Special Losses

D. Mirarchi

On behalf of many colleagues from:

BE-ABP, BE-BI, BE-OP, BE-RF, EN-SMM, EN-STI, TE-CRG, TE-MPE, TE-VSC

D. Amorim, G. Arduini, N. Biancacci, E. Bravin, G. Bregliozzi, X. Buffat, R. Bruce, P. Chiggiato, P. Collier, L. Carver, M. Giovannozzi, A. Gorzawski, L. Grob, E. B. Holzer, J. M. Jimenez, B. Lindstrom, A. Milanese, G. Iadarola, A. Lechner, T. Levens, L. Mether, E. Metral, D. Perini, S. Redaelli, G. Rumolo, B. Salvant, R. Schmidt, R. Steerenberg, M. Valette, D. Valuch, J. Wenninger, D. Wollmann, C. Yin Vallgren, C. Zamantzas

9th Evian Workshop, 31th January 2019

CERN

LHC Collimation Project CERN

MANCHESTER 1824 The University of Manchester

Outline

I. UFO
II. ULO
III. 16L2
IV. 10Hz
V. Conclusions

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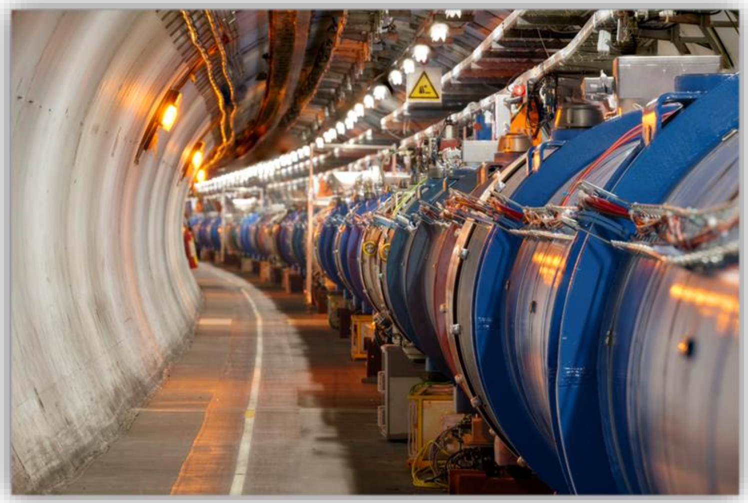
Introduction

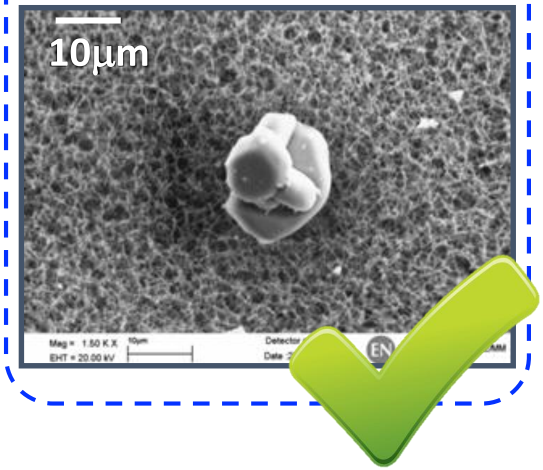
There are UFOs and UFOs…

Can this

Stop this?

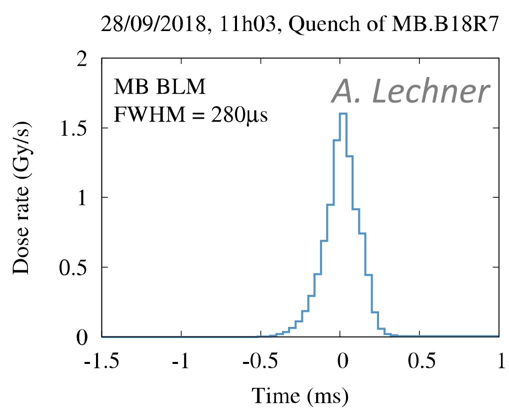


And this?



Very fast failure!
Few turns!

- **U**nidentified **F**alling **O**bject:
  1. **Dust** particles falling into the beam (**tens of μm**)
  2. **Inelastic** proton-UFO **collisions**
  3. **Hadronic showers** and **energy deposition** on magnets **coil**
  4. **Quench**



UFO detection

- **UFO detection** based on **B**eam **L**oss **M**onitor
- **Several studies** during the years and **changes on BLM threshold**

To dump or not to dump?

Initial strategy:
BLM threshold set to **avoid quenches**

↓

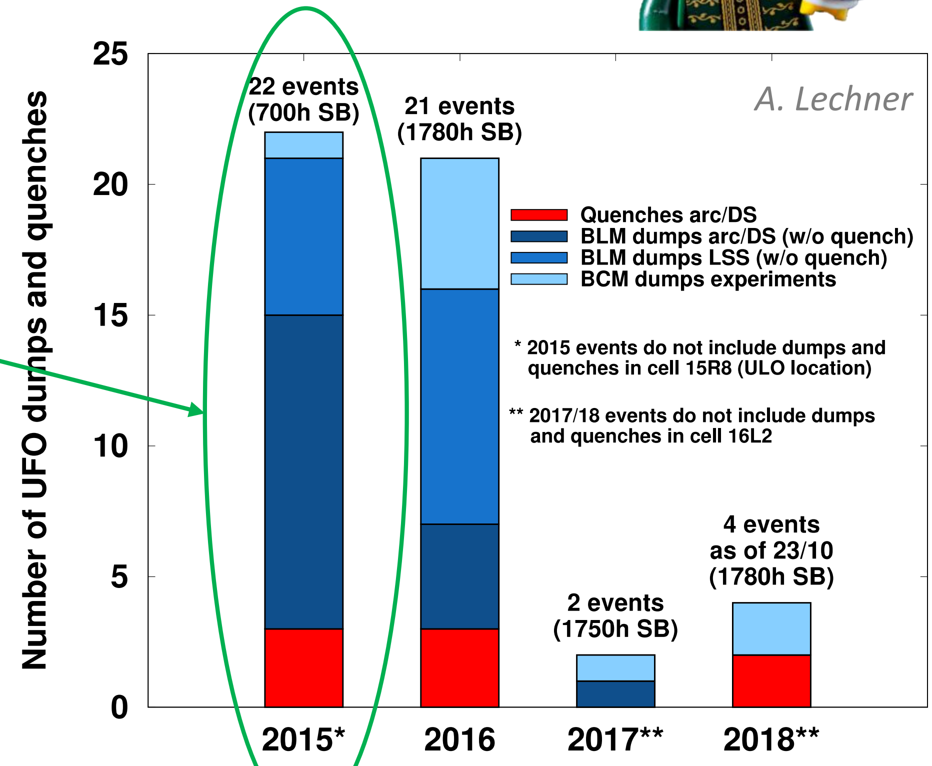
Spurious dump on UFO that won't lead to a quench

↓

Downtime
quenches < spurious dumps

↓

Let's **increase thresholds!**

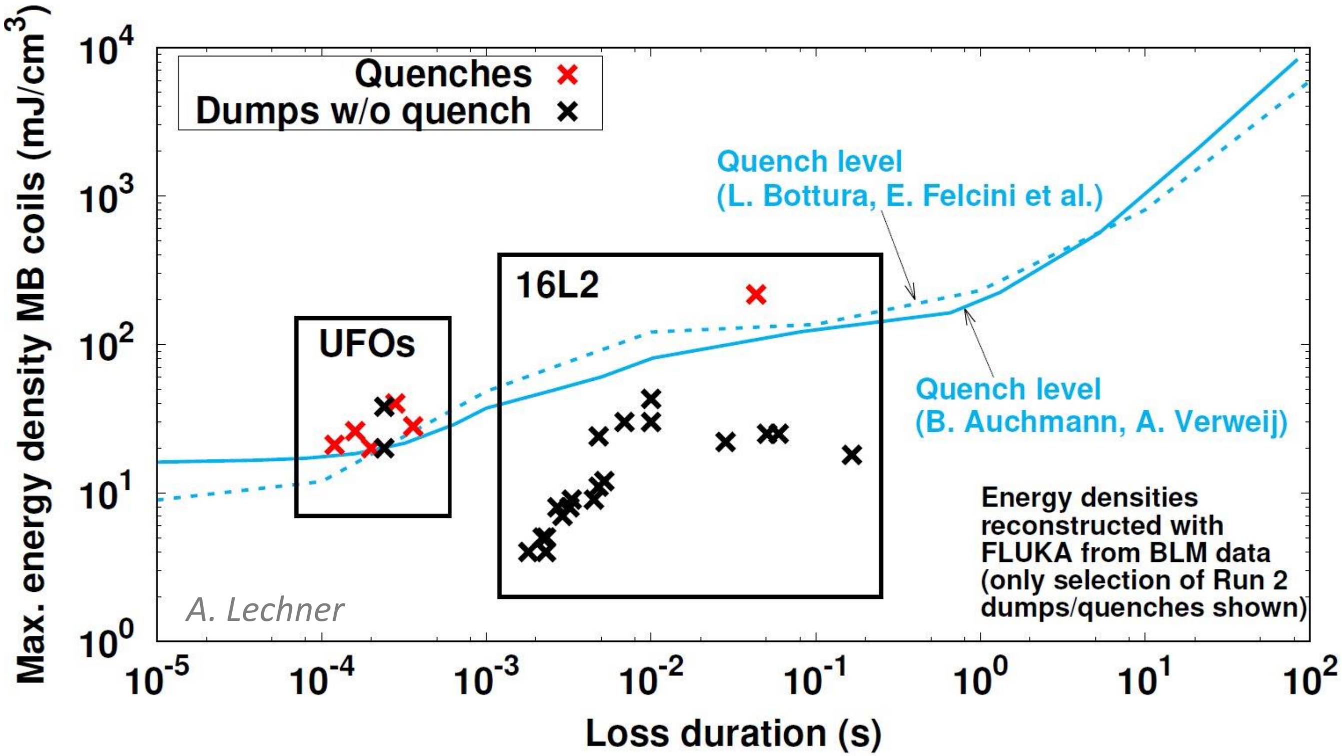


Arc/DS at 3 x quench level

LSS at quench level
Opt. at TCLs/TCTs/XRPs

Quench level and BLM threshold

Tight connection between **quench level**, **BLM threshold** and **energy deposition simulations**

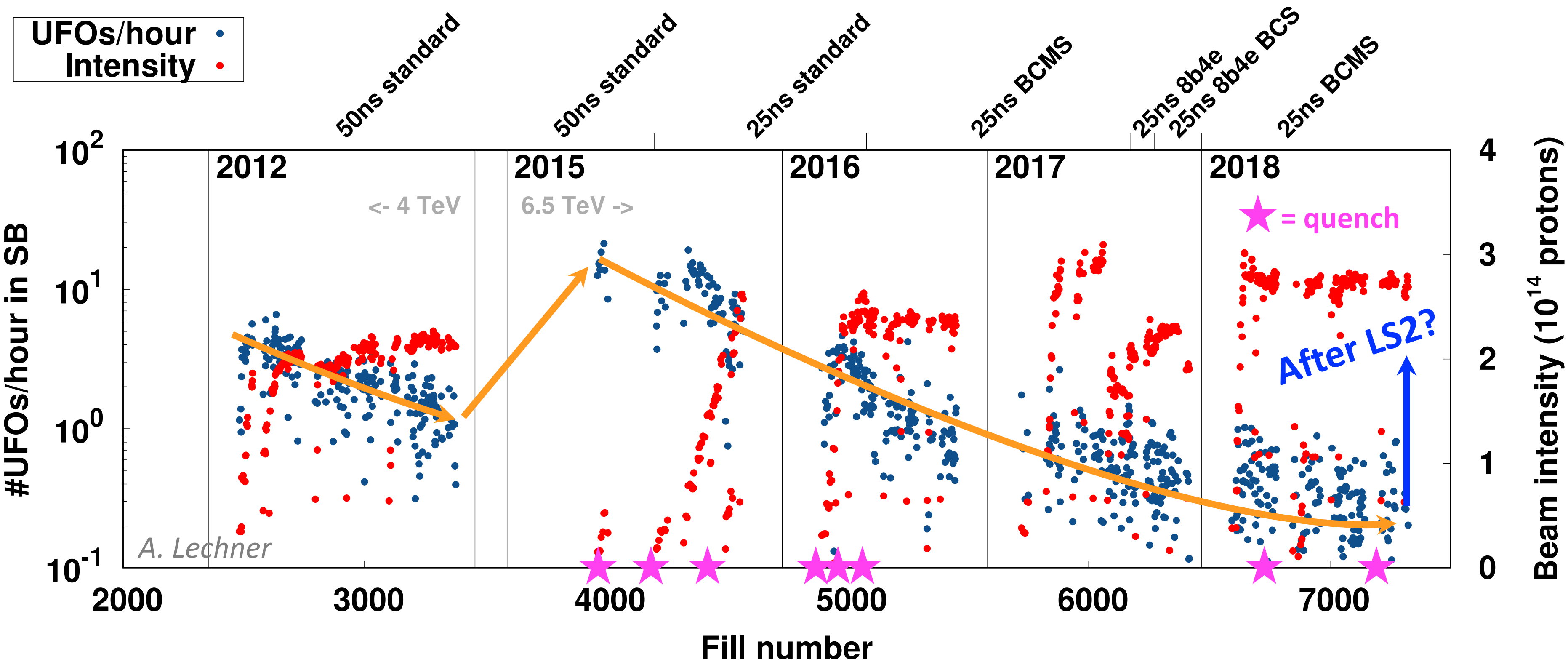


- **Main lessons learnt:**
  - ✓ **Similar losses** in all quenches (within a factor of 2)
  - ✓ **Inelastic collision** in the range of **6×10^7-1.2×10^8**
  - ✓ **UFO radius** in the range of **40-100 μm**

Experimental validation of quench level models!

UFO rate evolution

UFO rates in the arc (cells ≥12) in stable beams



- Clear **de-conditioning** during **LS1** and **re-conditioning** during **Run 2**

→ **Similar UFO rate** as end of Run 1 achieved **after about 1.5-2 years**

What to expect after LS2

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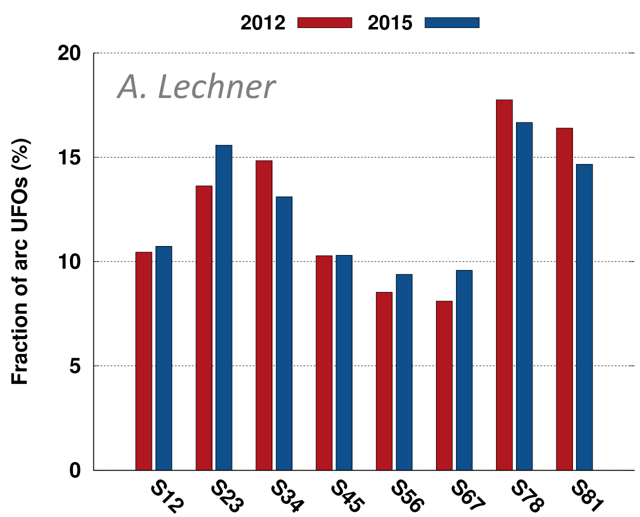
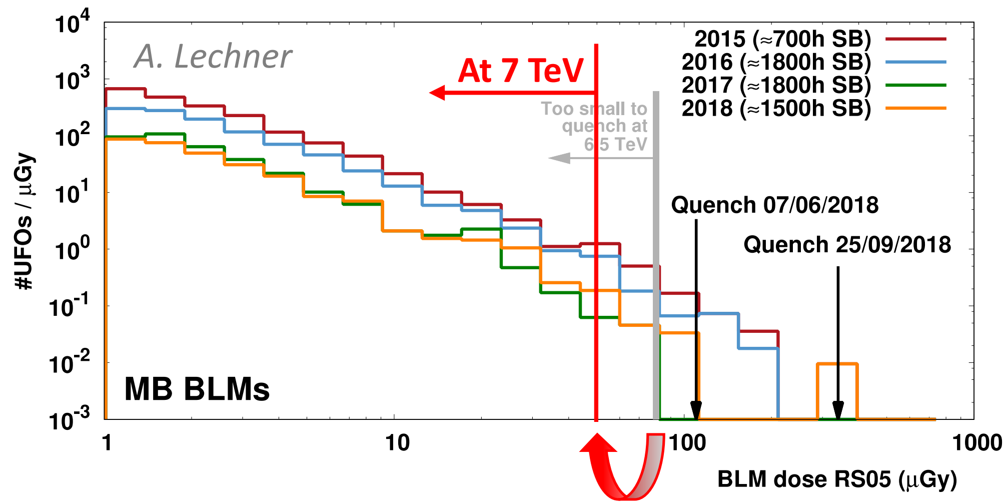
Any redistribution of UFOs?



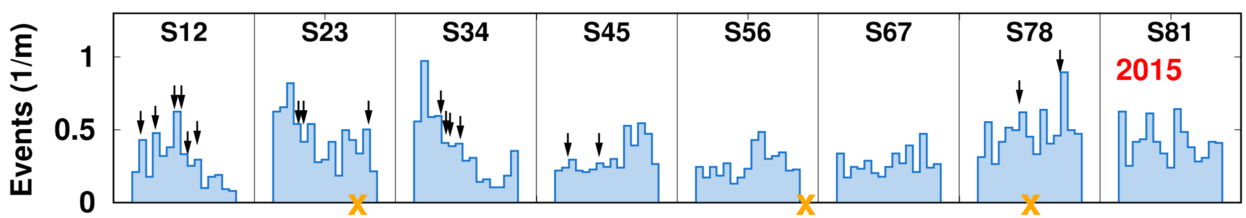
No significant changes due to LS1

Any difference between 6.5 TeV and 7 TeV?



Smaller UFOs can lead to a quench!

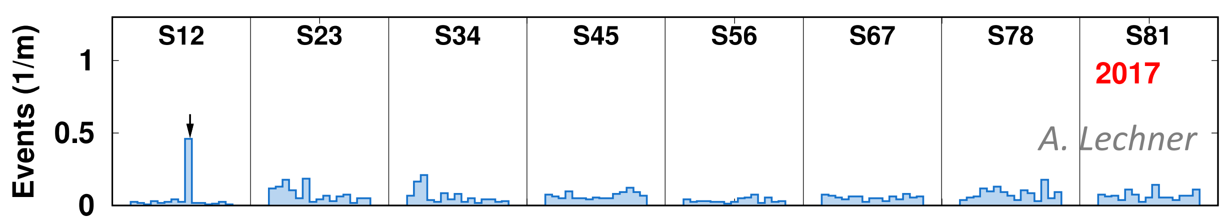
Any influence of magnet exchange?



X = quench

↓ = magnet exchange in LS1/EYETS

- Exchange of some magnets created hot spot
- No correlation quench – hot spot



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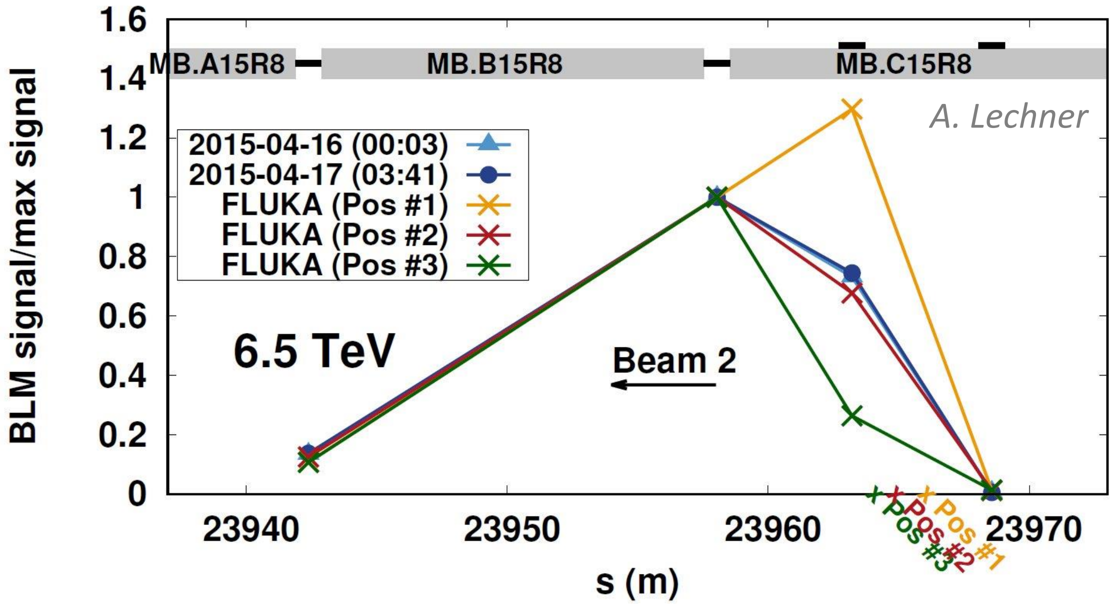
Introduction

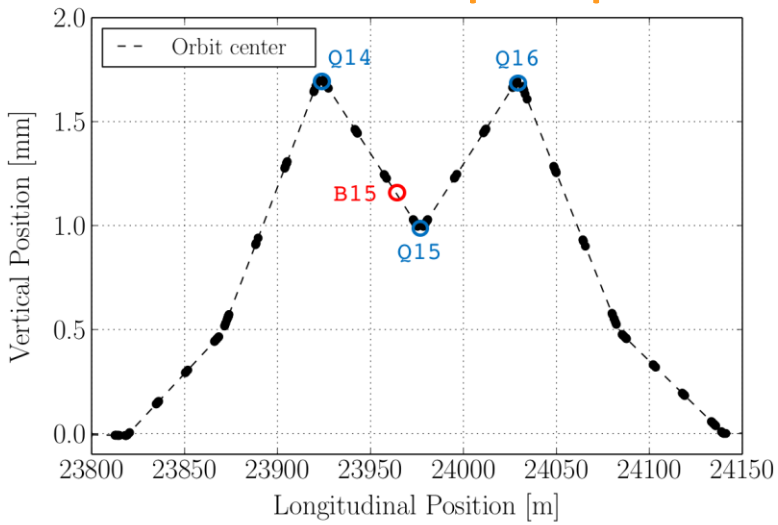
- **Significant UFO activity in cell 15R8** during commissioning in 2015 (14 dump, 3 quench)
- **First actions taken:**
  - ✓ **Energy deposition simulations**
    - ⇨ Located vertex of hadronic showers at **MB.C15R8.B2 centre ±1m**



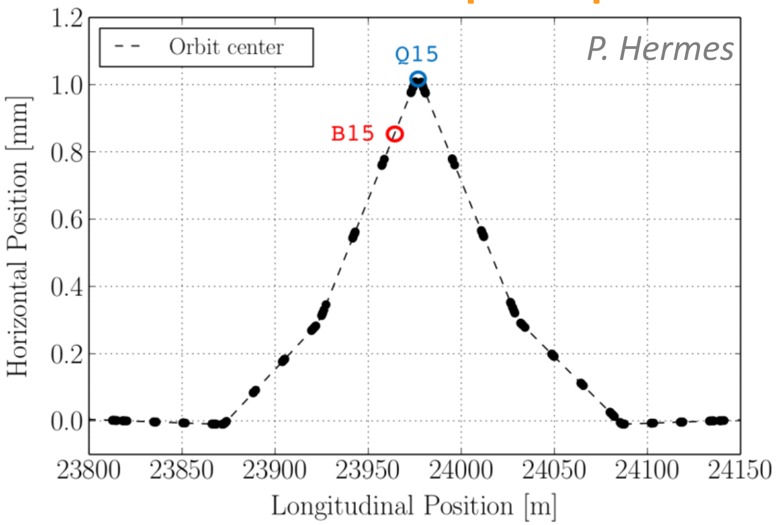
  - ✓ **Local aperture measurements**
    - ⇨ Revealed presence of an **U**nidentified **L**ying **O**bject

ULO measurements

4 correctors bump in V plane

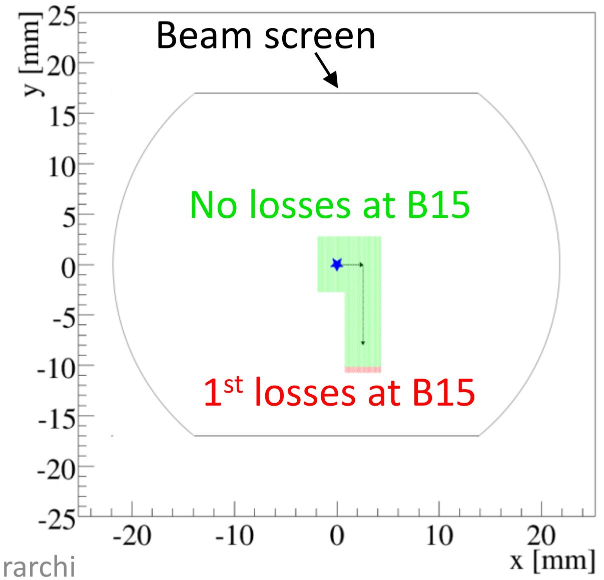


3 correctors bump in H plane

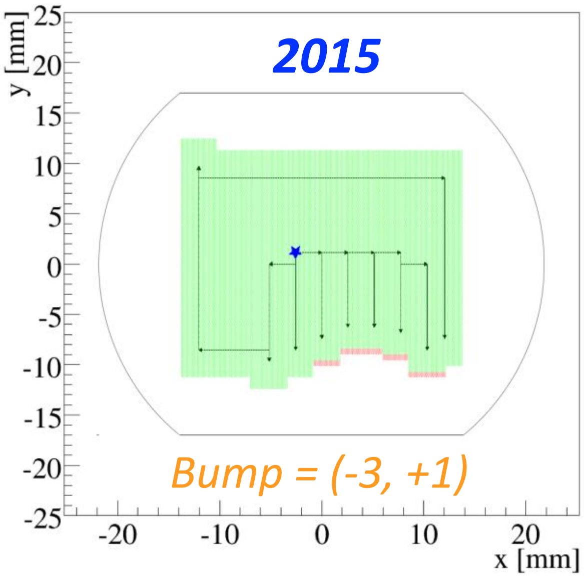


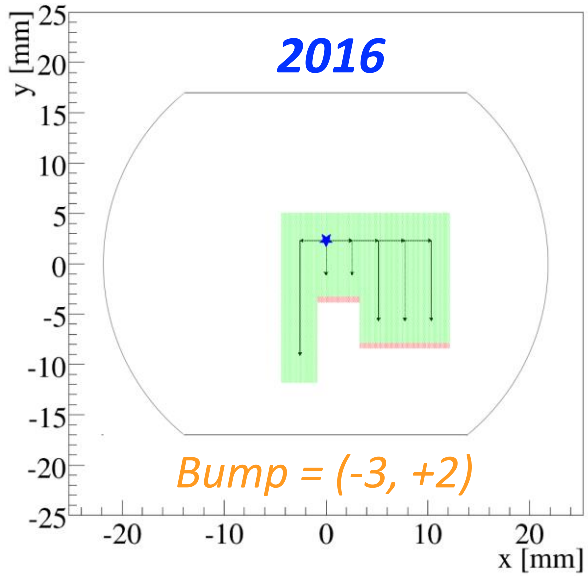
Measurement procedure:

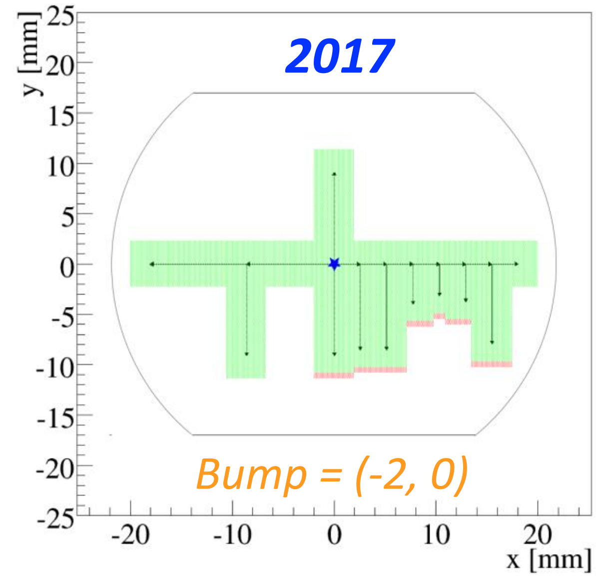
1. **Beam shaped with IR7-TCPs**: 2/4σ in H/V
2. **Local aperture probed** systematically:
   - H/V bump steps of **3/0.5mm**
3. **Max bump** excursion:
   - in **H ~ ±14mm** (losses at Q15)
   - in **V ~ ±8mm** (losses at Q14 and Q16)



ULO evolution and mitigation







- **Mitigation strategy:**

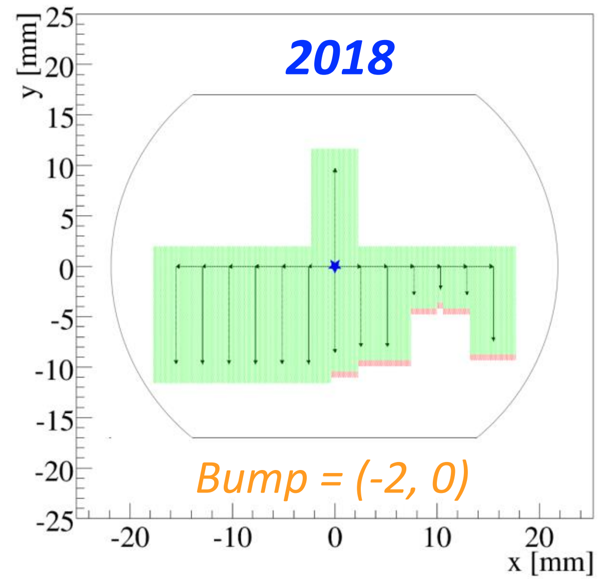
  ⮡ Orbit bump to bypass it, while ensuring 10σ at injection

- **Constant monitoring during Run 2**

  ⮡ ULO scan during commissioning to deploy optimal bump

Limitation successfully removed!

Access planned mid-April, let's see what it is!



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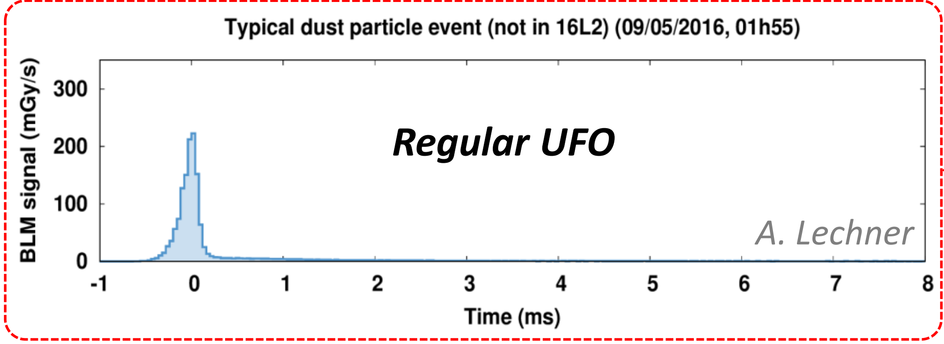
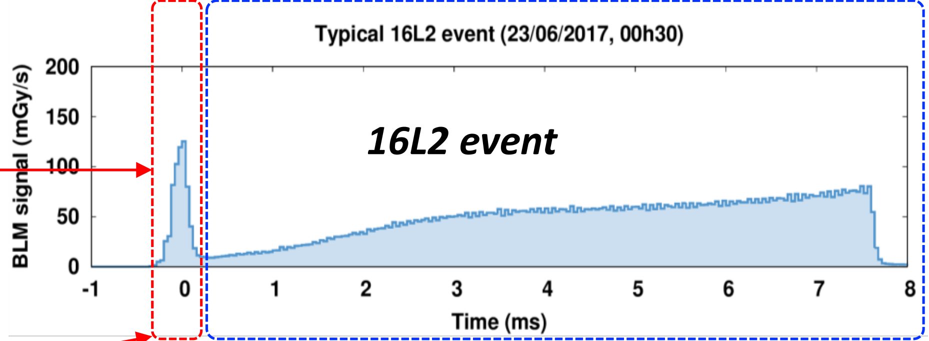
Introduction

- Sudden increase of losses in the half-cell **16L2** represented **"The" machine limitation in 2017**

  → **67 dumps** induced: only two at injection, one quench induced at high energy

- *Three stages of loss rate:*
  1. **Steady loss** in 16L2 arising during the ramp along the **entire fill** (~ few 1e-6 Gy/s)
  2. **Sharp rise of losses in 16L2 "UFO-like"** (1e-3 ÷ 1e-2 Gy/s)
  3. **Very fast rise of losses at collimators** triggering a dump (few ms)





FFT BLM: Revolution frequency in 16L2
dBLM: Vertical losses from all bunches

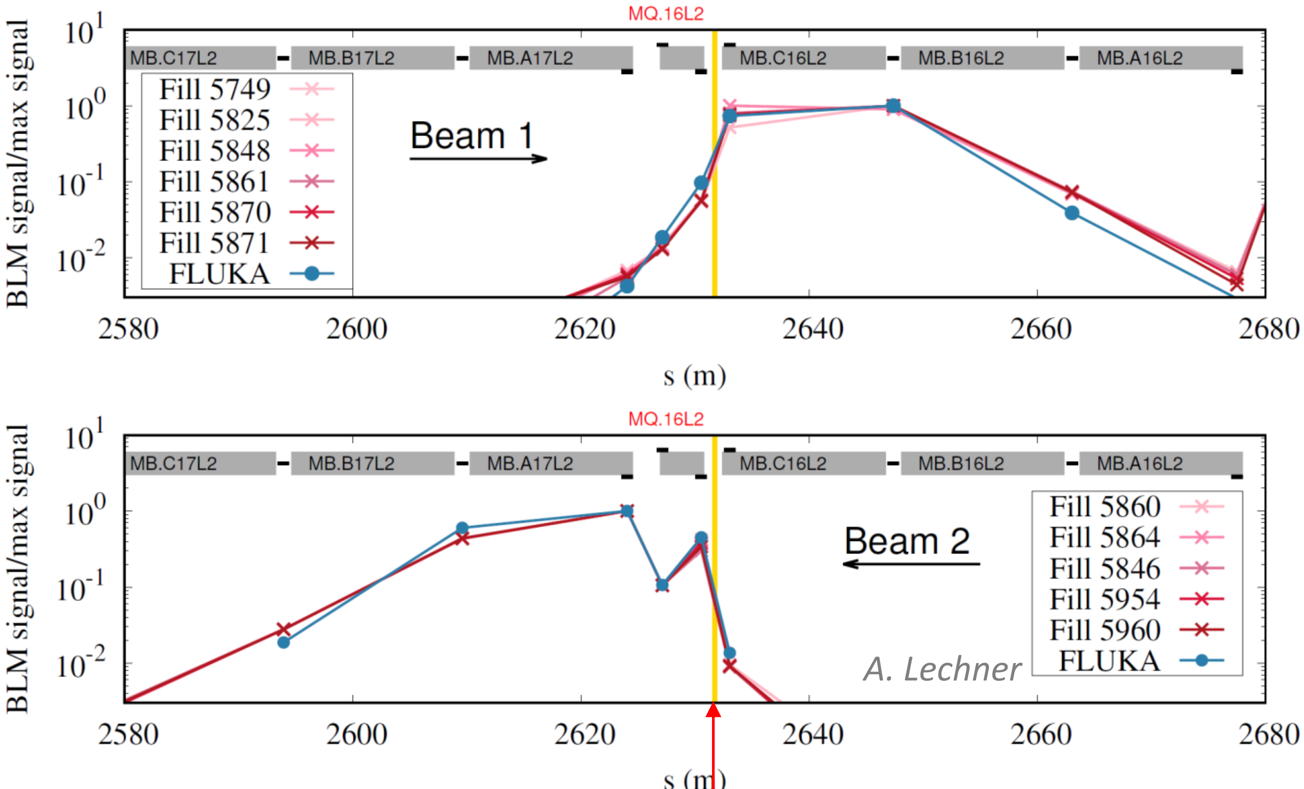
Something touched at every turn

FFT BLM: Tune at primary collimators
BLM: Losses in the plane of MQ.16L2 polarity

Beams undergo betatron oscillations
Scattered particles reach primary collimators

Localization of the source

- **Energy deposition simulations** to identify longitudinal location of **hadronic showers vertex**



- ***Estimated position:***

2630.7 m ↔ 2632.0 m

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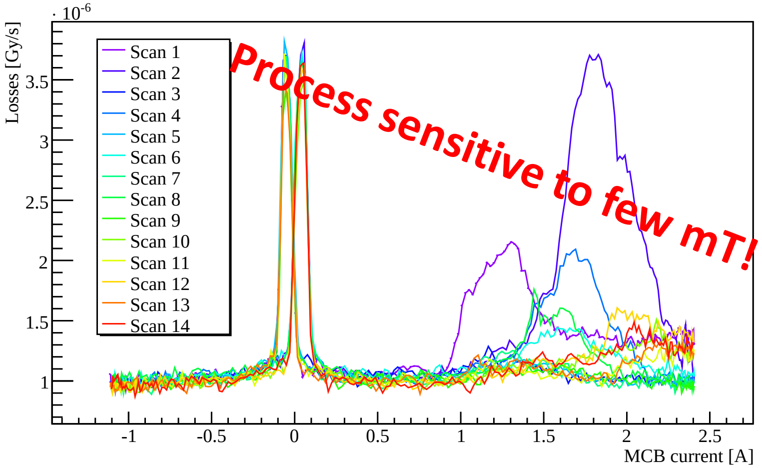
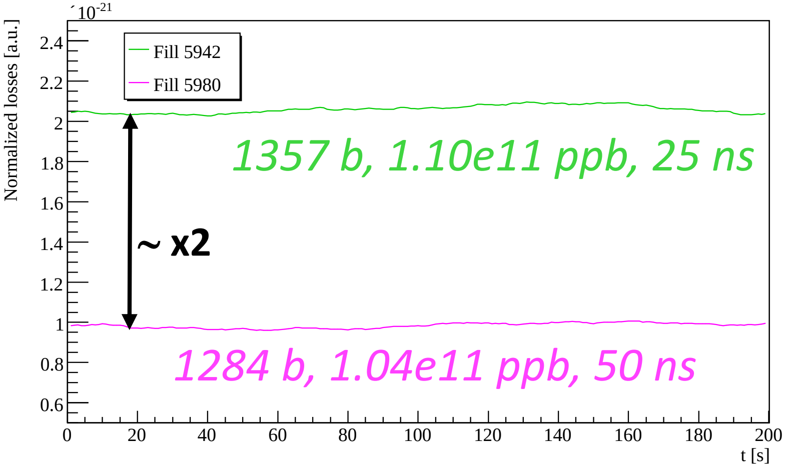
Main correlations and mitigations

Clear correlation between losses and MCB current



Significant contribution by e-cloud on losses and Q shift along the train



- **Mitigation strategy:**
  - ✓ Dipolar field of **MCBs**
  - ✓ **8b4e** filling pattern

  → **Prevent "UFO-like" events** suppressing multipacting
  - ✓ **Solenoid** in the field free region of the interconnection → **10% increase of ppb in 2017** **Mitigation at inj. in 2018**
  - ✓ **BCM** production scheme → **Brighter beams**

Lessons learnt and actions taken

- **Team work made the difference:**
  - ✓ **Many people** involved and **actions** also discussed in a dedicated **Task Force**
  - ✓ Additional **hardware** installed with impressive schedule

- Most probable scenario: **Accidental air venting** during the removal of the mobile group for the final pinch-off (**EYETS 2016-2017**)
  - ✓ **Upgraded pumping ports** design
  - ✓ **New pumping scheme and procedure** integrated into a dedicated QA and checklist

- Temperature up to **80-90 K and analysis of gas** released (**YETS 2017-2018**)
  - ✓ Compromise between risks associated to bring a sector to room temperature and vacuum quality reached

- Few dump events in **2018** with gradual **conditioning along the year**
  - Mitigated with few hours in SB with 900 bunches

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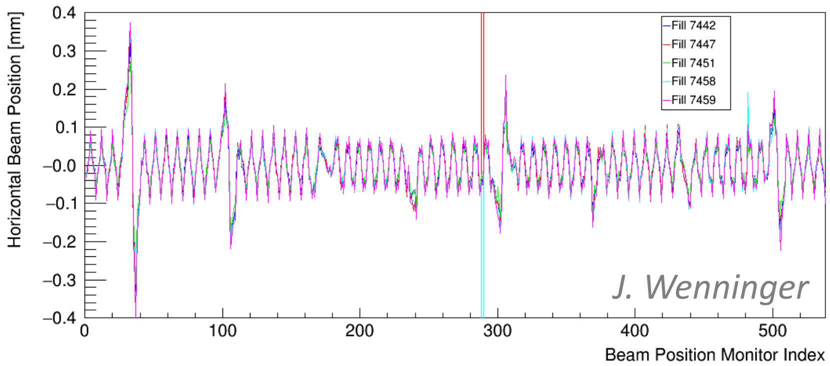
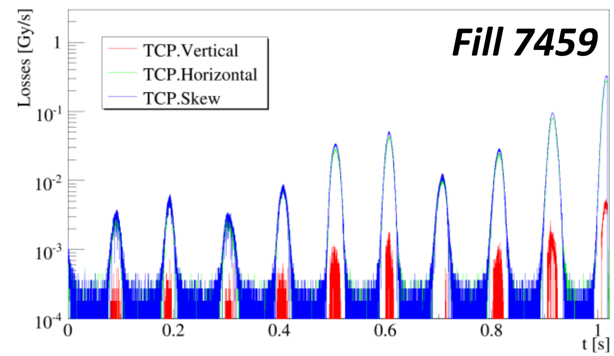
- **8 dumps** with similar signature in 2018:
  - **1** during the **p-p** run
  - **7** during the **Pb-Pb** run (out of 48 physics fills)

1. Hor. trajectory oscillation at 8-12 Hz

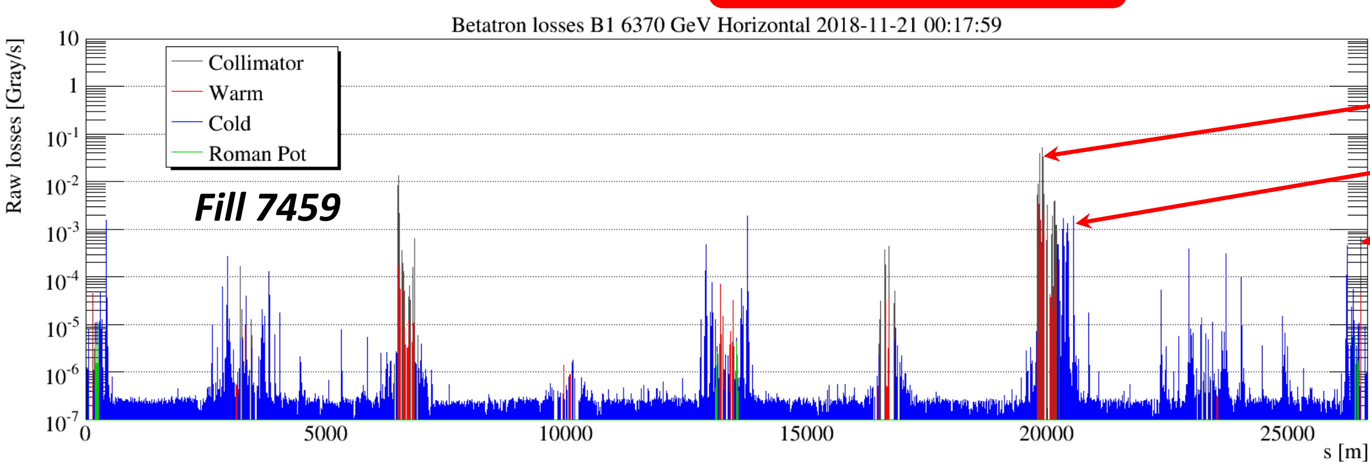


2. Increasing losses at the TCPs



Horizontal losses
f = 8-12Hz

3. Dump on losses



Limiting locations:

TCSG.A5L7.B1
MQ.13R7.B1
TCTPH.4L1.B1

Losses above BLM threshold (set at quench level)

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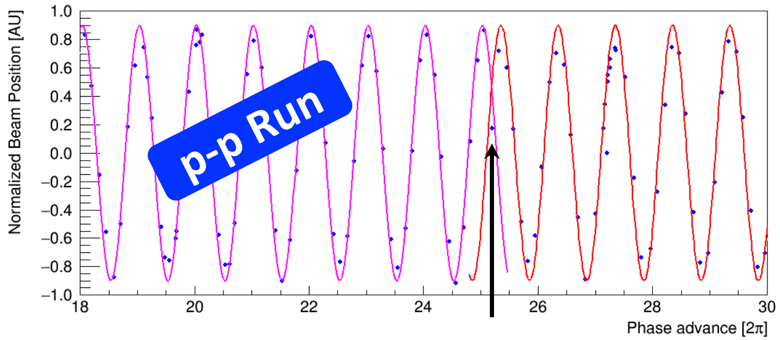
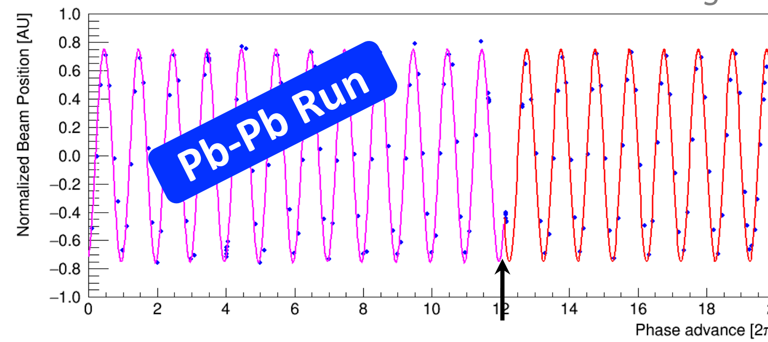
Present understanding

- **Where is the origin** of these oscillations?

J. Wenninger

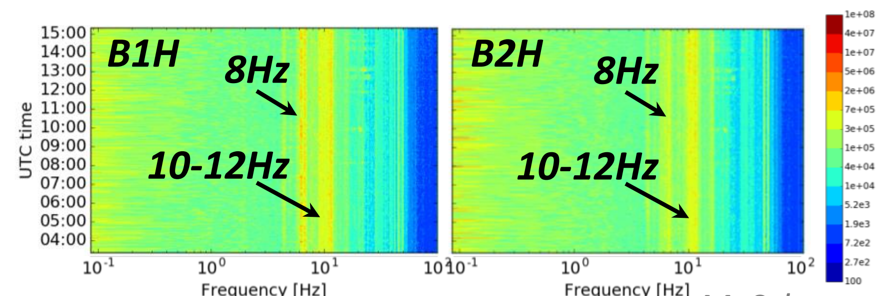




Q21L4 *ITR2 ↔ Q5R2*

Kink** and **orbit displacement** of both beams **compatible with horizontal movement of MQ

- **At which point** of the cycle do they start?
  - ADT and 100Hz BLM at TCPs show that are **always present**



M. Schaumann

- **No ITR2 cryostat movement measured** by survey team
  - **Internal vibration? Origin at Q4-Q5?**

- First time that **IP2 squeezed to 50 cm** during **Pb-Pb** run: induced **displacement amplified**
  - **Why 21L4** during **p-p** run (β_x=180m)?

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Possible actions and mitigations

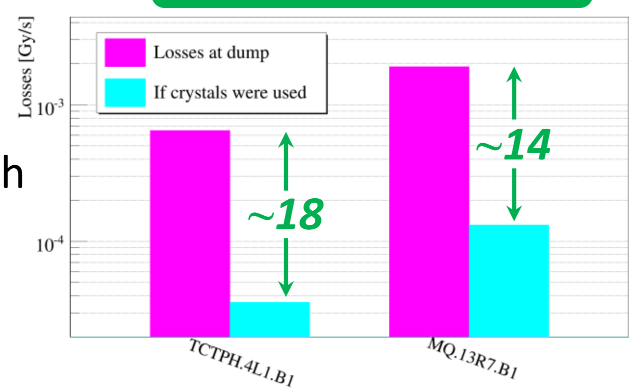
- Crucial **better understanding** of the events:
  - ✓ **What is the trigger** of sudden amplitude increase?
  - ✓ Will the **amplitude keep increasing**?

- **Present studies** based on dump events and **PM data:**
  - ✓ **More observations needed** and study events not leading to dump
  - ✓ **T-b-T BPM acquisition** triggered when these oscillation are detected?
  - ✓ **Accelerometer on cryostat** of suspected MQs?

- **Dump** triggered by **losses** due to **beam halo** intercepted by TCPs: **possible mitigations**?

Improved cleaning

Measured margin of a factor >10 with **crystal collimation**



+ Installation of **TCLD** in **IR7-DS** planned in LS2

Active halo control

Estimated orbit displacement ~0.5σ

Hollow electron lens could efficiently deplete it (Run 4?)

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Conclusions

- **Unidentified Falling Object:**
  - Experimental **validation of quench level** models and **improved BLM threshold** strategy
  - **Hard to predict** UFO rate right after LS2: in the range 2012-2015, if equivalent to LS1
- **Unidentified Lying Object:**
  - Successfully **mitigated during Run 2** by means of local orbit bump
  - **Access mid-April:** if something found, **remove it**. If nothing found, **replace magnet?**
- **16L2**:
  - Significant limitation in 2017, **successfully mitigated** and target integrated lumi reached
  - Most probable **cause identified** and actions taken to **avoid repetition**
  - Should literally **“evaporate” during LS2** with warm up to room temperature
- **10Hz**:
  - **Sound explanation** found for events during 2018 **Pb run**
  - Still **more to understand** on the trigger and dump during p run (**improved diagnostic?**)
  - Possible **loss mitigation**: **crystal collimation** and **TCLD** (Run 3?), **hollow e-lens** (Run 4?)

Team work: many people** involved, **many ideas**, **many actions** taken and **mitigations found!

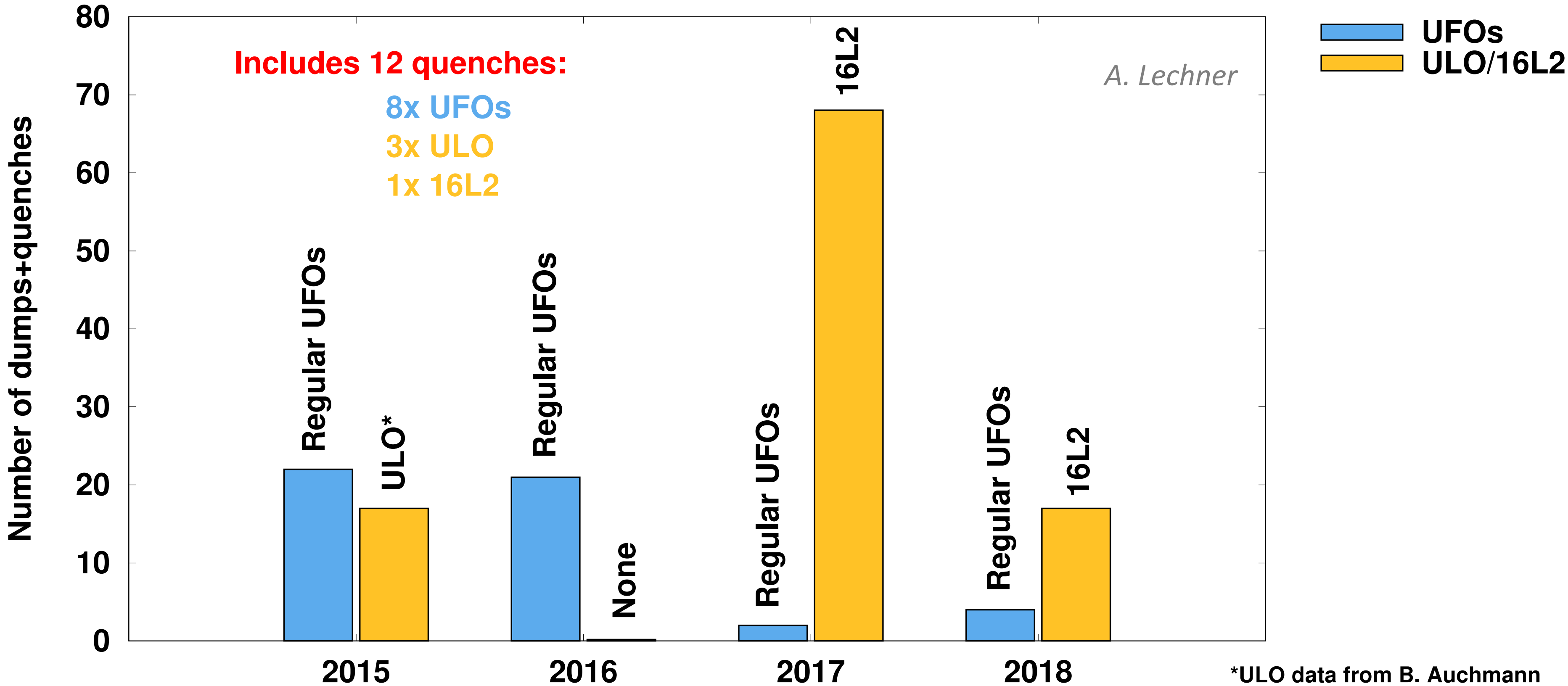
Thanks for your attention!

BACKUP

Outline

UFO…

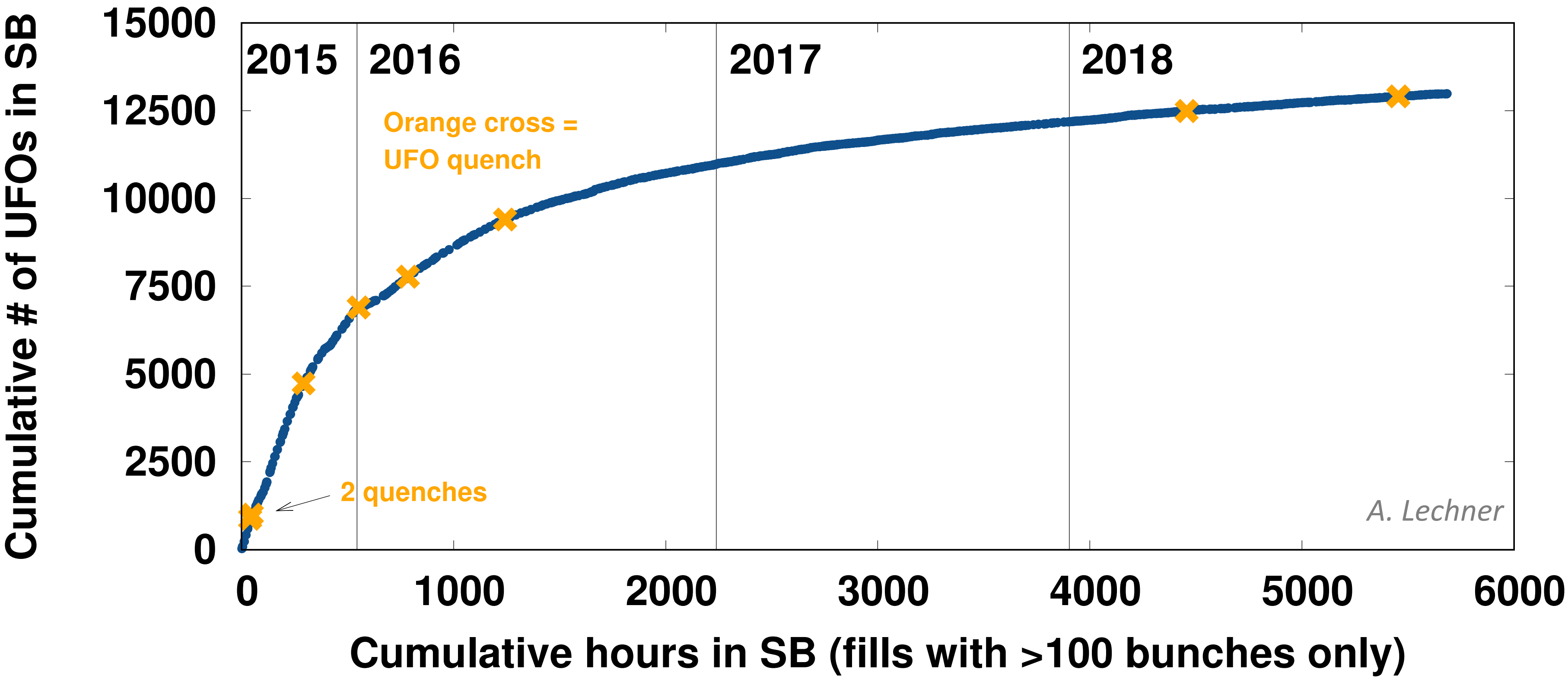
BLM dumps and quenches: regular UFOs vs ULO/16L2



*ULO data from B. Auchmann

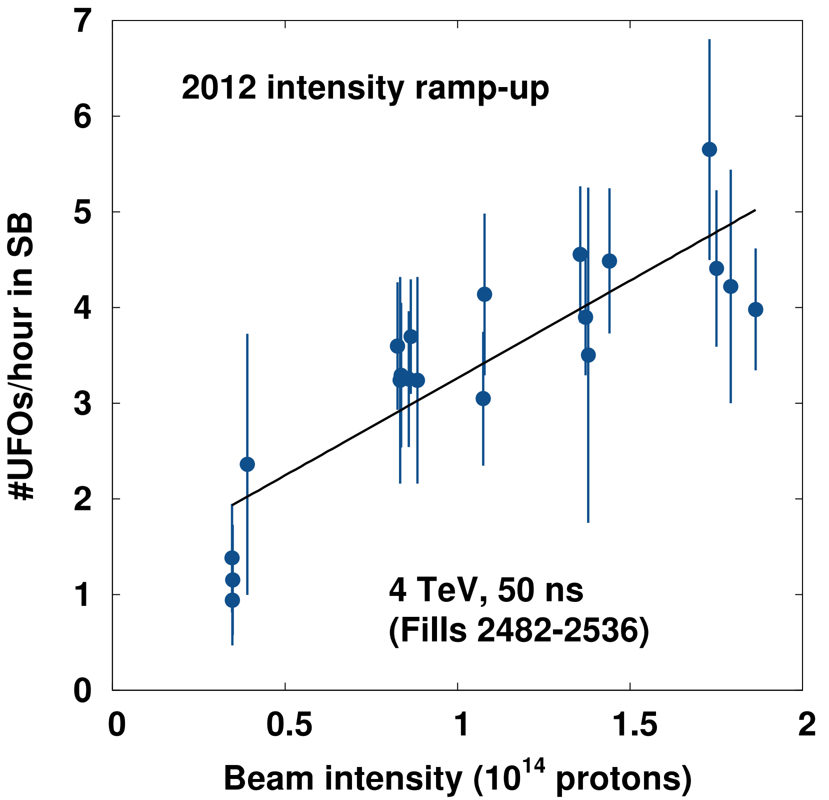
Cumulative number of UFOs (cells ≥12) in stable beams (2015-2018)

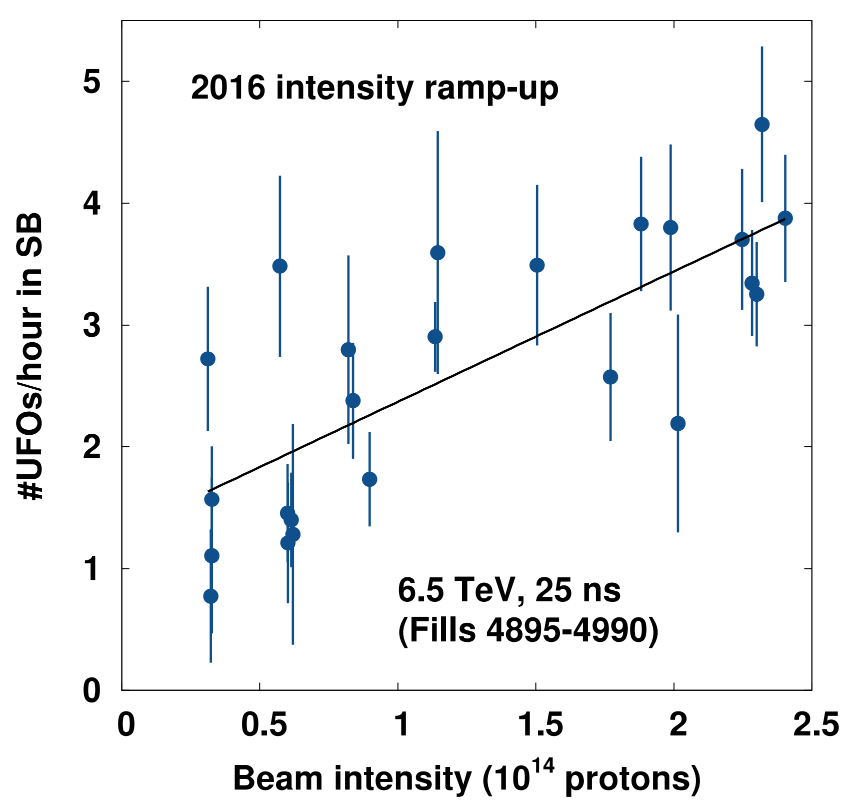
⇒ more relevant for the likelihood of a quench → # of UFO events accummulated over time



Only fills with >100b per beam, includes triggers on all Run 2 standard BLMs (RS04 detection threshold: 2×10^{-4} Gy/sec)

Arc UFO rate (cells ≥12) vs beam intensity



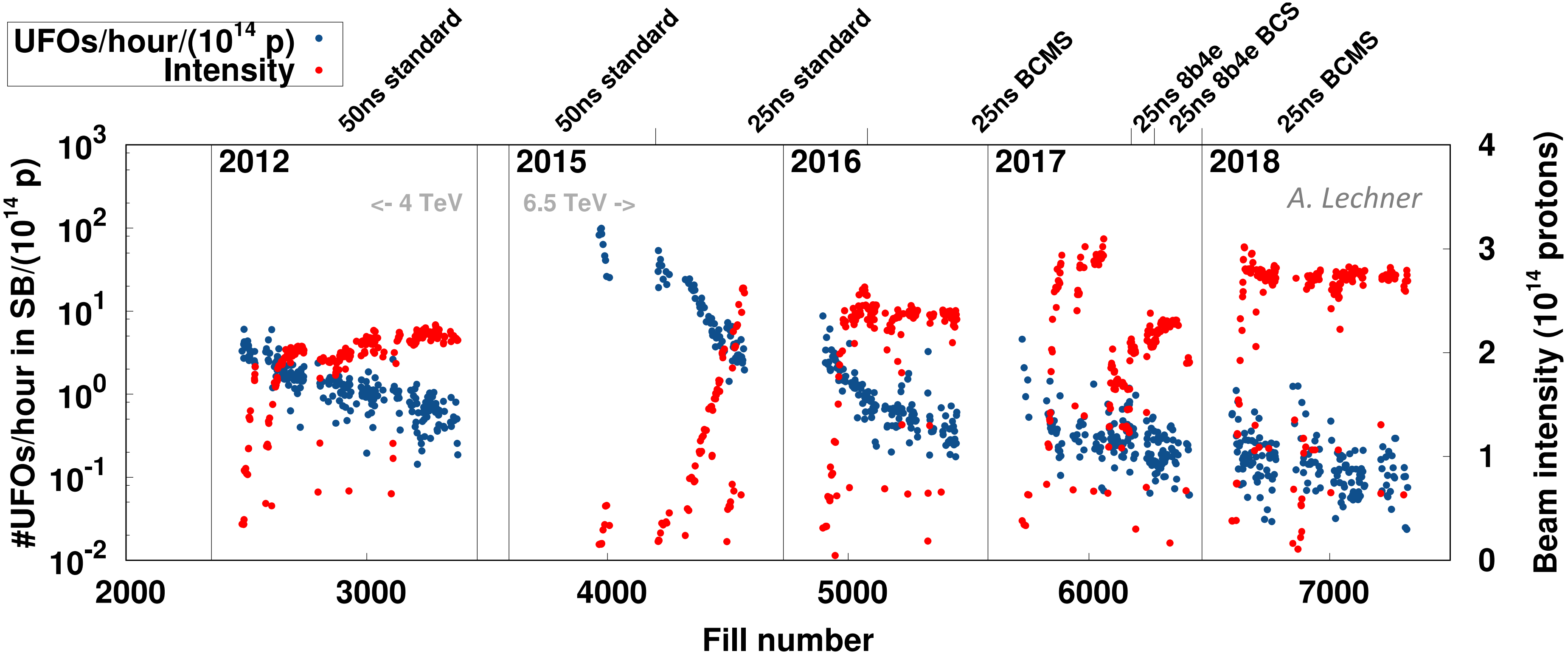


Only fills with ≥1 h in STABLE and with >100b per beam.

A. Lechner

Normalized fill-by-fill arc UFO rates (cells ≥12) in stable beams (2012-2018)

UFO rate (cells $\geq$ 12) in stable beams, normalized to beam intensity:



Only fills with $\geq$1 h in STABLE and with >100b per beam, only BLMs common to Run 1 and Run 2.

Can we compare Run 1 and Run 2 UFO rates?

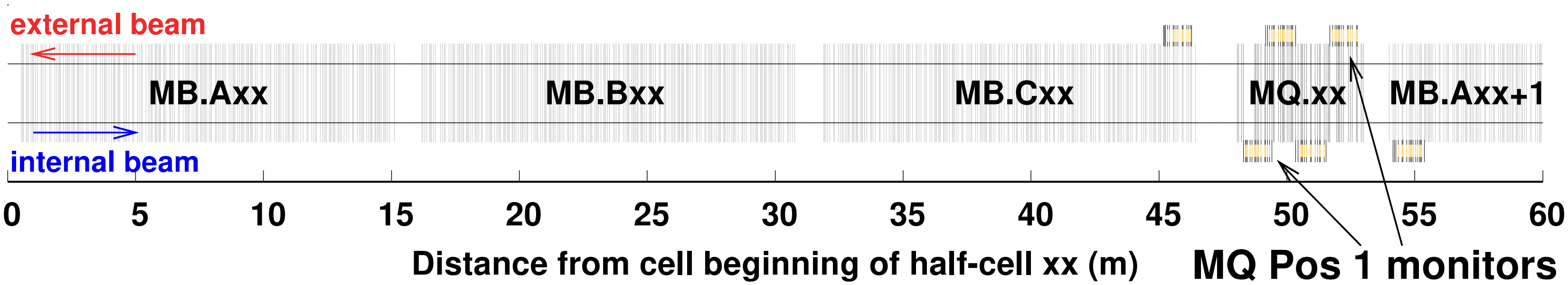
A. Lechner

Yes (at least to a good approximation), if ...

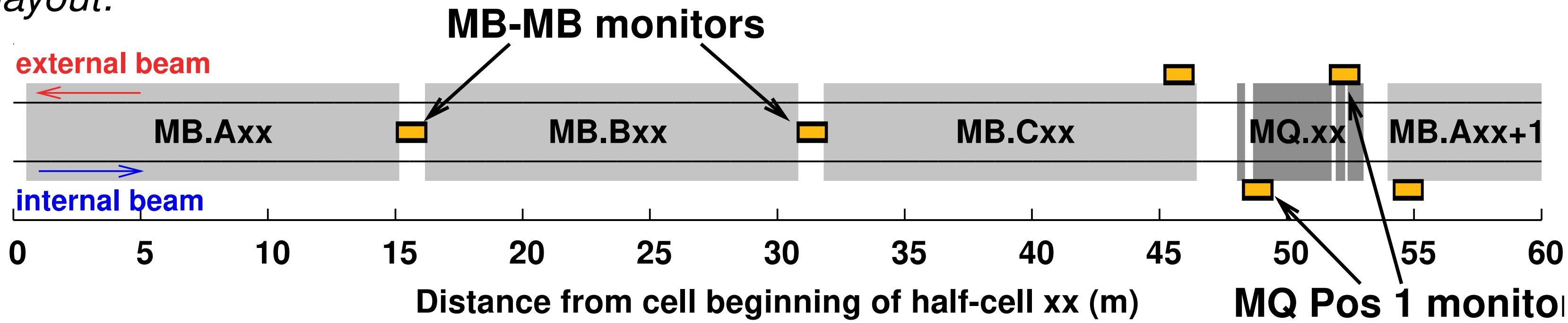
... we use different detection thresholds to account for the different beam energy

... we focus on a subset of BLMs common to both runs

Run 1 BLM layout:



Run 2 BLM layout:



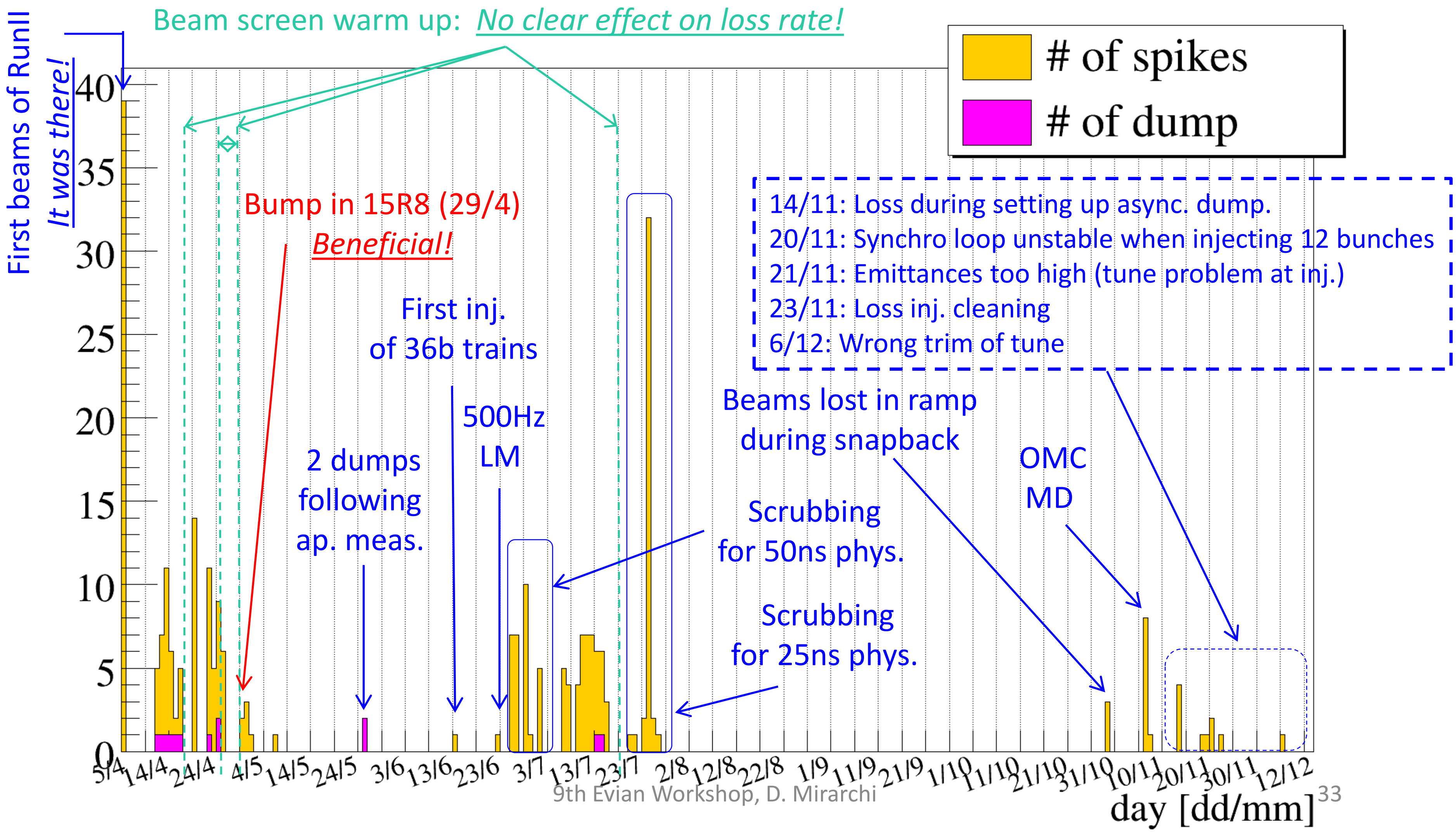
Outline

ULO…

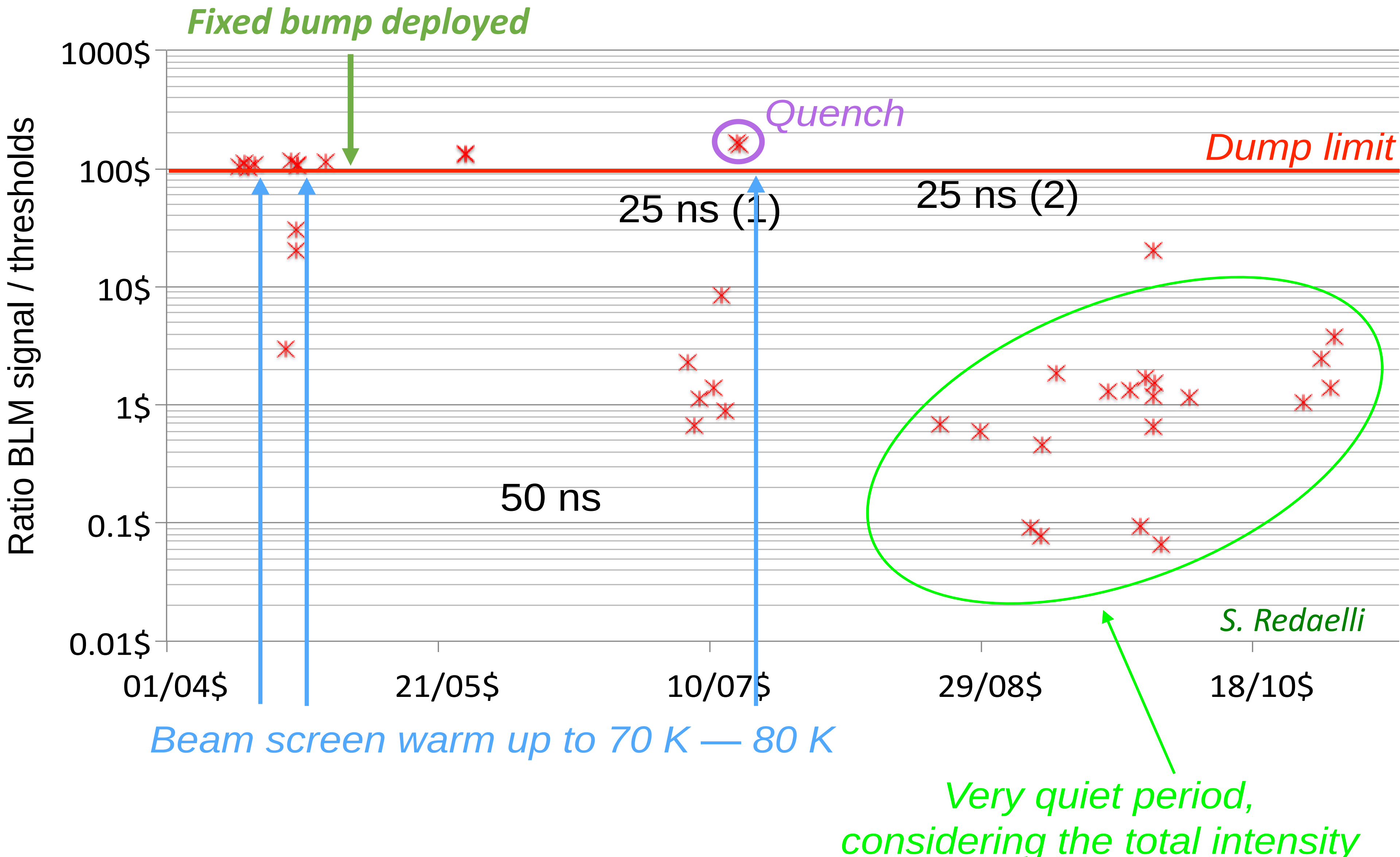
Parasitic monitoring of beam losses

- Clear **loss spikes** (i.e. exp. decay and peak > 1e-6 Gy/s) looking at **1.3s BLM running sum**

*Most of them **synchronised** with **injection or inj. cleaning***



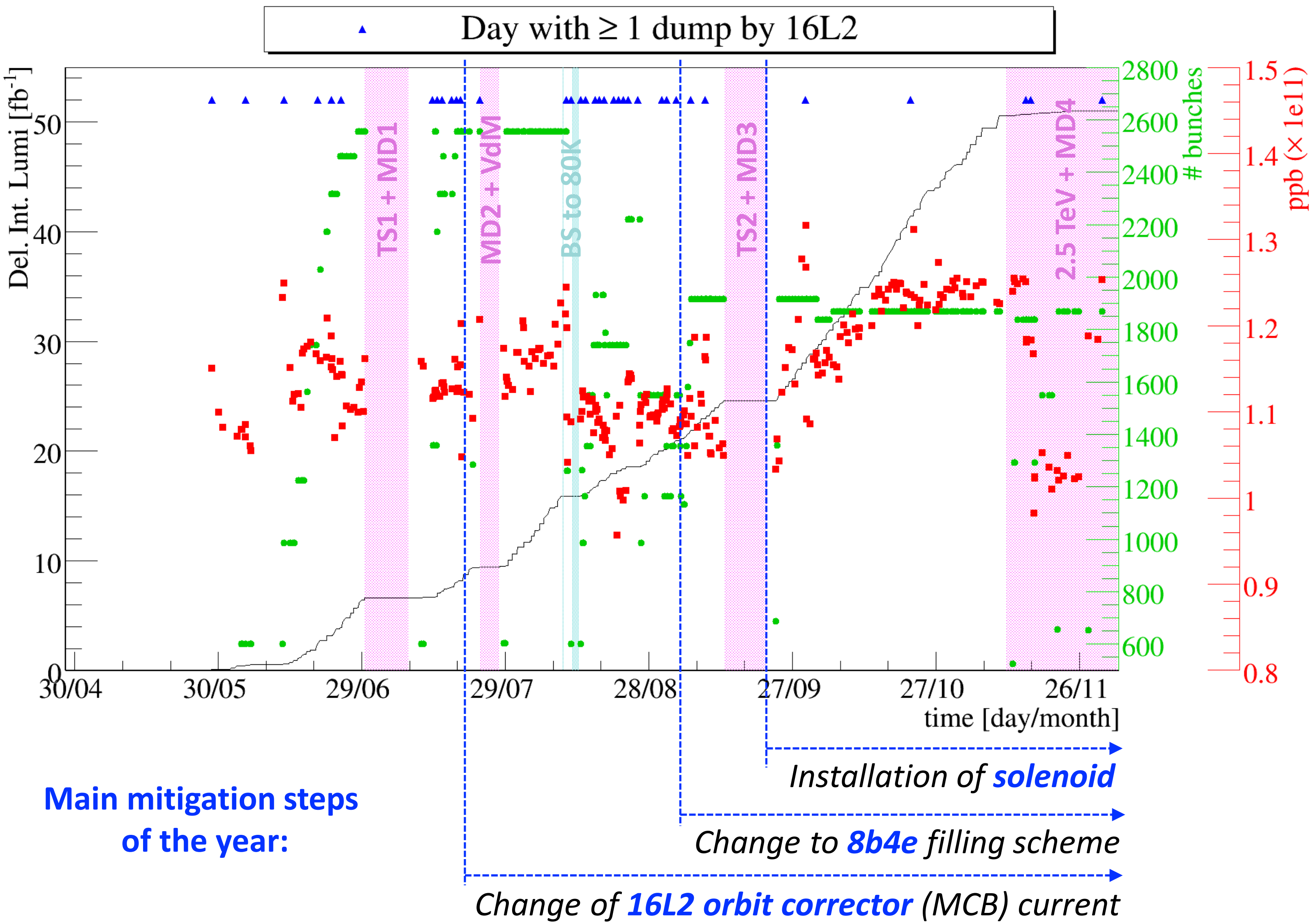
UFO at the ULO



Outline

16L2…

Overview of 2017 run

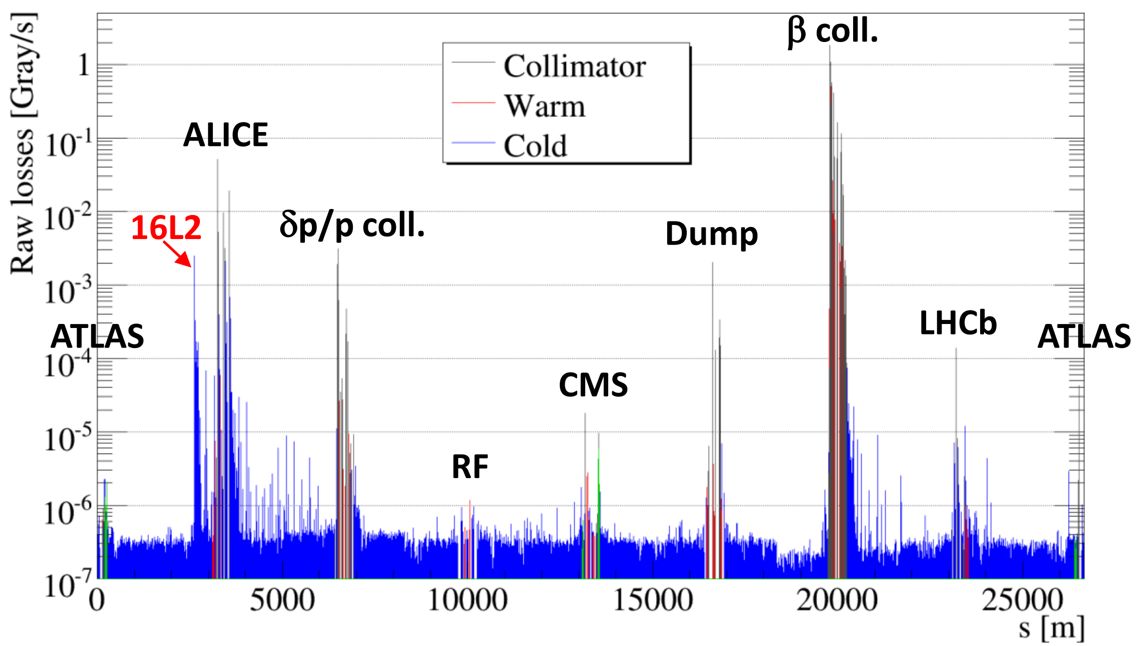


Main mitigation steps of the year:

First dump by 16L2

- First dump event: **First fill with 72b trains** during Scrubbing run (1236b)

Fill 5725, 29th of May

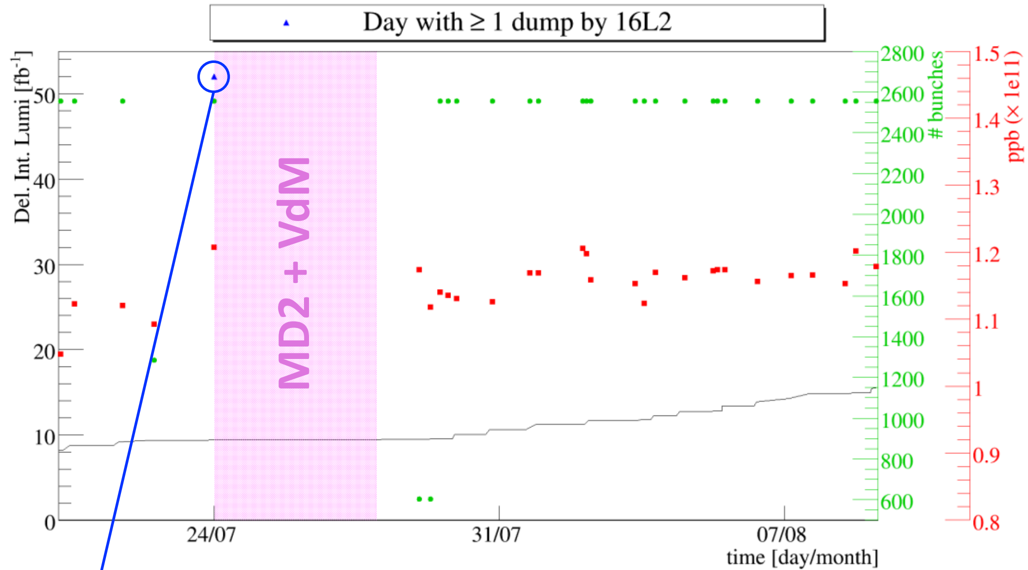


- *First action taken right after this event:*
  - ✓ Local aperture measurements → **No evident aperture restriction found**
- *First hints on the source of this event:*
  - ✓ Clear signature of losses from both beams → **Both beams interacting with nuclei**

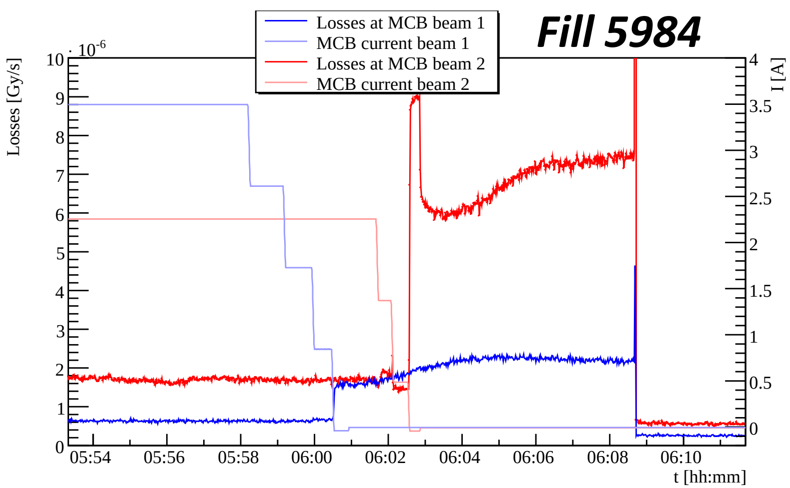
Mitigation using MCB field

- <u>Action taken the 20th of July:</u>
  - ✓ **Operational bump to set I_{MCB} > 2.5 A**
  - ✓ **MCB removed from orbit feedback**

  <u>Smooth 25 ns operations restored!</u>



I_{MCB} set to ~ 0 A after ~ 2 h in Stable Beams:

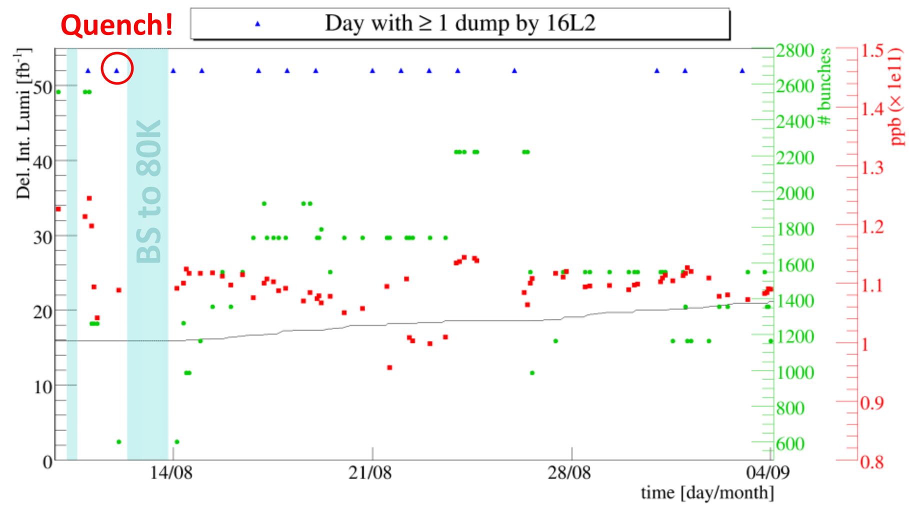


Beams dumped by 16L2 event about 6 min after I_{MCB} ~ 0 A

Beam screen to 80K

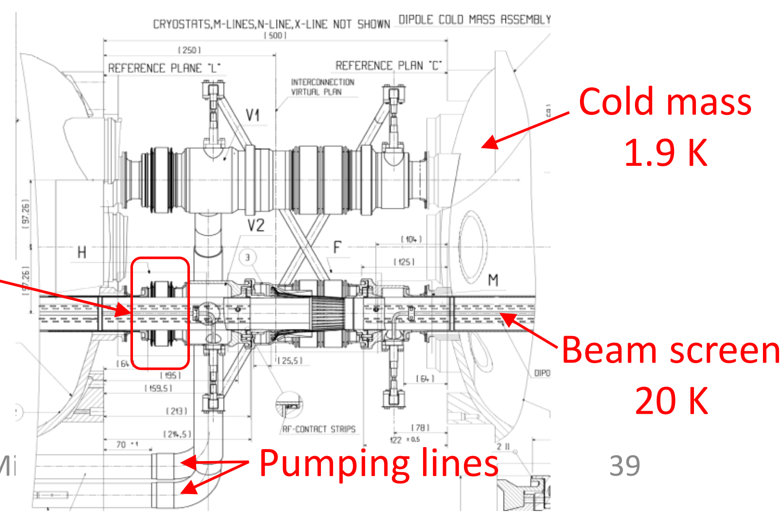
- **Two warm up of the beam screen only**, performed between 10th and 13th of August
  → **Abnormal increase of pressure** observed by additional gauges installed (up to 2e-3 mbar!)

- Main effects:
  - ✓ **Change of I_{MCB} no longer sufficient**
  - ✓ **Steady losses reduced but significant spikes**
  - ✓ **Clear correlation between spikes and dumps**
  - ✓ **Reduced intensity to get to Stable Beams**



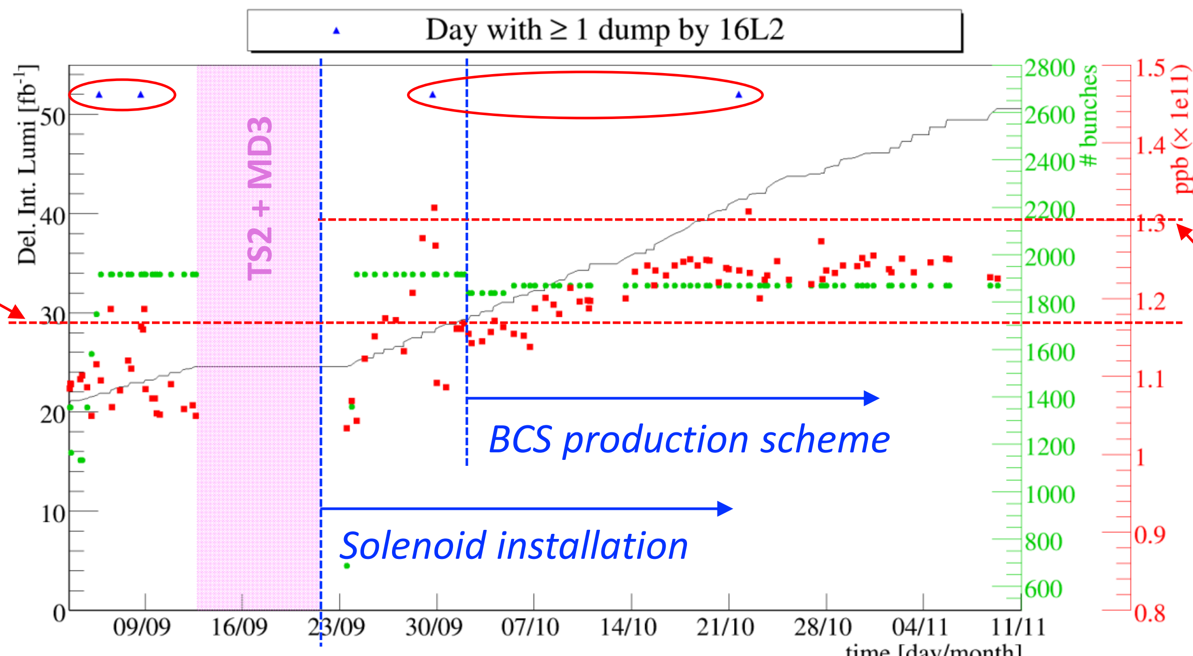
- Possible explanation:

1. **Accidental air venting during at the end of EYETS**
2. **Part of the evaporated gas condensed in cold spots in the interconnection area during beam screen thermal regeneration**



Change to 8b4e plus solenoid

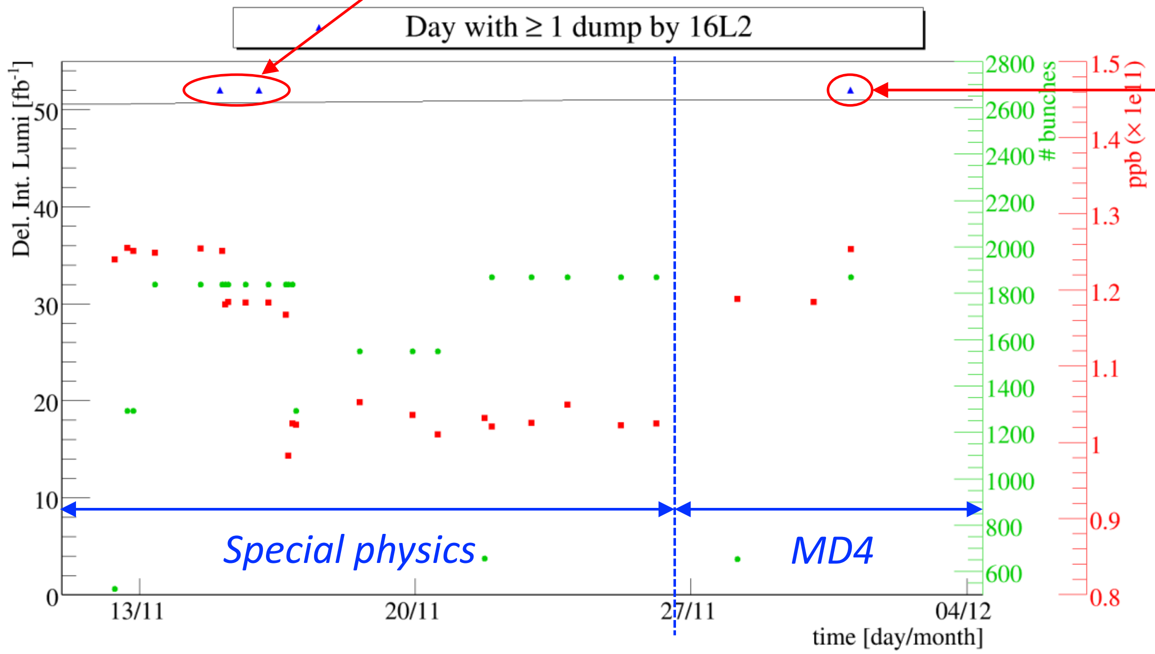
- **Significant contribution by e-cloud** on losses from tests with 50 ns beams and Q shift along the train observable in the post-mortem of the dump occurring as a result of the instability
  - Change to **8b4e** filling pattern to reduce multipacting
    - **Loss spikes reduced significantly and smooth operations restored!**
    - **16L2 events occurred when ppb > 1.17e11**
  - Installation of **solenoid** and change to **BCS** production scheme to increase bunch brightness
    - **Multipacting reduced also in the field free region of the interconnection**
    - **16L2 events occurred when ppb > 1.3e11!**



Latest events

- Operational bump to **change of I_{MCB} not incorporated in the 2.5 TeV cycle**

→ **I_{MCB} of Beam 2 at ~ 0 A** → **Dumps occurred in Beam 2** → **Confirmation impossible to run with I_{MCB} ~ 0 A**



- **Limited time during MD4** to perform systematic tests on the effect of the solenoid:

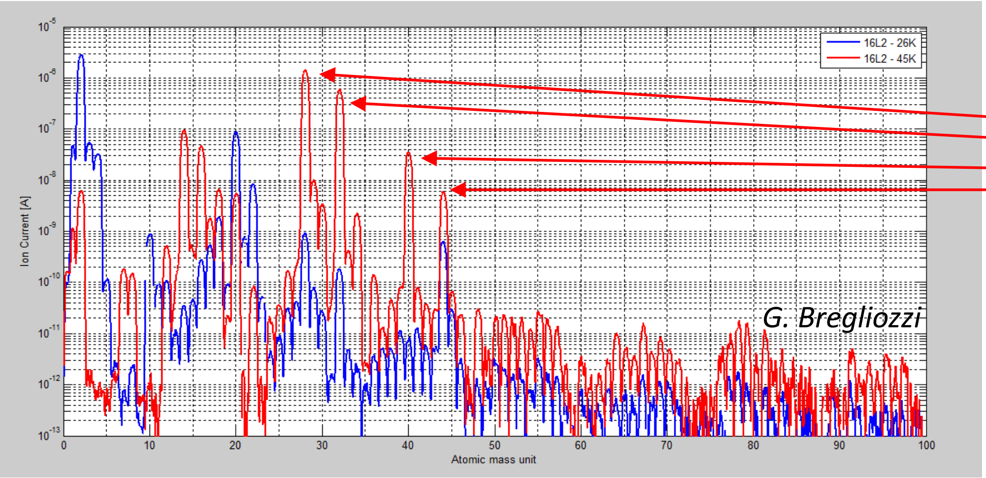
→ **Single fill with physics beams but solenoid OFF** (8b4e BCS, 1868b, 1.25e11 ppb)

Dump during ramp confirmed beneficial effect of solenoid on intensity threshold

YETS plans

- **Initial plan:** bring all sector 12 to **room temperature**
- **First action:** temperature increased up to **80-90 K (including cold mass) and analysis of the gas** released

Confirmed contamination by atmospheric air



Composition of Atmospheric Air

Gas	Volume %	Partial Pressure (torr)
N_2	78.08	5.94×10^{2}
O_2	20.95	1.59×10^{2}
Ar	0.93	7
CO_2	0.033	2.5×10^{-1}
Ne	1.8×10^{-3}	1.4×10^{-2}
He	5.24×10^{-4}	4.0×10^{-3}
CH_4	2.10^{-4}	1.5×10^{-3}
Kr	1.1×10^{-4}	8.4×10^{-4}
H_2	5.0×10^{-5}	3.8×10^{-4}
N_2O	5.0×10^{-5}	3.8×10^{-4}
Xe	8.7×10^{-6}	6.6×10^{-5}
O3	7×10^{-6}	5.3×10^{-5}
H_2O*	1.57	1.19×10^{1}

*50% relative humidity at 23°C

- **Estimated air entered:** 7 bar l per beam pipe → > 99.96% pumped → Amount of gas reduced by 10^5
- **Estimated amount of water vapor:** 0.1 g per beam pipe → Condensed on the pumping lines
- **Warm up stopped:** *Compromise between risks associated to bring a sector to room temperature and vacuum quality reached*

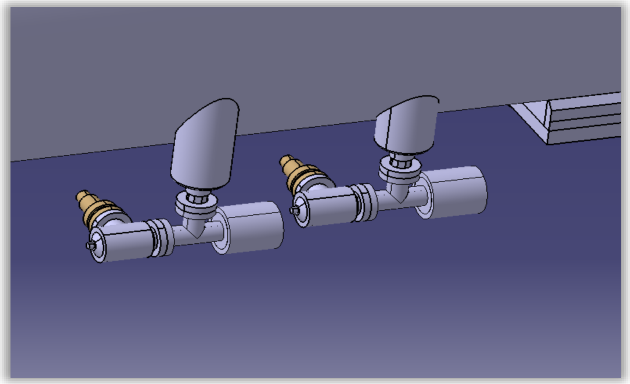
Avoid repetition

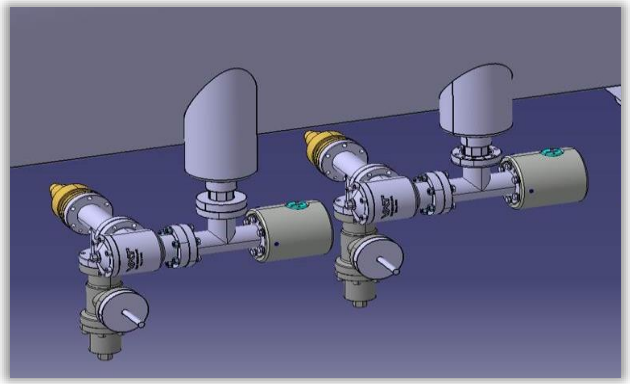
- **Most probable scenario:** *Accidental air venting, during the removal of the mobile group for the final pinch-off*

- **New pumping scheme:** All the pump groups installed in positions equipped with vacuum gauges

  Detection of air entering during mechanical activities

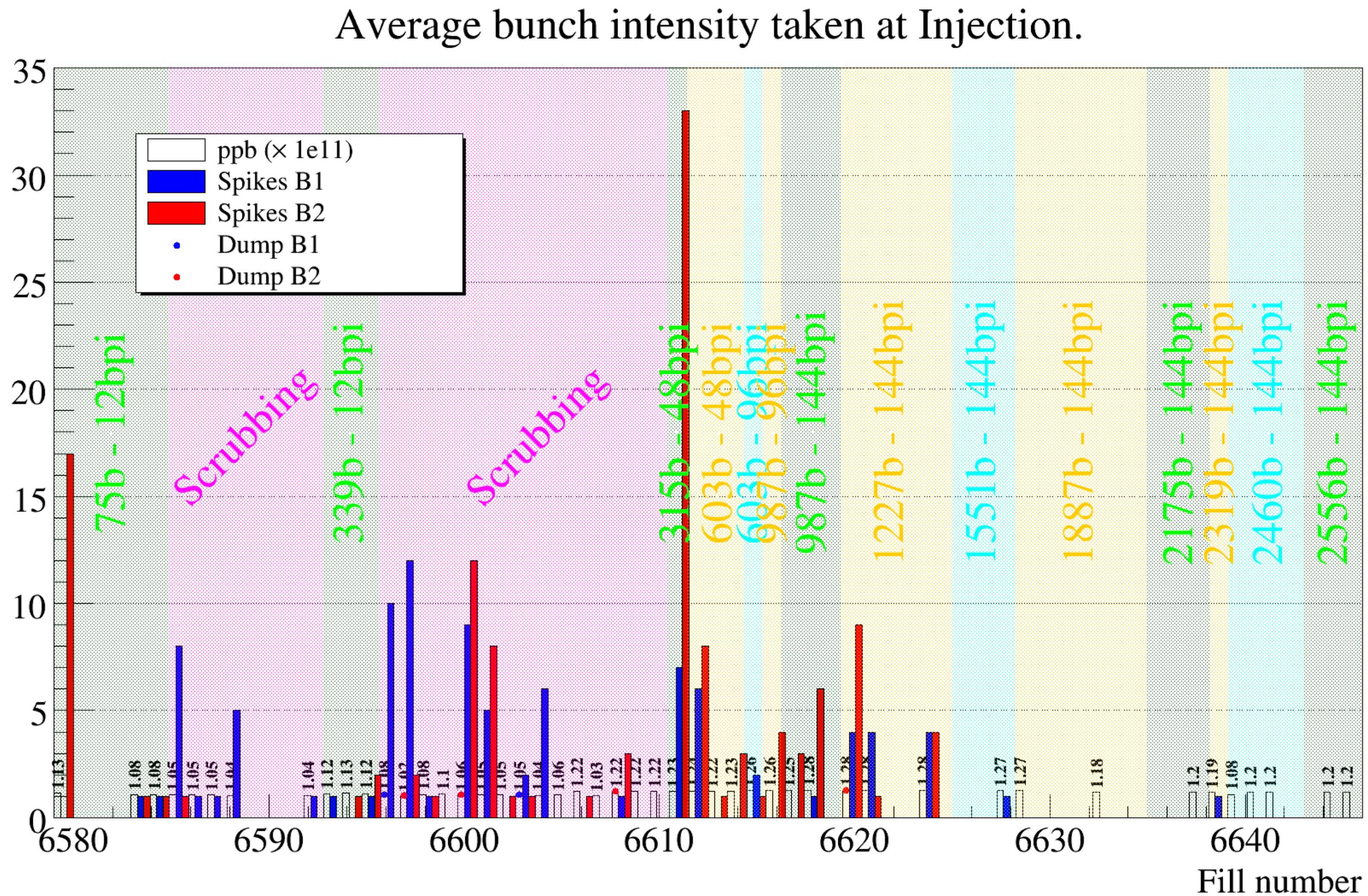
Pumping port upgrade:





- **Removal of pumping groups before cool down:** *Quick re-pumping in case of air leak, no need of magnet warm up*

Intensity Ramp up 2018



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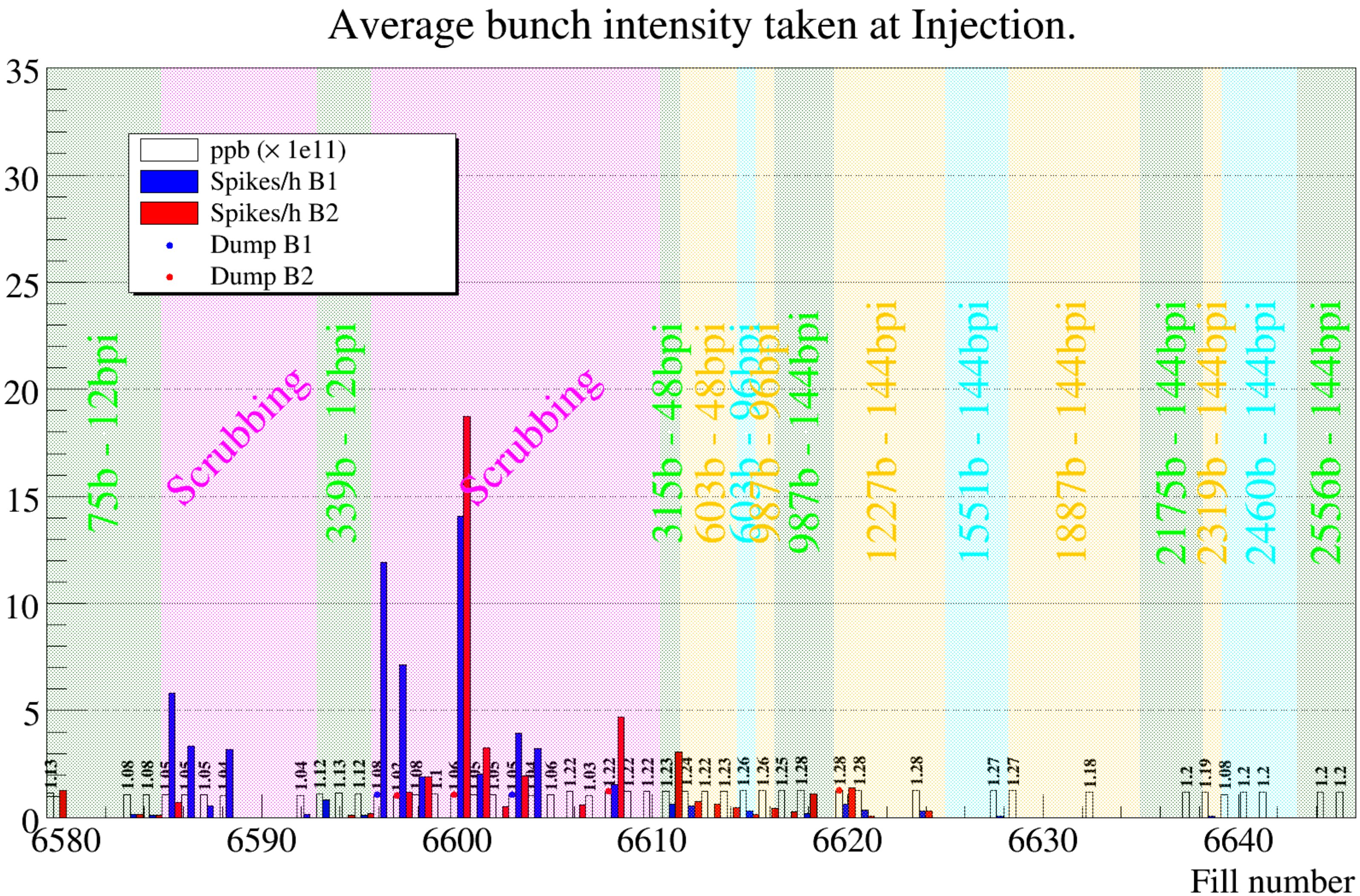
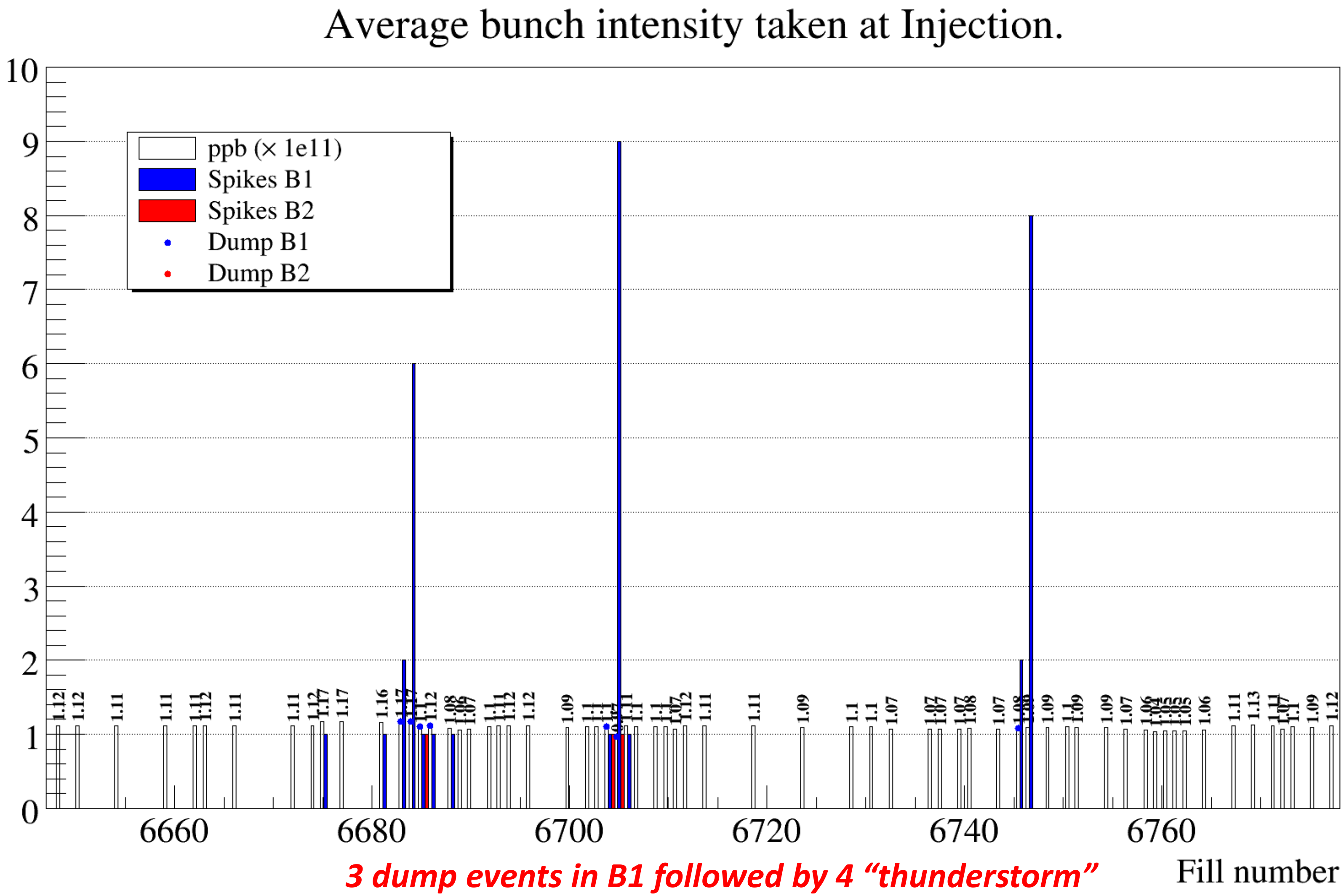
Intensity Ramp up 2018 (normalized)



Very early activity w.r.t. 2017 but clear conditioning after scrubbing

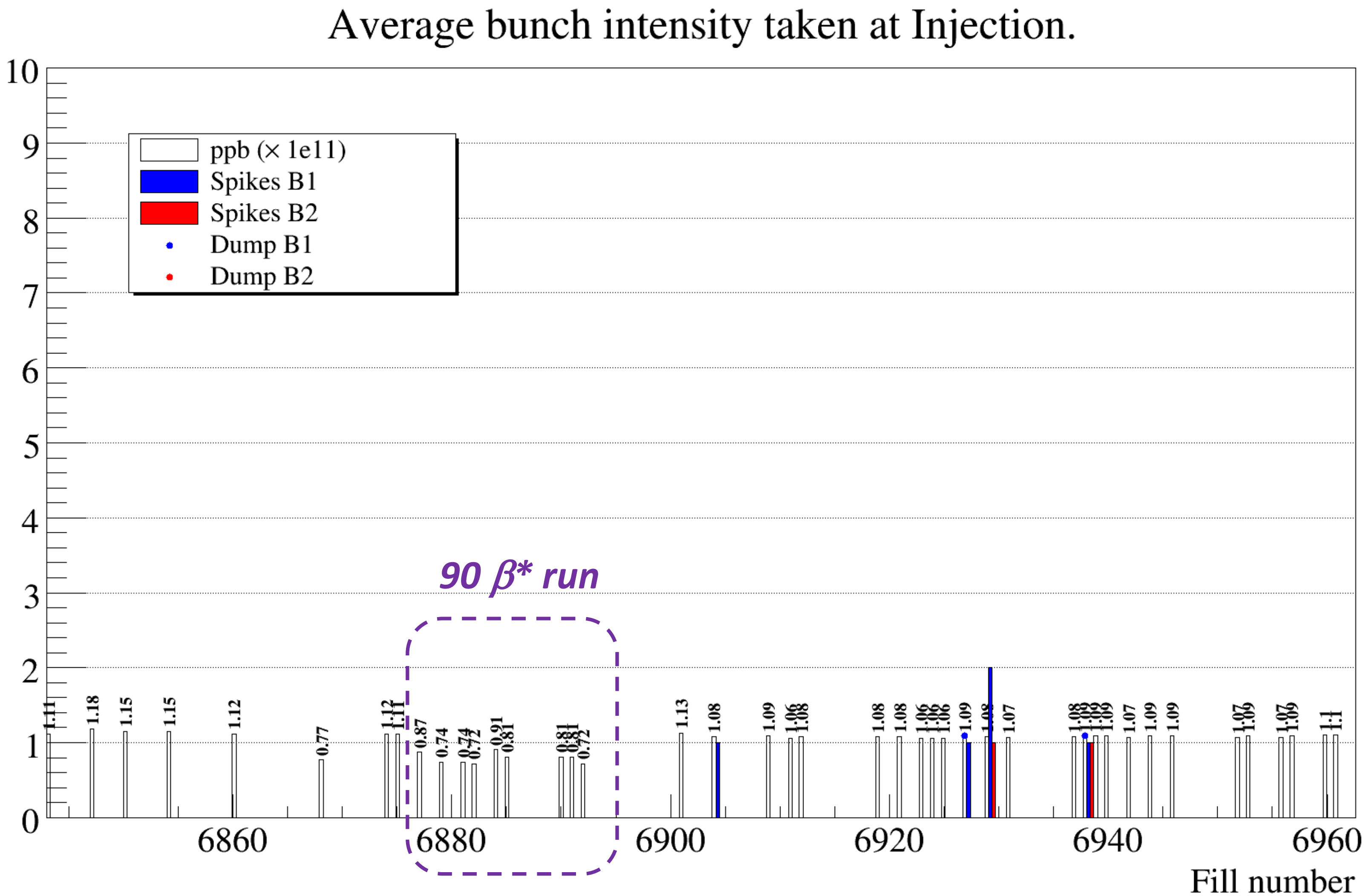
Full Machine until TS1 (2018)



3 dump events in B1 followed by 4 "thunderstorm"

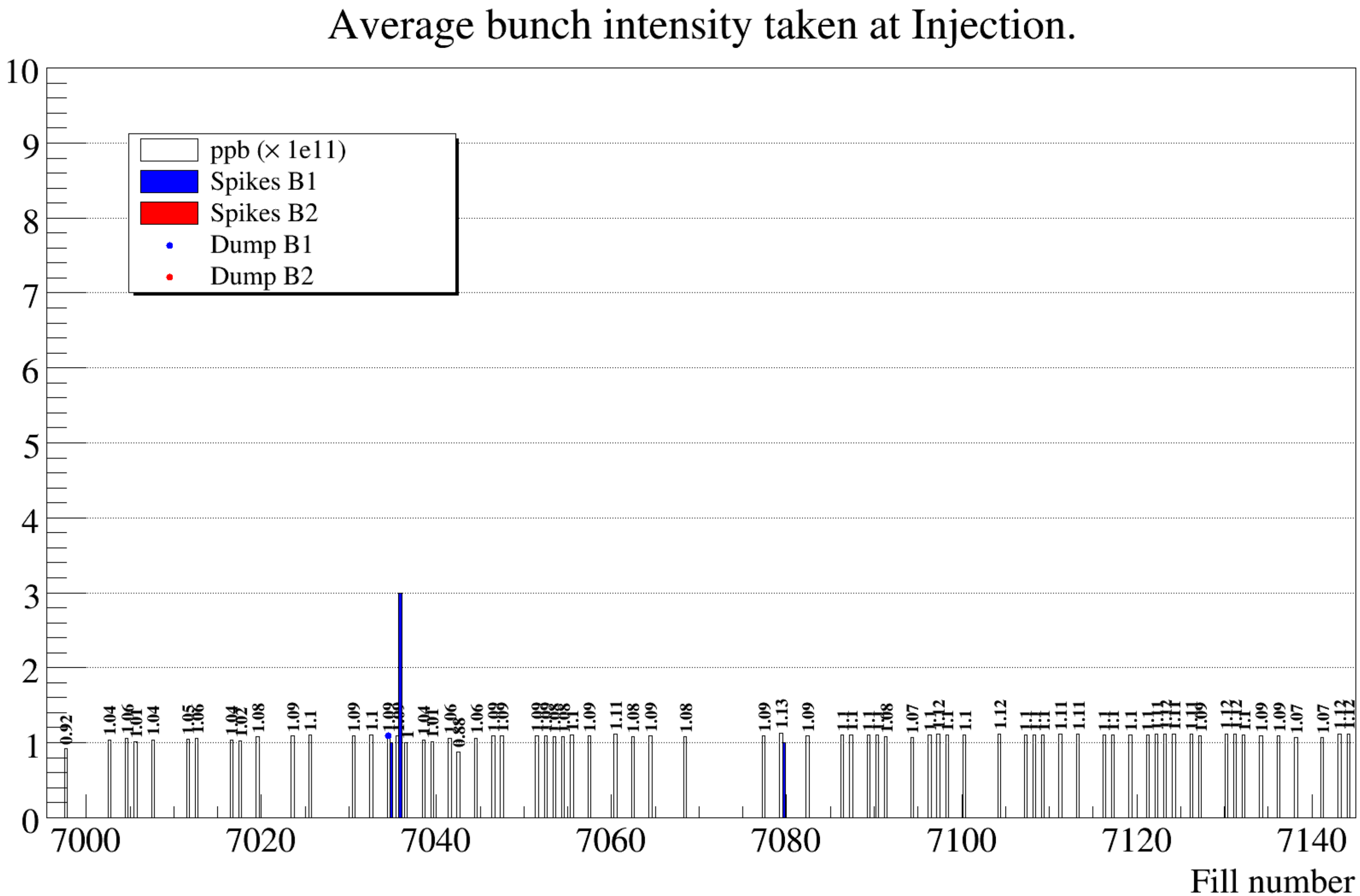
Cured after fill 6746 with 900b recovery fill

From TS1 to MD2 (2018)



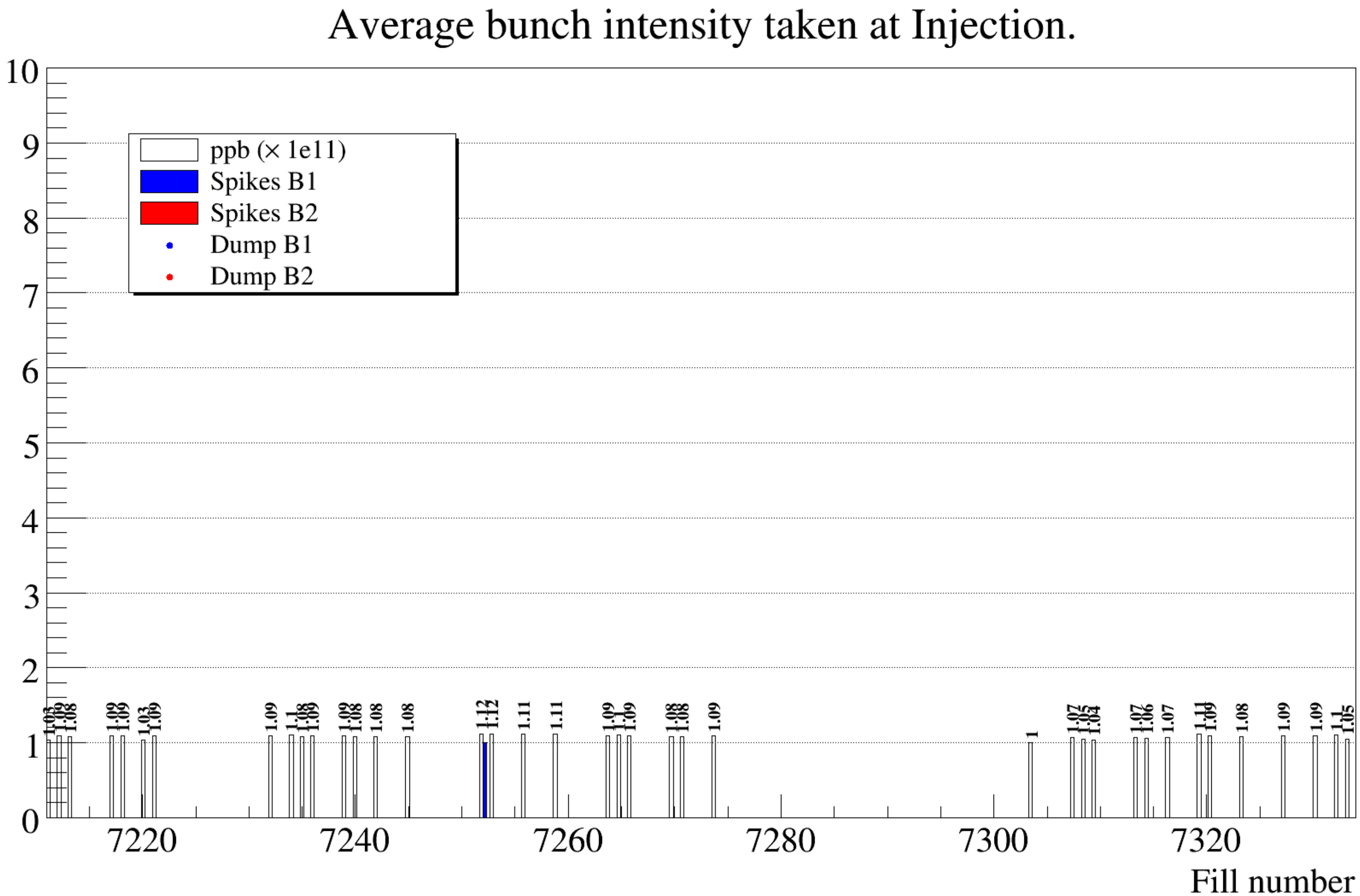
Two dump events in B1 without following dumps due to "thunderstorm"

From MD2 to TS2 (2018)



One dump event in B1 without following dumps due to "thunderstorm"

From TS2 to end of Run2 p-p run (2018)



No dump events, only one single spike in B1

Summary

- **Very early activity w.r.t. 2017** obseved during intensity ramp up
  (first observation in 2017 during scrubbing run, in 2018 already visible with 75b)
- **Clear conditioning** after scrubbing and intensity ramp up
- Still **7 dumps caused between end on intensity ramp up and TS1**
  (4 dumps caused by following ”thunderstorm”)
- **Mitigation strategy** of the ”thunderstorm” **of recovery fill with 900b** worked from fill 6746
- **Two dump events in B1 between TS1 and MD2** without following dumps due to “thunderstorm”
- **One dump events in B1 between MD2 and TS2** without following dumps due to “thunderstorm”
- **No** dump and only one single spike in B1 **from TS2 to end of Run 2 p-p run**

Outline

10Hz…

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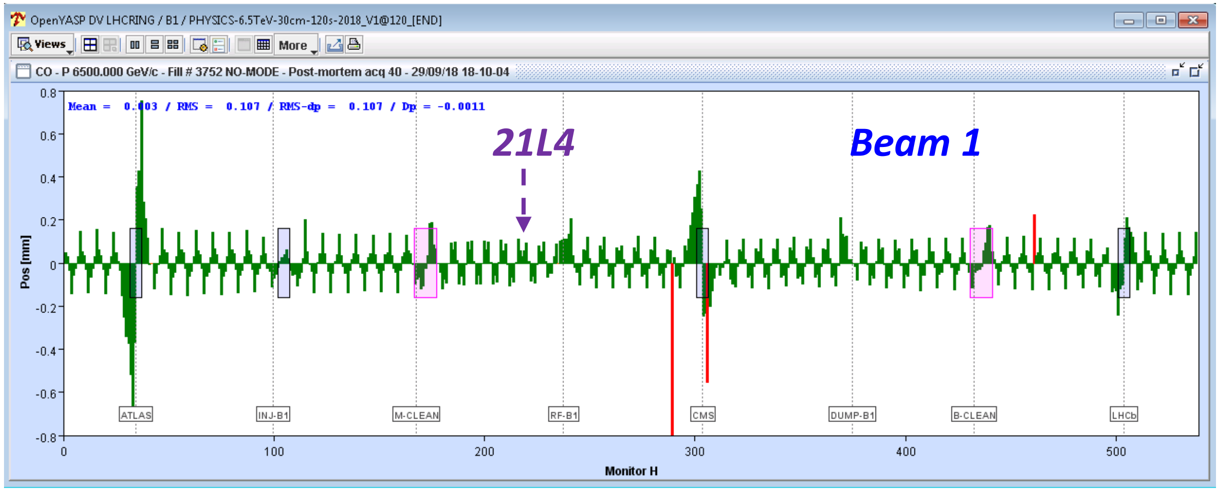
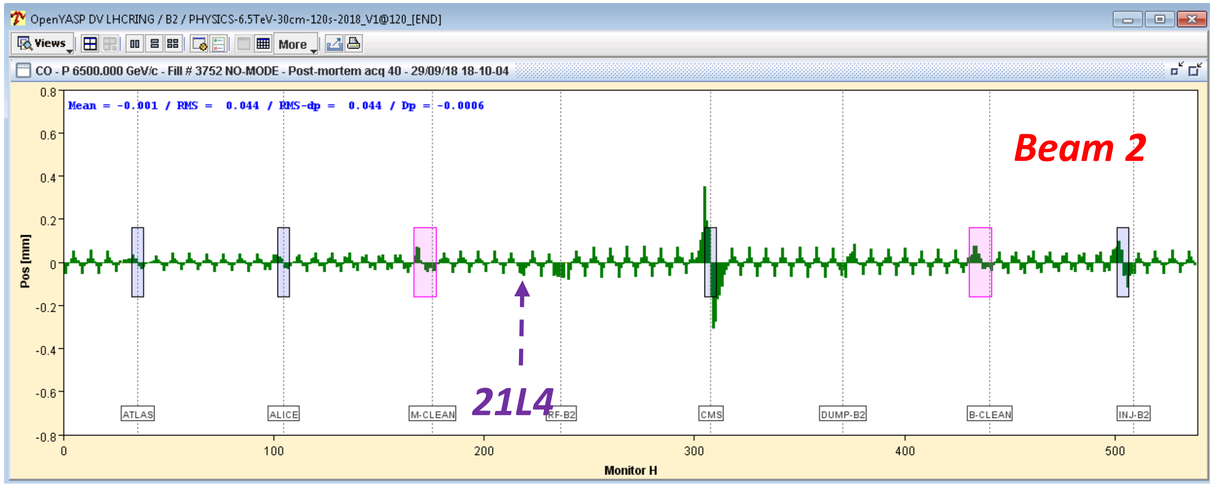
Fill 7235 / pp

- Extreme peak-to-peak trajectory on B1 and B2, ratio B1/B2 ~2.4.
  - A kink is visible @ 21L4 for B1.
  - MICADO points to cell **21L4** for both B1 and B2, kick ~ 1 µrad @ MQ (on p2p traj excursion), consistent between B1 and B2 (also sign !).

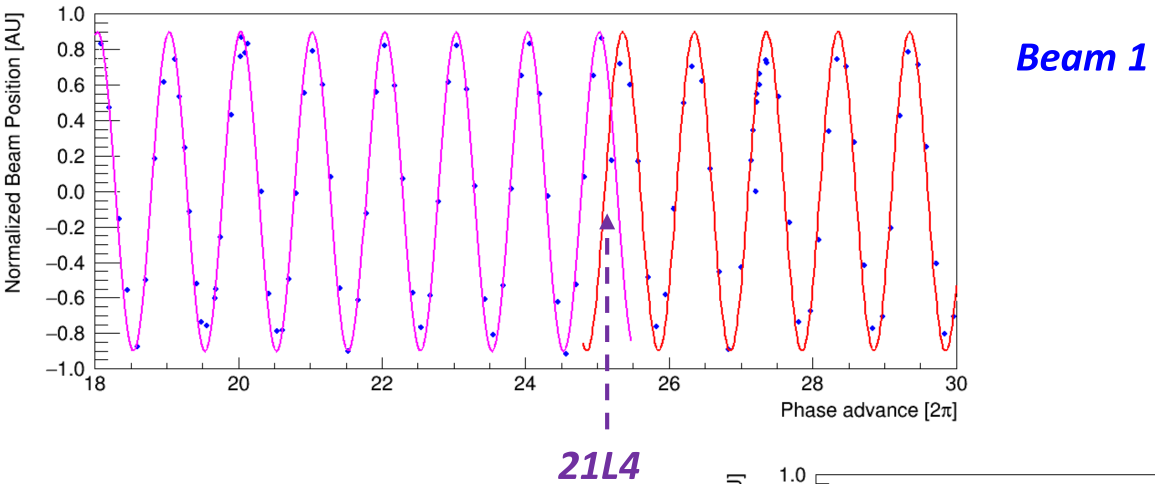


J. Wenninger

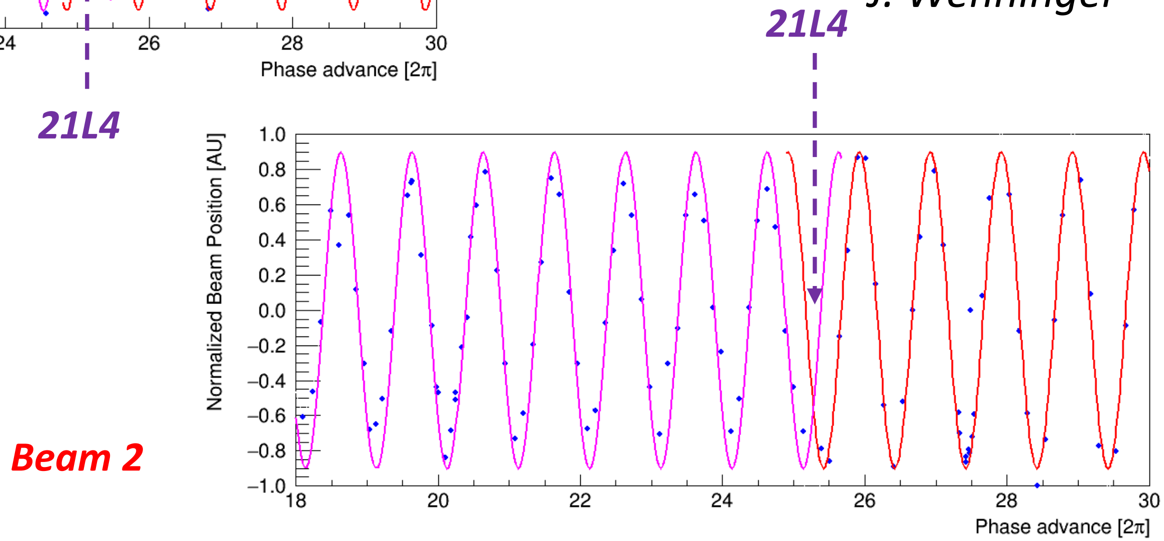


Fill 7235 / pp kink

- Kink @ 21L4 clearly visible on normalized position of B1 and B2.



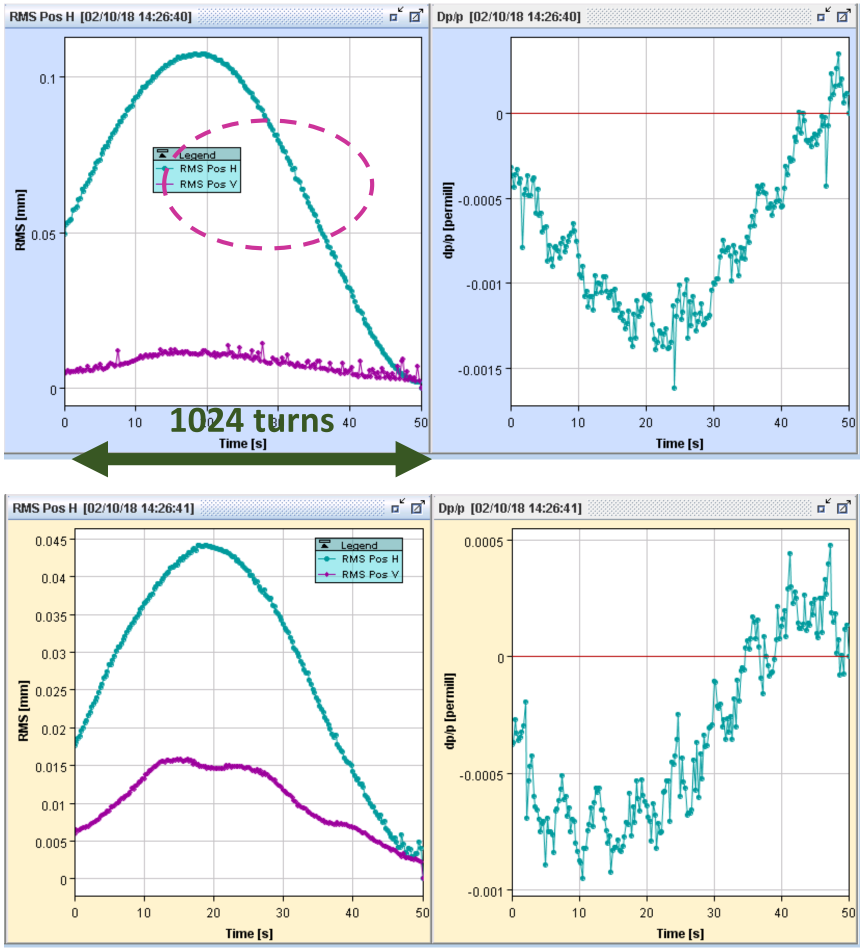
J. Wenninger



Evolution of the trajectory

- Time evolution: estimate period ~1300 turns ~ 9 Hz.

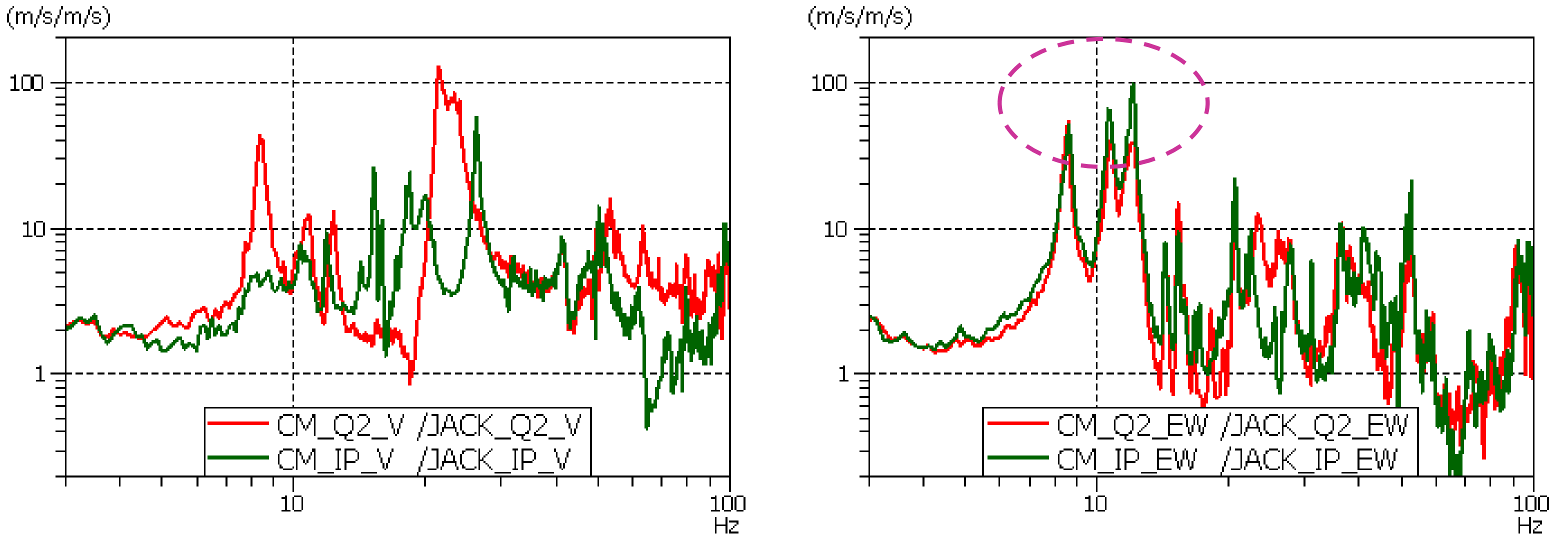
- Ratio B1/B2 ~ 2.44, matches the ratio of $\sqrt{\beta_{x1}}/\sqrt{\beta_{x2}}$ for the H plane of cell 21L4.
- Consistent with a horizontal movement of the MQ in cell 21L4.
- Kick of 1 μrad → 37 μm quad displacement (p2p).
  - ~20 μm oscillation amplitude.



J. Wenninger

IT transfer functions – H plane

- Triplet modes at ~8, 11 and 12 Hz in horizontal plane.
- Fits rather well the observed frequencies…



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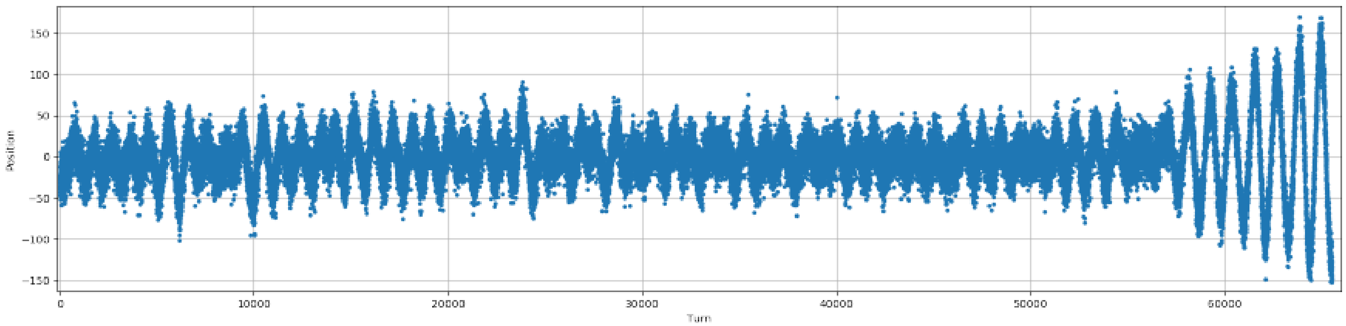
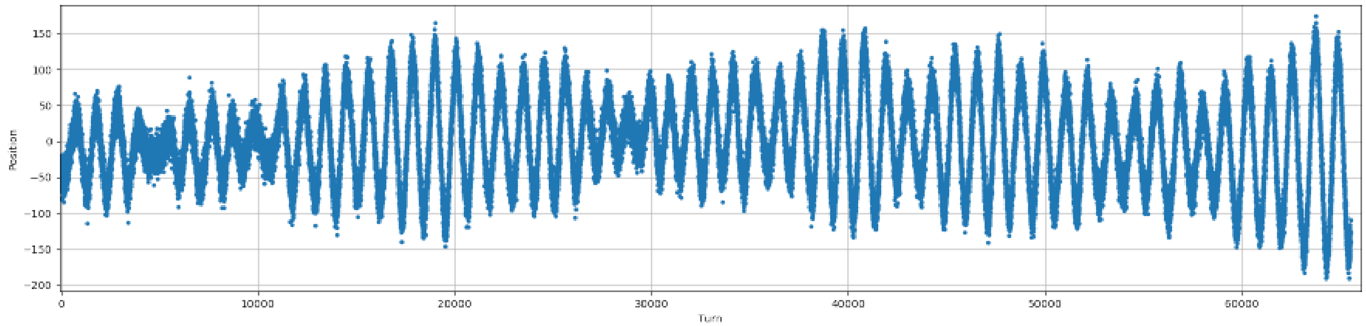
Raw Oscillation



(a) Ion fill 7442



(b) Ion fill 7447

Figure: Horizontal beam displacement observed in all cases

X. Buffat and A. Oeftiger

BPM Spectrum

Ions 50cm

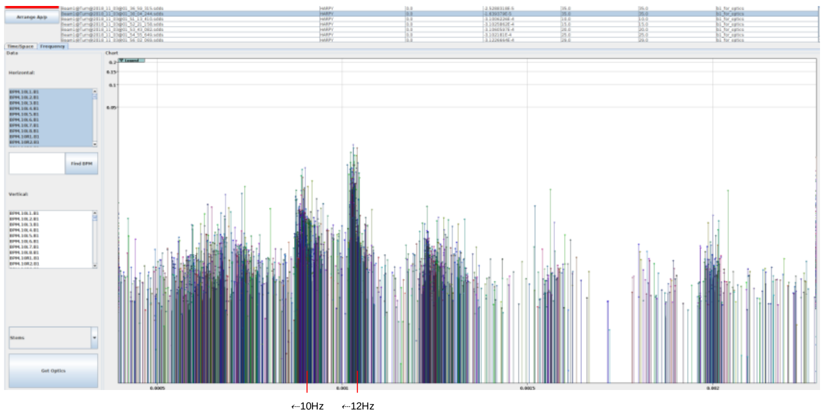


Figure: Beam 1 Frequency Spectrum of horizontal BPMs.

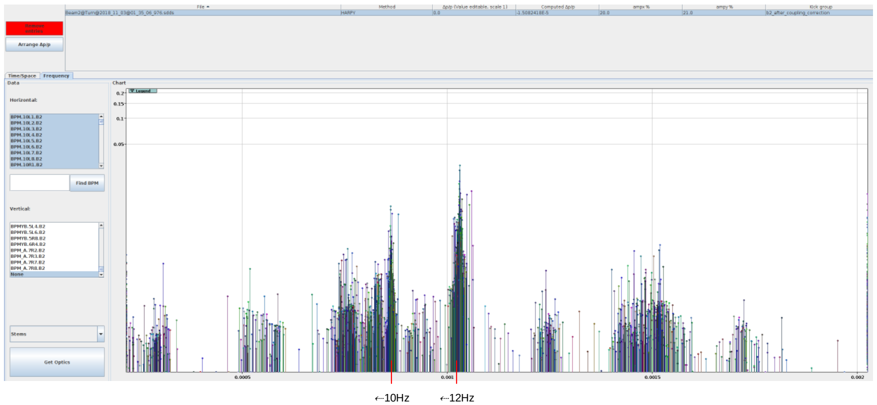
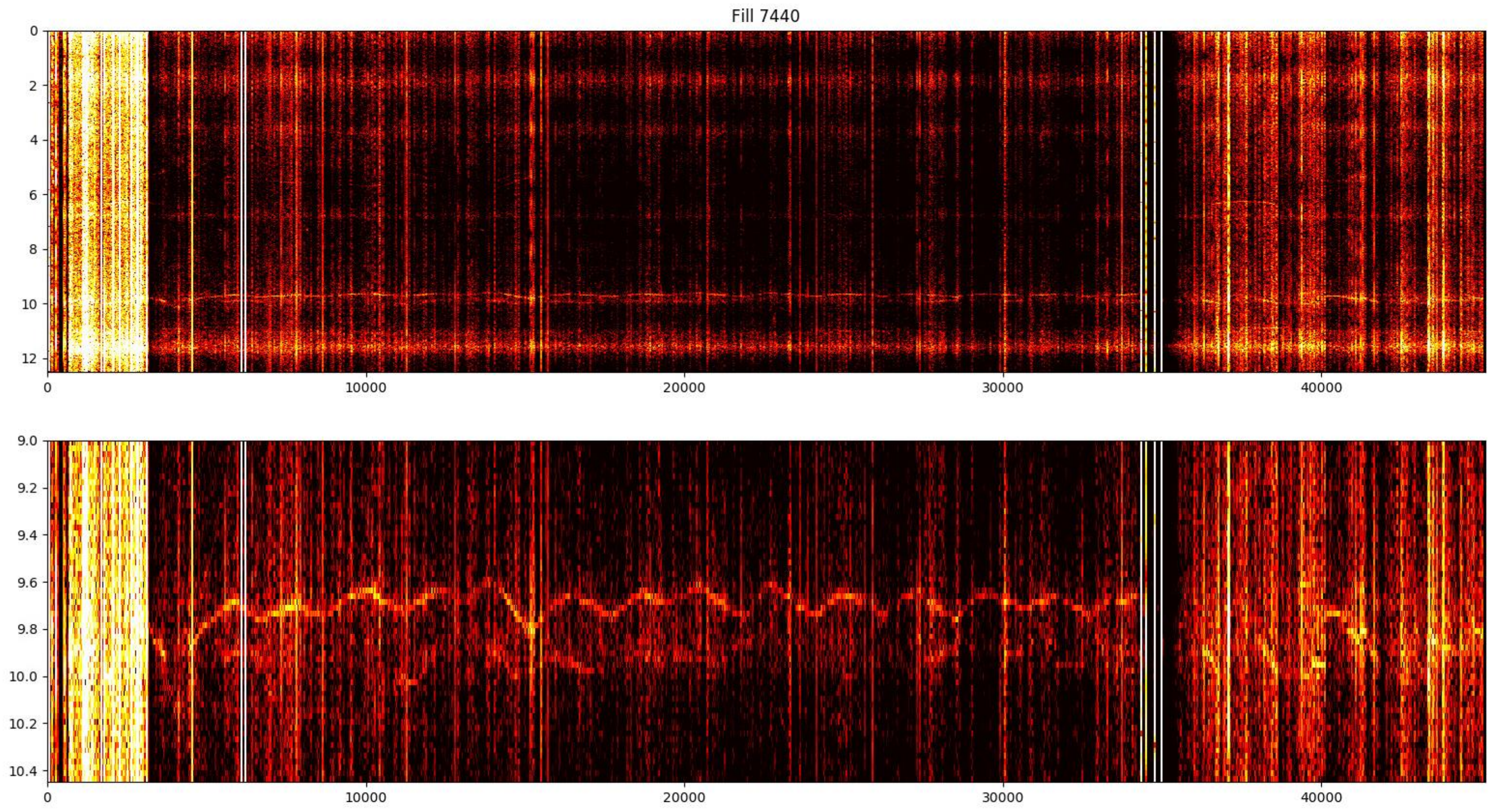


Figure: Beam 2 Frequency Spectrum of horizontal BPMs.

- Lines around 10Hz are **visible in the horizontal spectrum**
- **no lines** can be found in the **vertical spectrum**
- often two lines at around **10Hz and 12Hz**
- the **12Hz line** has usually **higher amplitude**
- sometimes only one line around 11Hz
- these lines are **visible for both**, Ions and Protons
- they are **more distinct for Ion optics**, especially in Beam 2
- **Injection does not show** clear lines.

J. Dilly

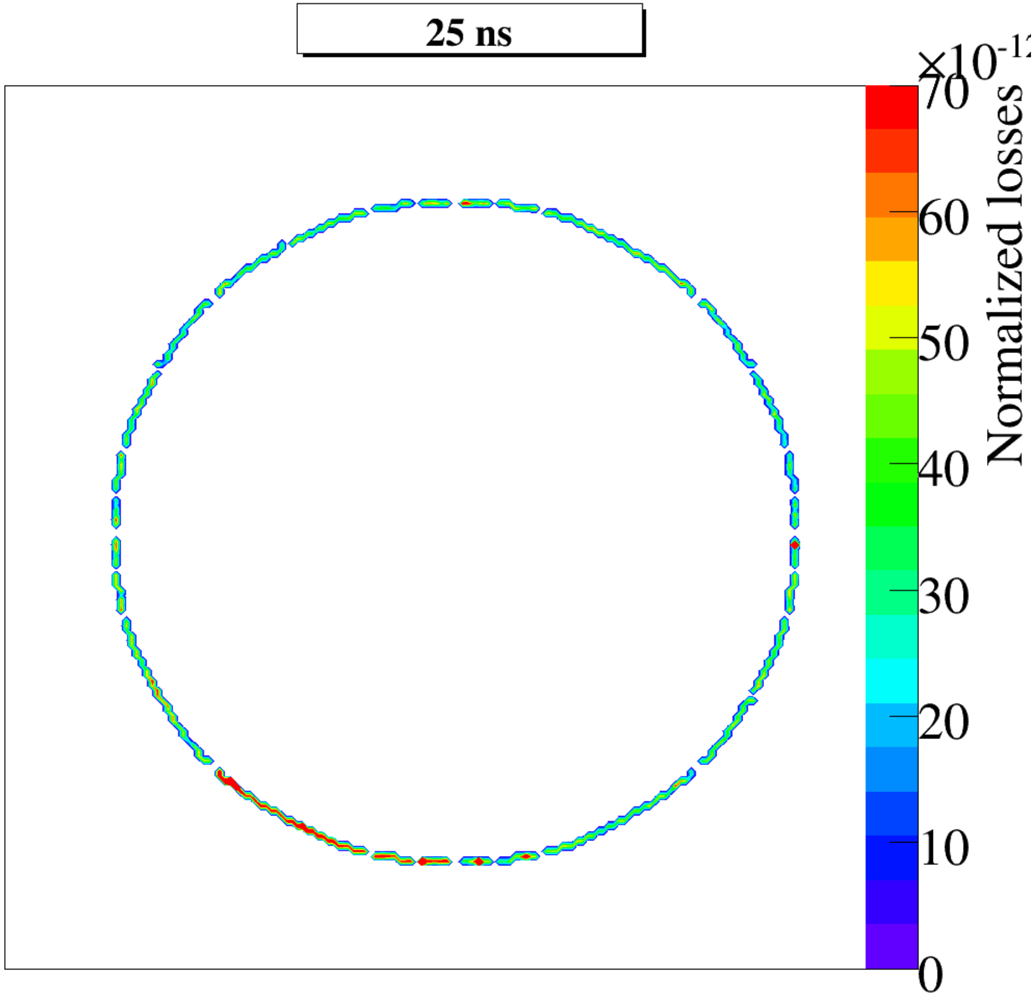
100Hz BLM FFT



G. Trad

Heat Load VS Losses…

25 ns



50 ns