# Overview of intensity limitations in the injectors and transverse stability aspects

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**JAP Workshop**
**5 – 7 December**

# OUTLINE

- **PSB, PS and SPS overview**
- **SPS**
  - Intensity reach and hardware limitations for different beams:
    - Intensity limitations with the Standard beam
    - Intensity limitations with the 8b4e beam

- **SPS wire scanners**
- **SPS vertical instability at injection**
- **SPS horizontal instability at injection**
- **Summary**

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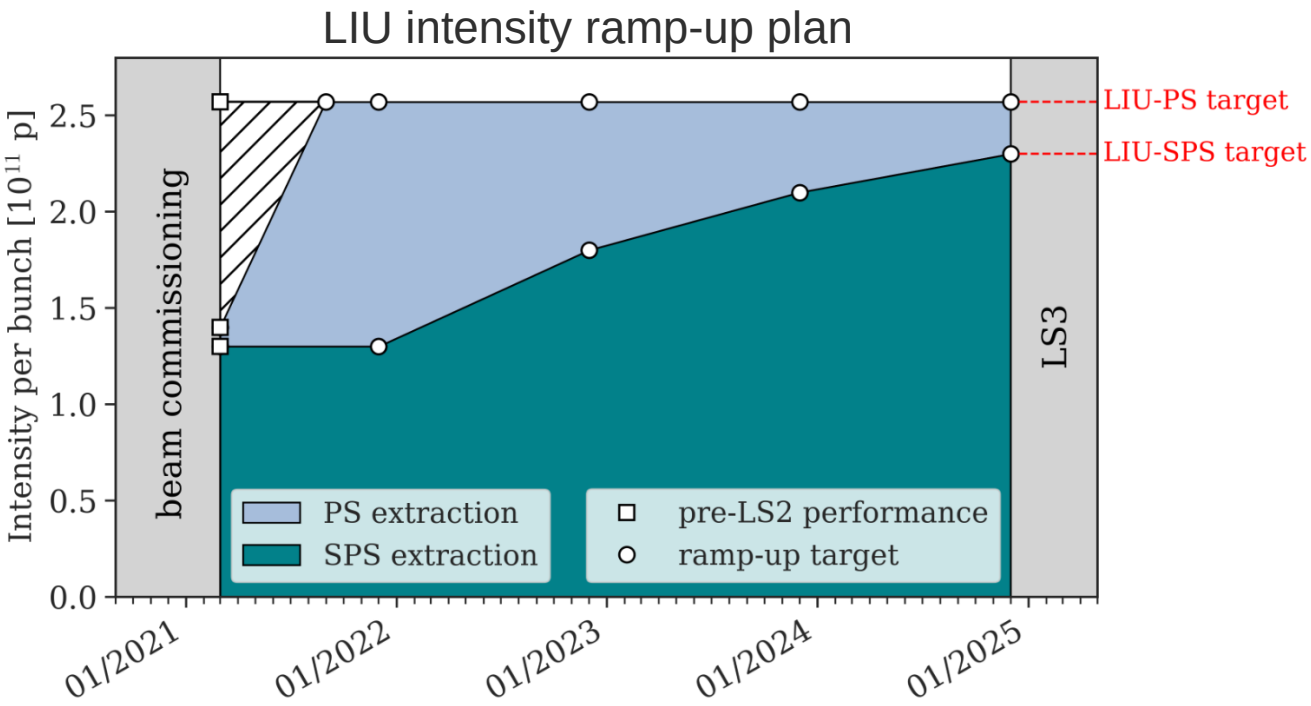
# PSB, PS and SPS overview

## PSB

**No intensity limitations in the PSB for the LHC beams intensity range.**

**The LIU target for LHC brightness was already achieved in 2021.**




## PS

**LIU beam parameters achieved at PS extraction**

- No transverse instability has been observed in the currently nominal 3 eVs below ~3.0e11 p/b.

  As of today, transverse instabilities do not represent a limitation in the PS.

- At high intensities, **reproducibility of beam parameters** needs to be improved as it impacts **SPS transverse stability** (especially bunch length).

**More details in I. Karpov's talk**

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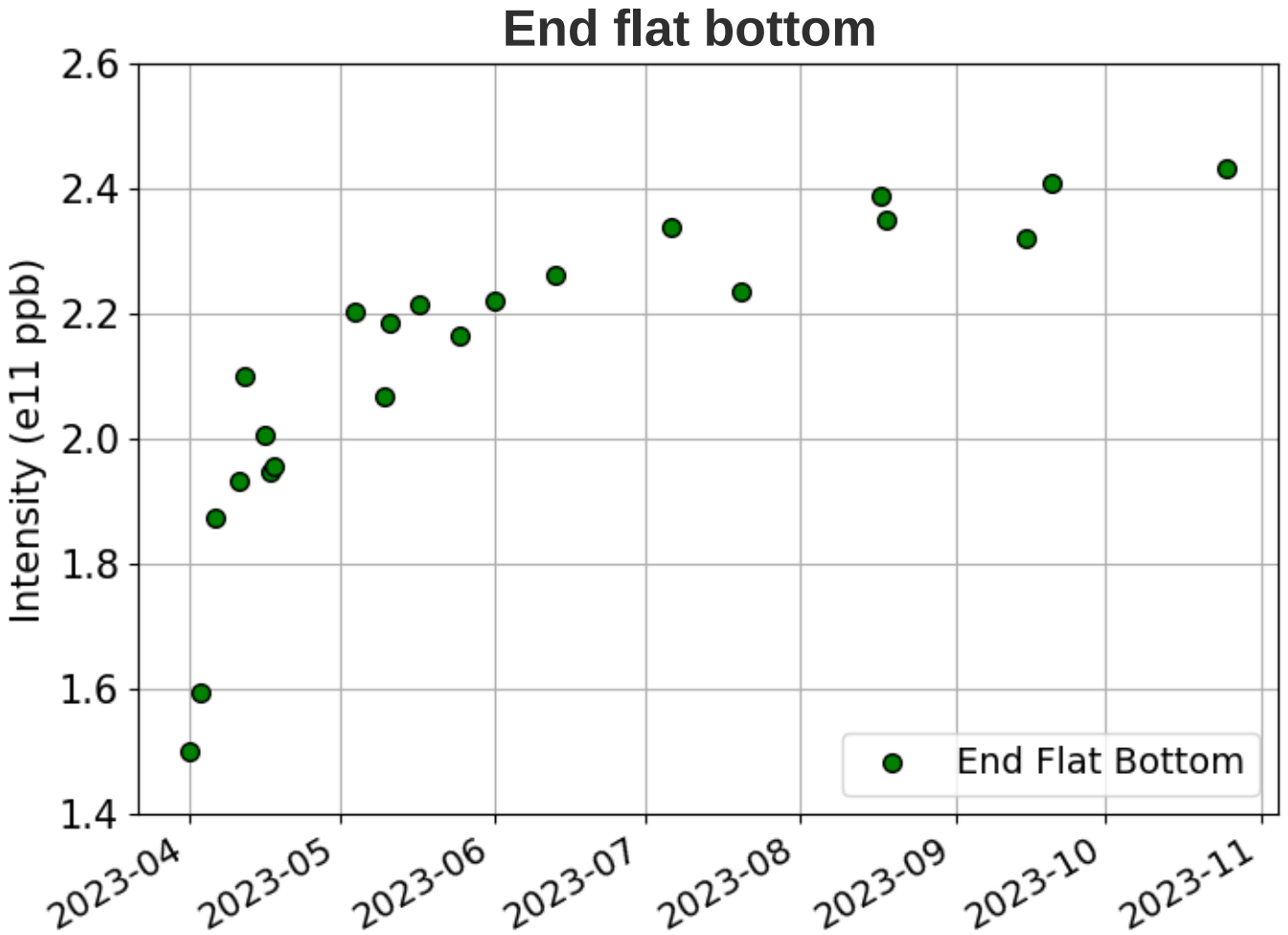
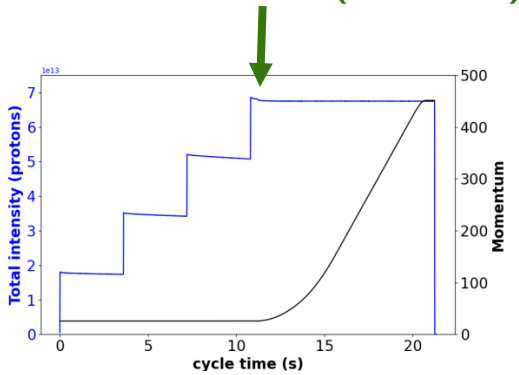
# SPS intensity reach. Standard beam 4 x 72 bunches.

**High intensity MD's in 2023**



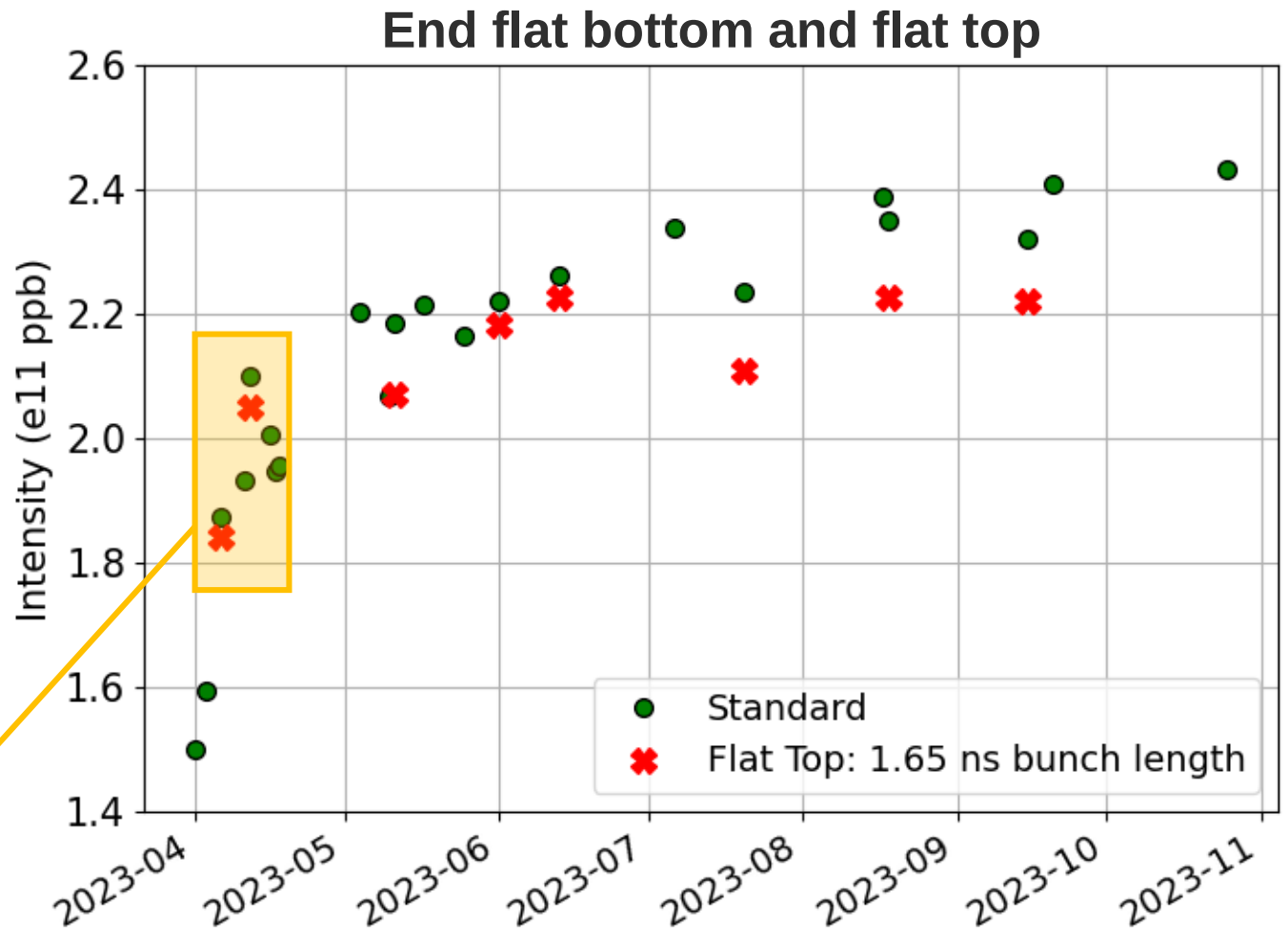

End flat bottom (26 GeV)




**Intensity ramp-up during the year**

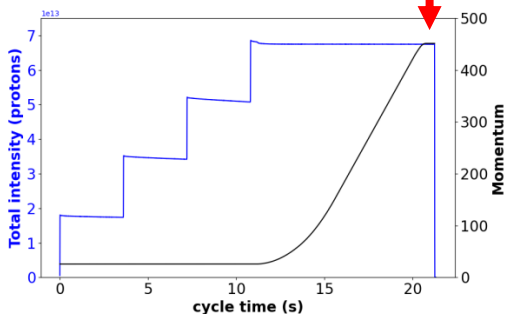
# SPS intensity reach. Standard beam 4 x 72 bunches.

**High intensity MD's in 2023**



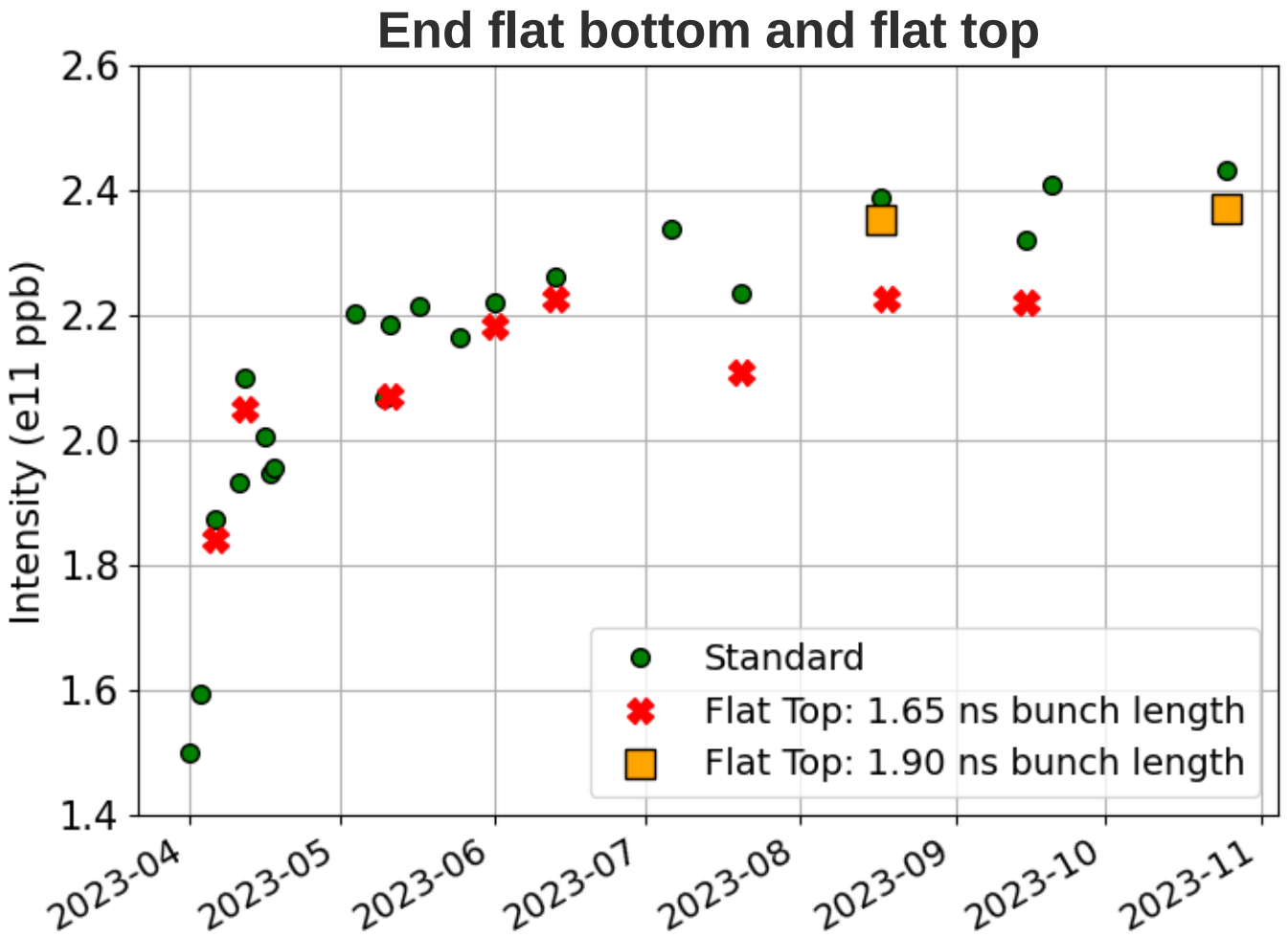

**Long flat top at 400GeV instead of 450GeV**

Flat top (450 GeV)



# SPS intensity reach. Standard beam 4 x 72 bunches.

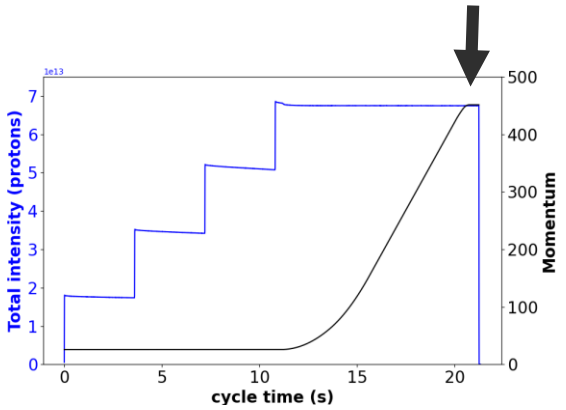
**High intensity MD's in 2023**




**Very important to have high intensity beams regularly in the SPS to preserve performance**

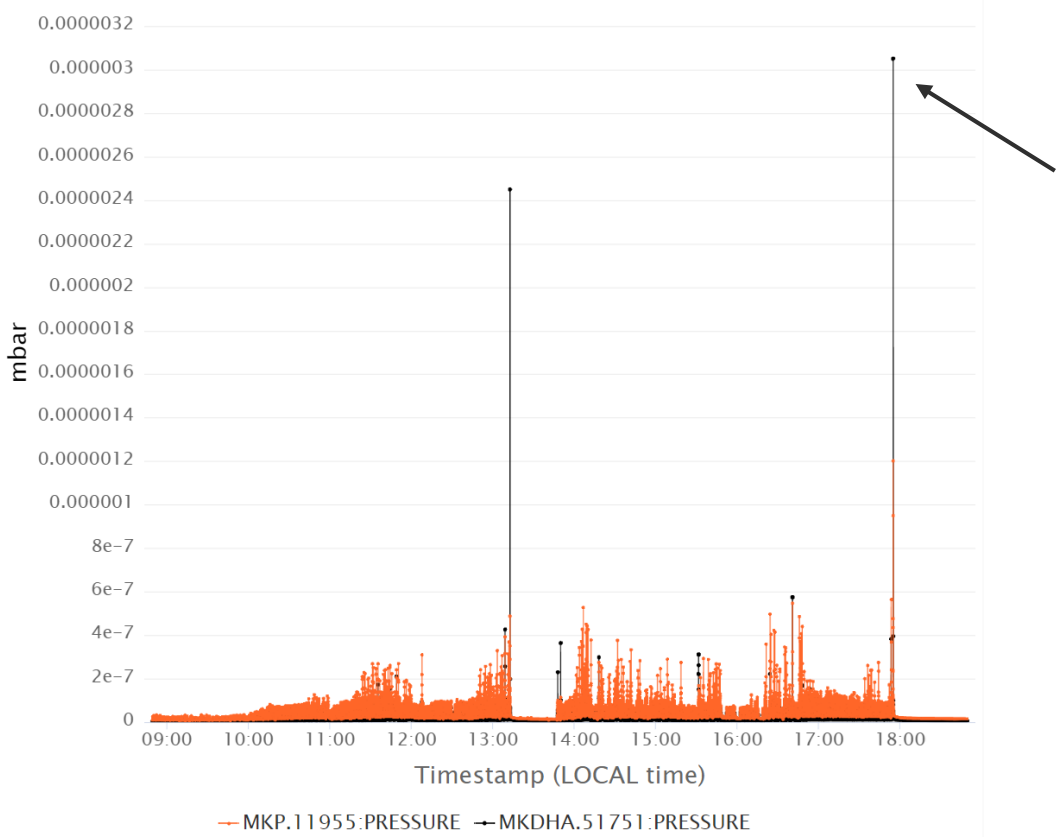
# SPS Intensity limitations.
# Standard beam 4 x 72 bunches.

Flat top (450 GeV)




**Main limitation: high pressure spikes on MKDH.**

Interlock triggered twice on August 17th when trying to go to 2.3e11 ppb.




4 x 72 bunches with **2.3e11 p/b** and **1.6 ns bunch length @450 GeV** was achieved on 17.08.23, but it caused an interlocking pressure spike on MKDH

**Need to scrub gently for this intensity step**

**More details in G. Iadarola's talk**

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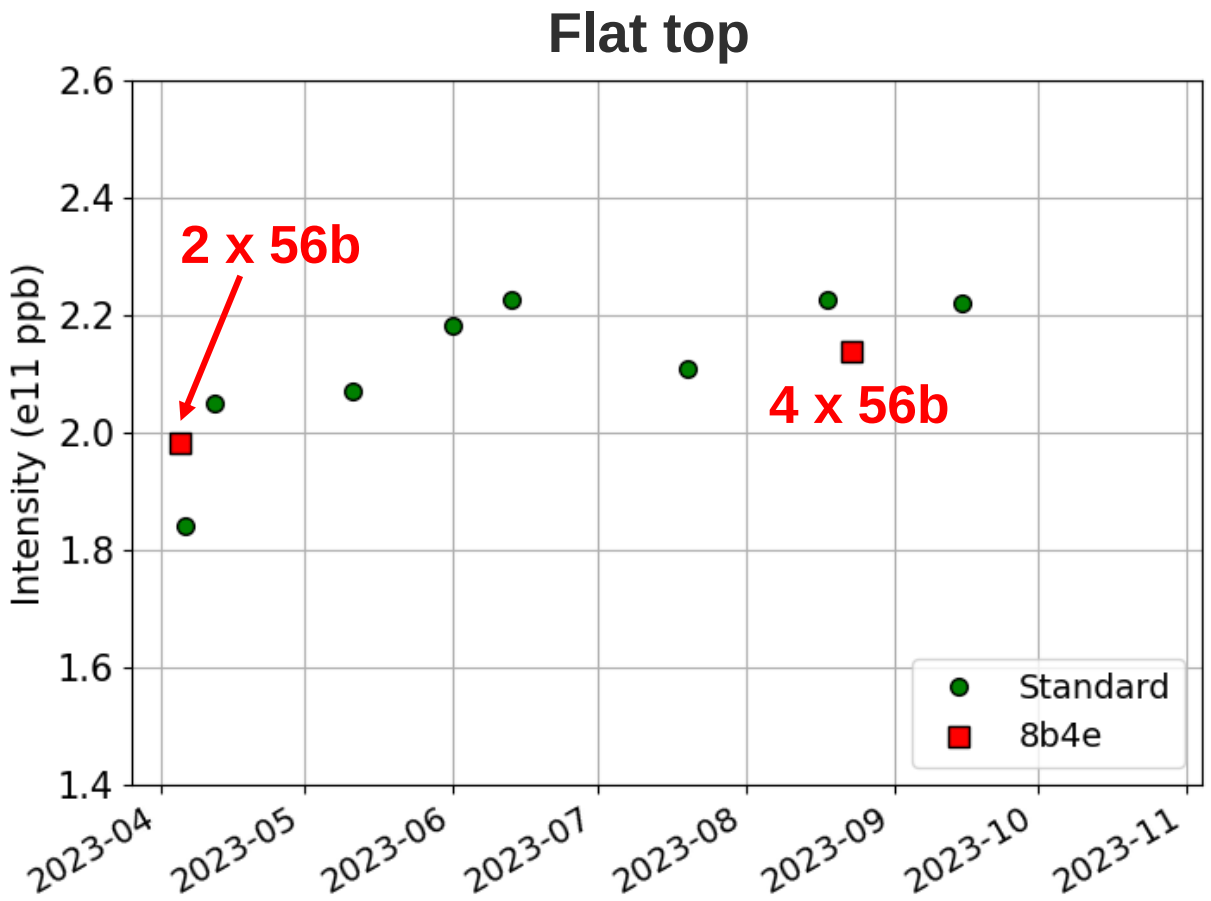
# SPS intensity reach. 8b4e beam.




**8b4e:** 2 x 56 bunches (April)
4 x 56 bunches (August)

**Standard:** 4 x 72 bunches

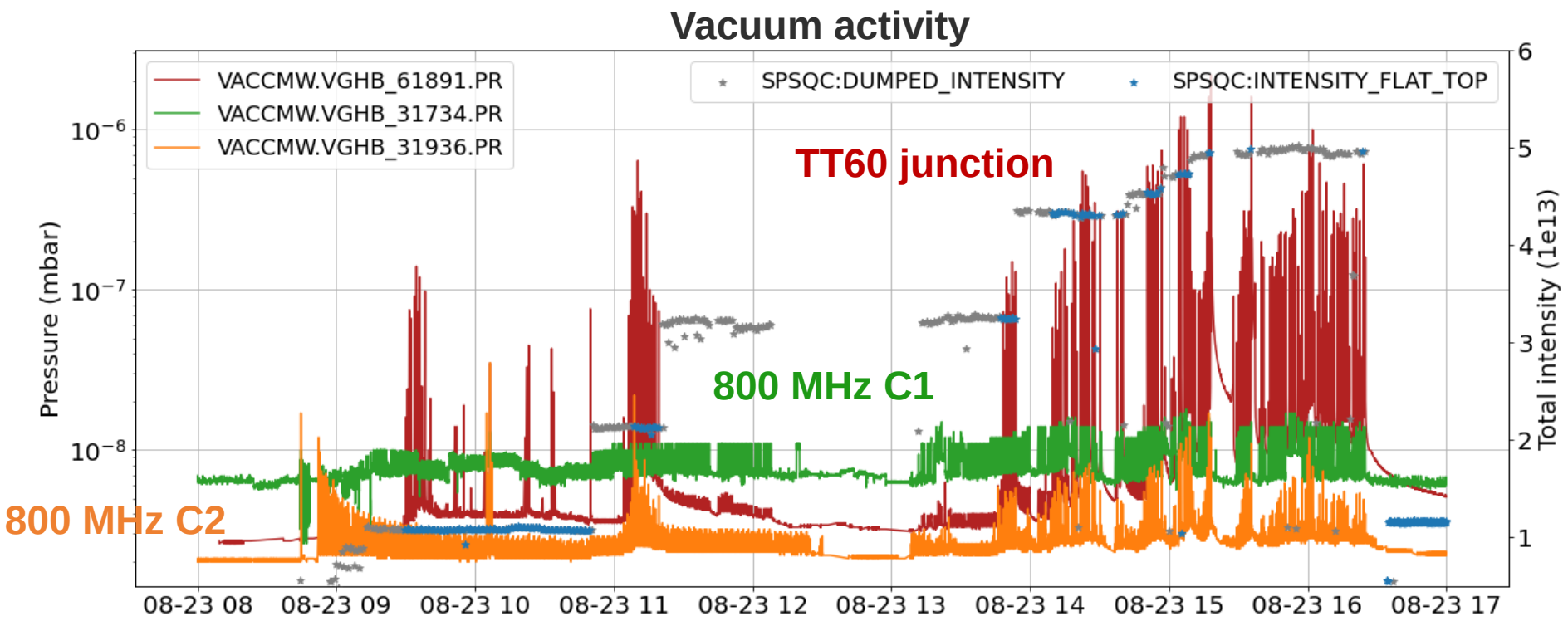
## Brief overview of the limitations in 2022

**5 batches of 56 bunches** accelerated at **flat top** with **1.5e11 p/b** and very good transmission.

**Limitations were encountered at higher intensities due to vacuum interlock on 800 MHz cavity 1**

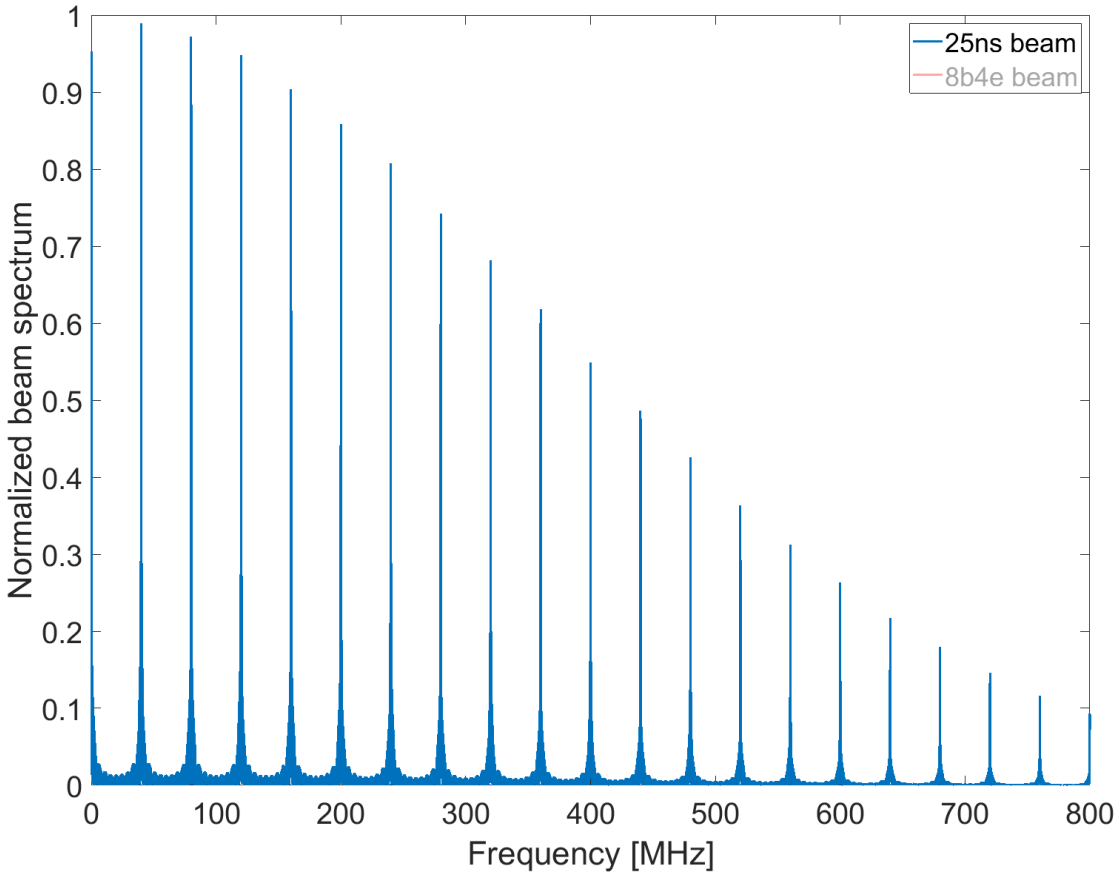
# SPS Intensity limitations. 8b4e beam.

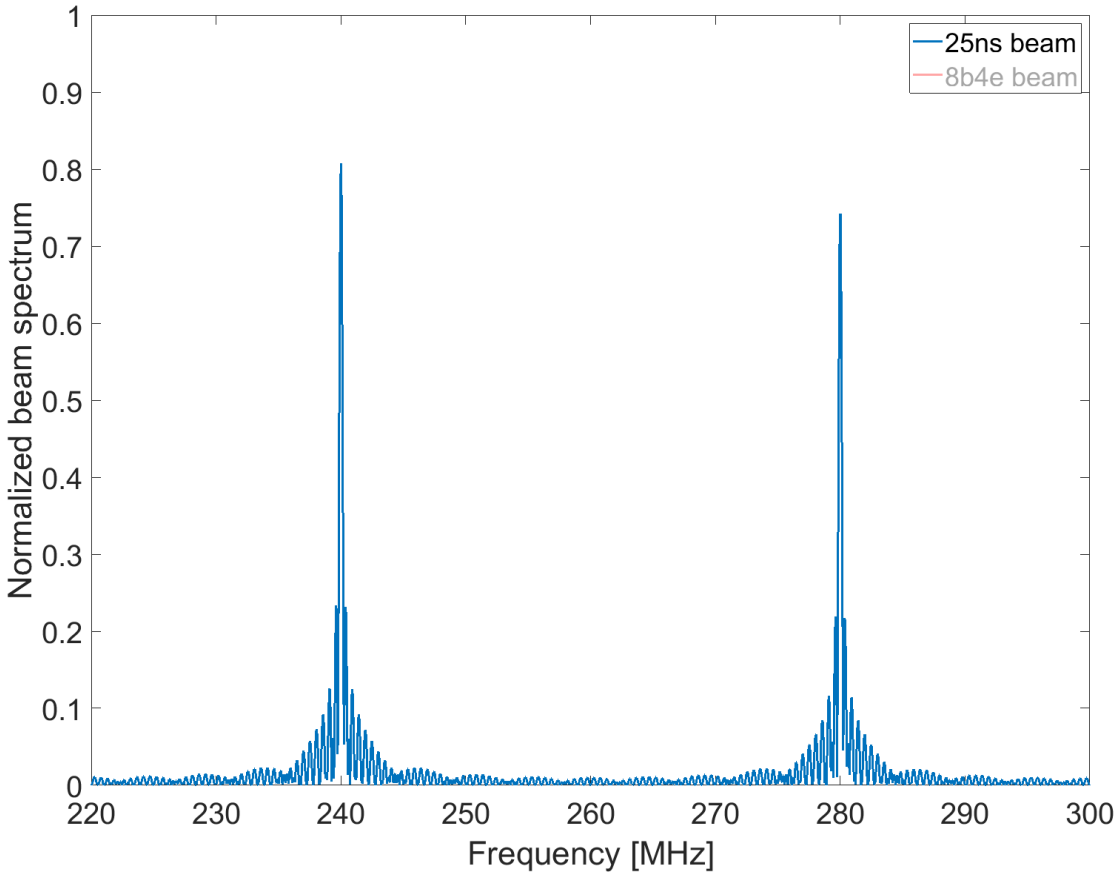
- **AUGUST 2023:** **4 x 56 bunches** accelerated to **flat top** with **2.15e11 p/b** with very good transmission**.**
  - **Very small vacuum activity in the 800 MHz cavity 1 (conditioning during the year)**
  - **Intensity reach is limited by vacuum activity near the TT60 junction**
  - Reverse protection interlock triggered for 200 MHz cavity 4 for bunch intensities above 2.0e11 p/b. Transmission lines will be inspected during YETS.



# SPS Intensity limitations. 8b4e beam.

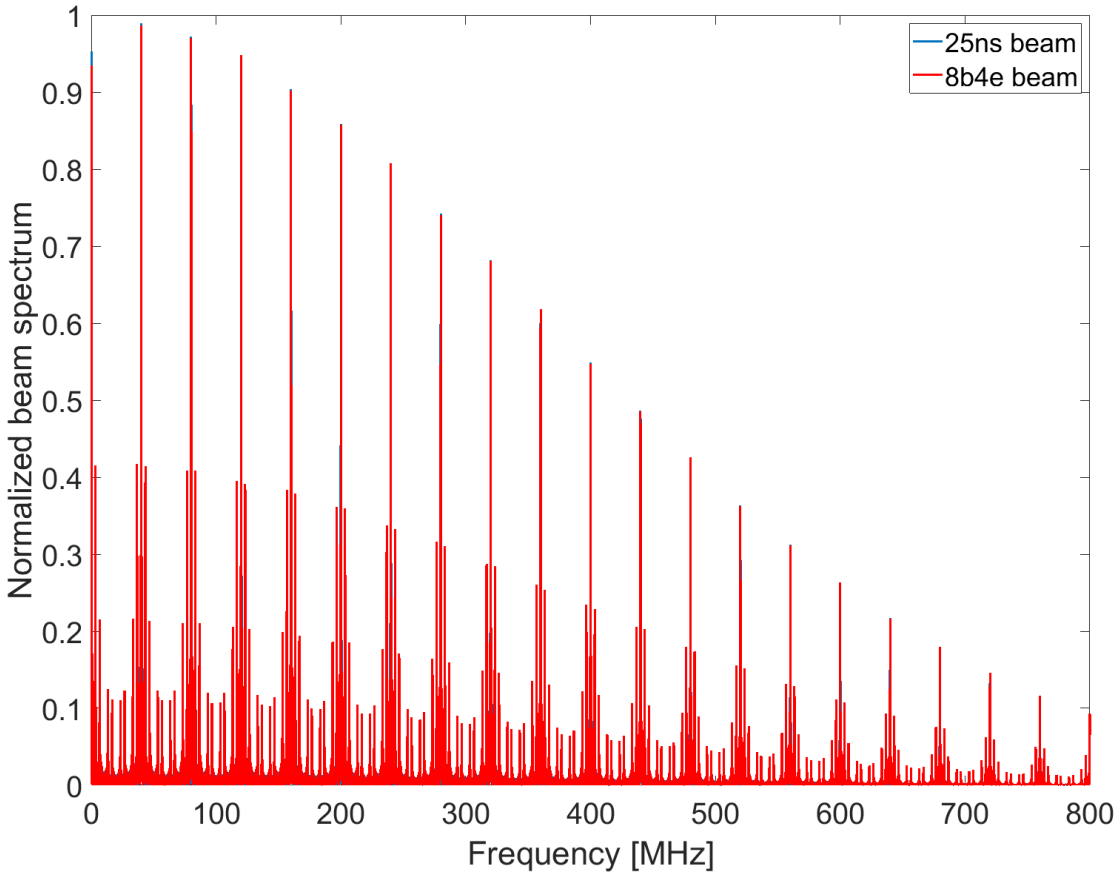
## Comparing beam spectrum 25 ns standard and 8b4e beams

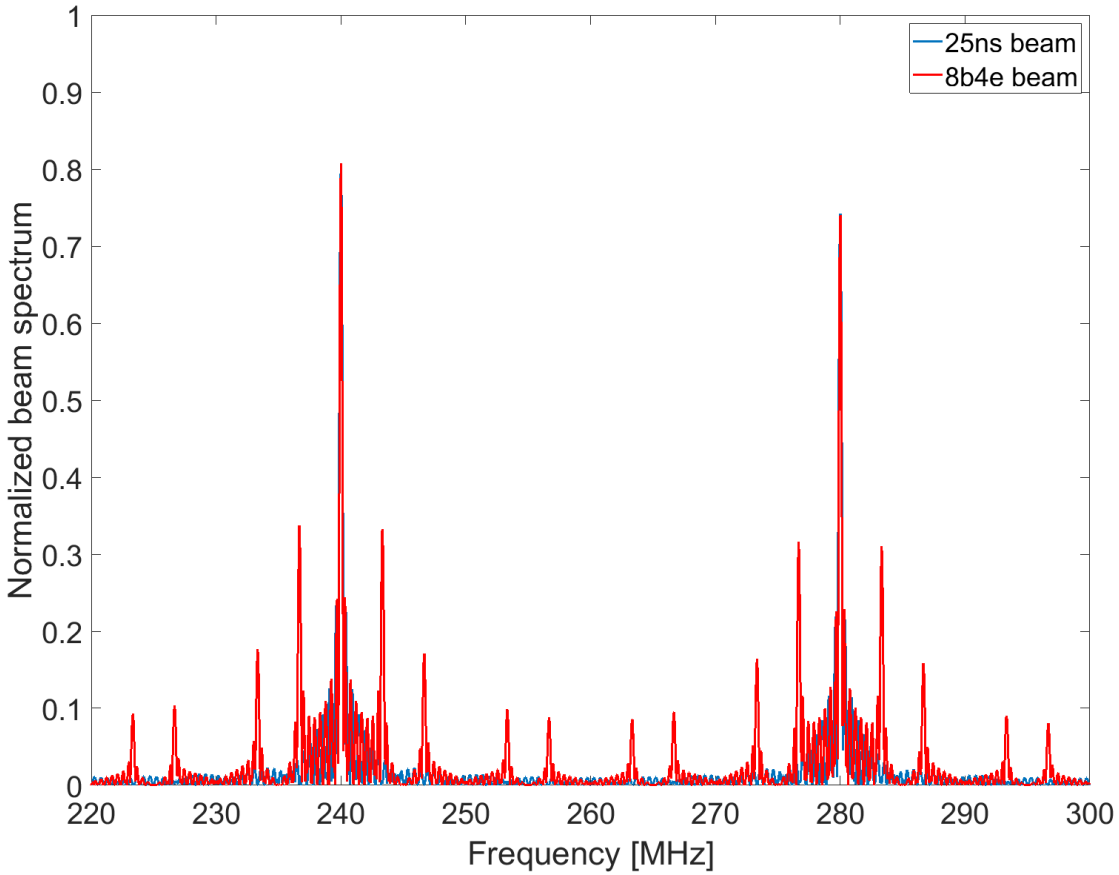


# SPS Intensity limitations. 8b4e beam.

## Comparing beam spectrum 25 ns standard and 8b4e beams




**Additional frequencies are excited with the 8b4e beam, compared to the 25 ns standard beam. Switching to 8b4e beam is not without risks; other devices may react to this in the future.**

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# SPS Wire scanners: Breakage and mitigations

## BREAKAGE during Scrubbing

12th of April 2023, SPS scrubbing run:
All four BWS' wires found **broken**
when in **parking position**
with intensities below the LIU target.

Replacement of 2 wires

## SECOND BREAKAGE

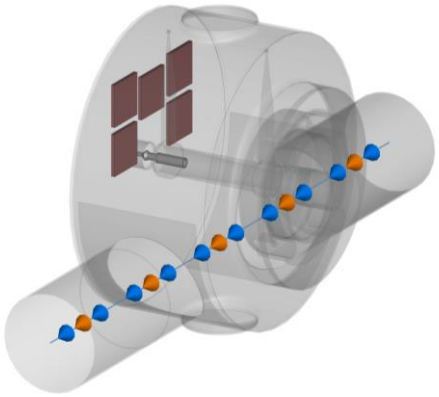
Breakage again with the standard flat top (4 x 72b, ~1.8e11 p/b)

**High repetition rate and long flat top with short bunches ~1.65 ns**

## MITIGATIONS IMPLEMENTED IN THE TECHNICAL STOP IN JUNE 2023

Equipment installed in BA4 to reduce the power loss on the wires:

- **ferrite tiles** in the tank (horizontal)
- **ferrite tiles** + **coupler** in the tank (vertical)



References: [1, 2, 3]

**Wire scanners survived up to ~2.2e11 p/b and nominal bunch length of ~1.6 ns at standard flat top**

# SPS Wire scanners: Breakage and mitigations

**It was not possible to perform the “stress test” planned in October 2023 with the long flat top.**

**Mitigations not tested with the long flat top and high repetition rate.**

**They have demonstrated their efficacy up to now**

The same solution
(**FERRITES + COUPLER**)
will be used in BA5

## YETS 2023-24

- Installation of four new wires.
- **Installation of ferrites and coupler in all 4 wire scanners tanks, both in BA4 and BA5.**

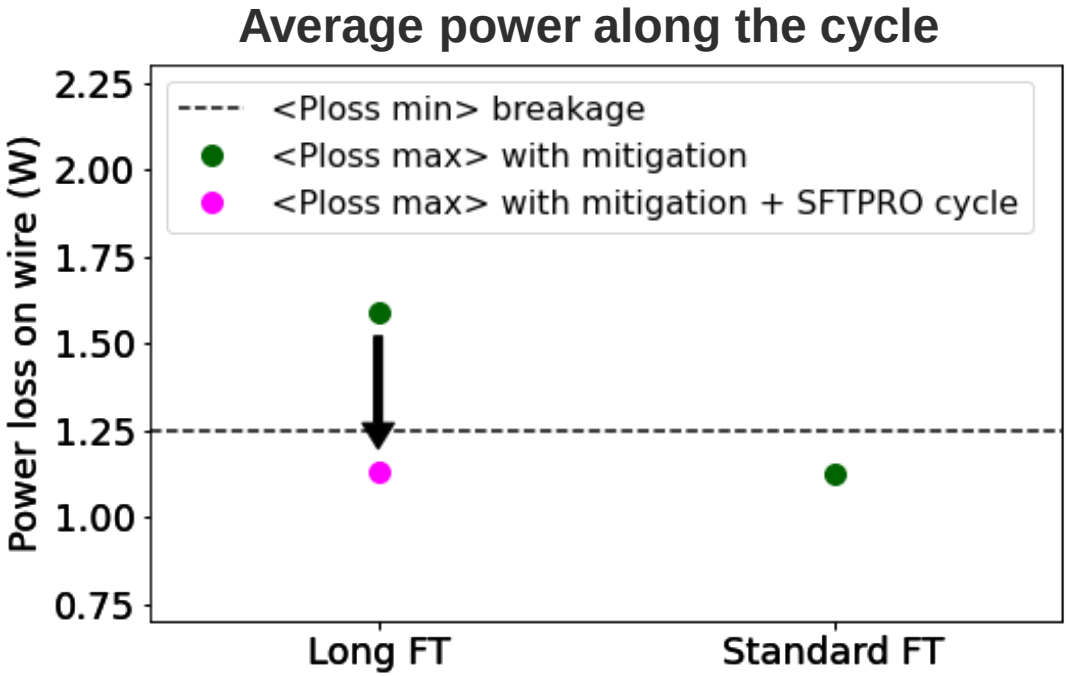
# SPS Wire scanners: WHAT IS EXPECTED FOR NEXT YEAR?

- **The long flat top will be needed again in 2024 scrubbing run.**
- **It is aimed to reach 2.3e11 p/b at flat top.**

**Will the wires survive?**

From power loss calculations [4], no issues are expected if considering **peak power on the wire along the cycle.**

If considering **average power on the wire throughout the cycle**:




From the power loss calculations (conservative approach):

- **No issues are expected with the standard flat top up to ultimate LIU intensity, even in dedicated mode.**
- But **some minimum risk** with **high duty cycle** and the **long flat top** due to **fatigue effects**.

- **No issues expected with the long flat top and SFTPRO cycle in parallel.**

- During the long flat top cycle next year, the activity of the wires will be monitored.

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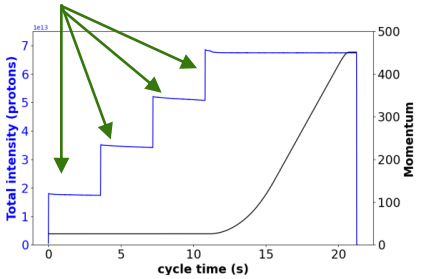
# SPS Vertical stability and working point

**Extremely fast vertical coupled bunch instability predicted in simulations**

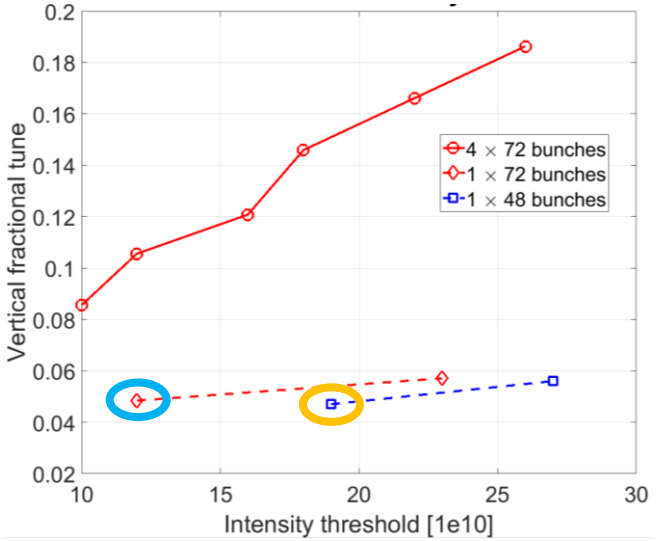
- Threshold depends on the set vertical tune (mainly driven by resistive wall)
- Experimentally confirmed with 1 batch and low intensity

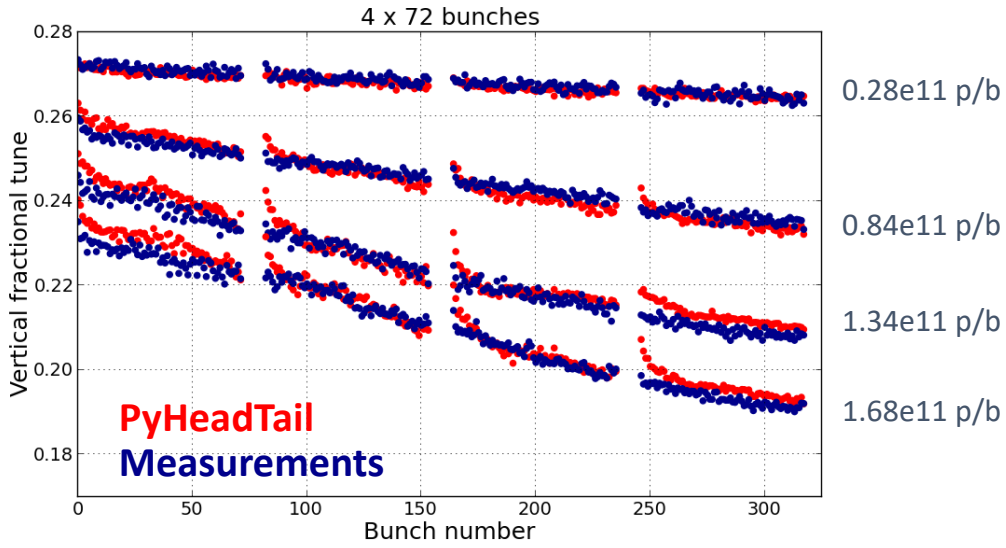
Injection (26 GeV)




**Vertical tunes close to 20.25 resonance required for LIU parameters**

- Control of tunes is critical due to large bunch-by-bunch tune shift from impedance – progress on operational correction (model-based application)



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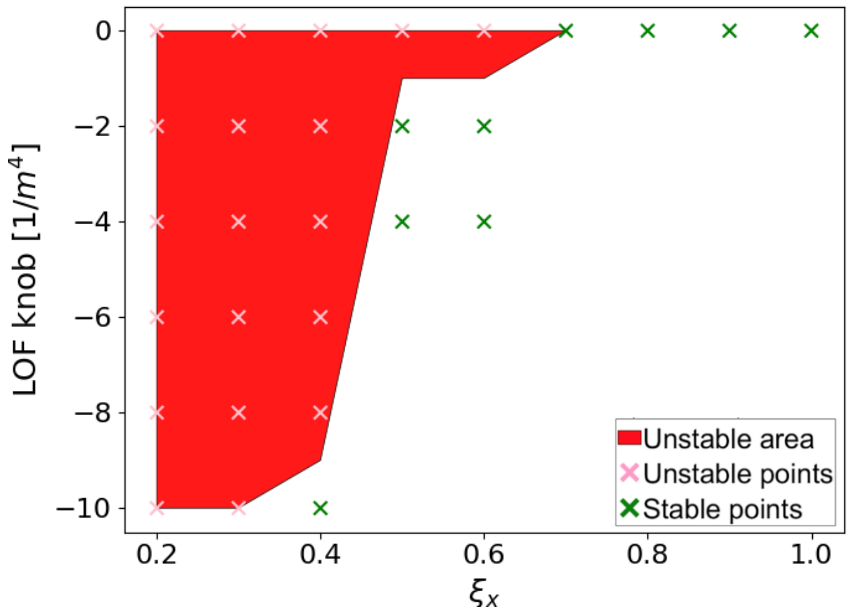
# SPS Horizontal stability at injection

**Horizontal headtail instability @26 GeV studied in detail in 2018 for 1.8e11 p/b**

- Mitigation strategy developed in simulations: high chromaticity + octupoles

**PyHT Simulations**
**4 x 72bunches, N = 2.6e11 p/b**




**Stabilization strategy**
Without octupoles stabilization at $\xi_x \geq 0.7$
With octupoles (-kLOF < 10) stabilization at $\xi_x \geq 0.5$

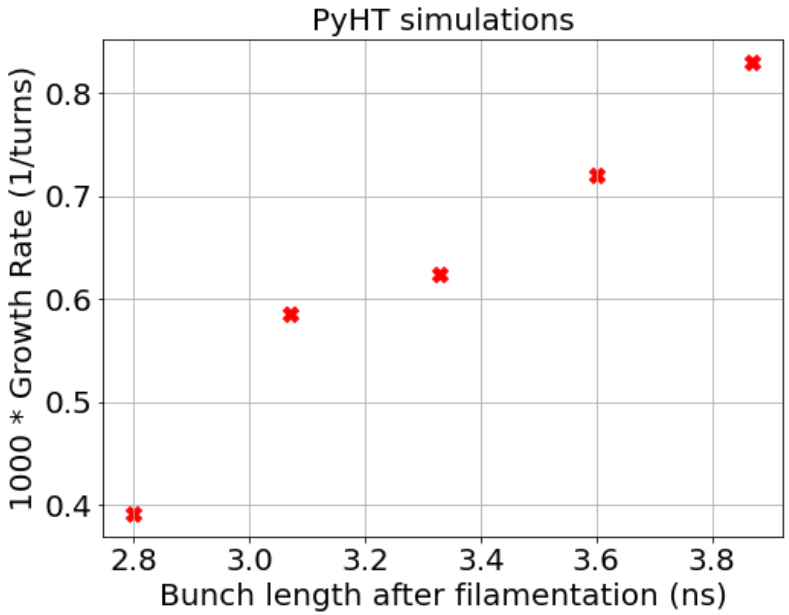
**Tested in 2023 with up to ~2.6e11 p/b injected**

- **4 x 72 bunches**
- **Discovered criticality of short bunches at injection to ensure stability**

# SPS Horizontal stability at injection

## MD 20 September 2023

**Unstable beam with long bunches at injection (~4.2 ns)**



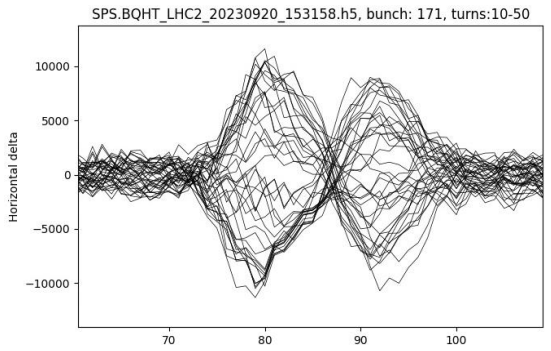

**Instability is very sensitive to bunch length.**

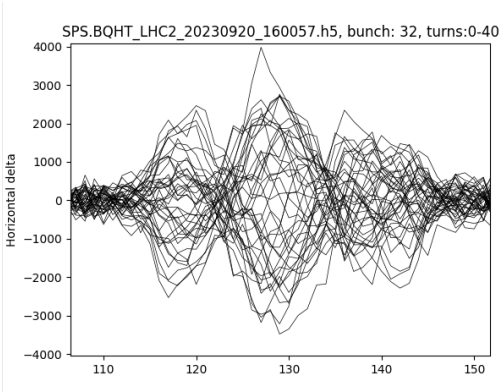
Observed a correlation between instability in the SPS and the injected bunch length:

- The longer the bunches, the more unstable (observed also in simulations)

**With 4.2 ns injected bunch length it was not possible to stabilize the beam (even with high chromaticity and using octupoles)**

**Measured mode 1 and mode 2 with the Head-Tail monitor**



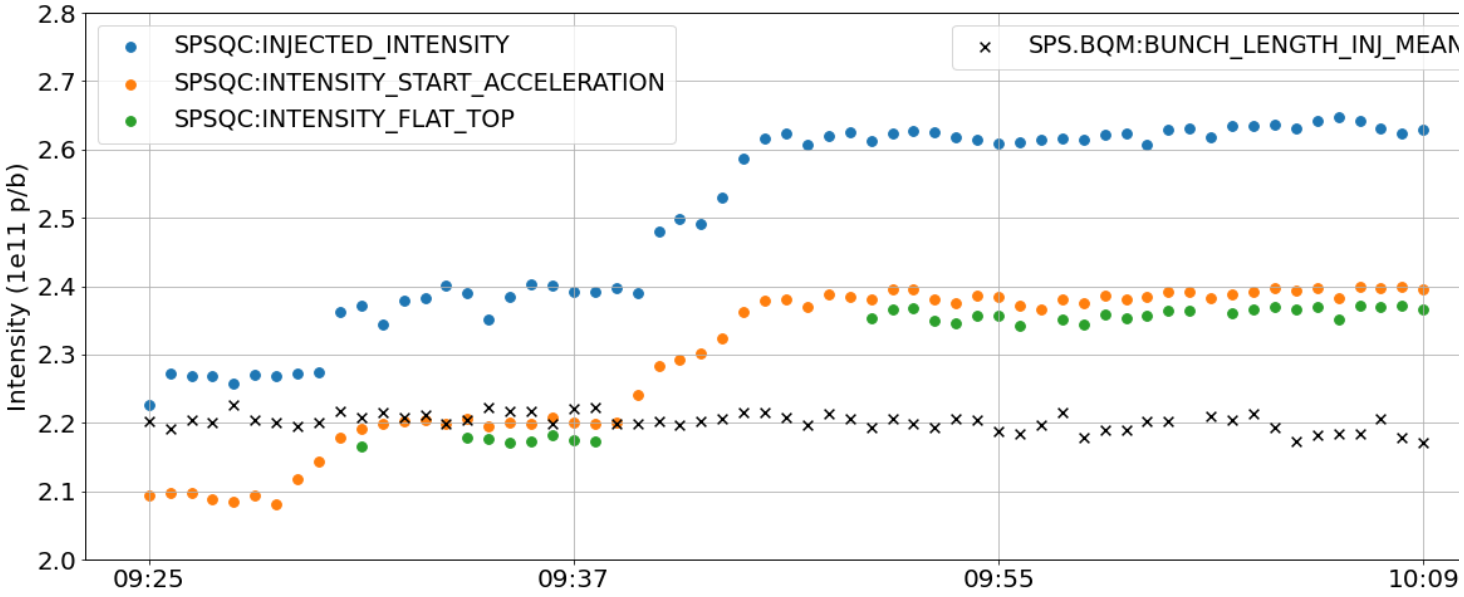



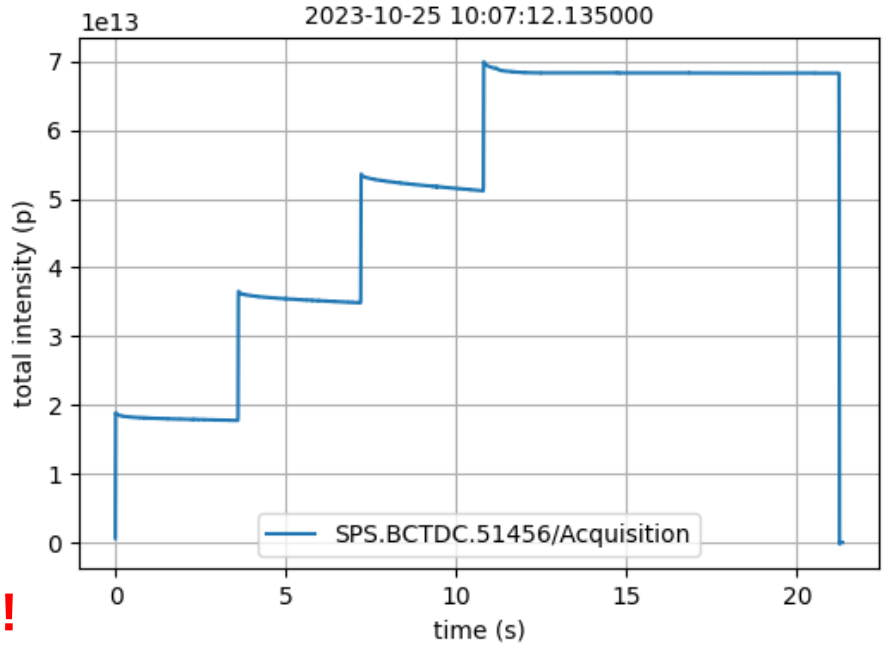

Mode 1 observed for $0.3 < \xi < 0.4$ with 2.6e11 p/b injected

Mode 2 observed for $0.45 < \xi < 0.55$ with 2.6e11 p/b injected

# SPS Horizontal stability at injection

## MD 25 October 2023




**Only ~40 minutes of MD time with this beam characteristics!**

**LIU intensity at injection was reached with the proper bunch length at injection.**

**The beam was stable with an injected bunch length of ~3.8 ns,
but transmission needs to be optimized.**

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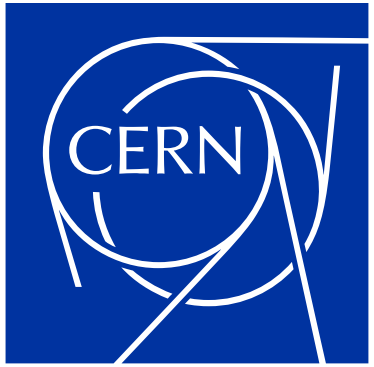
# SUMMARY

| Intensity at FT [p/b] | #bunches | Batch spacing [ns] | Bunch length [ns] | Beam type |
|---|---|---|---|---|
| ~2.2e11 | 4 x 72 | 200 | ~1.6 | Standard |
| ~2.15e11 | 4 x 56 | 200 | ~1.6 | 8b4e |

- **LIU target achieved in PSB and PS**
- **Limitations to ramp-up the intensity in the SPS**
  - MKDH pressure spikes limiting intensity for standard beam @450 GeV with nominal bunch length.
  - Significant pressure rise in sector 6 limiting intensity for 8b4e beam @450 GeV.
- **Mitigations in place for the wire scanners (ferrites + coupler)**
  - No issues expected during 2024 run (even during scrubbing with long flat top cycle if SFTPRO in parallel).
- **Transverse stability with LIU target intensity at flat bottom (@ 26 GeV)**
  - **Vertical plane**. Need to operate with $Q_y$ close to 20.25 resonance to ensure stability with standard beam.
  - **Horizontal plane.** Stabilization strategy tested for standard beam with ~2.6e11 p/b injected intensity, but **only for a short time in one MD**, and **only under the following conditions**:
    - Reproducible injected bunch length (~ 3.8 ns).
    - High horizontal chromaticity.

  Given this information, is the horizontal wideband feedback system needed?

# Thank you!

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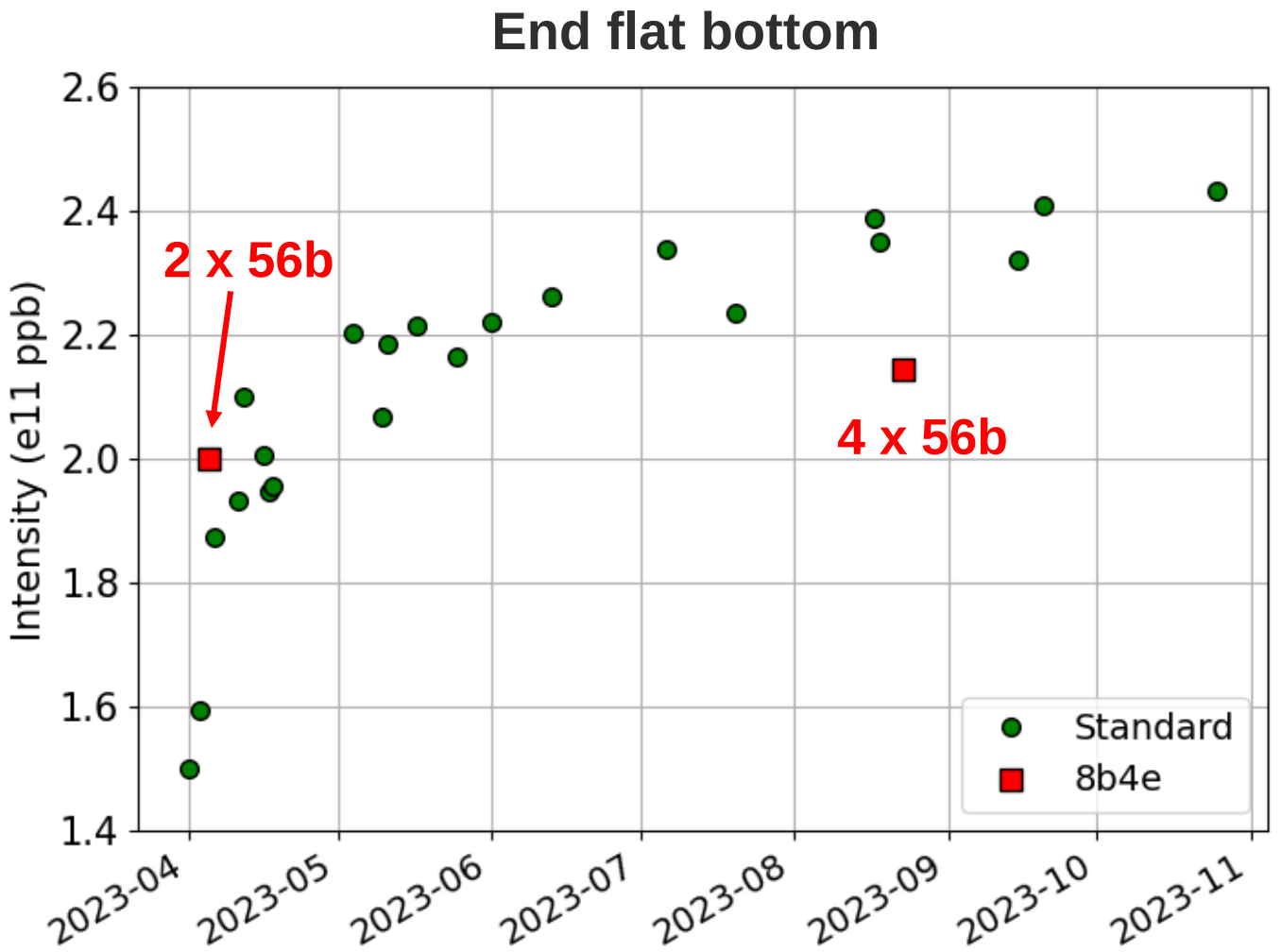
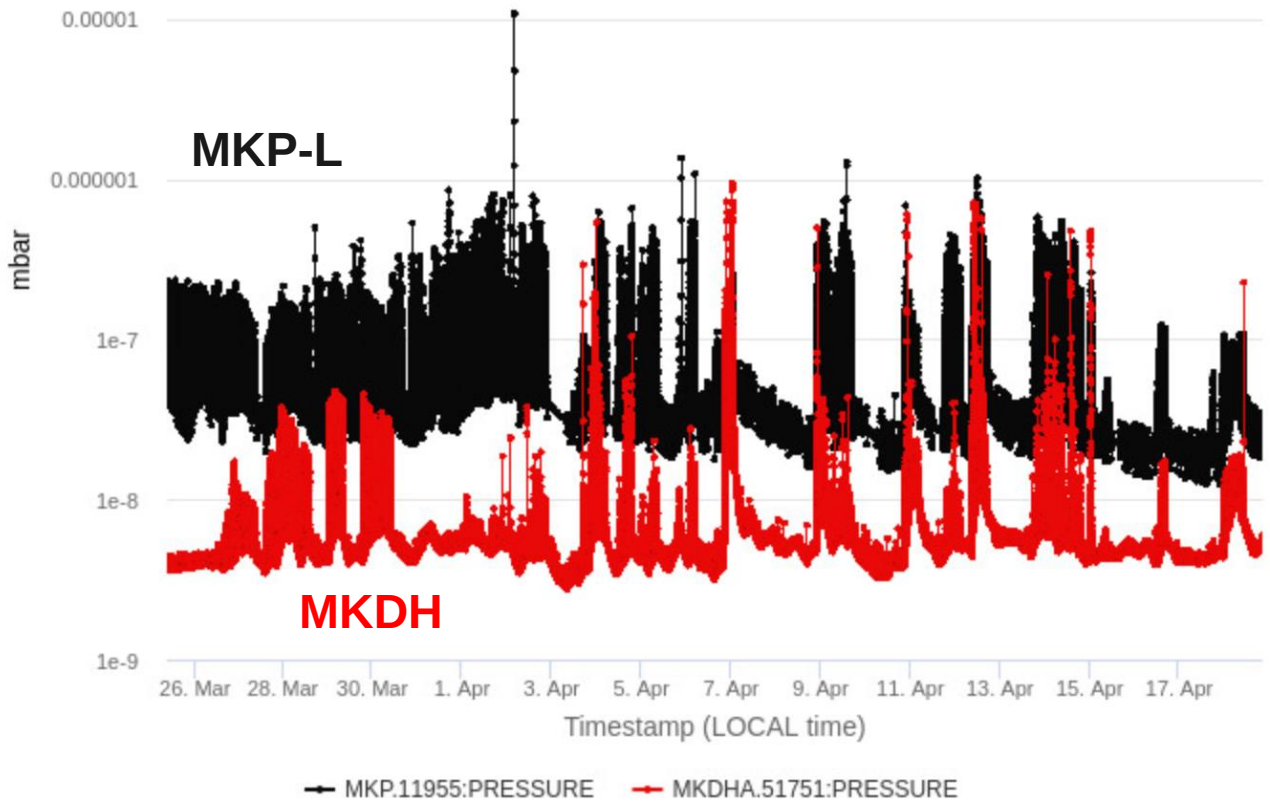
# SPS intensity reach. 8b4e beam.

**Standard:** 4 x 72 bunches

**8b4e:** 2 x 56 bunches (April)
4 x 56 bunches (August)




MKP-L
MKDH
0.00001
0.000001
1e-7
1e-8
1e-9
mbar
26. Mar
28. Mar
30. Mar
1. Apr
3. Apr
5. Apr
7. Apr
9. Apr
11. Apr
13. Apr
15. Apr
17. Apr
Timestamp (LOCAL time)
MKP.11955:PRESSURE
MKDHA.51751:PRESSURE

# Last year's intensity limitations due to kicker vacuum activity

| Intensity at FT [p/b] | Emittance H/V at FB end [µm] | #bunches | Batch spacing [ns] | Bunch length [ns] | Transmission without scraping [%] | Beam type | Date |
|---|---|---|---|---|---|---|---|
| 1.52e11 | 1.8/1.7 | 4 x 72 | 250 | 1.65 | ~95 | Standard | Apr. 5 |
| 1.85e11 | 1.9/1.7 | 1 x 72 | | 1.65 | ~94 | Standard | May. 3 |
| 1.8e11 | 1.6/1.5 | 5 x 48 | 200 | 1.66 | ~95 | BCMS | Sept. 22 |
| 1.8e11 | 1.9/1.8 | 4 x 36 | 200 | 1.65 | ~90 | BCMS | Nov. 8 |
| 1.5e11 | 2.0/1.9 | 5 x 56 | 200 | 1.73 | ~95 | 8b4e | Oct. 13 |
| 1.75e11 | 2.2/2.0 | 2 x 48 | 400 | 1.62 | ~95 | 8b4e | Nov. 8 |

Limited by MHDH vacuum spikes

Limited by RF800 MHz cavity 1 interlocking on vacuum

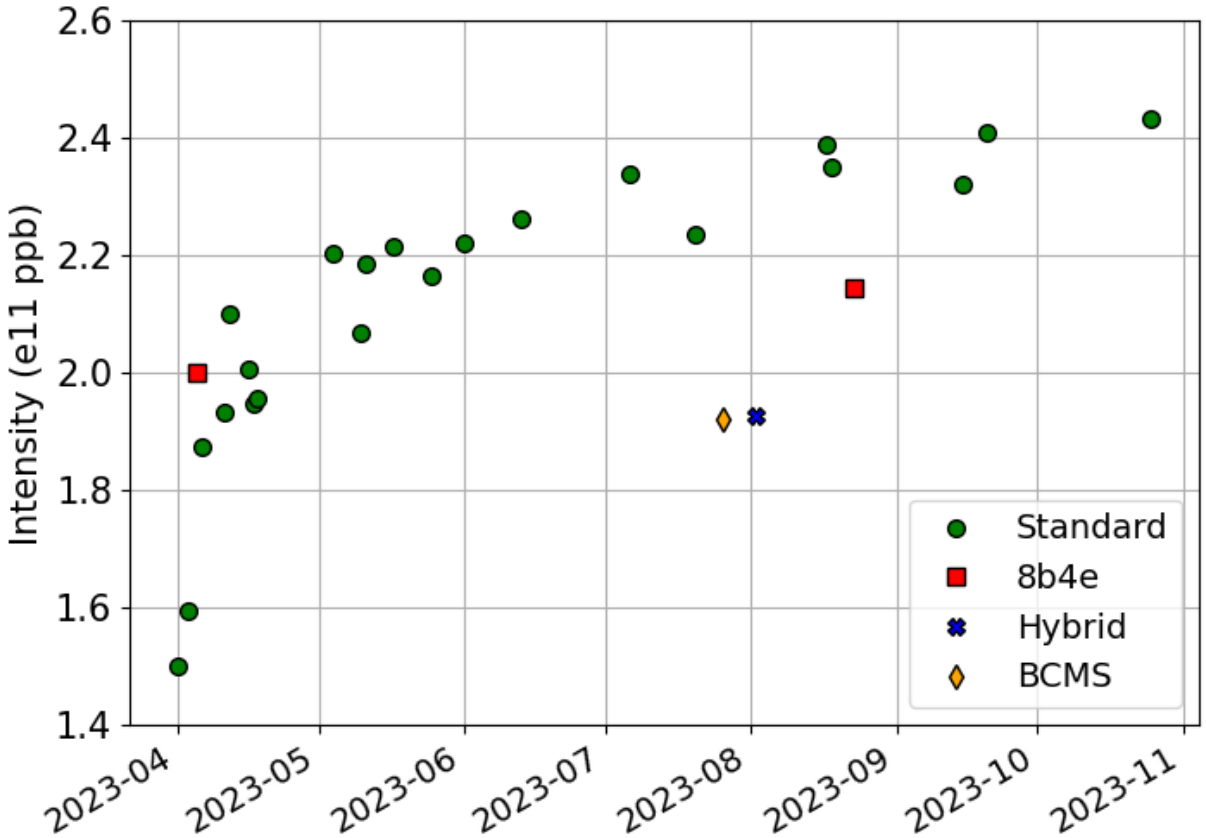
# Comparison to 2022

| Year | Intensity at FT [p/b] | #bunches | Batch spacing [ns] | Bunch length [ns] | Beam type | Date |
|---|---|---|---|---|---|---|
| 2022 | ~1.5e11 | 4 x 72 | 250 | ~1.6 | Standard | Apr. 5 |
| 2022 | ~1.75e11 | 2 x 56 | 400 | ~1.6 | 8b4e | Nov. 8 |
| 2023 | ~2.2e11 | 4 x 72 | 200 | ~1.6 | Standard | Aug. 18 |
| 2023 | ~2.15e11 | 4 x 56 | 200 | ~1.6 | 8b4e | Aug. 23 |

**Table from Carlo's talk on IPP:**
https://indico.cern.ch/event/1322532/contributions/5565561/subcontributions/440832/attachments/2713754/4712893/LHC_HI_MDs_IPP_Sep_13th.pdf

# Intensity reach end flat bottom

**Standard:** 4 x 72 bunches
**8b4e:** 2 x 56 bunches (April)
4 x 56 bunches (August)
**Hybrid:** 1 x 56 bunches (8b4e) + 5 x 36 bunches
**BCMS:** 4 x 48 bunches




For hybrid and BCMS beam, the high intensity was not taken.
There was no limitation, we didn't push intensity (just brightness measurements)

# OVERVIEW OF SCRUBBING

- **Main goal of scrubbing 2023**: to condition the **MKP-L injection kicker** upgraded during the YETS 2022-23.

- In 2022, erratic and unpredictable **pressure spikes** were observed on the **MKDH dump kicker** at flat top with the standard beam of 4 x 72 bunches. Consequently, the MKDH kicker needed to undergo conditioning as well during scrubbing 2023.

- **Gradually increased bunch intensity at flat bottom** from ~1.4e11 p/b up to ~2.2e11 p/b.

- **Scrubbing on the ramp and flat top** was difficult/critical due to pressure spikes on the kickers causing interlocks.

→

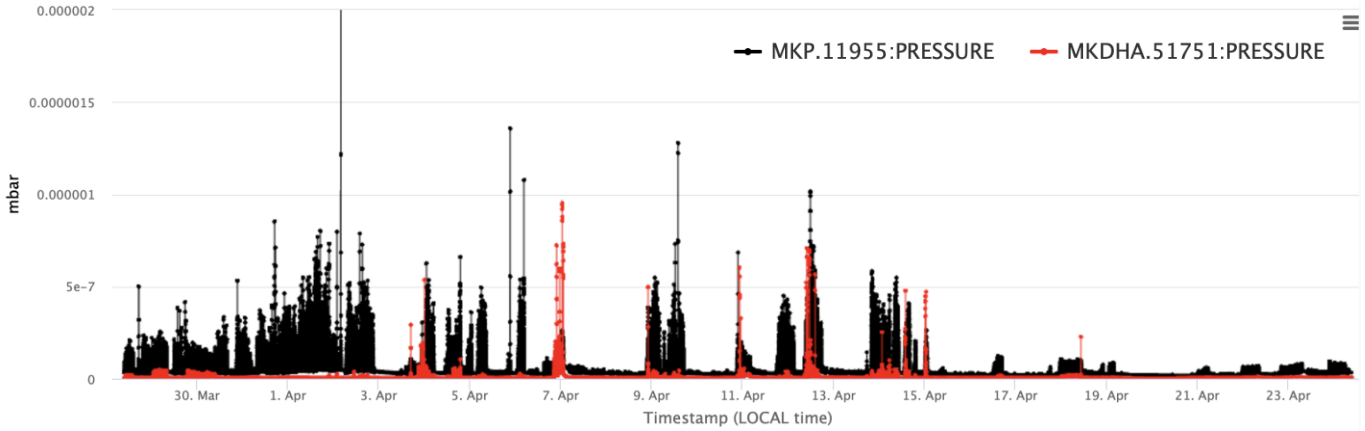
**A dedicated scrubbing cycle** was created, in order to **improve the efficiency of scrubbing**,

- **Longer flat top**
- **Lower energy** (**400 GeV**).

**First breakage of the 4 wires of the wire scanners during scrubbing with the long flat top**

# OVERVIEW OF SCRUBBING

## Conditioning of kickers




Around 20 days were needed to scrub the MKP-L and MKDH at flat top.

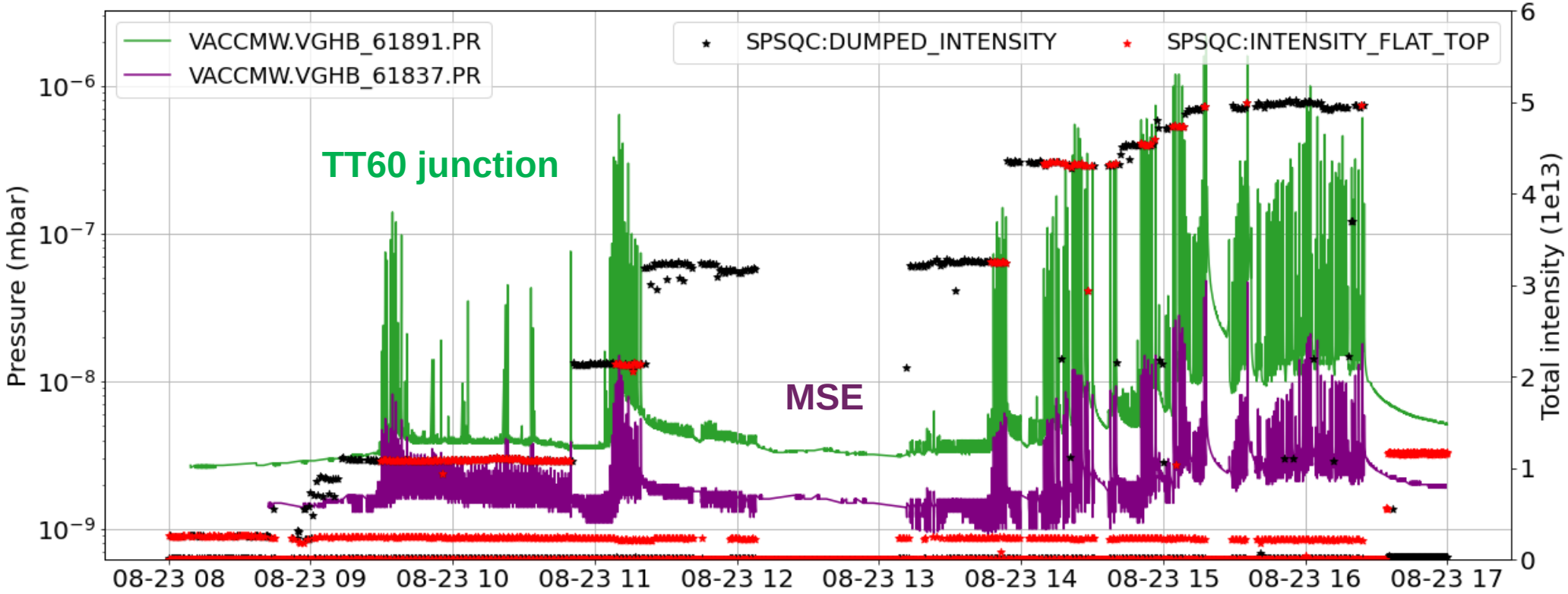
## Achievements reached during scrubbing 2023:

| Intensity at extraction [p/b] | #bunches | Energy [GeV] | Bunch length [ns] |
|---|---|---|---|
| 2.2e11 | 1 x 72 | 400 | 1.6 |
| 2.05e11 | 4 x 72 | 400 | 1.6 |

- Unprecedented amount of scrubbing beam accumulated at flat top (with nominal parameters)
- Erratic behaviour of MKDH can be conditioned

# SPS Intensity limitations. 8b4e beam.

## 23rd August 2023

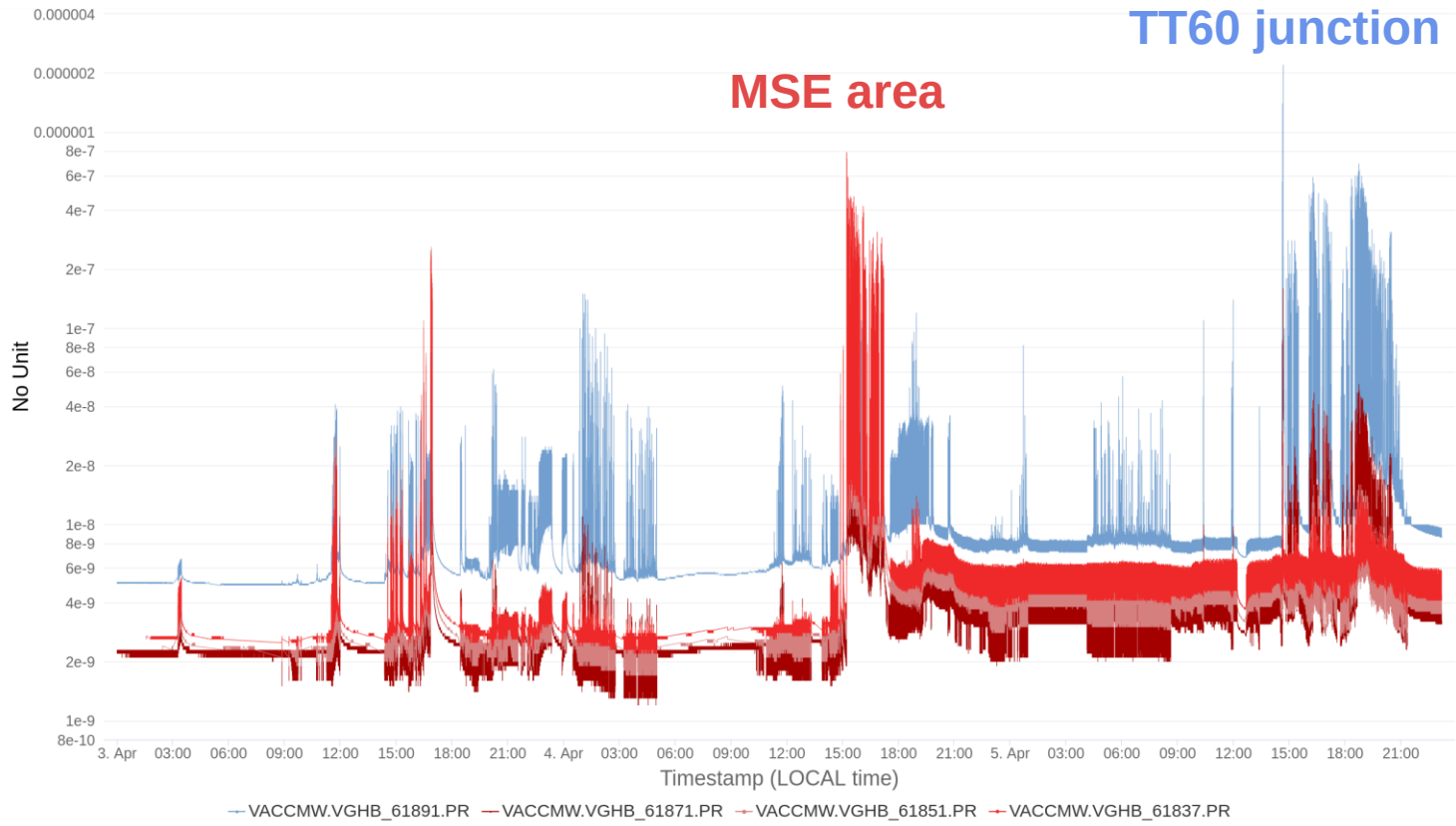


# Limitations due to pressure rise in other areas with 8b4e beam.

Not always limited only by the kickers, pressure rise in various vented devices/regions was also limiting

High pressures observed in **sector 6** at different points:

- Large spikes on **TT60 junction** pressure with **8b4e beam**
- MSE



# SPS Wire scanners: 1. BREAKAGE

**All four SPS wire scanners (two vertical in SPS BA4 and two horizontal in SPS BA5) stopped working during the second week of scrubbing**

**Conditions during the first breakage of the 4 wires:**

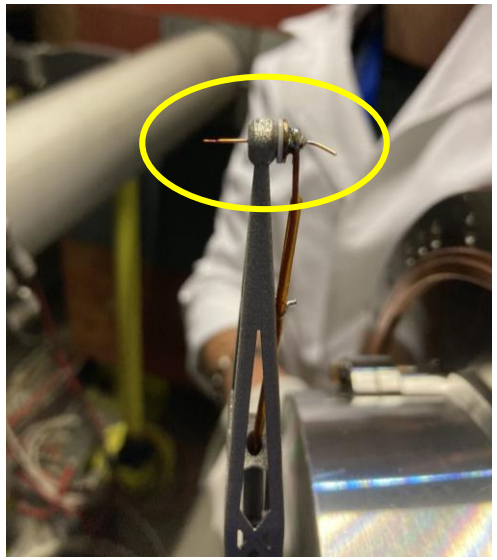
| Up to April 19 | | | | Max Intensity |
|---|---|---|---|---|
| LHC 25 | Long FT | 1 x 72b | 2.25e11 p/b | 1.62e13 |
| LHC 25 | Long FT | 4 x 72b | 2.05e11 p/b | **5.90e13** |
| 8b4e | Long FT | 2 x 56b | 2.00e11 p/b | 2.24e13 |

**April 19: Two spare wires were installed, but breakage happened again**

**Conditions during the second breakage of the 2 new wires:**

| April 20 – 22 | | | | Max Intensity |
|---|---|---|---|---|
| LHC 25 | Standard FT | 4 x 72b | 1.80e11 p/b | **5.18e13** |

- **Bunch Length @FT ~1.60ns**
- **Higher rate and higher total number of cycles reaching FT**



***Courtesy of F. Roncarolo et al***

# SPS Wire scanners: 2. MITIGATIONS

## Technical stop in June 2023:

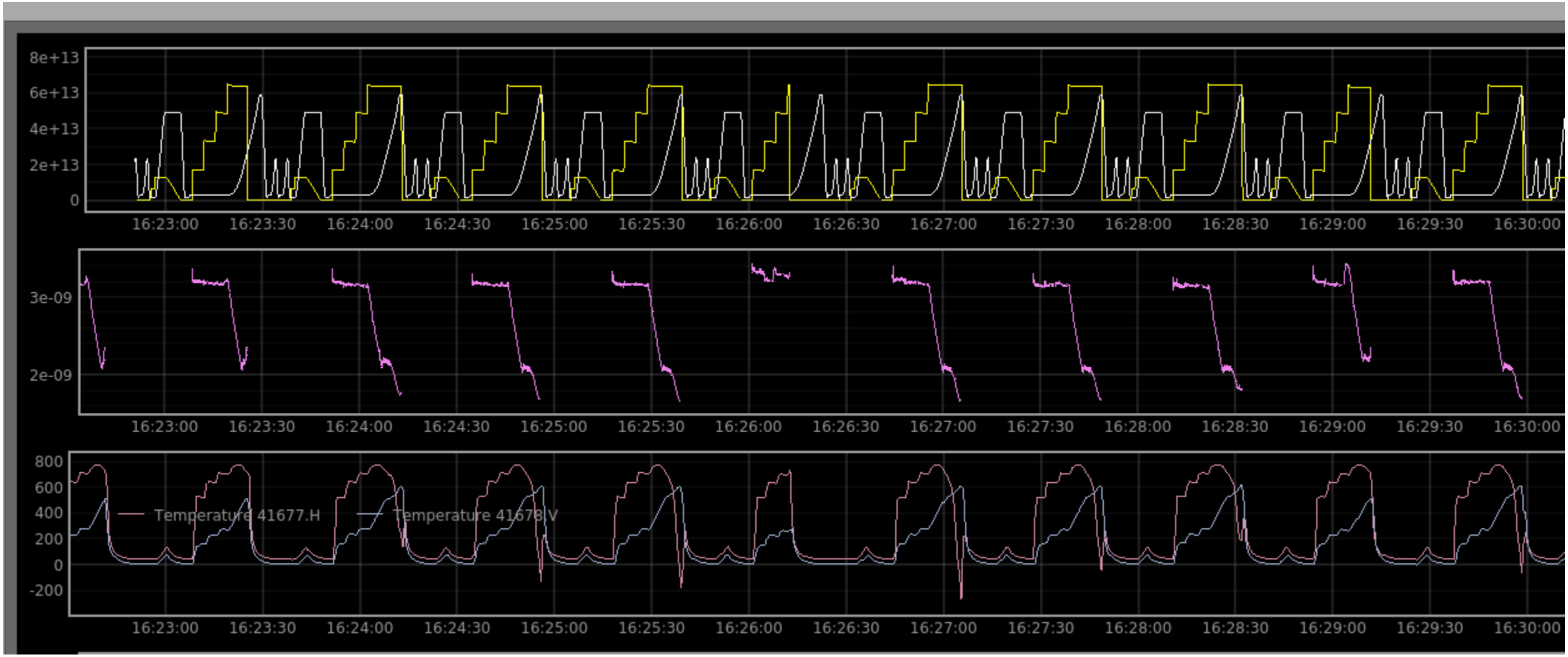
- **The orientation of the beam wire scanner instrument in position BWSRC.41677 was modified during the TS1 2023 (from vertical to horizontal)**

- **Mitigations have been implemented to reduce power loss on the wires. Additional equipment was installed:**
  - **ferrite tyles** in the tank (in BWSRC.41677 - horizontal)
  - **ferrite tyles** + **coupler** in the tank (in BWSRC.41678 - vertical)

| **August 18** | | | | **Max Intensity** |
|---|---|---|---|---|
| LHC 25 | Standard FT | 4 x 72b | 2.21e11 p/b | **6.37e13** |
| **August 23** | | | | |
| 8b4e | Standard FT | 4 x 56b | 2.15e11 p/b | **4.82e13** |

Wire scanners survived up to ~2.2e11 p/b and nominal bunch length of 1.60 ns at flat top.

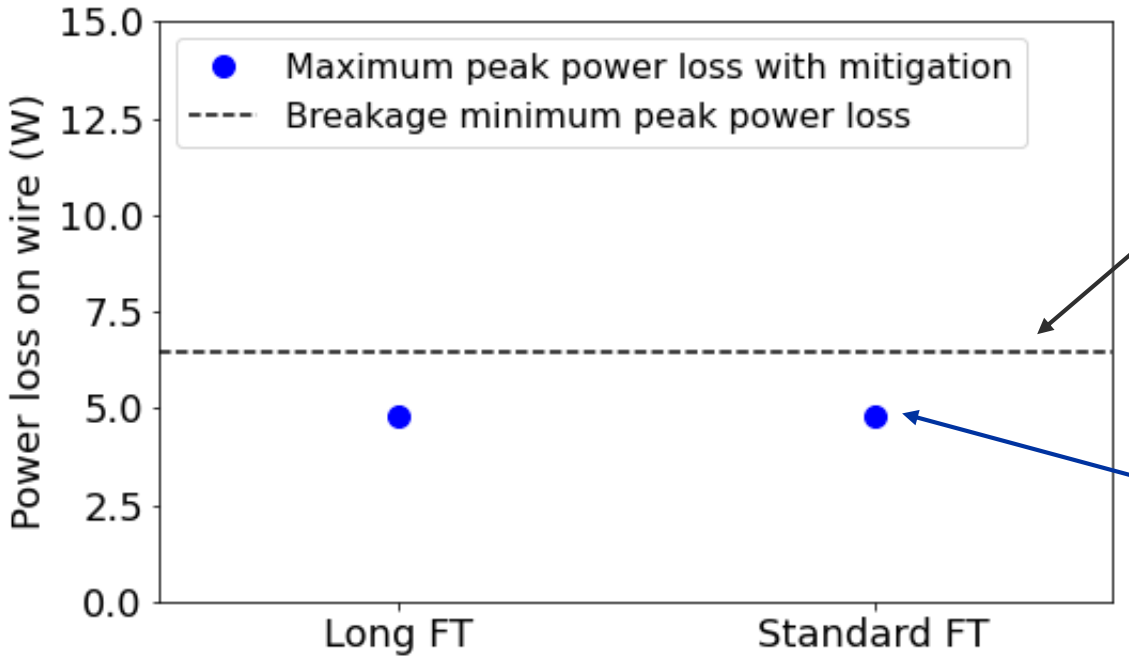
# Monitorization of the wire scanners behavior during high intensity MDs



# SPS Wire scanners:
# WHAT IS EXPECTED FOR NEXT YEAR?

- **The long flat top will be needed again in 2024 scrubbing run.**
- **It is aimed to reach 2.3e11 p/b at flat top.**

**Will the wires survive?**




Minimum peak power loss on the wire along the cycle with breakage conditions

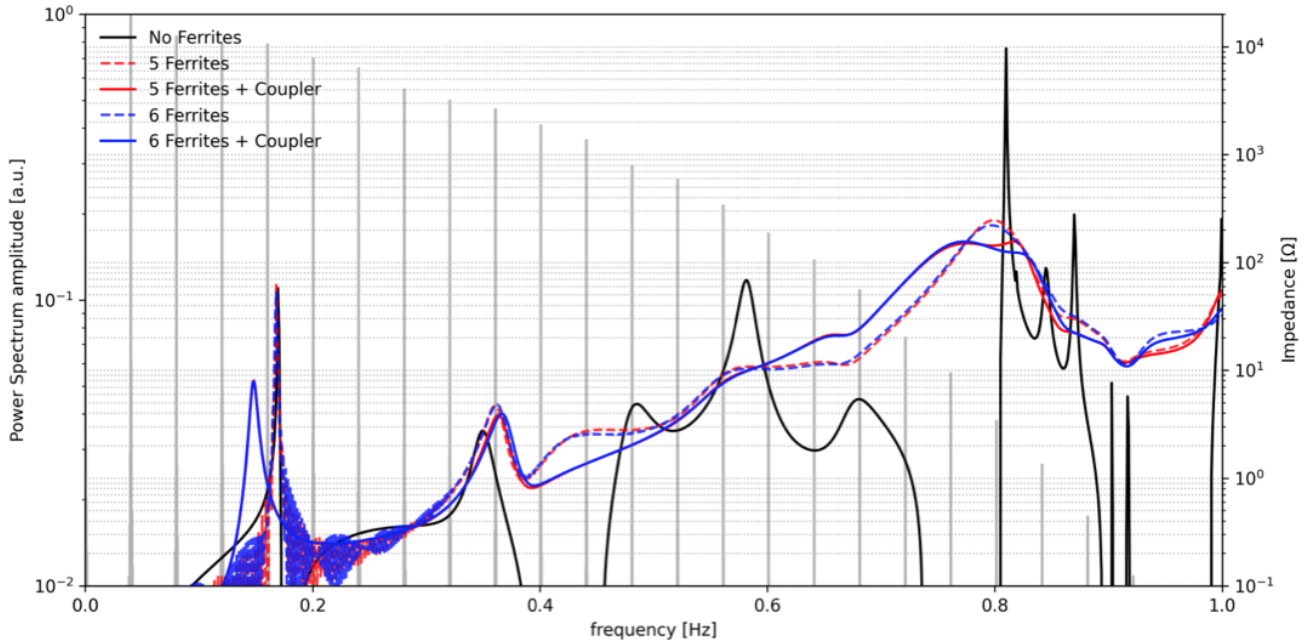
Maximum peak power loss on the wire along the cycle with mitigation (ferrites + coupler)

With the implemented mitigations, no issues are expected when considering **peak power**

# Impedance curves (II)

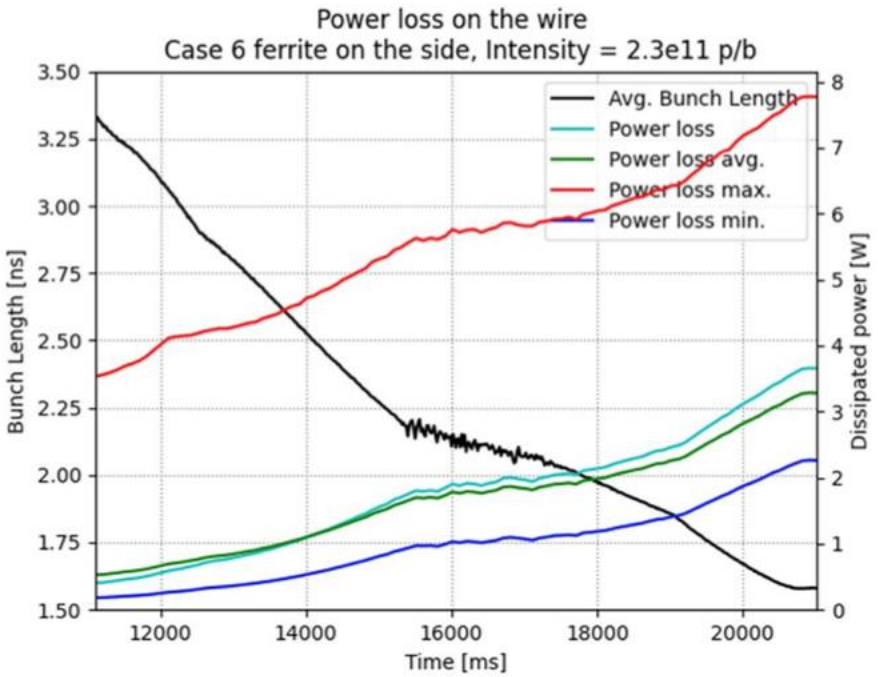
Four final scenarios:

- 5 ferrites
- 5 ferrites with coupler
- 6 ferrites
- 6 ferrites with coupler

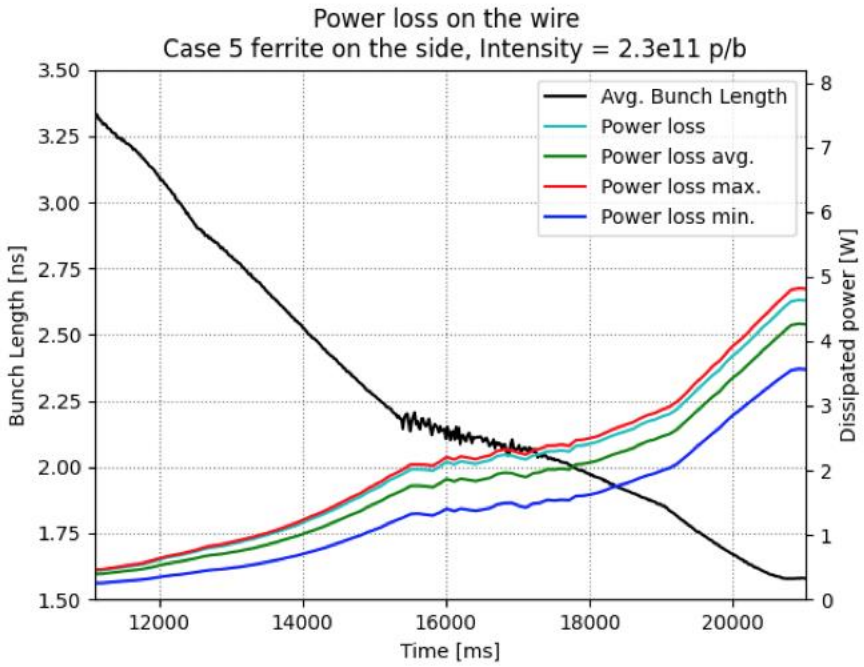



E. de la Fuente,
L. Sito

## H-BWS: 6 Tiles




## V-BWS: 5 Tiles + coupler

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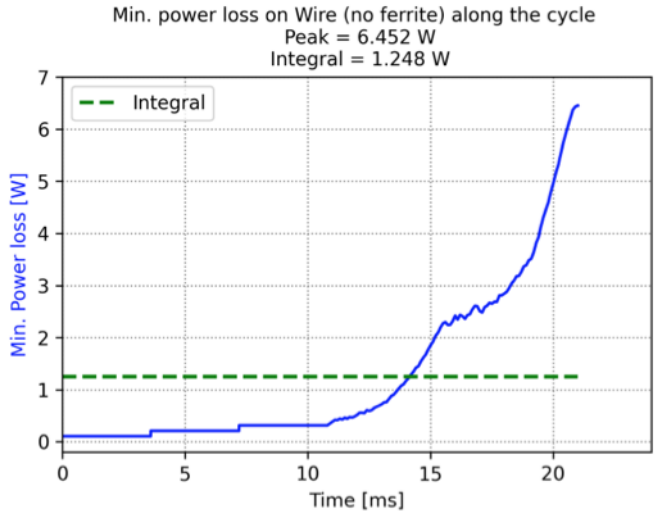
L. Sito

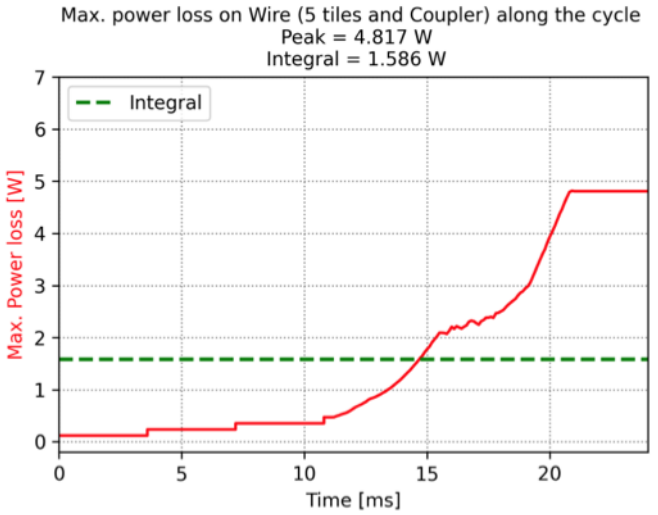
# Long flat top considerations

- Up to now only peak power considerations.
- Taking into account the cycle and a long flat top (3 s):

Breakage Condition
(standard flat top, 1.8e11 p/b)




Best Mitigation Solution
(long flat top, 2.3e11 p/b)

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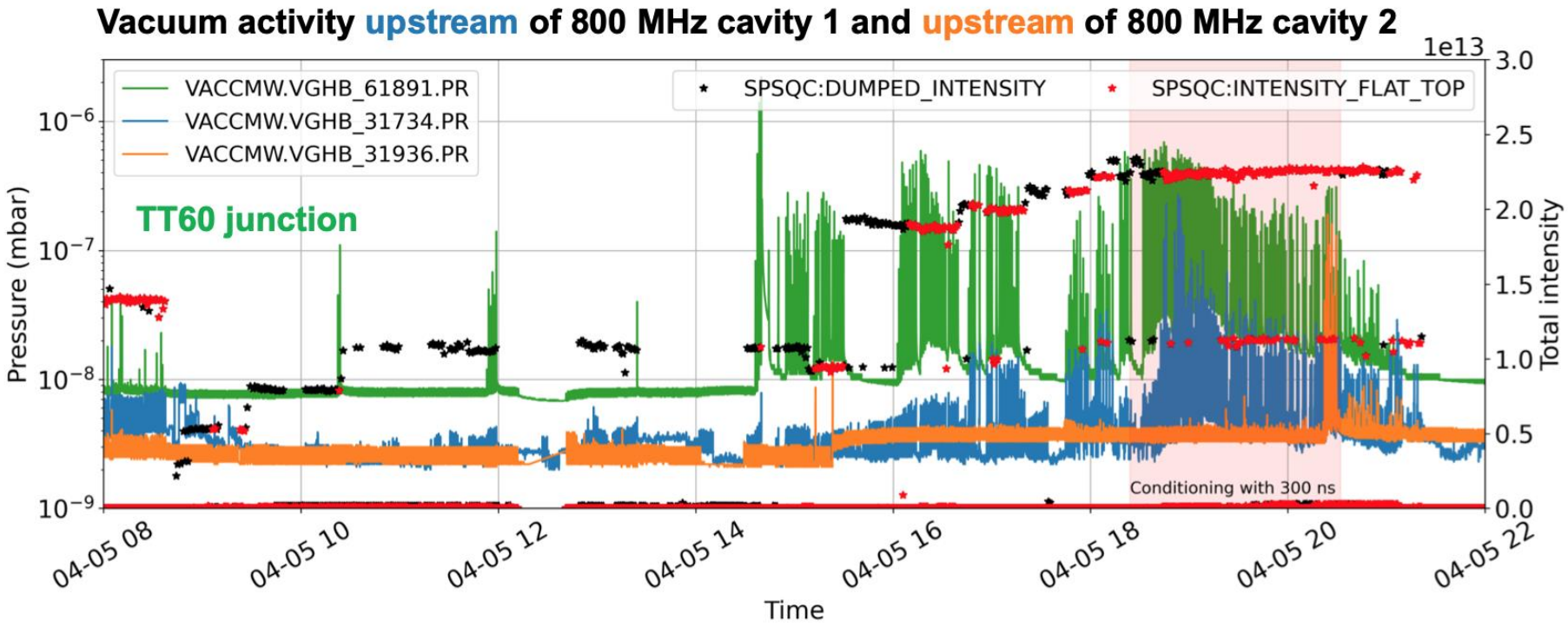
L. Sito

With 5 ferrite tiles and coupler, what is the minimum intensity that will result in the same integrated power of the breakage condition?

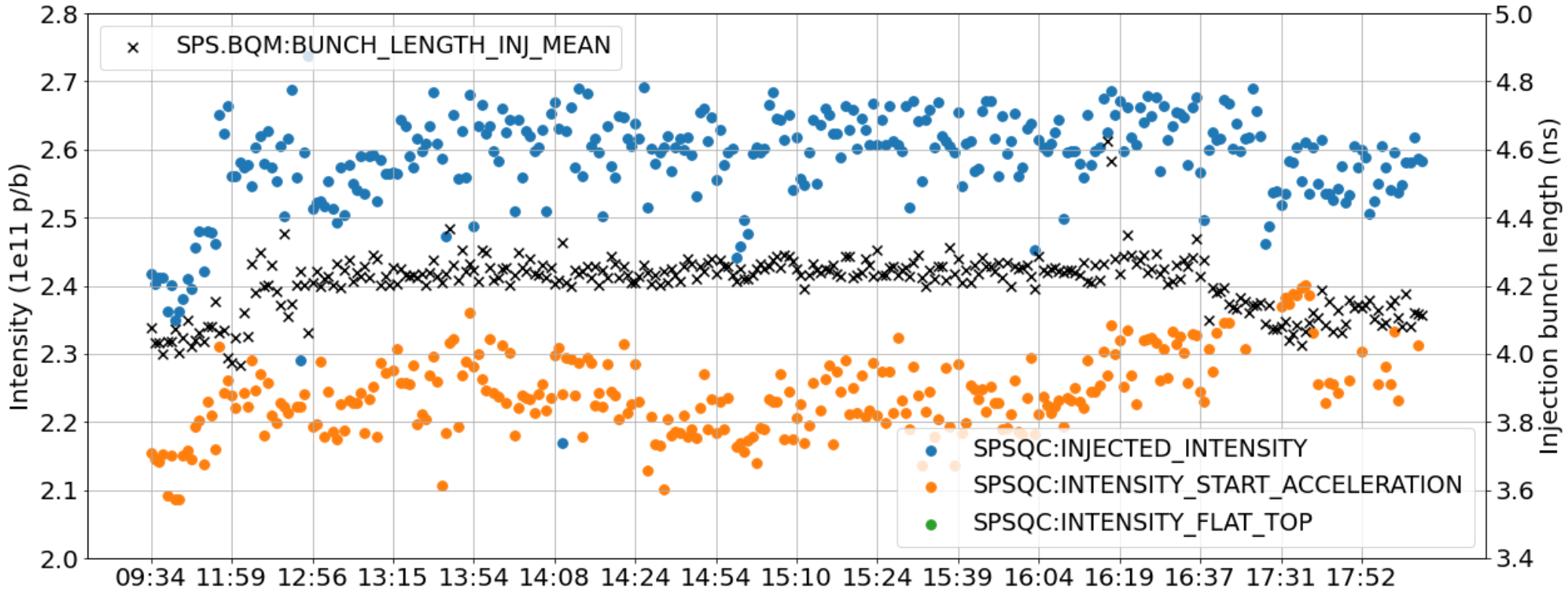
# Vacuum activity with 8b4e beam (2 x 56 bunches) 5th April 2023




I. Karpov, IPP 21 April 2023

# MD 20th September 2023

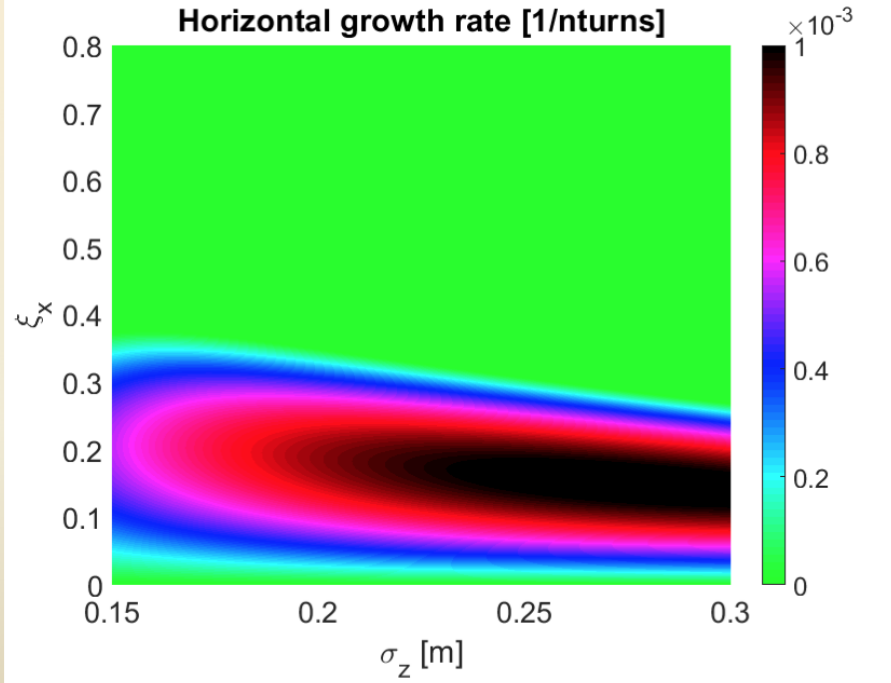
Injected bunch length ~4.2 → instability



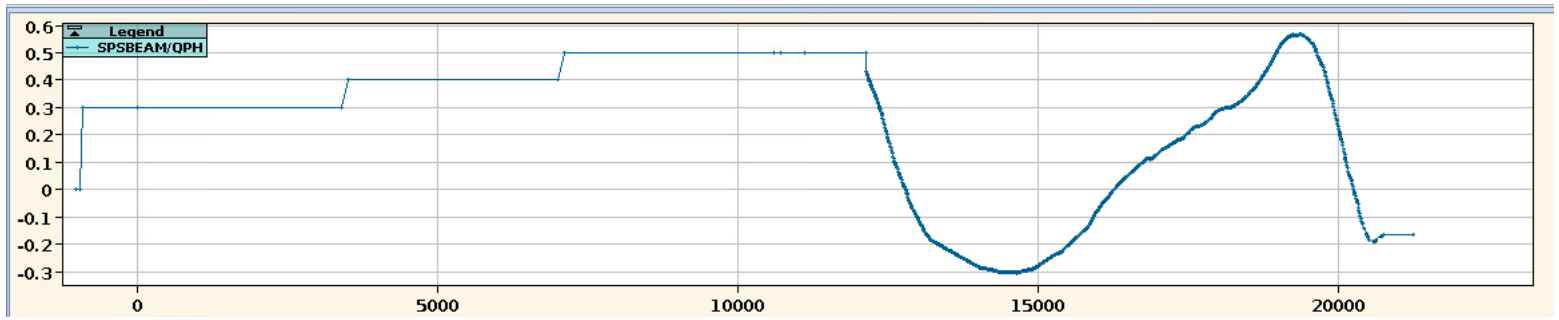
# SPS growth rates with SPS impedance model from Sacherer theory

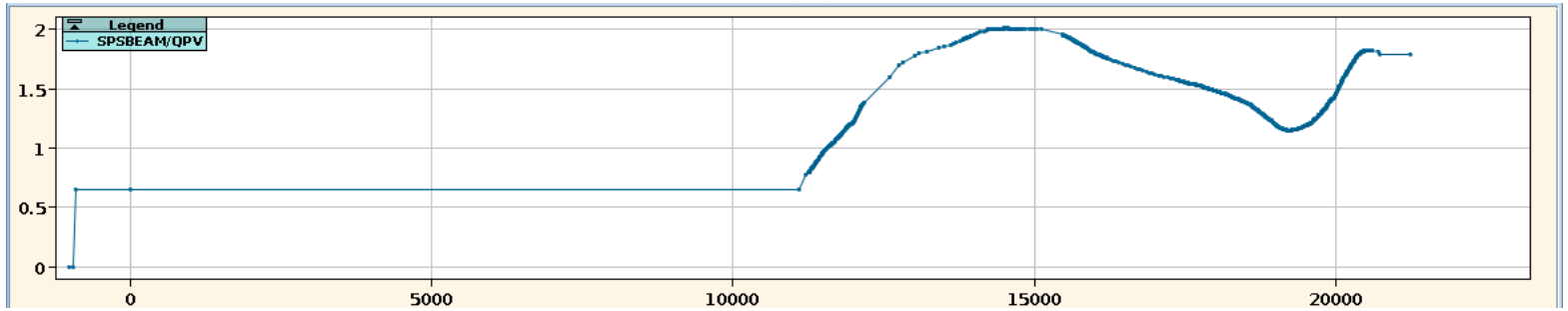
Mode 1 M=1

SPS impedance model (Sacherer theory)

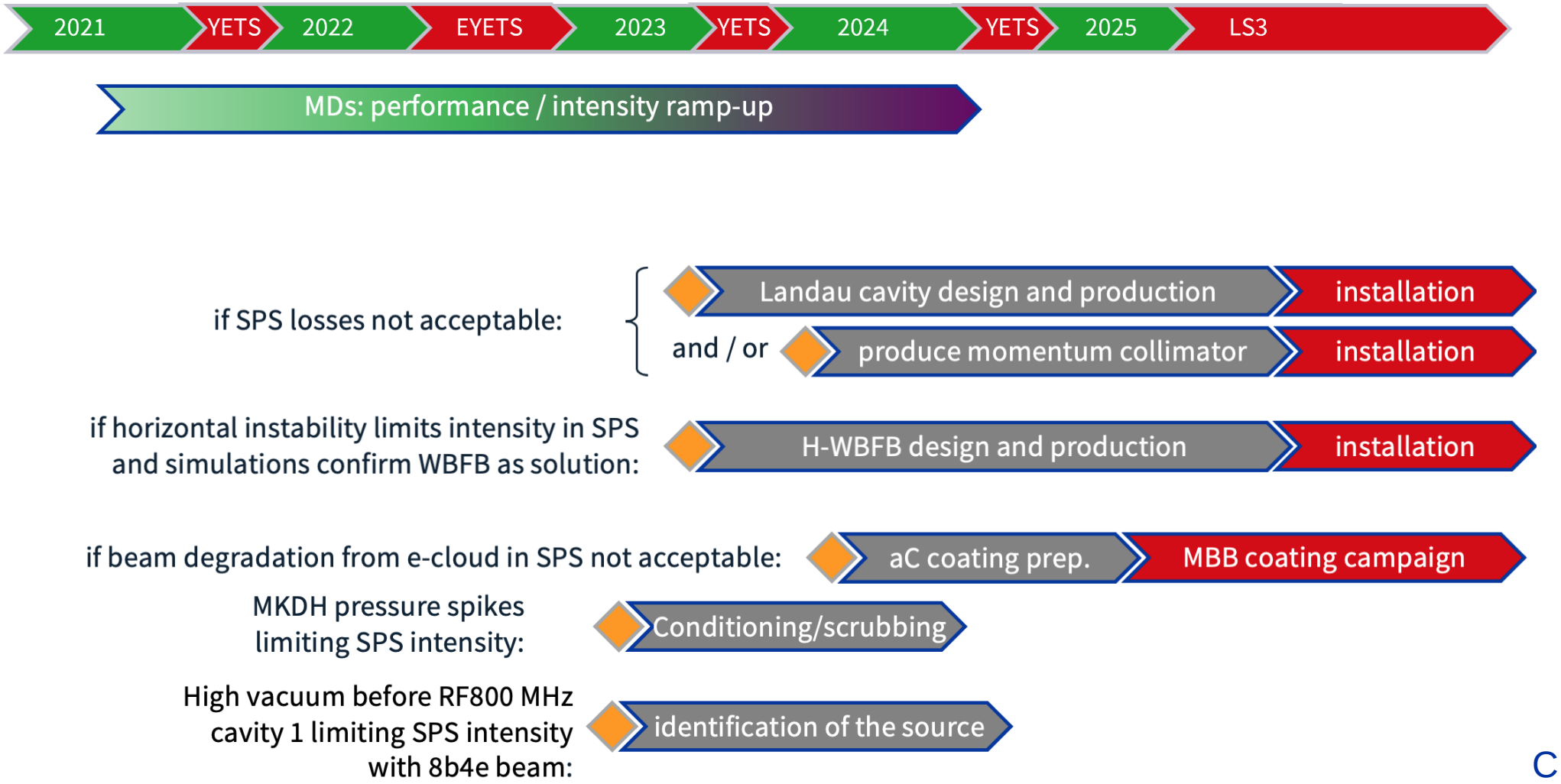


# Stabilization with chromaticity the 25th October
# No octupoles



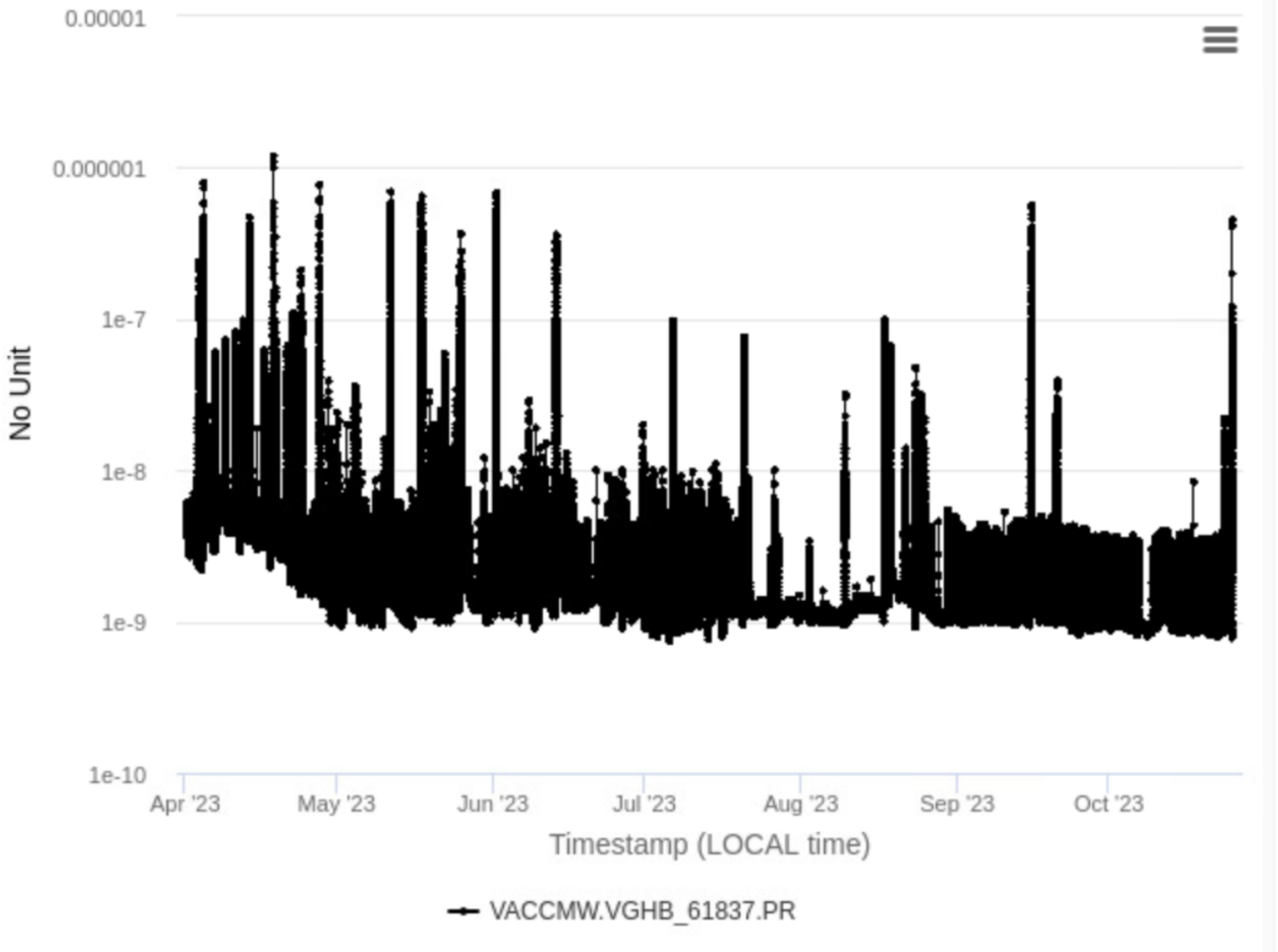



# Decision points based on beam studies during Run 3

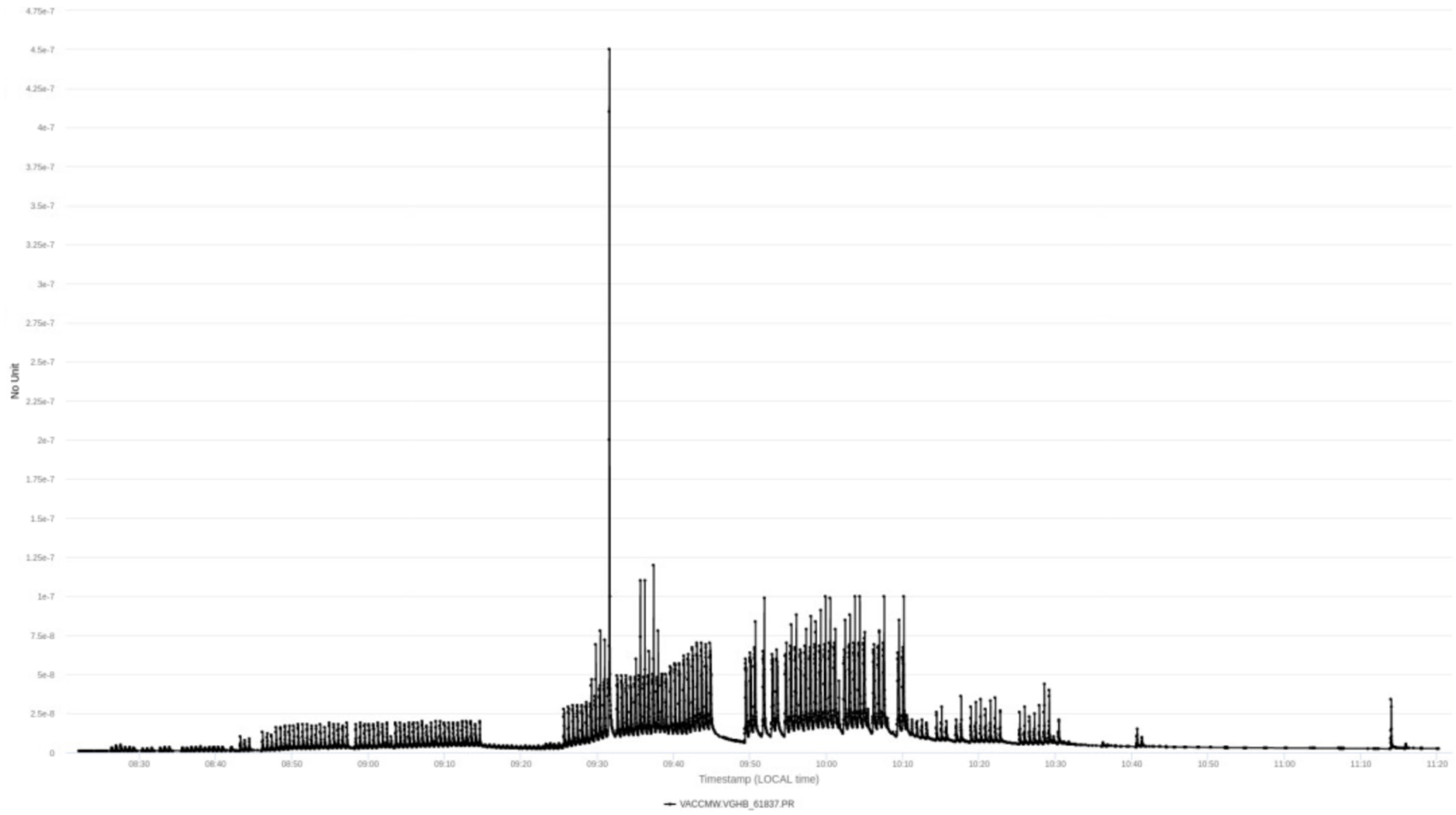


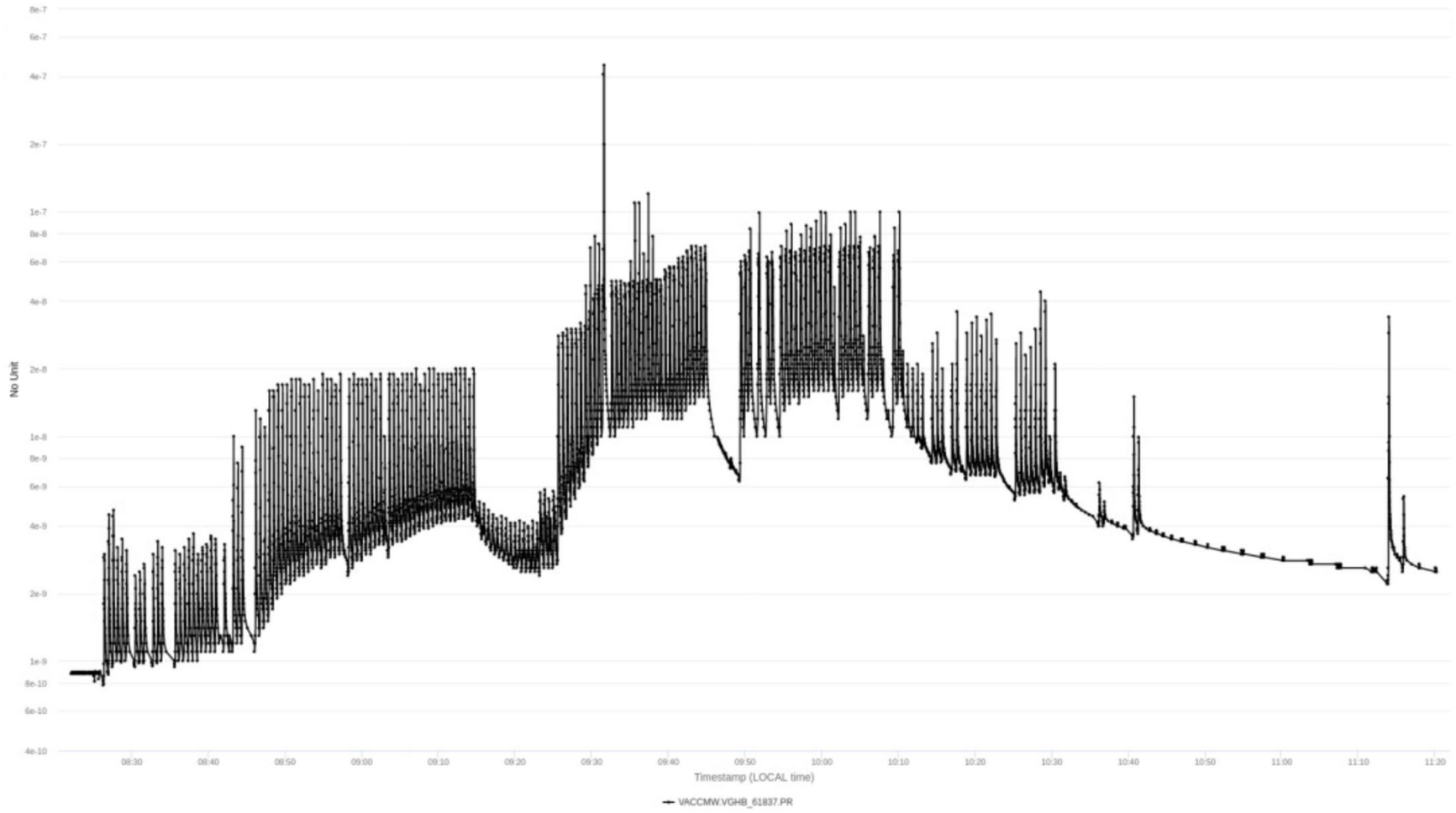

C. Zannini
JAP 2022

# MSE pressure along the year



# MSE pressure 25 Oct.




8e-7
6e-7
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