Electron clouds in the injectors

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Many thanks to:
M. Barnes, A. Harrison, A. Huschauer, G. Favia, J. Ferreira,
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C. Zannini, injectors OP teams

Outline

- **Electron cloud in the PS**
  - Dedicated scrubbing in 2021
  - Present situation
- **Electron cloud in the SPS**
  - Recap on past observations and LIU strategy
  - Scrubbing in Run 3
  - Scrubbing and kickers
  - Looking forward
- **Summary and next steps**

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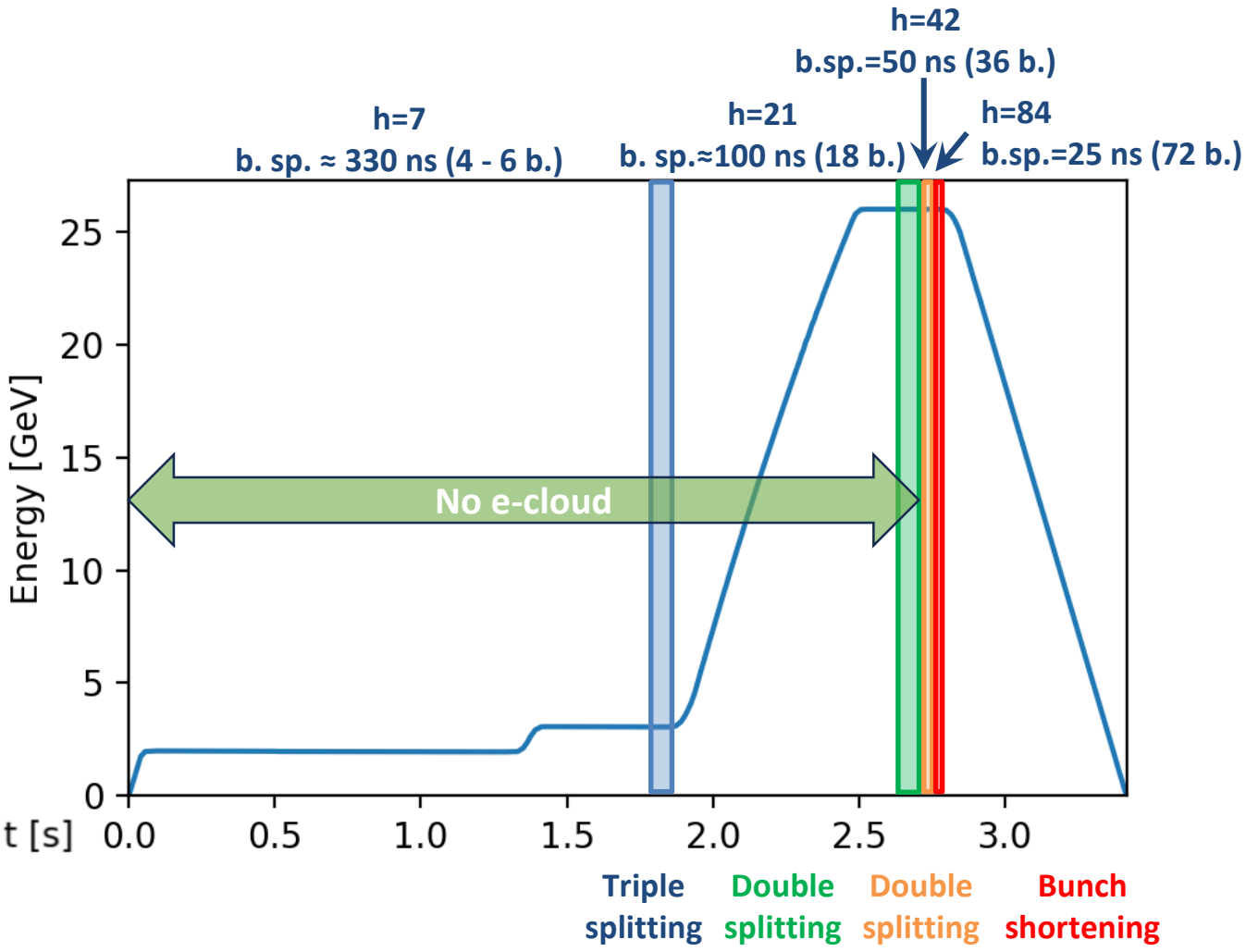
E-cloud in PS

In the PS, most of the cycle is e-cloud free. **E-cloud forms only at top energy** during the final RF manipulations in particular:

- **Last bunch splittings** to achieve 25 ns bunch spacing
- **Bunch shortening** to achieve bunch lengths compatible with the SPS bucket



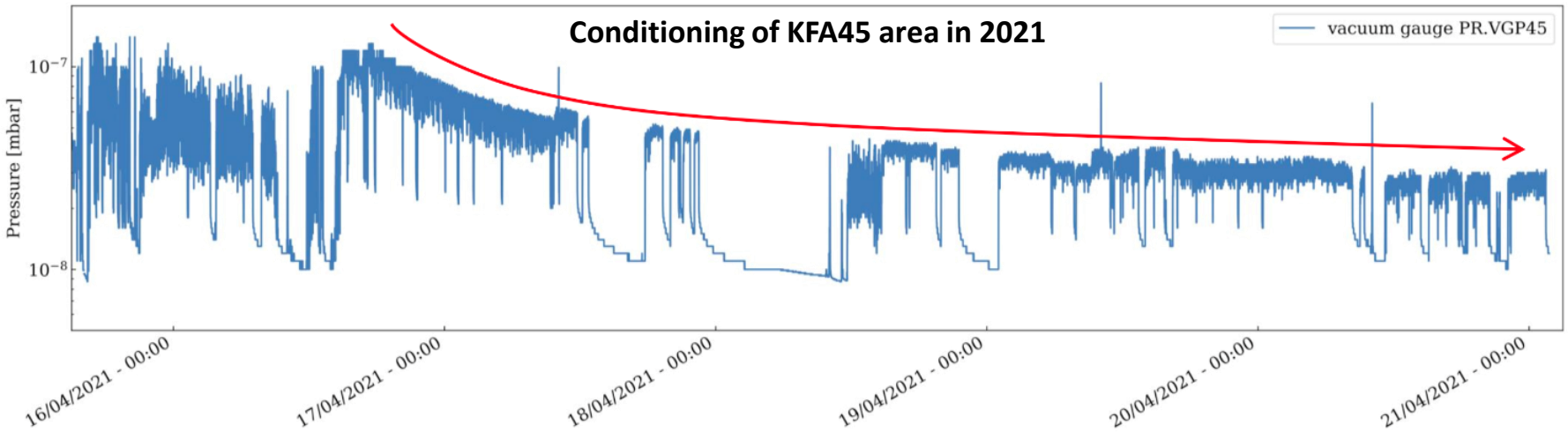
E-cloud in PS

First e-cloud observations in the PS **date back to 2002**.

- E-cloud observed to get **stronger after long shutdowns** (when large fraction of beam chambers exposed to air)
  - → **Vacuum pressure degradation** and/or **transverse instabilities**

Situation **particularly severe in 2021**, when restarting **25 ns** operation **after LS2**:

- Pressure rise in **injection kicker region** (KFA45) triggering vacuum interlock
- Needed **dedicated scrubbing period** to condition this areas
  - Keeping **several LHC-type cycles** in the PS supercycle
  - Continuously **optimizing beam parameters** (n. bunches, bunch length, total intensity) to maximize scrubbing efficiency compatibly with pressure interlocks
- Situation significantly **improved after four days of scrubbing**



For more details: see G. Rumolo, IPP#43

E-cloud in PS

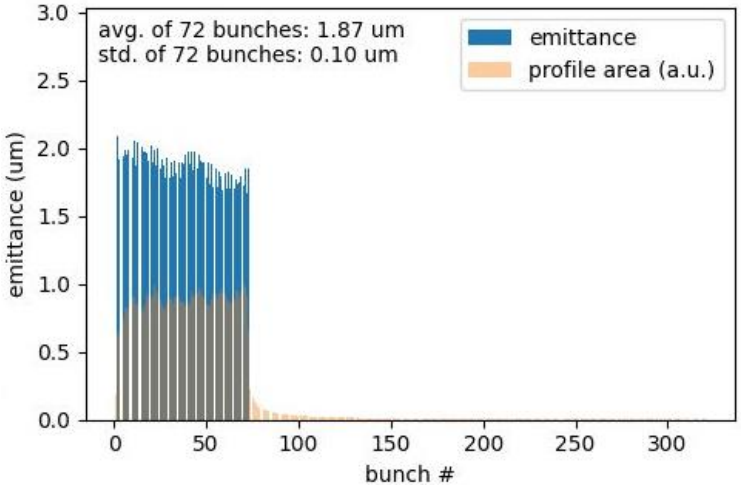
Vacuum activity remains present in the PS during operation with **25 ns** (sign that e-cloud is not fully suppressed)

Not enough to cause transverse instabilities or emittance degradation, also thanks to the fact that the beam is kept in the ring only very shortly after the last splitting

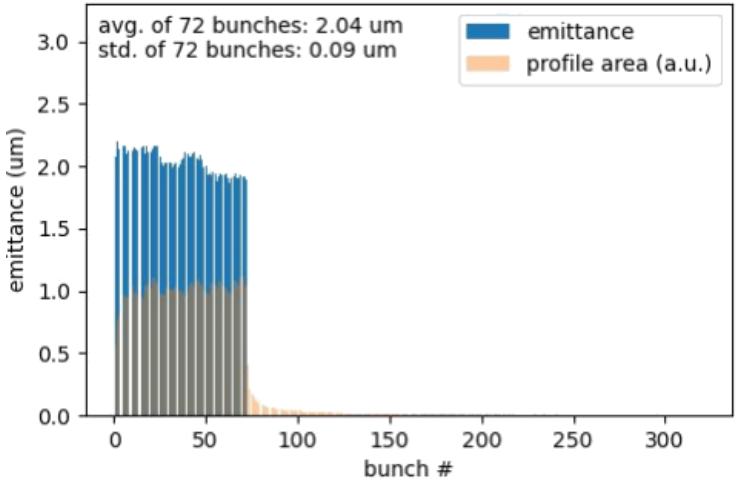
→ **No sign of e-cloud degradation from the PS** is visible on the beams injected in the SPS

Typical emittances measured at SPS injection

Horizontal



Vertical



Cortesy I. Mases

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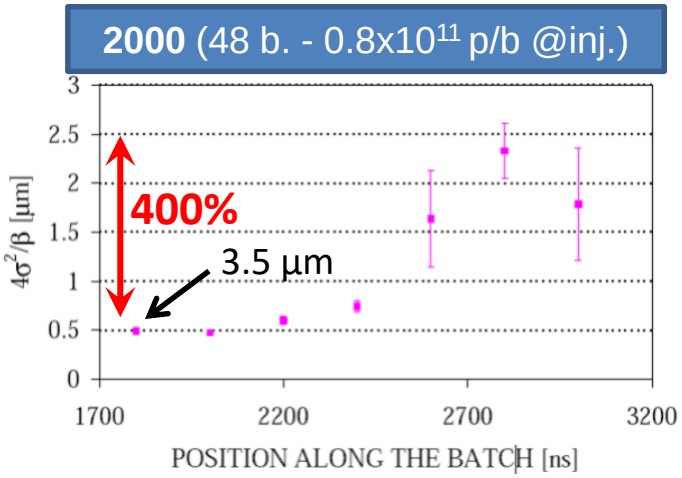
E-cloud in the SPS – early days

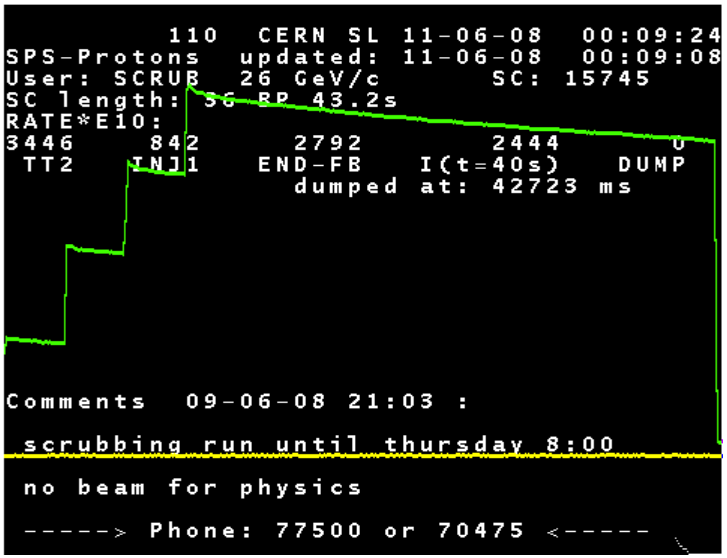
E-cloud was identified as a **main limitation for SPS operation as LHC injector** since the **early 2000's** when LHC-type beams were injected for the first time

- Strong **beam degradation**
- Severe **vacuum pressure rise** all around the machine

It took **several years with systematic scrubbing runs** to reach a point at which the SPS could **successfully accelerate the nominal LHC beams** (4x72 bunches, 25 ns 1.2e11 p/b) without significant beam degradation



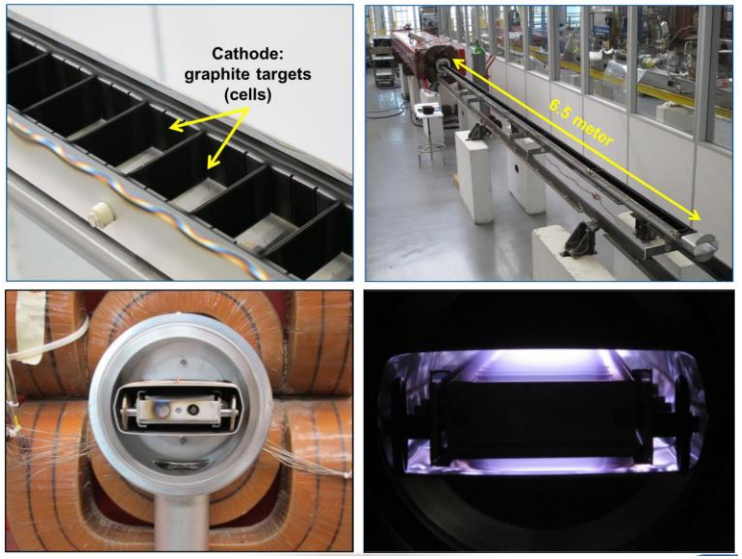
SPS page 1 during 2008 scrubbing run



E-cloud in the SPS – LIU strategy

- **Anti e-cloud coating** (amorphous carbon) developed as **part of the LIU project** but **not deployed over full ring**
- During LS2 **all quadrupoles of the QF type were coated** in the tunnel, exploiting synergies with the impedance reduction campaign to **practice large-scale deployment** of in-situ coating
  - → Ensure **readiness for deployment also in dipole magnets** in case of need

SPS aC coating



Courtesy P. Costa Pinto

- In **Run 3 scrubbing runs** took place at the **beginning of each year** as part of commissioning of the LIU beams to gradually **condition the ring** for operation with 25 ns beams and **intensities up to 2.3e11 p/bunch at 450 GeV**
  - Aim at **assessing whether a strategy based on scrubbing only is sufficient** to reach the target beam parameters

Scrubbing in Run 3 in a nutshell

Scrubbing in 2021

- **3 weeks** of scrubbing (interleaved with commissioning activity for MKP-L cooldown), followed by MD sessions with 25 ns beams
- **Recovered pre-LS2 performance**, 4x72b with 1.2 x 10^{11} p/bunch at 450 GeV

Scrubbing in 2022

- Scrubbing interleaved with commissioning over **5 weeks** (for MKP-L cooldown)
- Achieved about **1.5 x 10^{11} p/bunch** for 4x72b at 450 GeV
- Higher intensity, up to **1.8 x 10^{11} p/b at 450 GeV**, achieved during MDs but only with shorter bunch trains (limited by pressure spikes in MKDH)

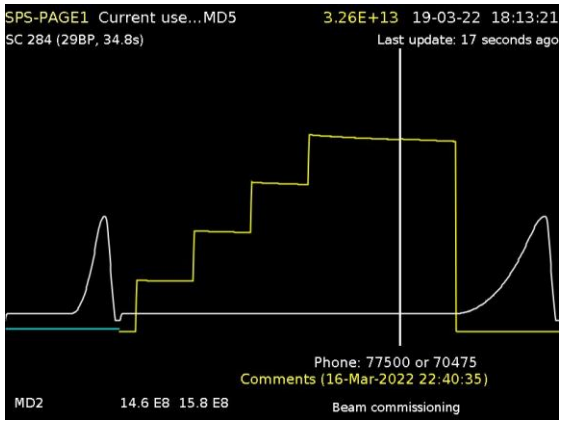
Scrubbing in 2023

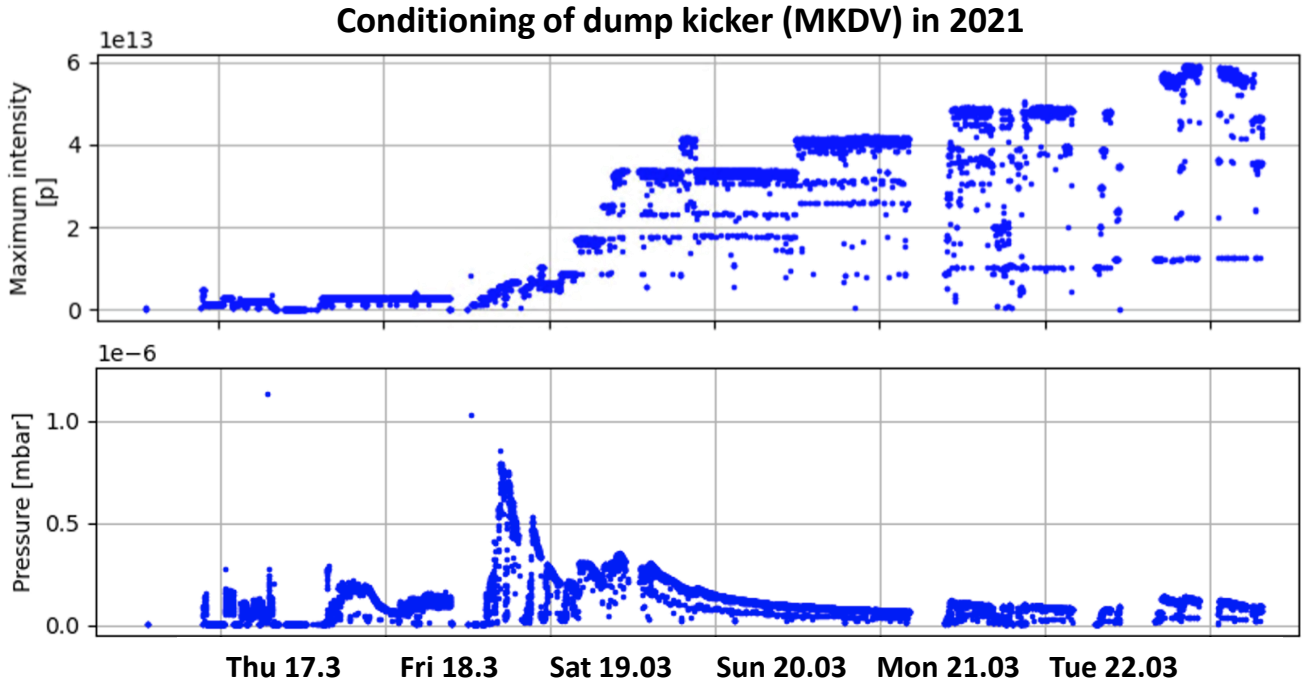
- Scrubbing interleaved with commissioning for about **4 weeks**
- Achieved about **2.0 x 10^{11} p/bunch for 4x72b at 450 GeV** at the end of scrubbing
- Higher intensities, up **to 2.2 x 10^{11} p/bunch**, achieved during MDs

Scrubbing strategy

SPS scrubbing is typically **done in stages**:

- First stage at **26 GeV** (using cycle with no acceleration)
  - Tune train length, number of batches, early dump in the cycle to maximize scrubbing efficiency while staying below vacuum pressure limit in most critical elements (those that need conditioning)





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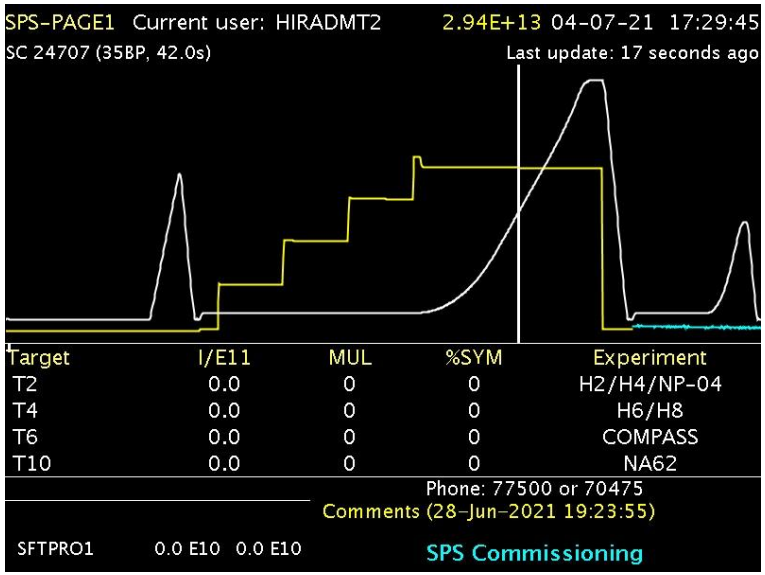
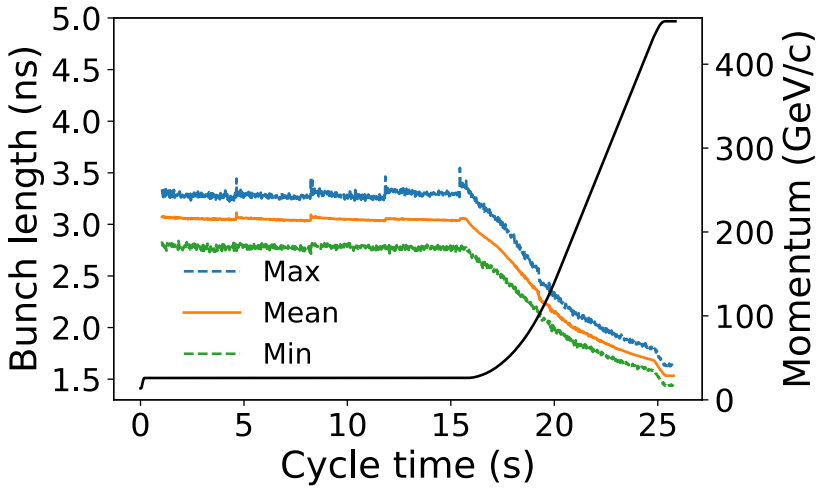
- Second stage using **acceleration to 450 GeV**
  - **E-cloud enhanced by strong bunch length reduction** happening during the ramp





Scrubbing strategy

Targets

- **Mitigate beam quality degradation** from e-cloud (typically visible only when large fractions of the machine are exposed to air, i.e. after Long Shutdowns)
- **Improve vacuum** level in **machine elements that are newly installed or exposed to air** (LS but also YETS)

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Scrubbing pace determined by:

- **Vacuum pressure** in elements that need scrubbing (by definition)
- **Impedance heating** in certain sensitive elements due to **prolonged use of beams with high-intensity and small bunch length**

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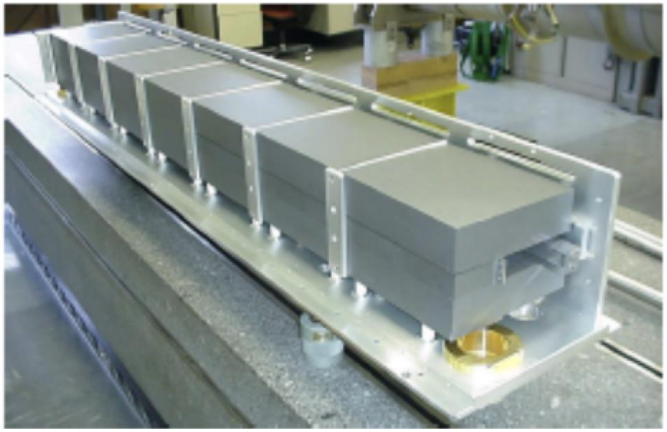
Scrubbing and kickers



In any machine, whenever we discuss scrubbing, we almost inevitably end up talking about **limitations from kickers**.

This is, in fact, **not surprising**:

- **Vacuum requirements** in kicker magnets are **significantly tighter** to allow high-voltage pulses without risk of damaging the device
  - Injection kickers and dump kickers **need to be fully functional during scrubbing** (cannot be just switched off for conditioning as done in other high-voltage devices, e.g. electrostatic septa)
- Kickers are particularly **subject to heating** during periods of continuous operation with high bunch intensity and short bunches

Conditioning of these devices is particularly tricky:

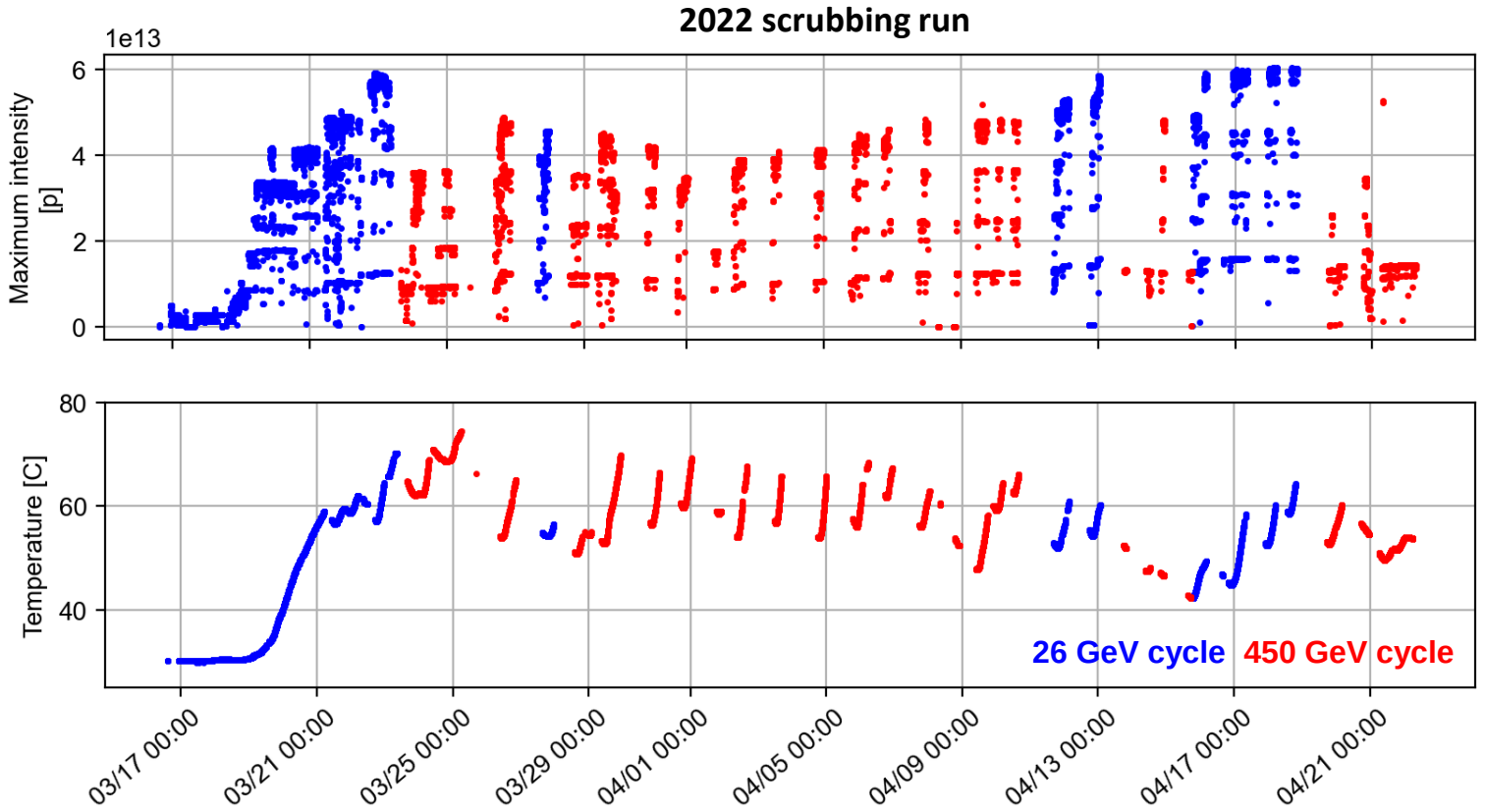
- During scrubbing periods kicker **pressure interlock levels need to be increased** compared to their operational values
  - Necessary to allow high-enough e-cloud levels to **condition device in acceptable time**
- Done by **equipment teams**, while behaviour of the devices is closely monitored by experts

For more info see: SPS kickers high intesity conditioning meeting

Limitations from kicker heating

Before 2023, efficiency of scrubbing runs in SPS was **severely limited by impedance heating in kicker magnets**

- **Before LS1** main limitation was from **extraction kickers (MKE's)** → solved by applying **serigraphy on ferrite blocks**
- As of Run2 **main limitation became MKP-L magnet**, showing a steep temperature increase when operating with 25 ns beams
  - Cool down very slow, need to **interleave 8h scrubbing / 16 h cooldown**



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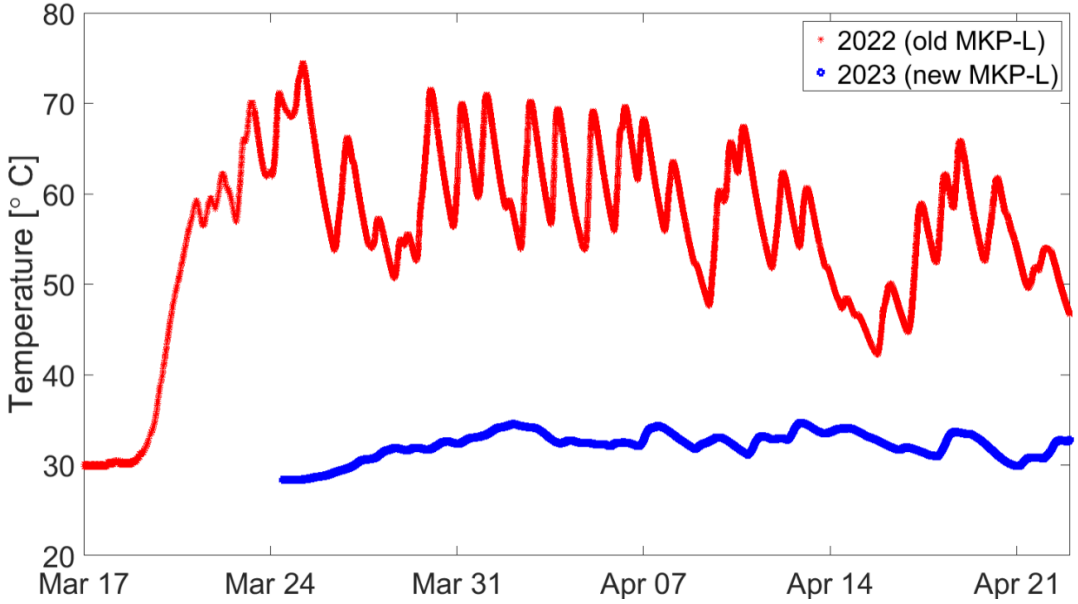
- As of Run2 **main limitation became MKP-L magnet**, showing a steep temperature increase when operating with 25 ns beams
  - Cool down very slow, need to **interleave 8h scrubbing / 16 h cooldown**
- **Major improvement in 2023** with the installation of **low-impedance MKP-L**
  - **Efficient scrubbing up to LIU intensities became possible** (still need to alternate scrubbing commissioning due to heating in MKP-S)



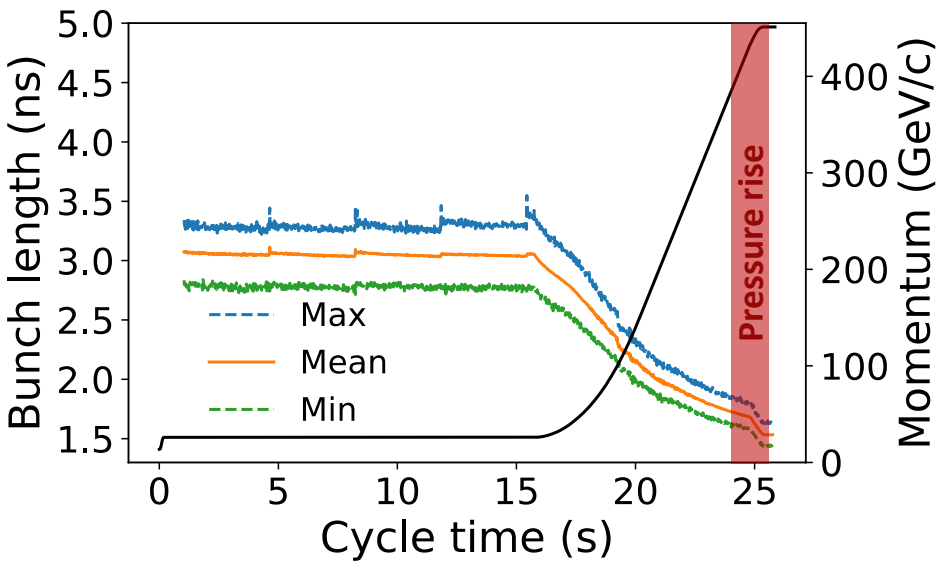
Fore more info see talk by G. Favia

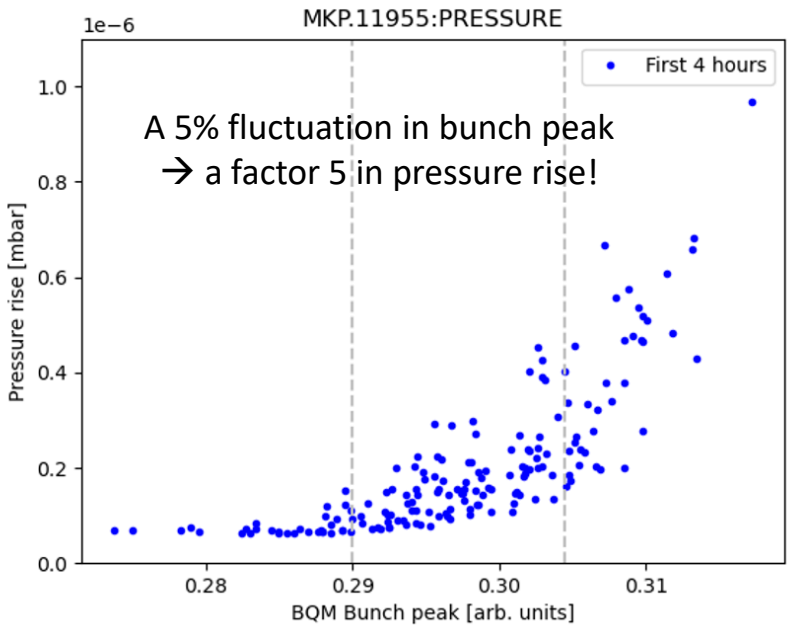
For more info see: SPS kickers high intesity conditioning meeting

Limitations from vacuum in kickers (MKDH and MKP-L)

Pressure in MKDH (dump kicker) and newly installed MKP-L (inj. kicker) **found to increase sharply toward the end of the energy ramp** (due to short bunches)

- Even after prolonged scrubbing at injection energy
- Practically **impossible to keep efficient scrubbing using standard LHC cycle**
  - Very **poor duty cycle**: less than 2 s every 30 s.
  - Very **sensitive to bunch length**: cycle-to-cycle fluctuations made a large fraction of the cycles useless while still triggering the HW interlock on other cycles (long stop, expert/piquet intervention)





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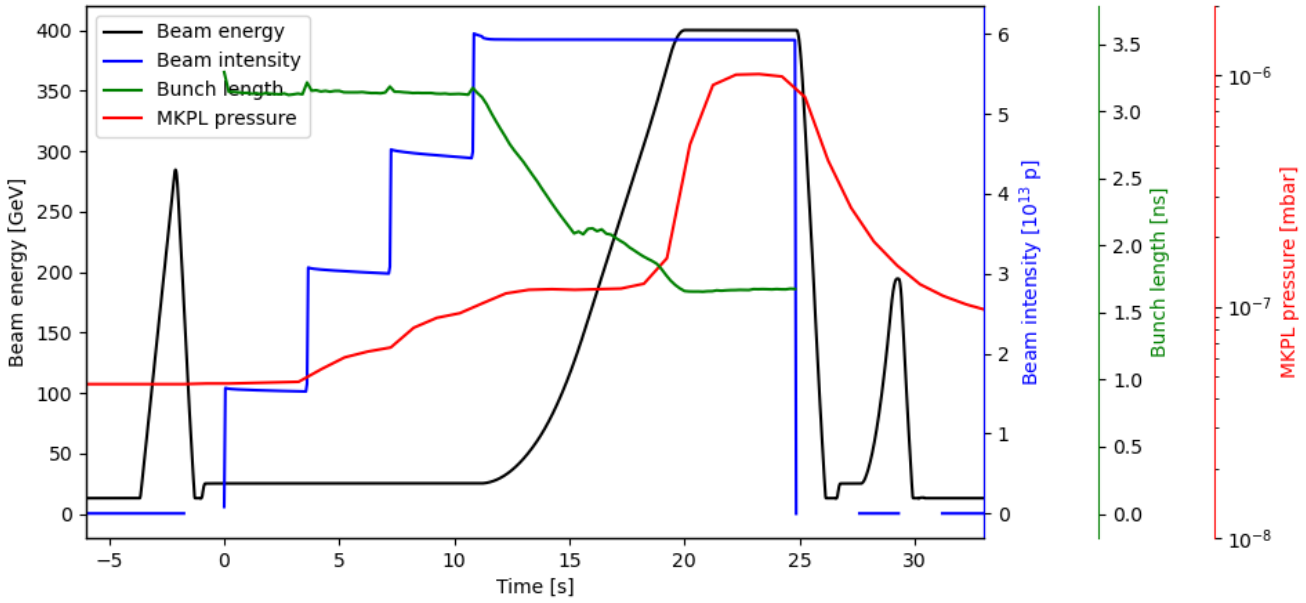
Pressure in MKDH (dump kicker) and newly installed MKP-L (inj. kicker) **found to increase sharply toward the end of the energy ramp** (due to short bunches)

To overcome these limitations, it was necessary to:

- **Optimize interlock logic**:
  - SIS **interlock on MKP pressure only enforced before injection**
  - **MKDH** pressure interlock **triggers only when two gauges exceed the threshold**
- Use a **special cycle with longer flat top at 400 GeV**, to allow for better duty cycle and more reproducible conditions



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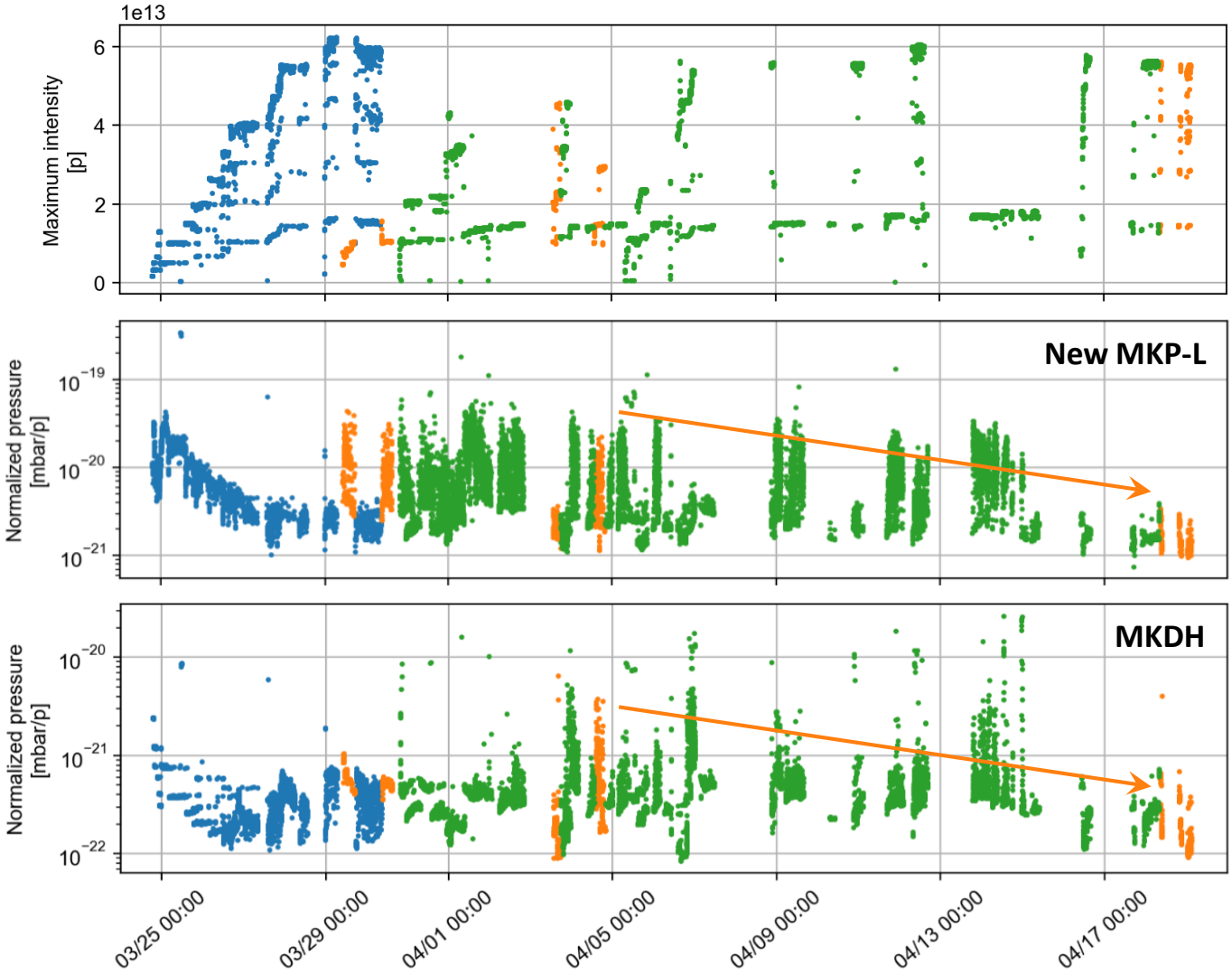
Limitations from vacuum in kickers (MKDH and MKP-L)

Conditioning with **long flat-top cycle found to be very effective**

→ After scrubbing period with long flat-top cycle it was **possible to reach ~2e11 p/b on the standard LHC-type cycle without triggering the interlock neither on the MKP-L**

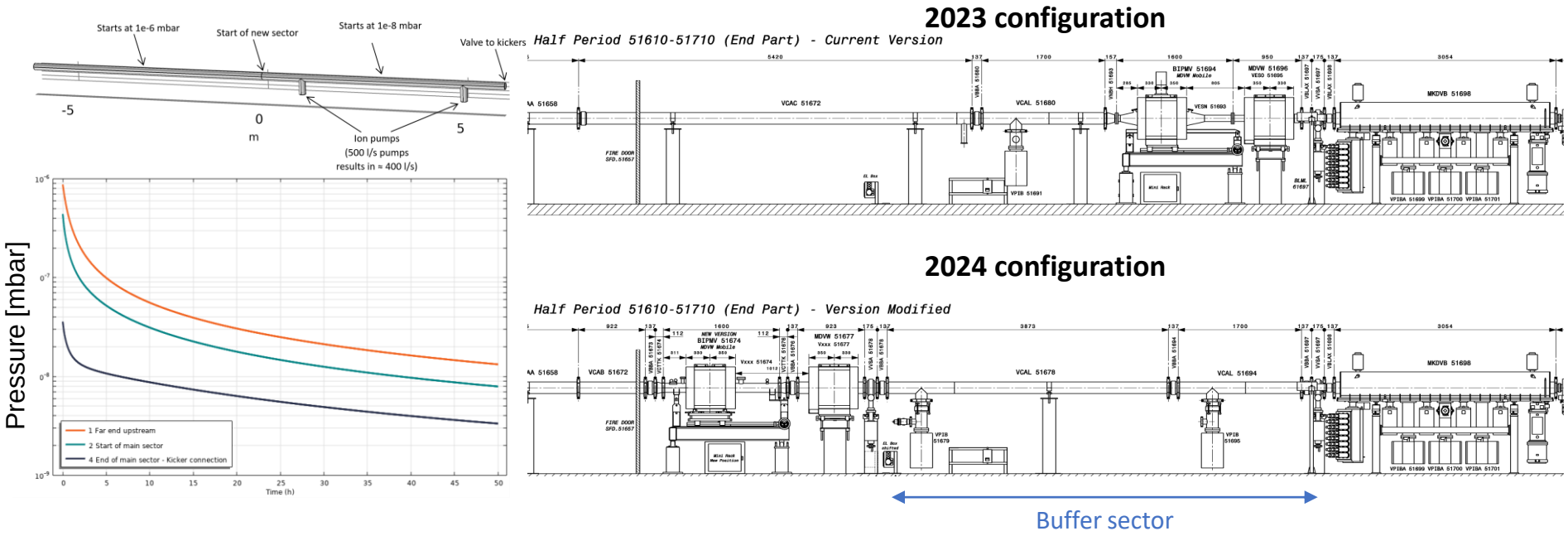


26 GeV cycle
Std LHC-type cycle (450 GeV)
Long flat-top cycle (400 GeV)

Improvement of vacuum sectorization in the kicker areas

It is evident that **re-conditioning of kickers can be very time consuming**, in case of replacement of exposure to air due to intervention in nearby equipment

- For this reason, in 2023 the **replacement of broken wire scanners** close to the dump kickers in point 5, was **postponed until the EYETS**
- **Equipment layout** being **modified** during EYETS in region close to the dump kickers
  - Introduction of **buffer vacuum sector**



- Pressure profile and pump-down times evaluated with simulations → **gaining one decade of pressure after 24h pumping**

Courtesy A. Harrison, J. Ferreira

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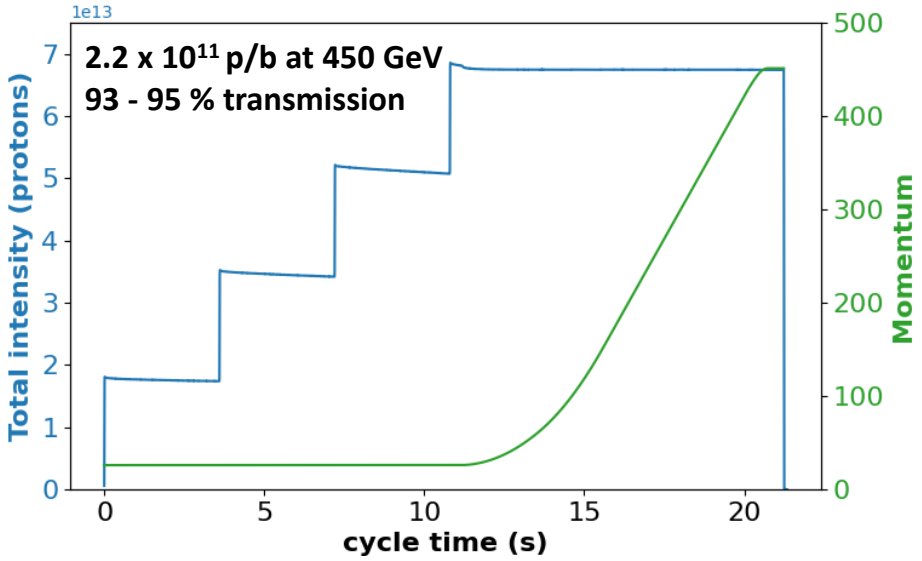
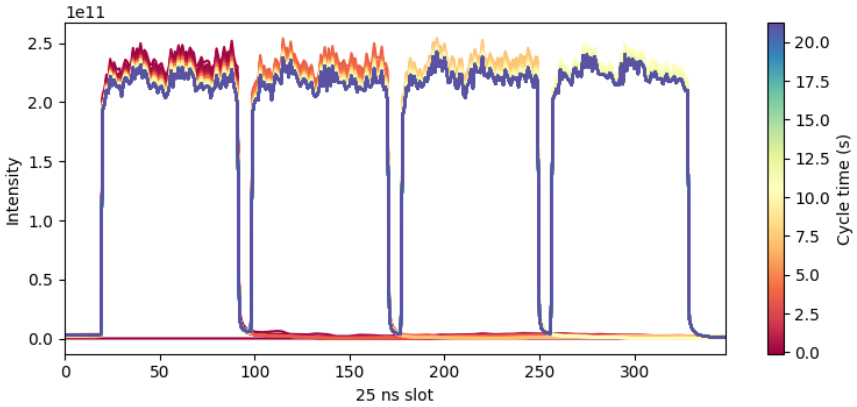
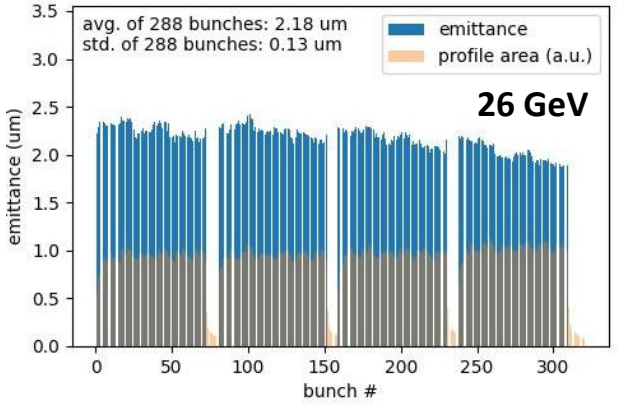
Experience from Run 3 shows that **beams with parameters very close to LIU targets can be produced** without significant degradation driven by electron cloud

- Coating of SPS dipoles is most likely not needed to meet the target



Courtesy I. Mases





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Experience from Run 3 shows that **beams with parameters very close to LIU targets can be produced** without significant degradation driven by electron cloud

- Coating of SPS dipoles is most likely not needed to meet the target

Furthermore, the **coating the bends would most likely not result in a significant saving in scrubbing time**

- In Run 3, scrubbing time was practically never determined by limitations in the arcs
- Instead, the **scrubbing pace and its duration were defined by conditioning of sensitive equipment** (mostly kickers) which were exchanged or exposed to air.

In fact, **investing e-cloud mitigations for kickers** (if technically feasible) would pay off better that coating the dipoles

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Summary

- In the **PS**, e-cloud formation takes place **only during RF manipulations performed right before extraction**
  - **No beam degradation observed** (the beam is kept in the ring only a short time after the last splitting)

- In the **SPS**, **limitations from e-cloud are much more prominent**
  - **Scrubbing runs** interleaved with beam commissioning tool place **every year in Run 3** as part of the LIU commissioning
  - Encountered **limitations mostly from heating and vacuum pressure rise in injection and dump kickers** (notably MKP-L and MKDH)
    - **Largely mitigated** by the installation of low-impedance MKP-L, the optimization of interlock logic and the usage of scrabbing cycle long flat top
  - Bunch intensity could be gradually increased up **2.2×10^{11} p/b at 450 GeV** as scrubbing progressed
    - **No measurable beam degradation from e-cloud**
    - **Not need for coating** of dipole magnets in LS3

Next steps

A **scrubbing run** (interleaved with beam commissioning) is foreseen at the **beginning of the 2024 run**. It will allow:

- Conditioning **areas exposed to air during EYETS interventions**
- **Further conditioning MKDH and MKP-L** kickers to allow reliable **operation with 2.3x10^{11} p/b at 450 GeV**
    - Needs scrubbing with **slightly higher intensities**

It would be important to **test the injection of these beams into the LHC**

- Only way to obtain **full characterization of beam quality of LIU beams** (in the SPS bunch-by-bunch emittance measurements are not possible at high energy)
- Strong **synergy with study of LHC intensity limitations** (e-cloud, RF, and others) in view of HL-LHC

Thanks for your attention!

e-cloud in the PS