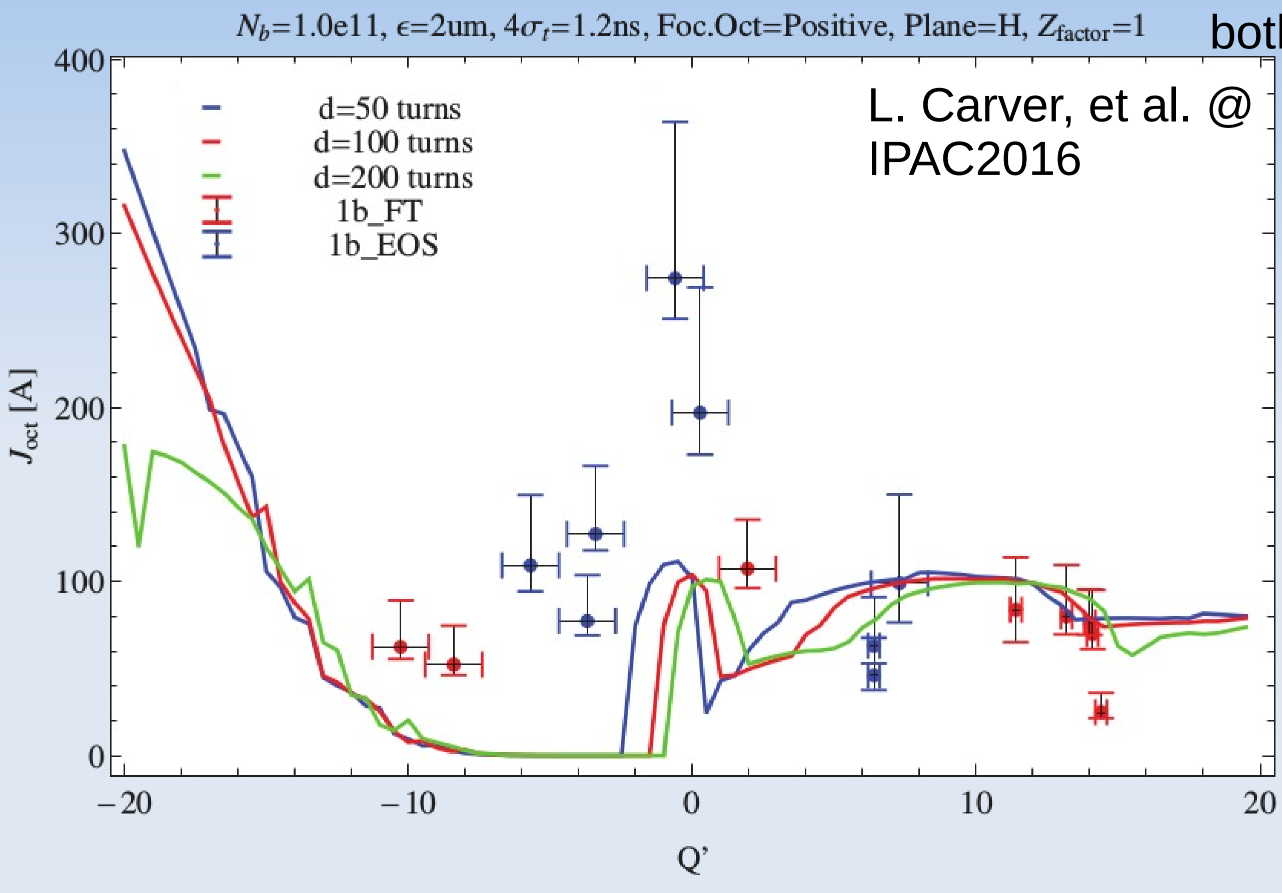




- For B1, the octupole threshold in the horizontal plane seem underestimated by a factor 2 to 4 at flat top, slightly reduced at the end of the squeeze, with and w/o ADT
- For B2, the thresholds are closer to predictions

Backup
Single bunch threshold 2015

Horizontal, both beams

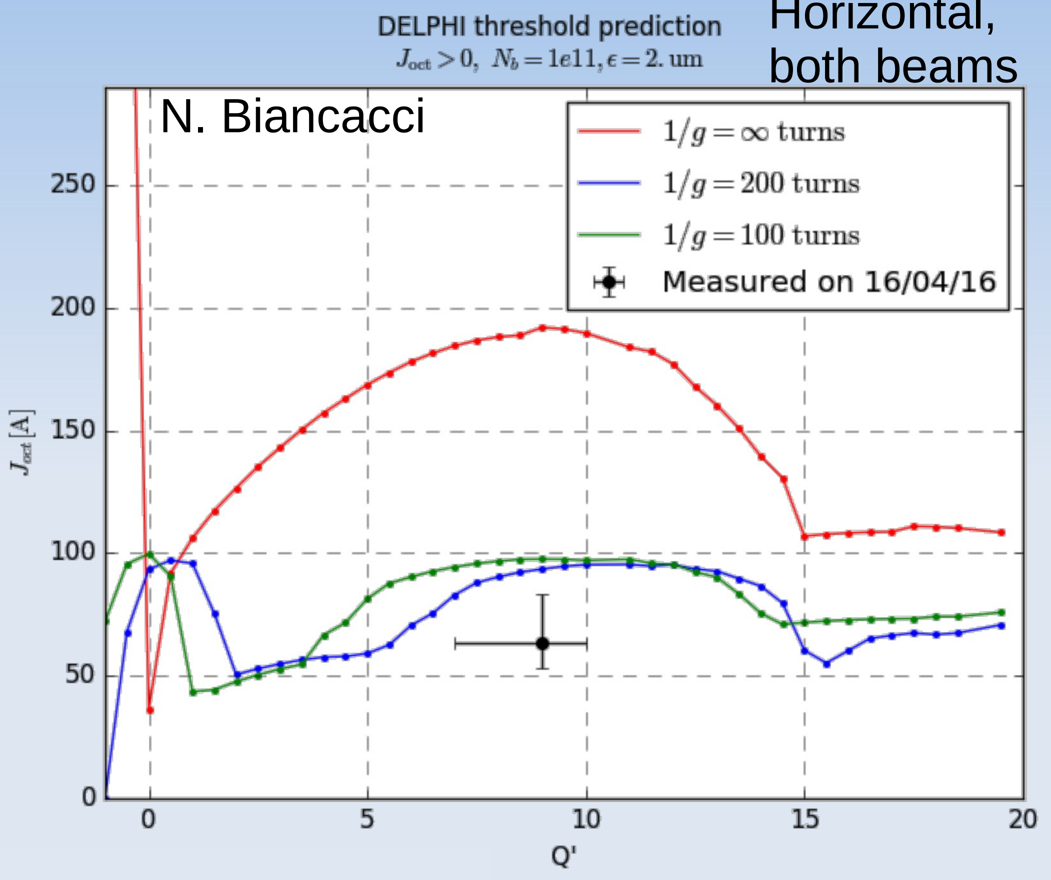


- Good agreement between observed and predicted octupole current requirement with operational Q' at flat top and at the end of the squeeze

Std Optics	IPs 1&5	IP2	IP8
β* Flat top [m]	11	10	10
β* Squeezed [m]	0.8	10	3.0
Half crossing (ext.) [μrad]	145	120	250

BACKUP

Single bunch threshold 2016



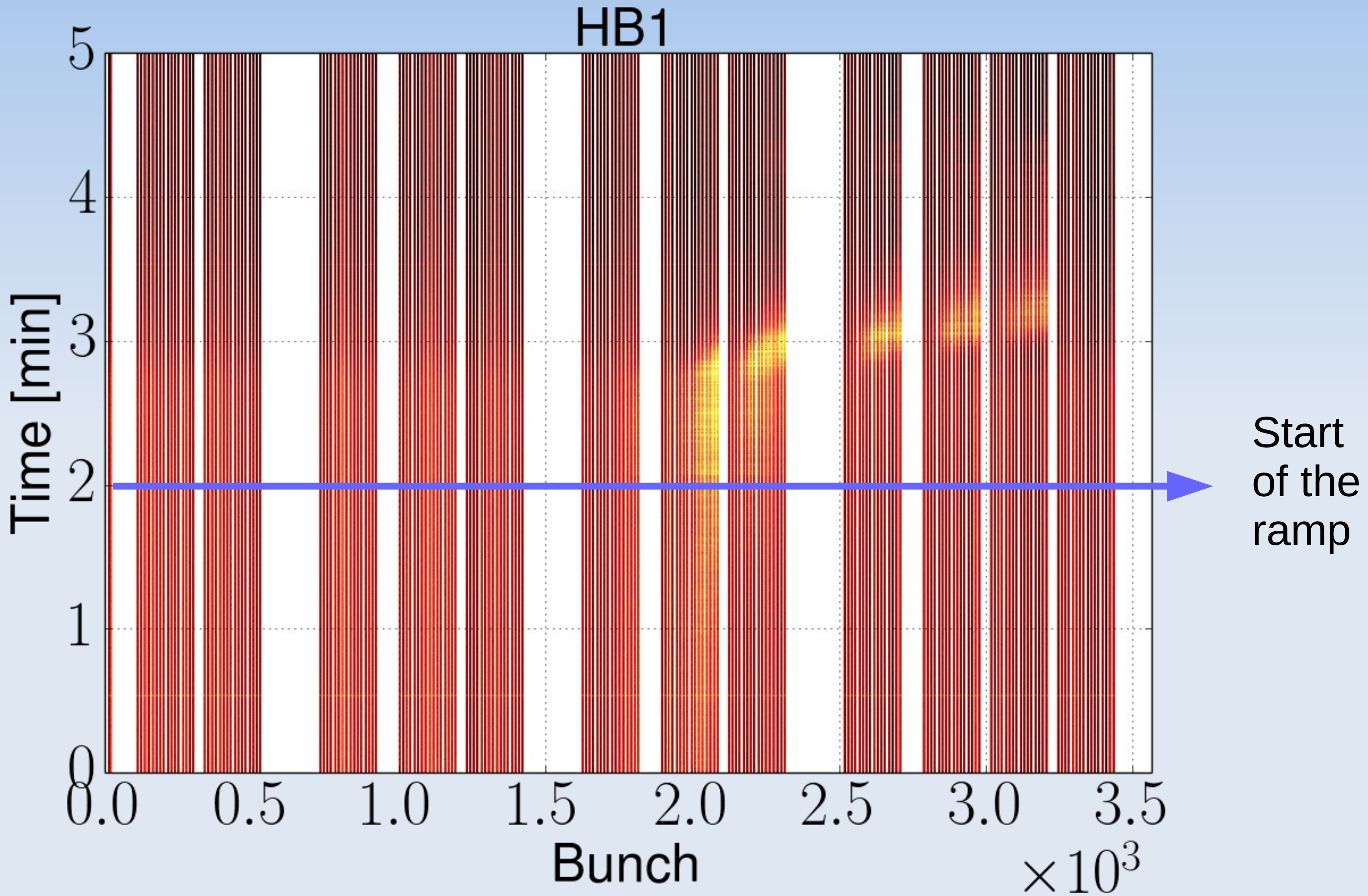
- Good agreement between observations and predictions with operational Q', at flat top
- Important effects of the non-linearities and Q'' observed at the end of the squeeze
- Few unexplained instabilities during and after the execution of the TOTEM bump (Vertical B1)

Std Optics	IPs 1&5	IP2	IP8
β* Flat top [m]	3.0	10	6.0
β* Squeezed [m]	0.4	10	3.0
Half crossing (ext.) [μrad]	185	200	250

+ TOTEM bump in ADJUST

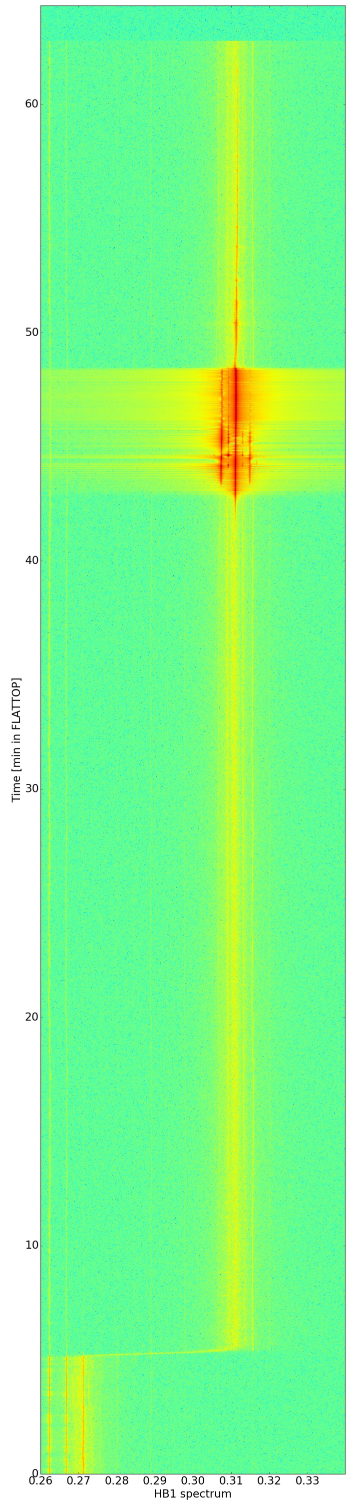
BACKUP

Transverse activity during the ramp



- A larger transverse activity was observed at the start of the ramp during fill 6399
  - No significant impact on the emittances

Fill 5665 – High latency instability at flat top



- A single nominal of B1 became unstable in the horizontal plane
- Latency of 40 minutes with respect to the tune change
  - No changes on B1 (loss maps on B2)
  - Q' or |C-| decay is too small at flat top to explain the latency (M. Solfaroli, T. Persson)
  - Longitudinal and transverse emittance decay are not sufficient to explain the instability
- BBQ trigger, LIST and HT acquisition worked perfectly (many thanks to BI en in particular T. Levens)

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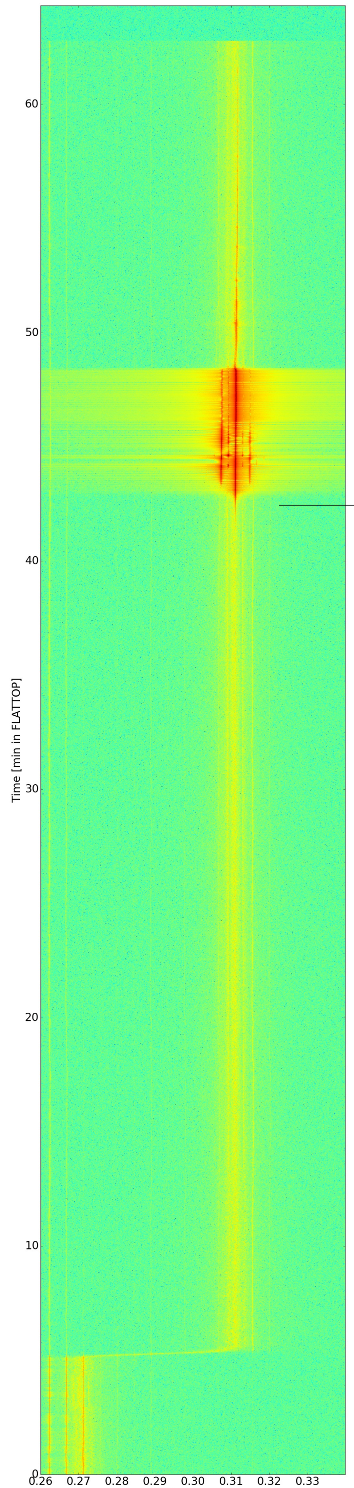
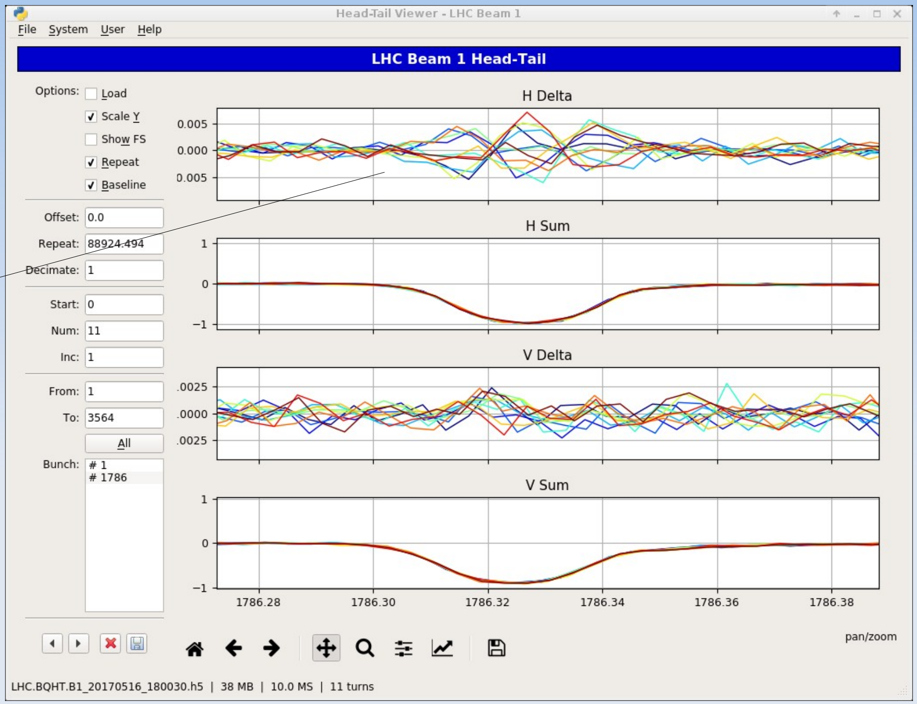


(0,2)



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BACKUP
Settings proposal

- Assumed an emittance at flat top of the best injected emittance (ε) + 0.5 μrad
- Assumed that the reduction of the secondaries from 6.5 to 6.0 σ leads to an increase of 20% of the threshold (conservative)

H. Bartosik **LHC physics beam menu for 2018**

	Intensity [1e11 p/b]	Emittance [um]	pattern	Octupole current at flat top [A] 6.5σ	6.0σ
25 ns standard (like 2017)	1.15	2.5 (2.4)	1-4 x 72 → 288	317	381
25 ns standard (high intensity)	1.30	2.8 (2.7)	1-4 x 72 → 288	325	390
25 ns BCMS (like 2017)	1.15	1.7 (1.4)	1-3 x 48 → 144	484	581
25 ns BCMS (high intensity)	1.30	1.9 (1.6)	1-3 x 48 → 144	495	594
25ns BCS (like 2017)	1.25	1.15 (1.0)	1-4 x 32 → 128	666	800
25ns BCS (high intensity)	1.30	1.20 (1.0)	1-4 x 32 → 128	693	832
8b4e (like 2017)	1.20	1.8 (1.6)	1-3 x 56 → 168	457	548
8b4e (high intensity)	1.60	2.4 (2.1)	1-3 x 56 → 168	492	590
8b4e BCS (like 2017)	1.25	1.15 (1.0)	1-4 x 32 → 128	500	600
8b4e BCS (high intensity)	1.60	1.55 (1.2)	1-4 x 32 → 128	565	677

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- ADT gain at 50 turns at top energy (16L2 boost of the gain not needed anymore)

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- ADT gain at 50 turns at top energy (16L2 boost of the gain not needed anymore)
- Chromaticity at 15 for the full cycle, possibly to be reduced to 5 units in collision