CERN

LHC Injectors Upgrade

MCBI

HiLumi HL-LHC PROJECT

MCBI for CERN LHC Injectors Upgrade (LIU) and High Luminosity LHC (HL-LHC)

Giovanni Rumolo, CERN, Genève, Switzerland

ICFA Mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators – MCBI 2019

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LHC Injectors Upgrade

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- Why upgrades and what are the upgrades for LHC and its injector chain?

- Present intensity limitations and future performance of the LHC injectors
  - Where do we need mitigation of coherent beam instabilities?
  - How far we can go with the upgrades

- Mitigation of beam instabilities for HL-LHC

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Goals of upgrades in a nutshell (HL-LHC)

The **High Luminosity LHC (HL-LHC)** upgrade

- Aims at **3000 (4000) fb^{-1}** total integrated luminosity over HL-LHC run (2026 – 2037)
- Based on operation at levelled luminosity of **5 (7.5) x10^{34} cm^{-2}s^{-1}** by lowering β^*

Beam properties @LHC injection

	N_b (x 10^{11} p/b)	$\varepsilon_{x,y,}$ (μm)	Bunch spacing	Bunches
HL-LHC beam	2.3	2.1	25 ns	4x72 per injection

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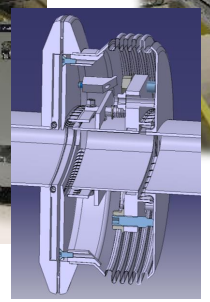
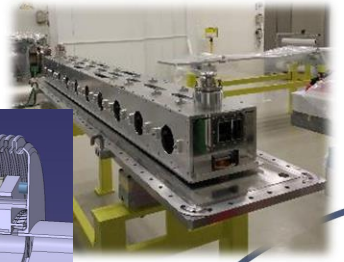
HL-LHC target	**2.3**	**2.1**	**25 ns**	**4x72 per injection**
Present	1.3	2.7	25 ns	4x72 per injection

The **LHC Injectors Upgrade (LIU)**

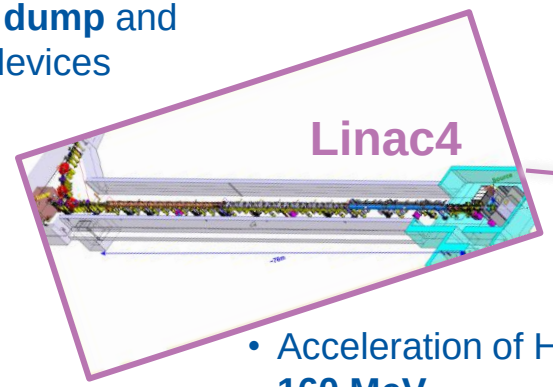
- Aims at **matching the beam parameters** at LHC injection with HL-LHC target
- Needs to deploy **means** to overcome **performance limitations** in all injectors!

A view on LHC Injectors and LIU

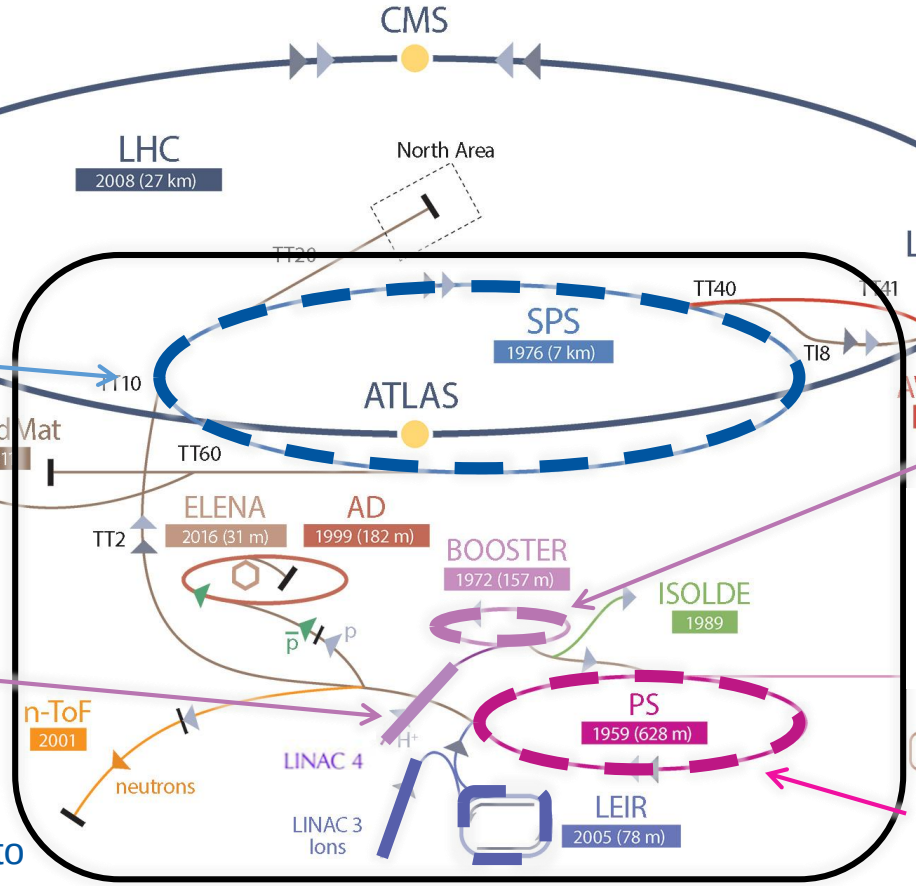


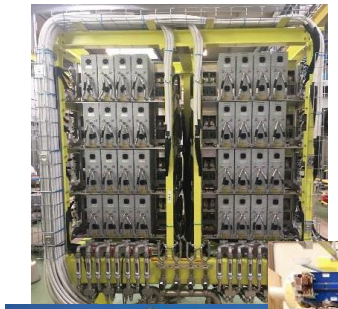


- Main **RF** system (200 MHz) upgrade
- Longitudinal **impedance** reduction & anti-ecloud coating
- New **beam dump** and protection devices



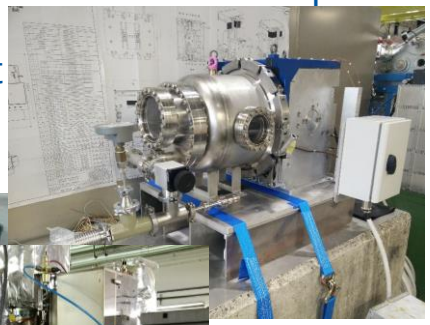
- Acceleration of H^- to **160 MeV**
- Nominal 40 mA within 0.4 μm

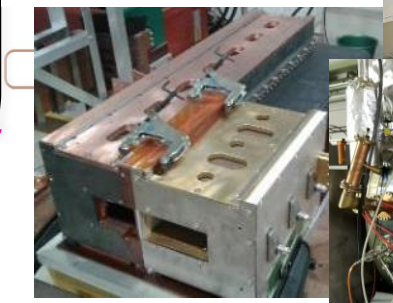




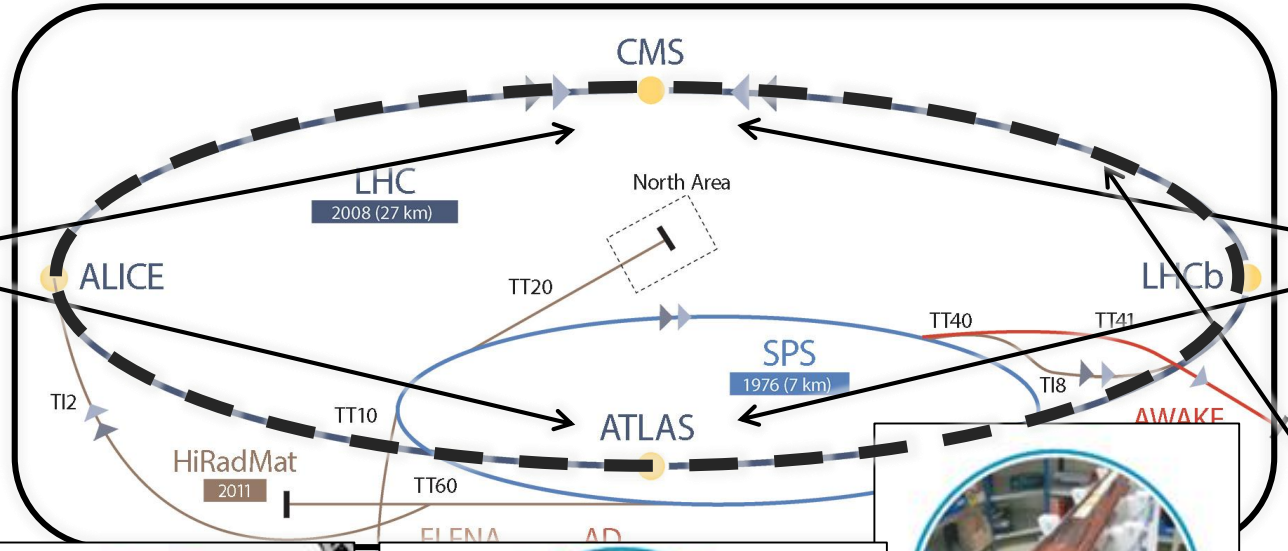
- **160 MeV** H^- charge exchange injection
- Acceleration to **2 GeV** with new main power

- **2 GeV** injection
- New **RF** equipment including broad-band feedback





A view on LHC and HL-LHC



"CRAB" CAVITIES
8 superconducting "crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

CRYOGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS

CIVIL ENGINEERING
2 new caverns and two new 300-metre service galleries, two new large shafts; new technical buildings on surface in P1 and P5 (ATLAS and CMS)

BENDING MAGNETS
2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

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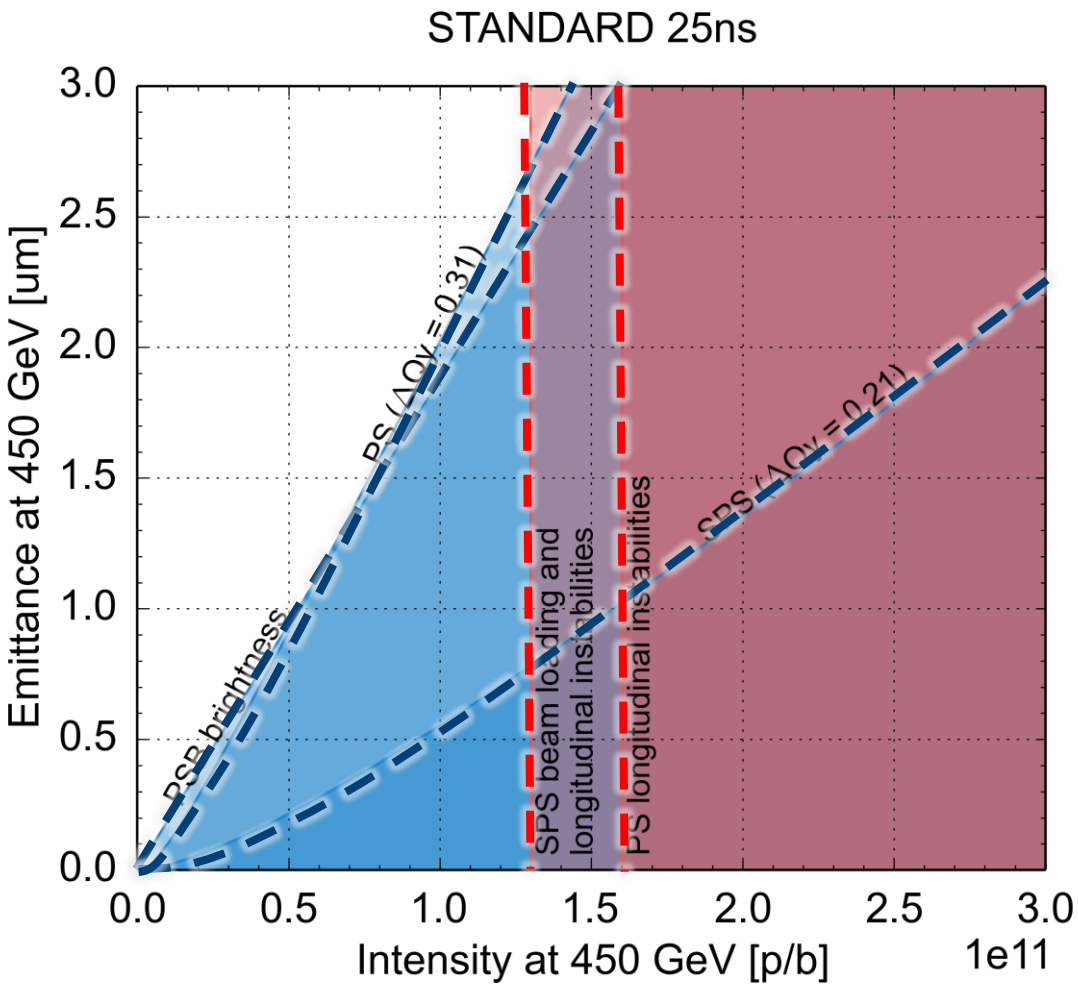
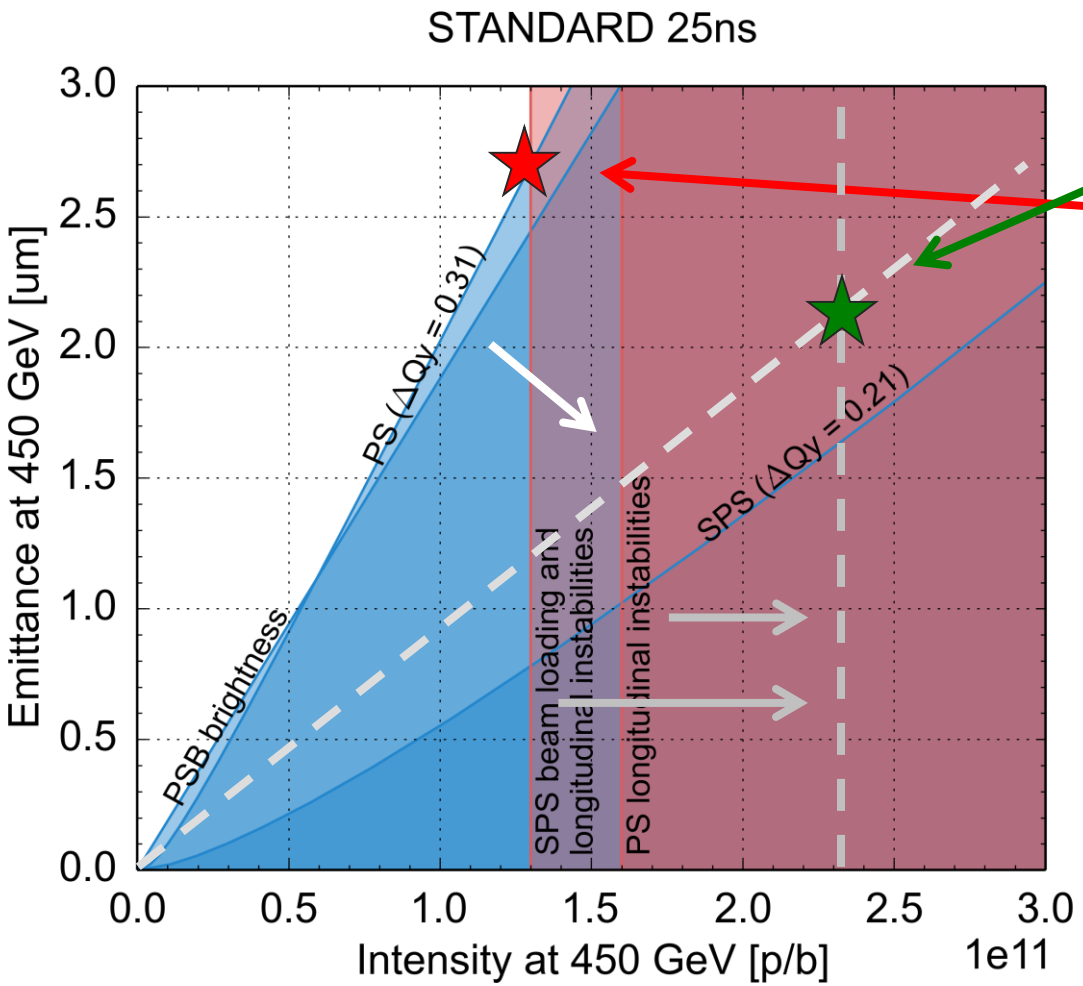
Present performance limitations



	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	**2.3**	**2.1**
Present	1.3	2.7

- **PSB injection**: Brightness limited by efficiency of multi-turn injection process and space charge effects
- **PS and SPS injection**: Brightness limited by space charge – ΔQ<0.31 (PS) and 0.21 (SPS), to limit beam degradation
- **PS cycle**: Bunch intensity limited by longitudinal coupled bunch dipolar instability
- **SPS cycle**: Bunch intensity limited by RF power, longitudinal coupled bunch instability

Present performance limitations



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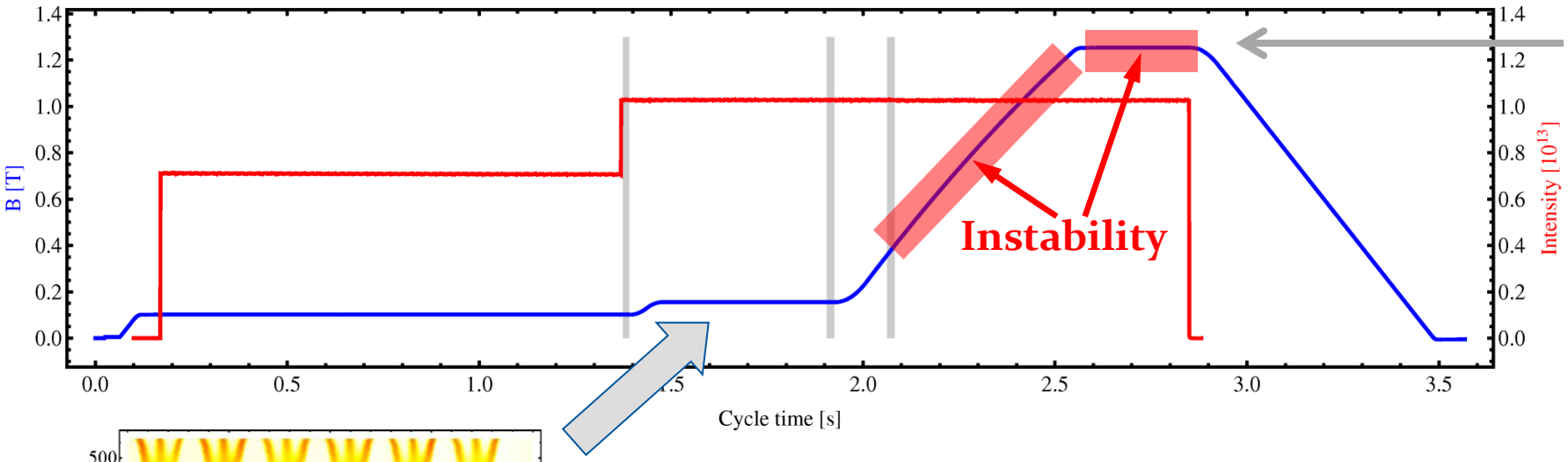
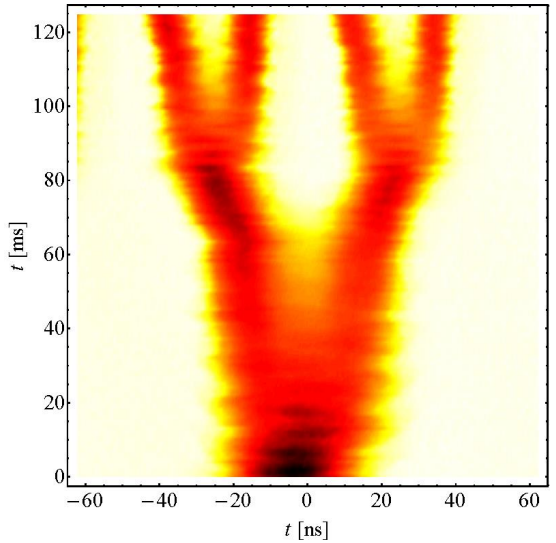
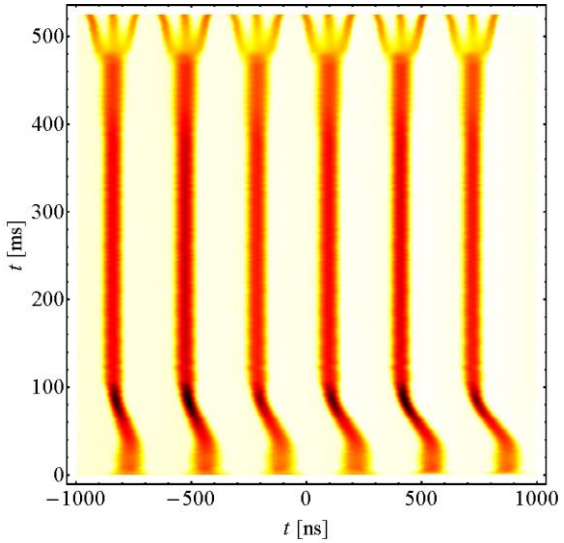
Lifting the brightness limitations

- Halve the slope of the **PSB brightness line**
  - 160 MeV H^- charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2 (demonstrated in simulations)
- Reduce **space charge at PS injection** to accommodate same tune spread as current LHC beam ($\Delta Q_y = -0.31$)
  - Increase of PS injection energy from **1.4 GeV to 2 GeV**
  - Increase of **longitudinal emittance** (compatibly with other constraints) at transfer in order to gain from decreasing λ_{max} and increasing $\delta = (\delta p/p_0)$
- Concerning **beam stability**:
  - PSB H instability due to extraction kicker not expected to be an issue → Eirini's talk
  - Larger longitudinal emittance beneficial to beam stability

Lifting the PS intensity limitation



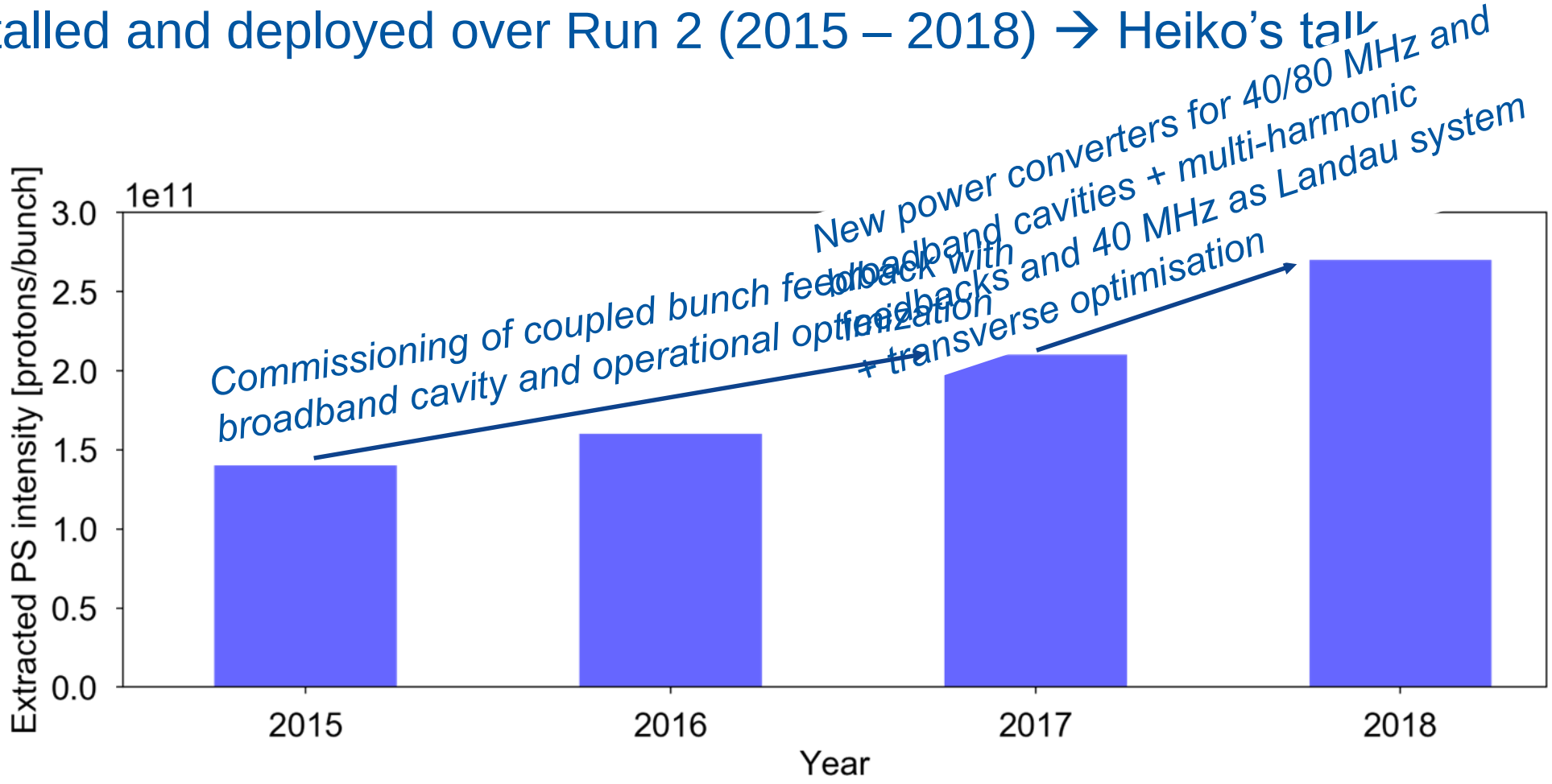




- Bunch current limited around **1.6e11 p/b at extraction**
- Above 1.6e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
  - Dipolar oscillation, caused by **10 MHz RF system impedance** (as found also in simulations)

Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over Run 2 (2015 – 2018) → Heiko's talk

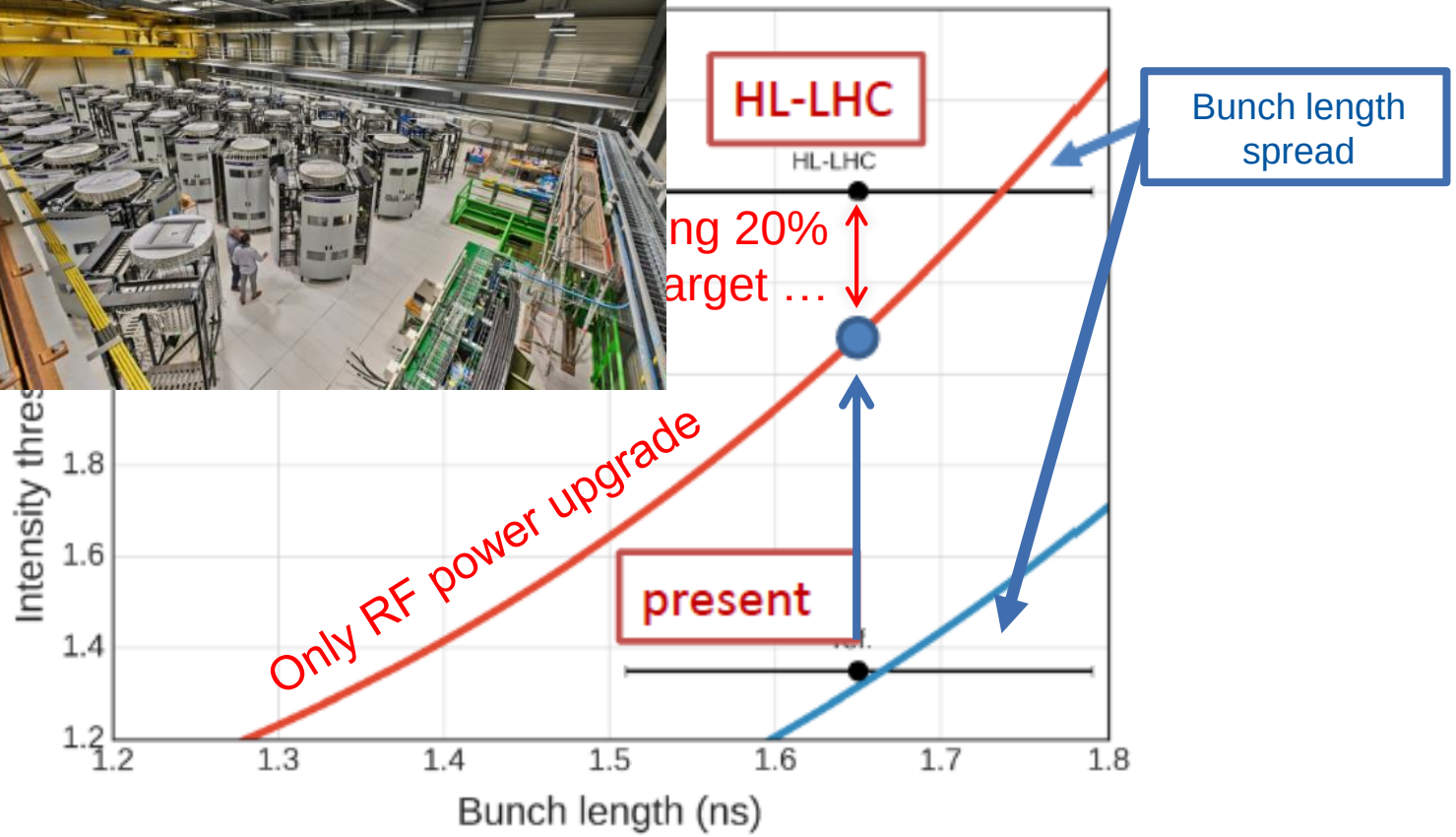


Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over Run 2 (2015 – 2018) → Heiko's talk
- Goal in terms of **intensity out of the PS** reached!
  - However, we may need to seek further stabilization in order to decrease the longitudinal emittance into the SPS (requirement to minimize capture losses)
  - In this case, the option of installing a Landau cavity in the PS with the right tuning range to cover ramp + flat top remains viable as a post-LIU action

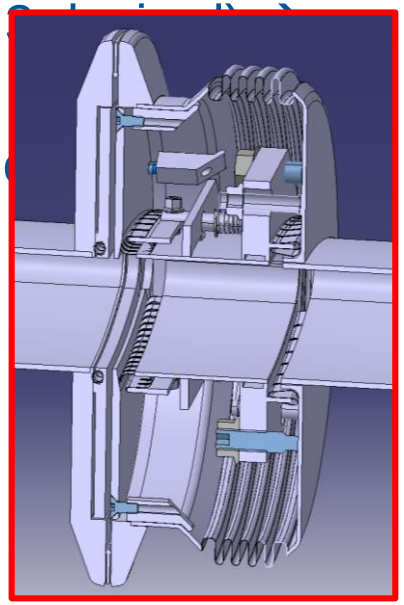
Lifting the SPS intensity limitation

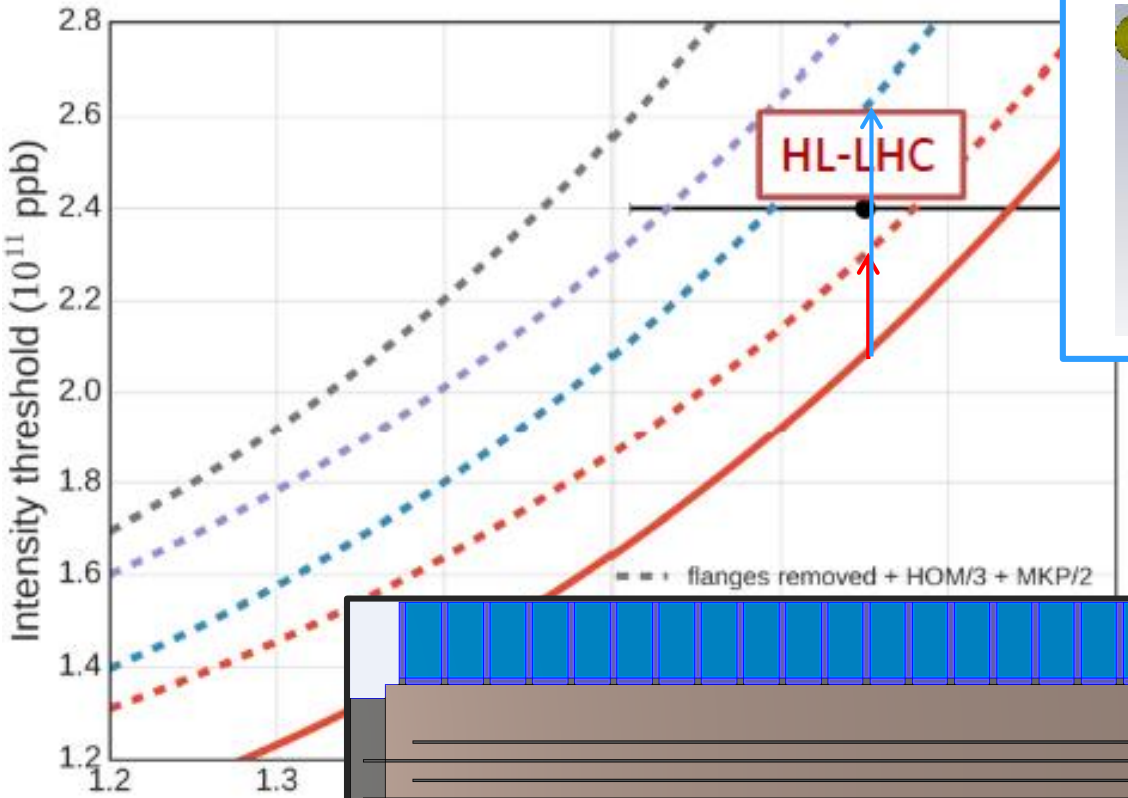
- **Beam loading** in the present 200 MHz TW RF system – intensity limited to about 1.3e11 p/b
- **Longitudinal instabilities** during ramp with very low threshold cured by
  - 800 MHz RF system in bunch shortening mode
  - Controlled emittance blow-up (with constraint of 1.7 ns bunch length at extraction) – not needed in Q20

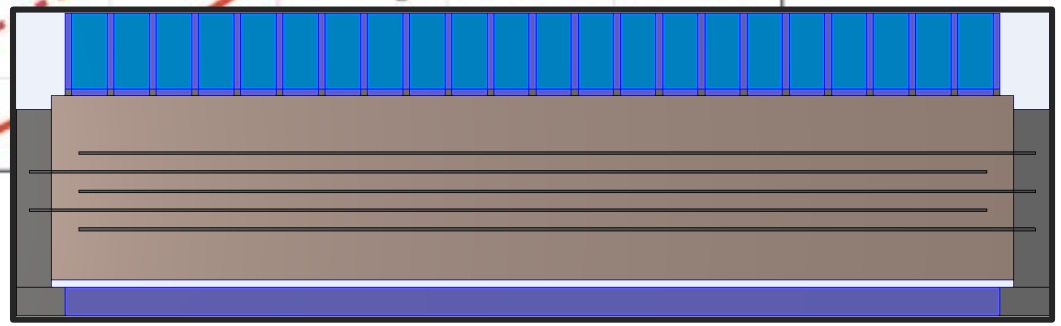


Mitigation of the SPS longitudinal instability

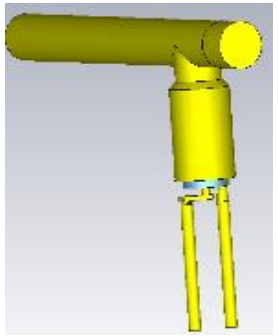
- **Impedance reduction** needed in addition
  - Shielding of a subset of vacuum flanges
  - Enhanced damping of HOMs of 200 MHz (factor
    baseline for LIU
  - Serigraphy on th
    kickers MKP





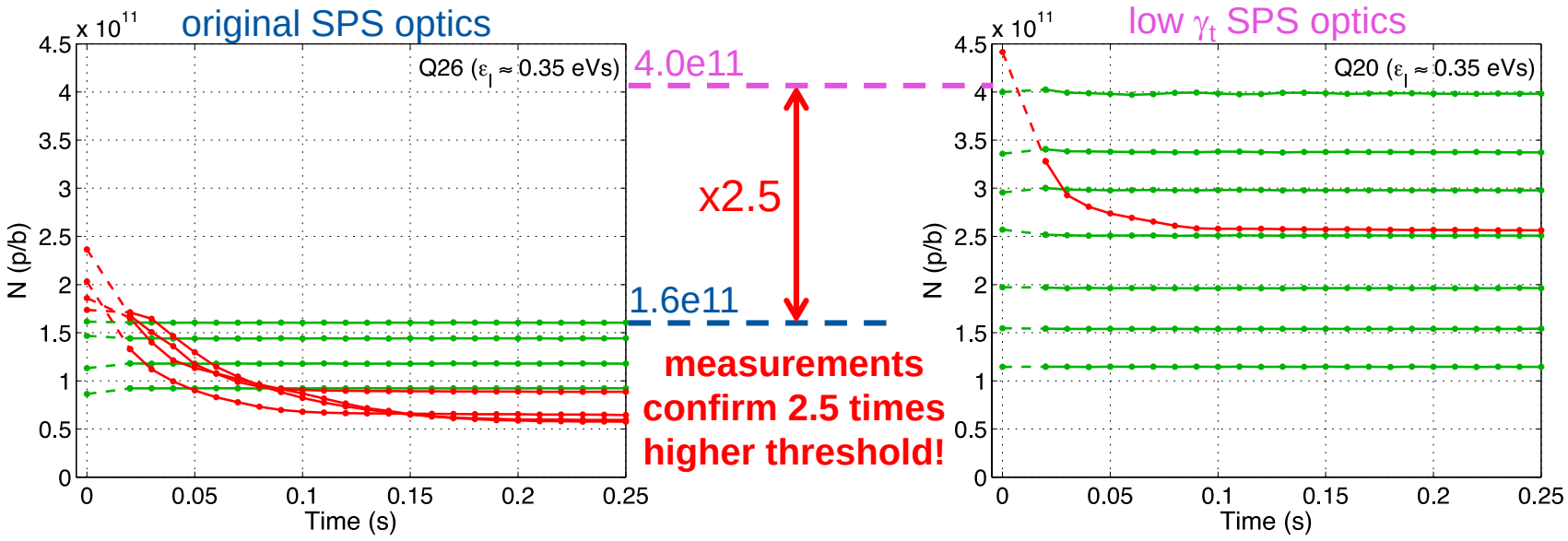


new HOM coupler



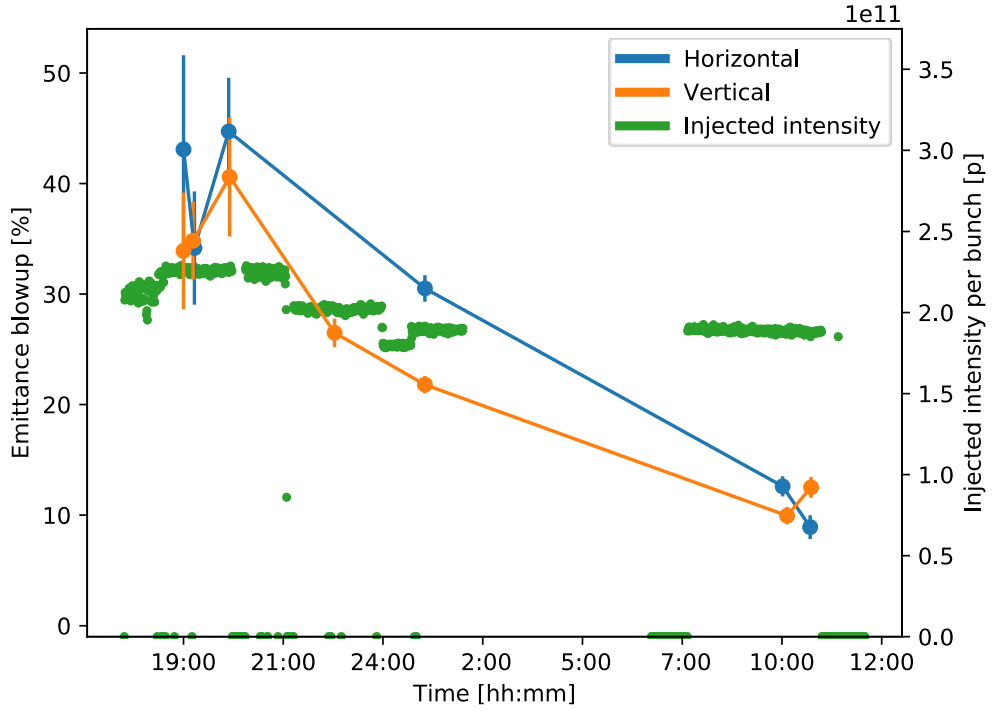
Mitigation of the SPS transverse instability

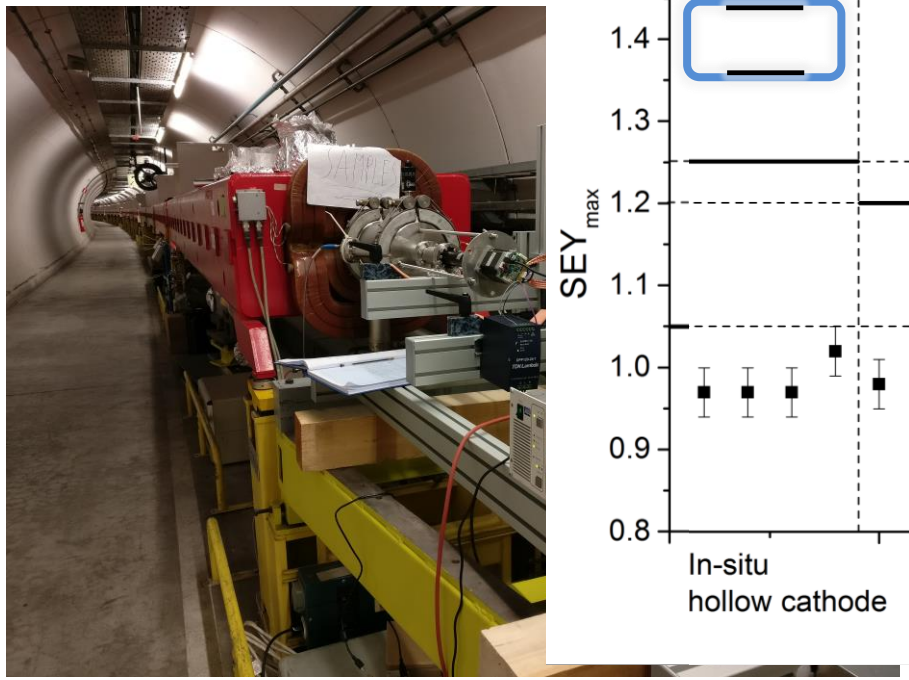
- **Transverse Mode Coupling Instability (TMCI)** threshold was raised from 1.6e11 p/b to 4e11 p/b when switching to a low gamma transition (γ_t) optics → See Yannis' talk

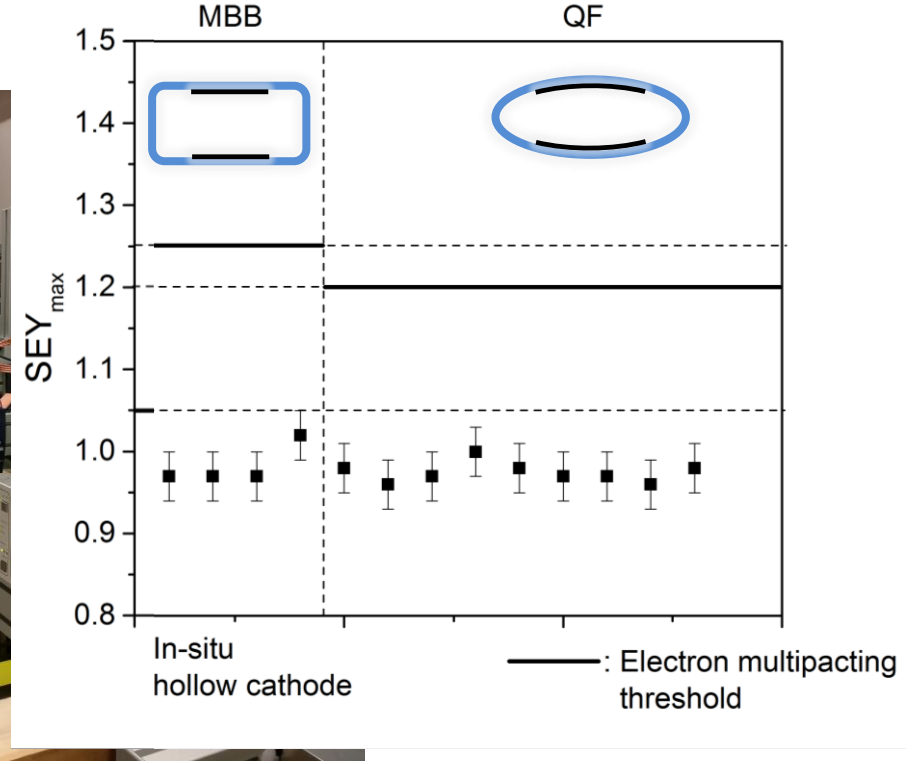


Mitigation of the SPS transverse instability

- **Electron cloud** responsible for instabilities, can be **mitigated by**
  - Beam induced scrubbing
  - Coating with a-C the chambers of the focusing quadrupoles and adjacent drift chambers

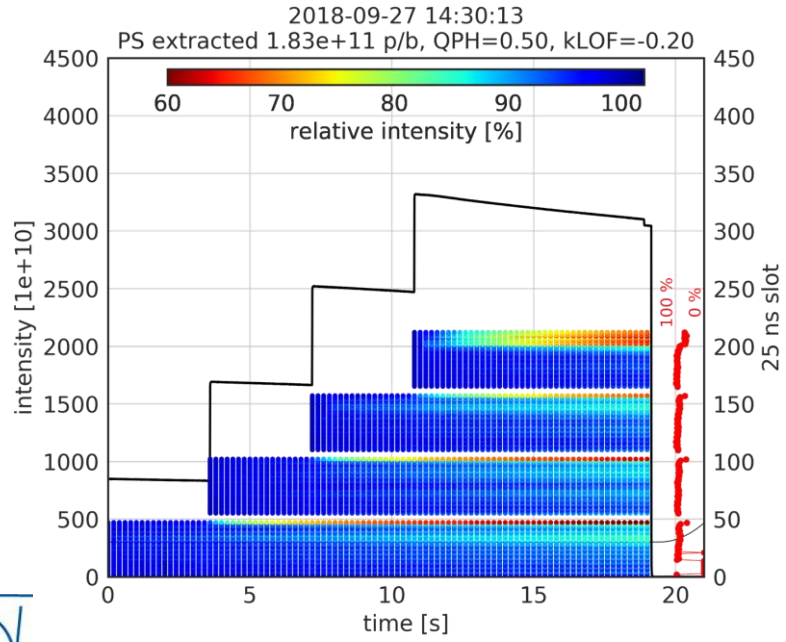


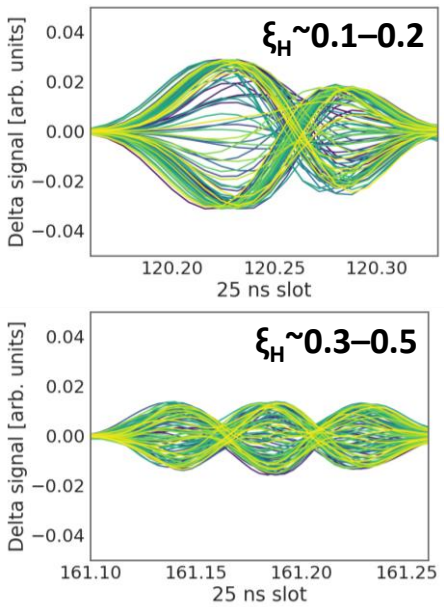


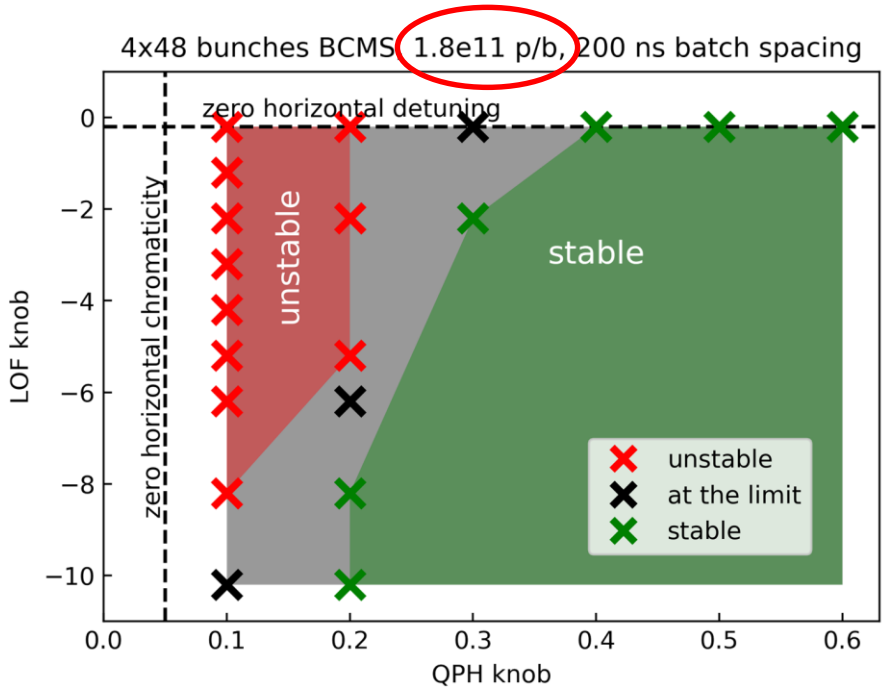


Mitigation of the SPS transverse instability

- **Horizontal coupled bunch instability**
  - Observed in 2017-18 for intensities above 1.8 x 10^{11} p/b
  - Driven by resistive wall and narrow band horizontal impedances, but also destabilizing effect of impedance reduction → Carlo's talk
  - Needs to be operationally stabilized for future operation – tradeoff with beam lifetime

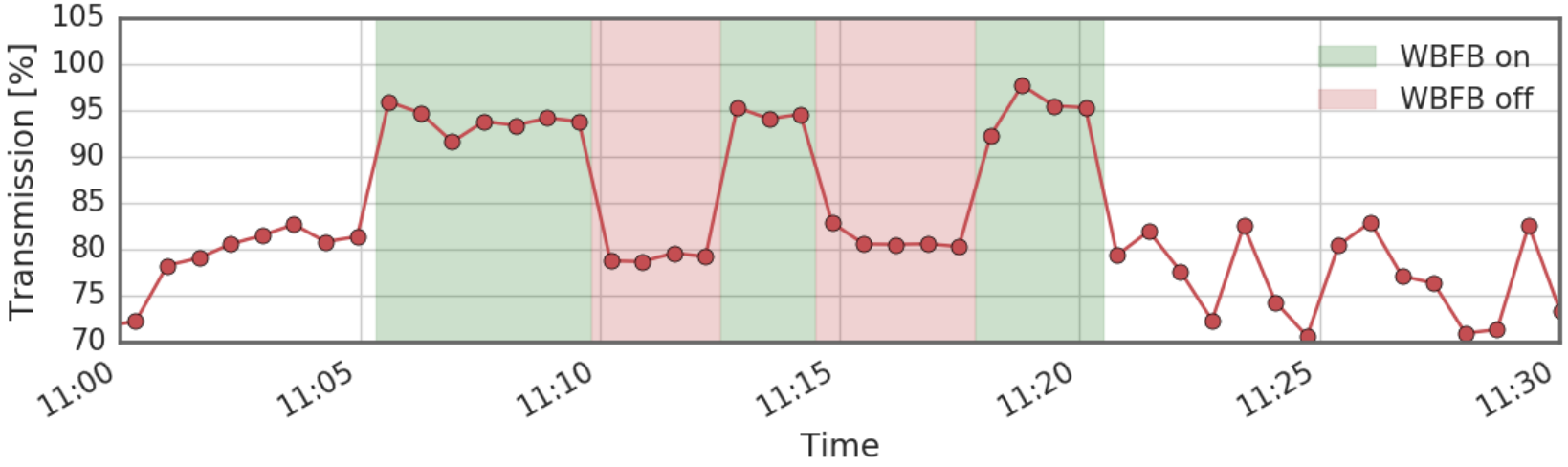




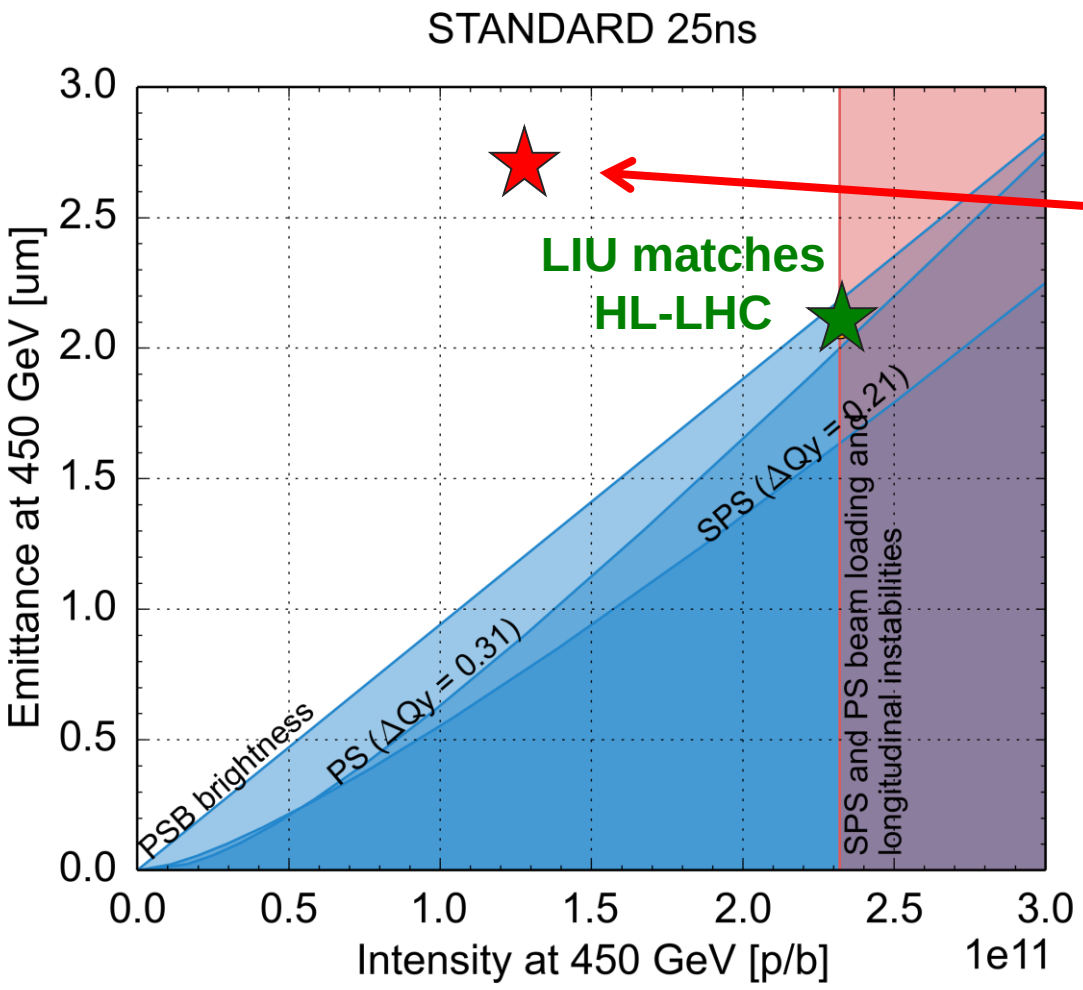


A possible weapon for the unexpected …

- Prototype of **vertical (V) wideband feedback** system deployed at SPS
  - Using stripline pick-ups + two stripline kickers and a slotline kicker, bandwidth up to 1 GHz, power > 1 kW
- Damping of Transverse Mode Coupling Instability (TMCI) with single bunch demonstrated in machine experiments in 2017-18



Summary: Future LIU performance



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HL-LHC target	**2.3**	**2.1**
Present	1.3	2.7

- **PSB injection**: from Linac4
- **PS injection**: 2 GeV, larger longitudinal emittance
- **PS cycle**: Longitudinal coupled bunch feedback system, impedance reduction
- **SPS cycle**: RF power upgrade, longitudinal impedance reduction, beam scrubbing & partial a-C coating, low γ_t optics

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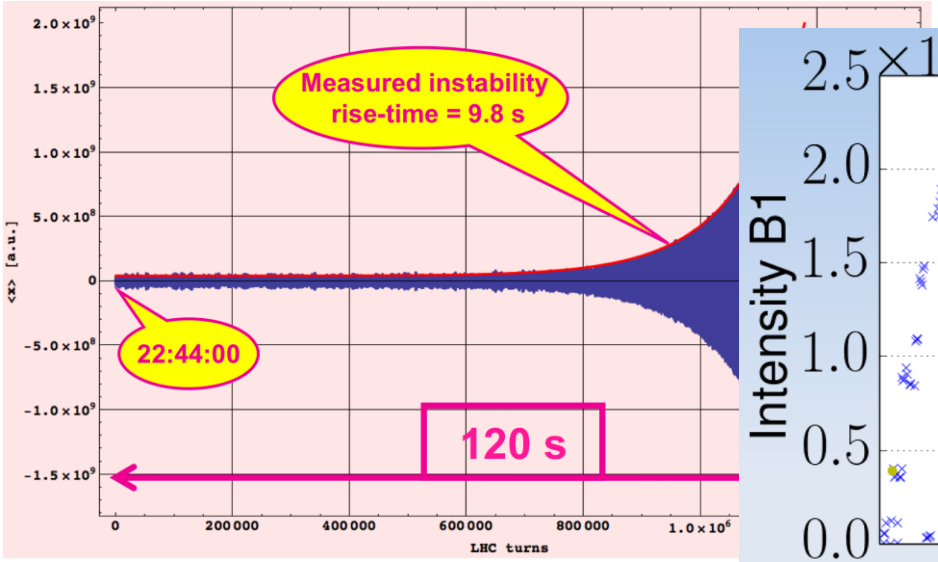
  - How far we can go with the upgrades

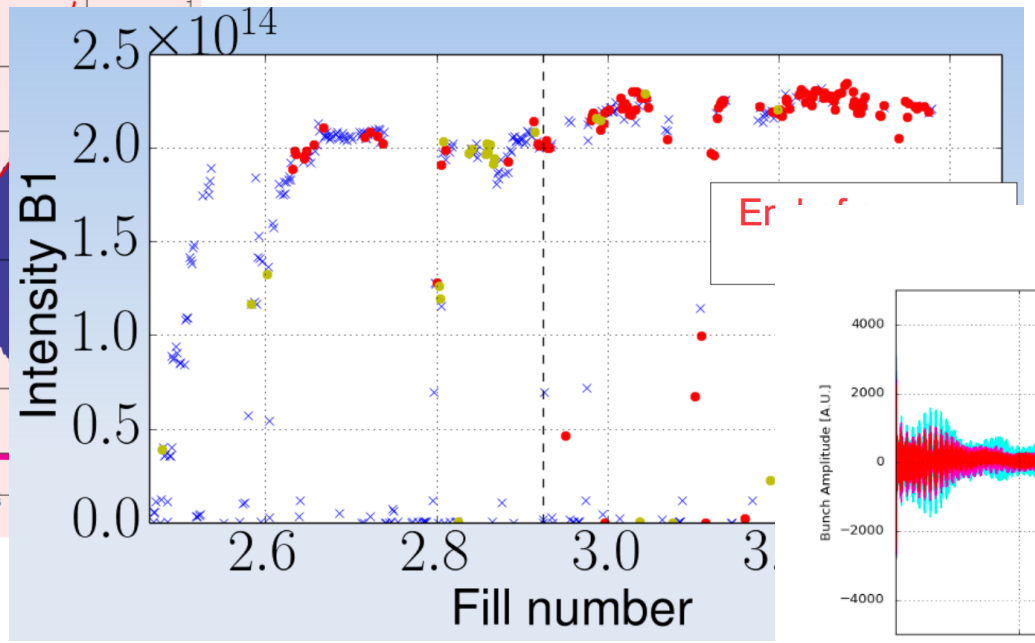
- Mitigation of beam instabilities in the LHC

LHC beam stability

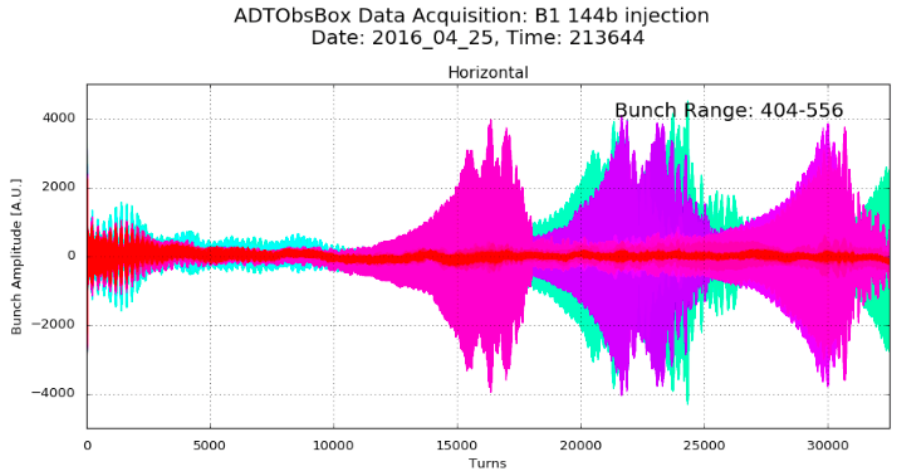
- **LHC transverse beam instabilities** observed with different types of beams and at different stages of the LHC cycle (see Xavier's talk)



2010, **single bunch** during the ramp



2011-12, **50 ns beam** during β^* squeeze or while adjusting the beams to collide

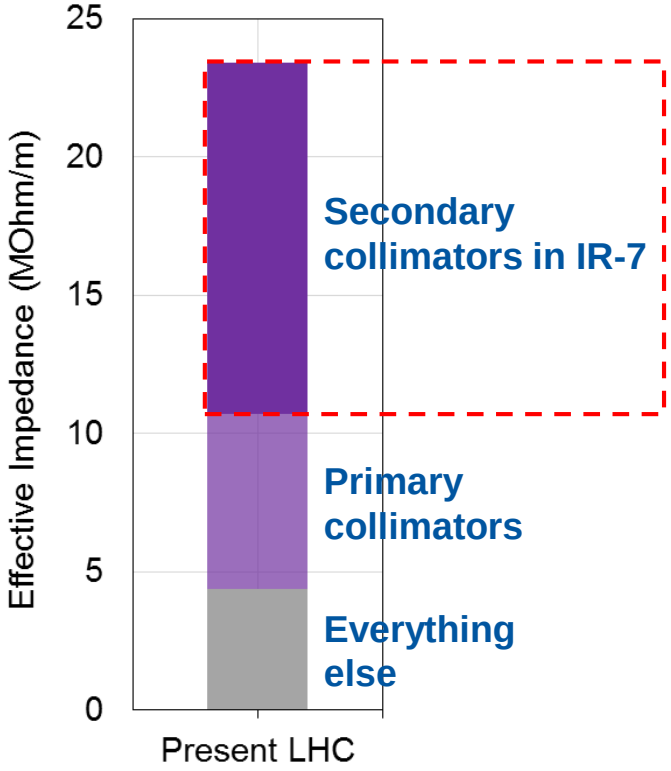


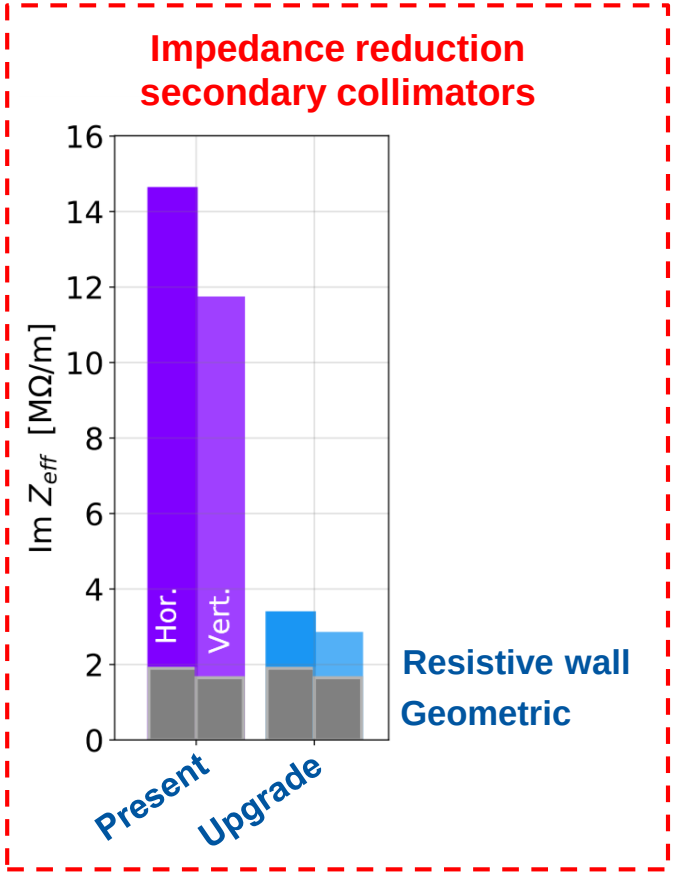
2015-18, **25 ns beam** at injection

LHC beam stability

- **LHC transverse beam instabilities** observed with different types of beams and at different stages of the LHC cycle (see Xavier's talk)
- Sources are mainly
  - **Transverse impedance** (dominated by collimators, especially when closed at top energy) through loss of Landau damping due to beam-beam, electron cloud, linear coupling, cut tails, noise induced modifications of distribution
  - **Electron cloud,** at least with 25 ns beams
- Controlled through **"extreme" machine settings**, e.g. at 6.5 TeV Q'=+15-20, octupole strength close to maximum, maximum damper gain and bandwidth
  - ⊙ Need to gain some margin with stabilisation knobs **for operation with HL-HLC beam parameters** (double intensity, double brightness) → Impedance reduction, electron cloud understanding and partial mitigation

LHC beam stability



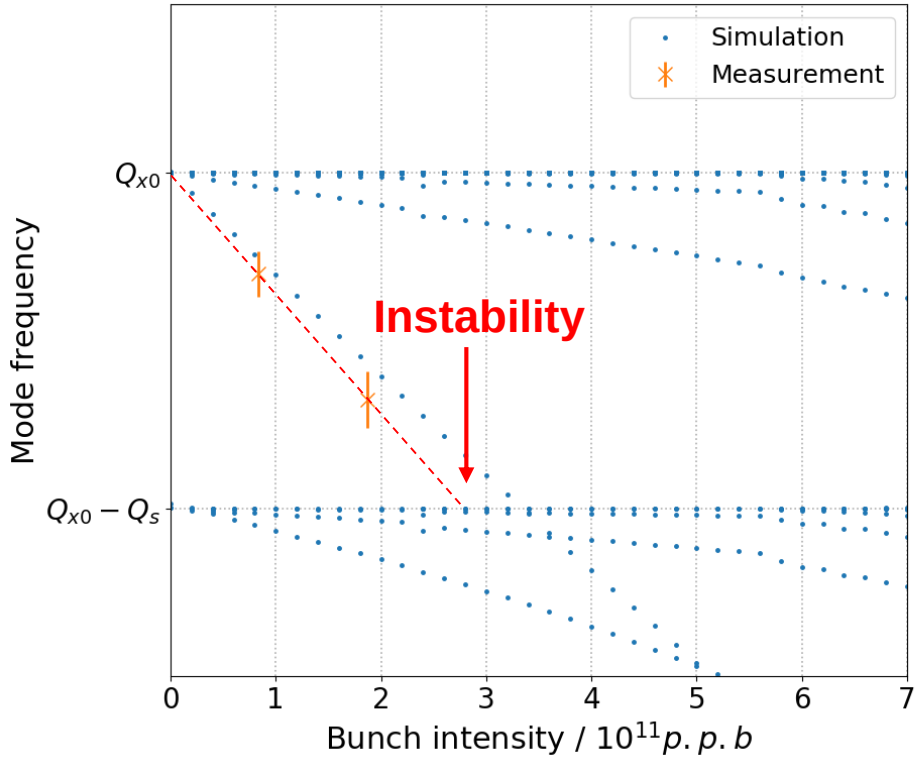


- Due to the small gaps, at 6.5 TeV the most critical impedance contributor (80%) is **collimators**
- Within HL-LHC primary and secondary collimators replaced by new ones **with Mo-Gr jaws** having same robustness and higher conductivity (with Mo coating on secondaries) → Alessio's talk

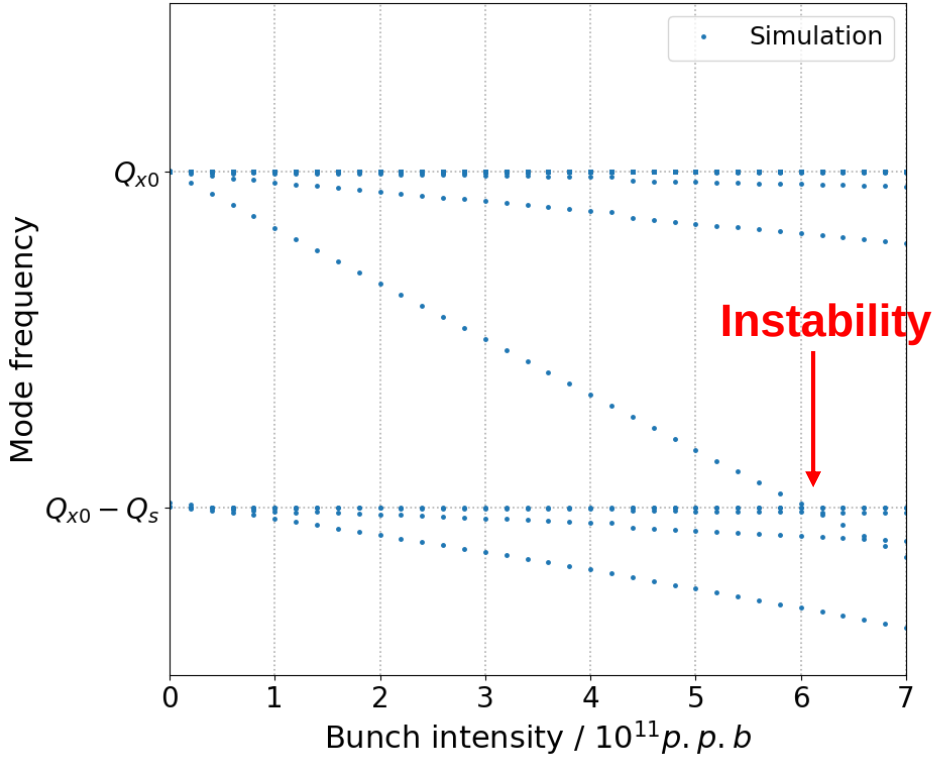
LHC beam stability

- Example: Effect of impedance reduction on **TMCI threshold**

Present LHC impedance model



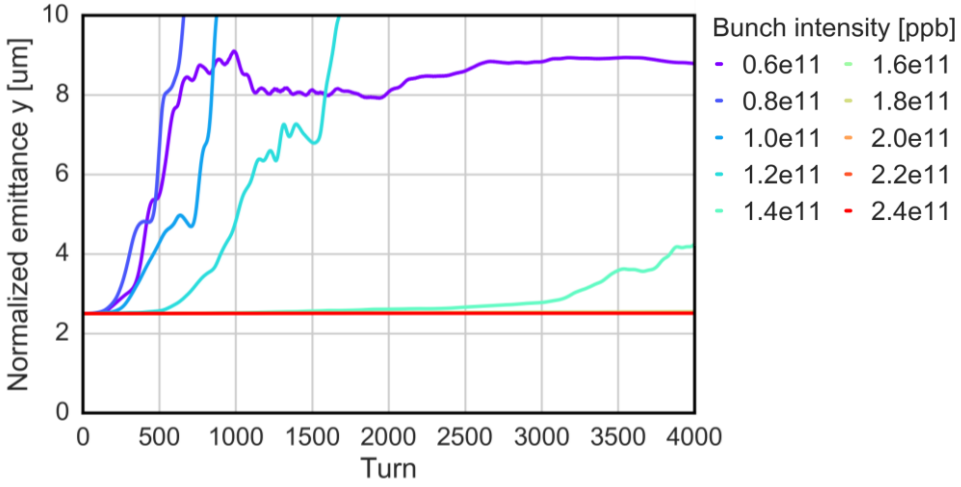
HL-LHC impedance
(after collimator impedance reduction)



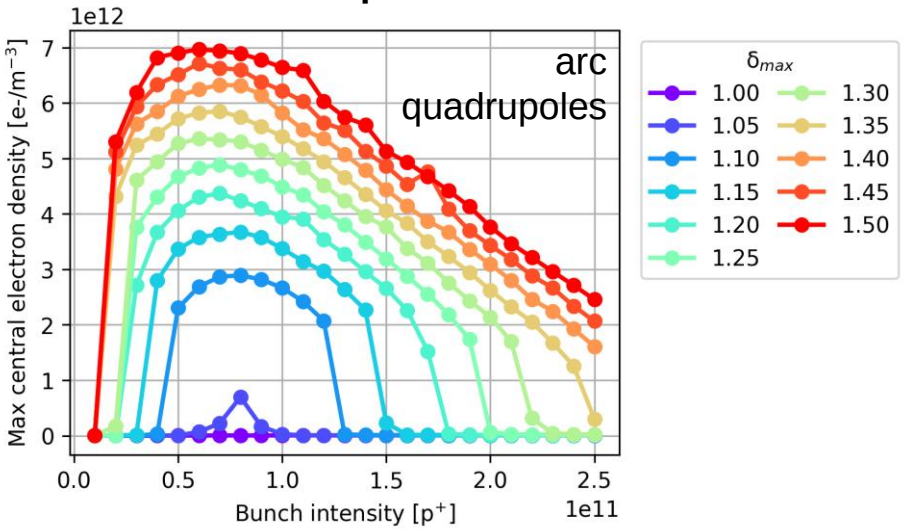
LHC beam stability

- Strong instabilities observed at 450 GeV with 25 ns beams, in both x and y
  - Stabilized with high chroma (Q'=20), high octupole strength (ΔQ=1.5e-3)
  - Caused mainly by electron cloud in quadrupoles
- Simulations predict more stability for HL-LHC

Instability simulations (450 GeV)
(e-cloud in the arc quadrupoles - SEY 1.3)



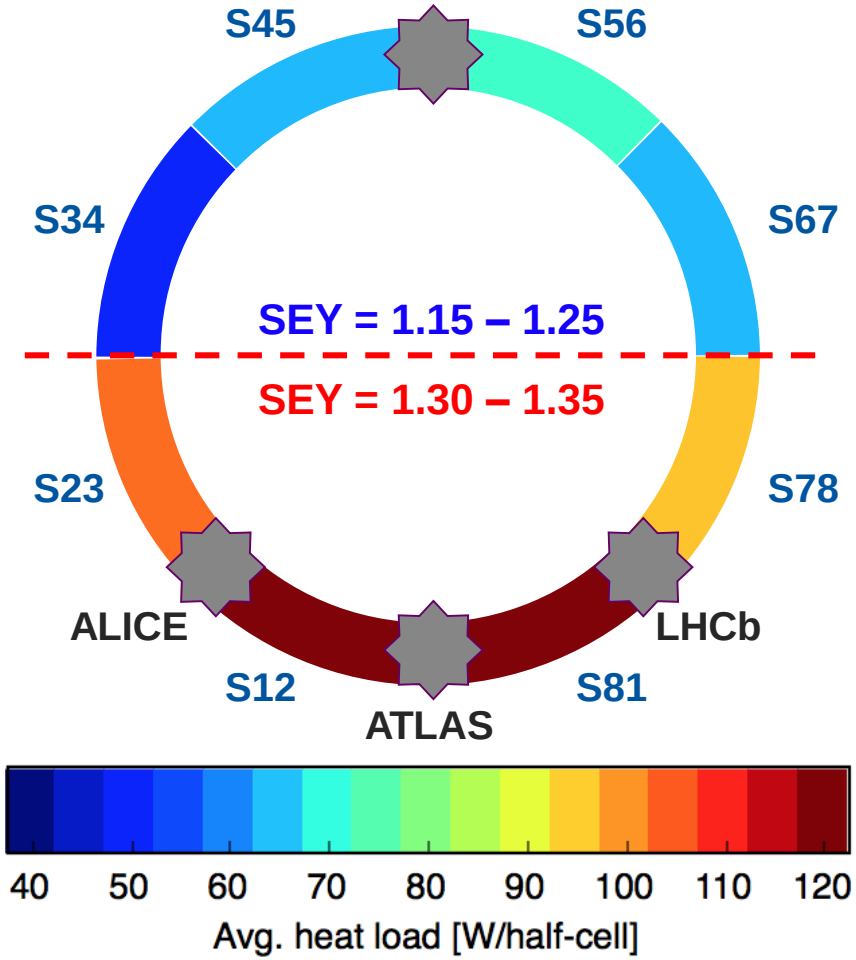
e-cloud buildup simulations



LHC beam stability

- Strong instabilities observed at 450 GeV with 25 ns beams, in both x and y
  - Stabilized with high chroma (Q'=20), high octupole strength (ΔQ=1.5e-3)
  - Caused mainly by electron cloud in quadrupoles
- Simulations predict more stability for HL-LHC (thanks to lower electron cloud)
- More electron cloud instabilities have been observed e.g. at flat top induced by decaying intensity and onset of central stripe in dipoles

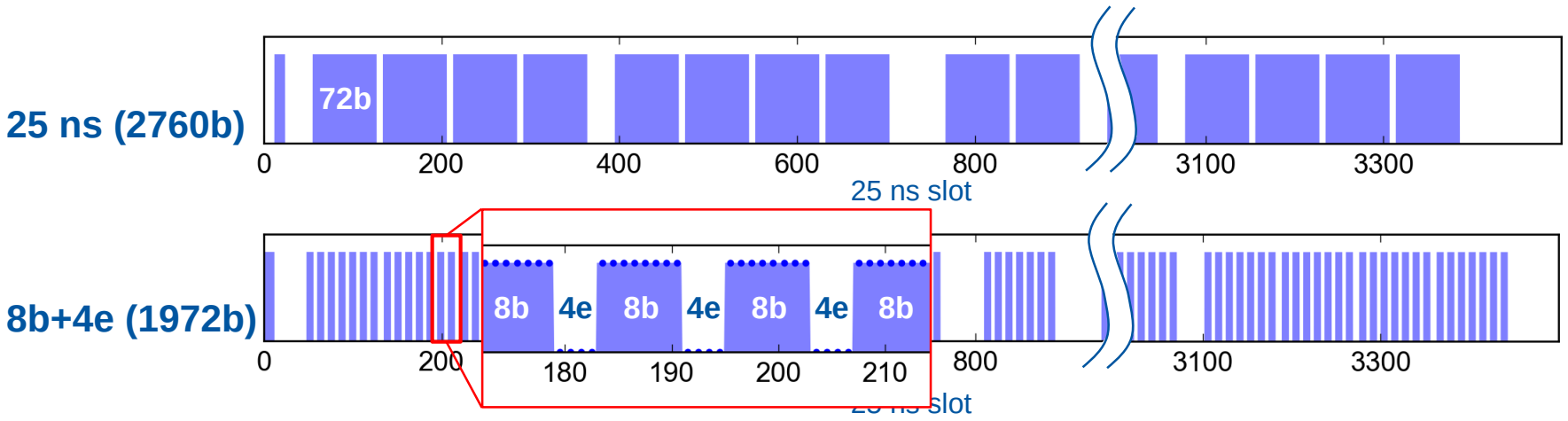
Electron cloud mitigation



- In general, **low SEY** after scrubbing is crucial to cure e-cloud instabilities
- Heat load measurements show that SEY may remain as high as 1.35 (in average) in some cells
  - Reason for high remaining SEY under close scrutiny to improve opening procedures in the future
- Critical sections like the new triplets will be a-C coated

Electron cloud mitigation

- If electron cloud remains a problem with HL-LHC operation, a last resort safety net is the filling scheme …



→ Pure 25 ns and 8b+4e can be combined to reach the maximum heat load

LHC beam stability: longitudinal

- Instabilities at injection → Theodoros' talk
  - Persistent oscillation, and even instability, from injection errors
  - Improved injection matching (voltage, energy)
- Controlled longitudinal emittance blow up during the ramp (target bunch length 1.1-1.2 ns) to avoid onset of instabilities → Helga's talk
- Possible instabilities at flat top if bunch length decreases below 0.9 ns

To wrap up and conclude

- LHC and its injectors set to major upgrades: **LIU, HL-LHC**
  - Injectors upgraded in 2019-2020, LIU beam commissioning in 2021-2024
  - LHC upgraded in 2024-2025 and HL-LHC era >2026
- Mitigation of beam instabilities is **key to goal performance in the LHC injectors**
  - PSB, PS → Mainly rely on active feedback systems
  - SPS → Impedance reduction, electron cloud suppression, longitudinal emittance blow up, enhanced Landau damping, optics change
- Preservation of **beam stability in LHC** → Avoid loss of Landau damping, operational scenarios, impedance reduction, electron cloud build up & instability scaling, low electron cloud filling pattern

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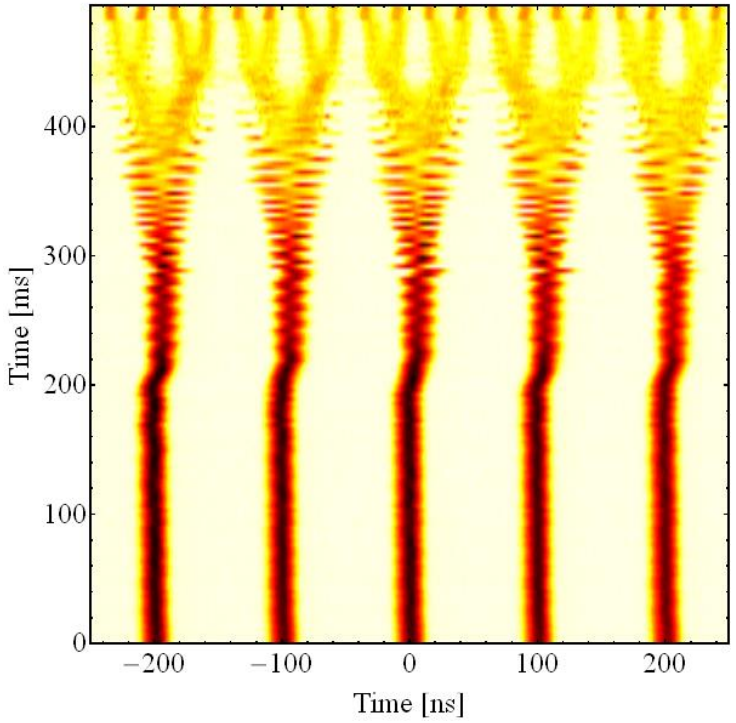
THANK YOU FOR YOUR ATTENTION

Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over Run 2 (2015 – 2018)

Feedback off ($N_b = 1.8 \cdot 10^{11}$ ppb)



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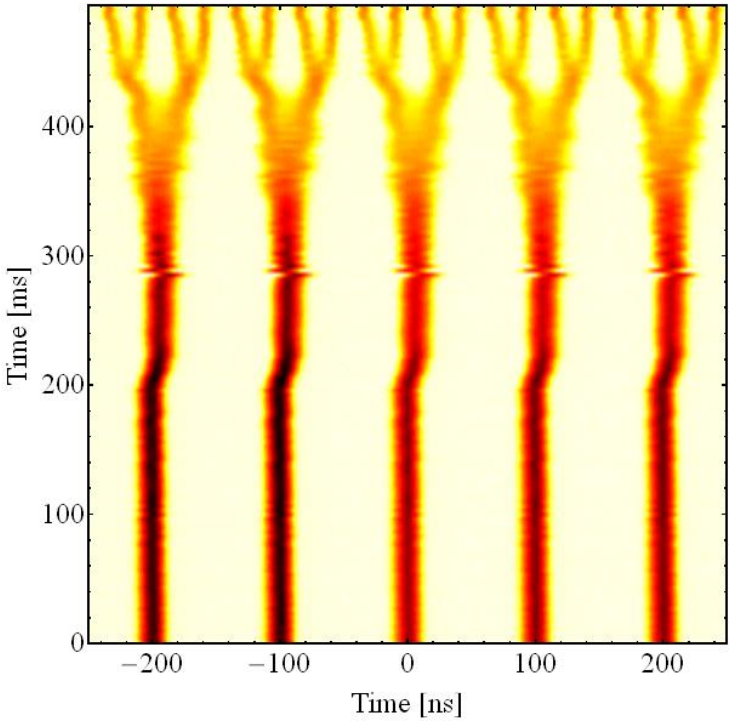
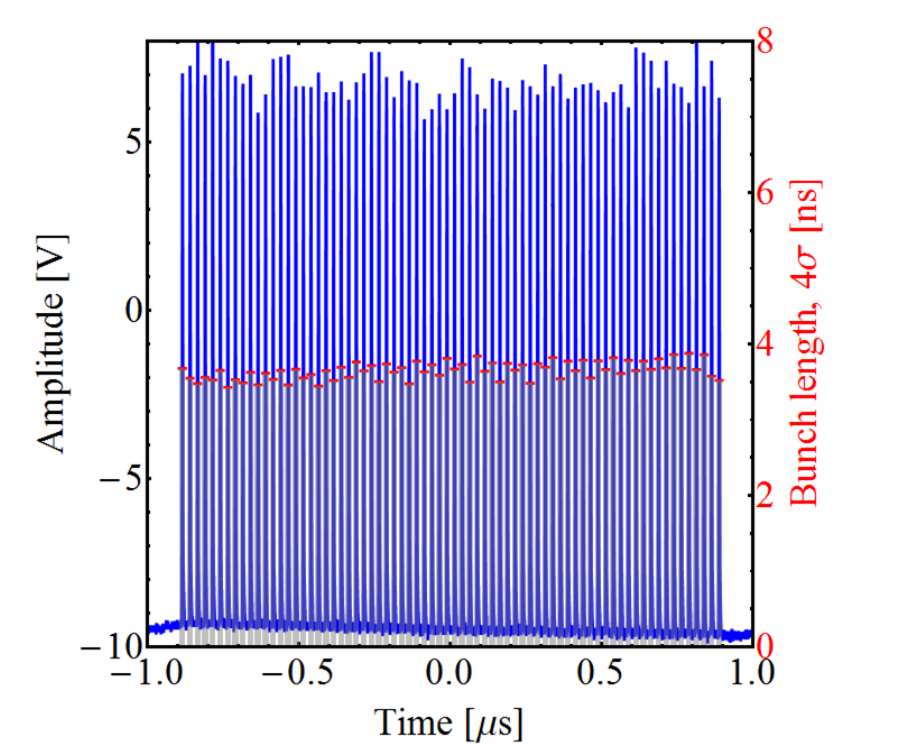
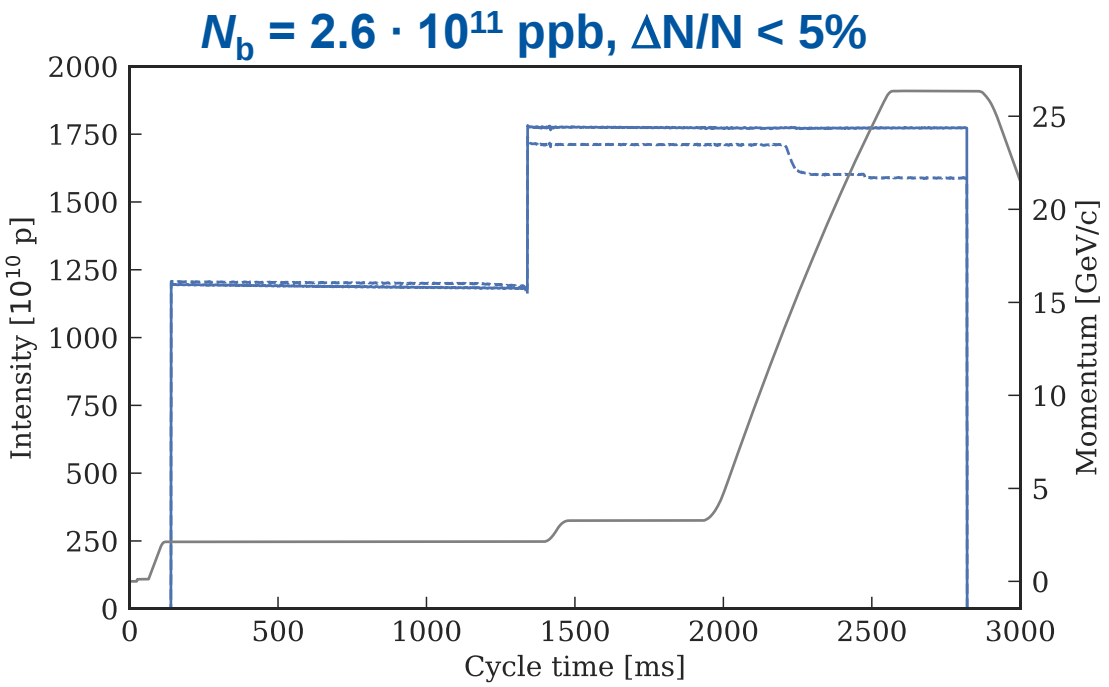


Mitigation of the PS longitudinal instability

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years
- With transverse optimisation, beam is now stable up to **2.6e11 p/b**





Timeline of the projects

Proton Runs

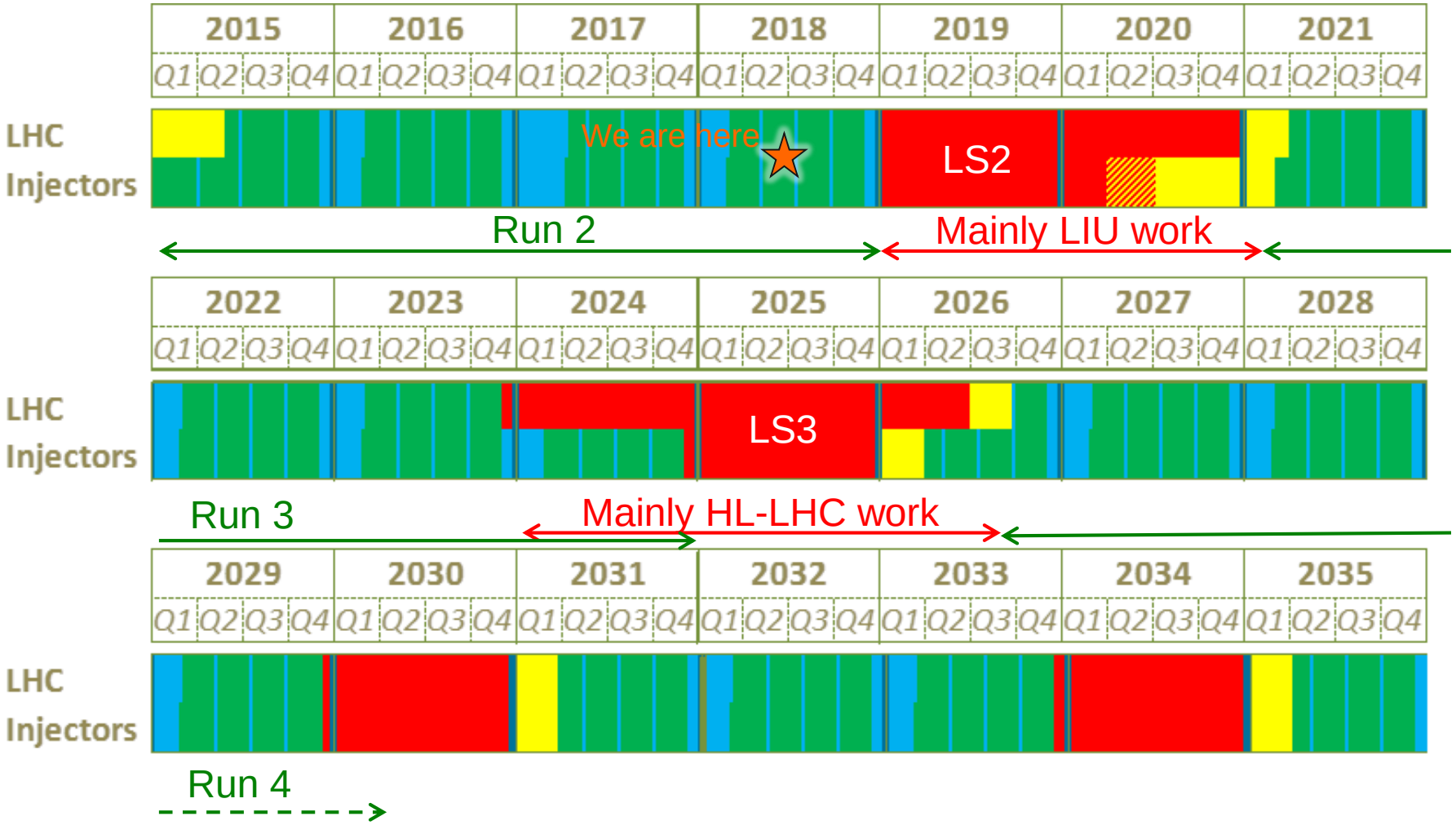
Technical Stops

Long Shutdowns

Beam Commissioning

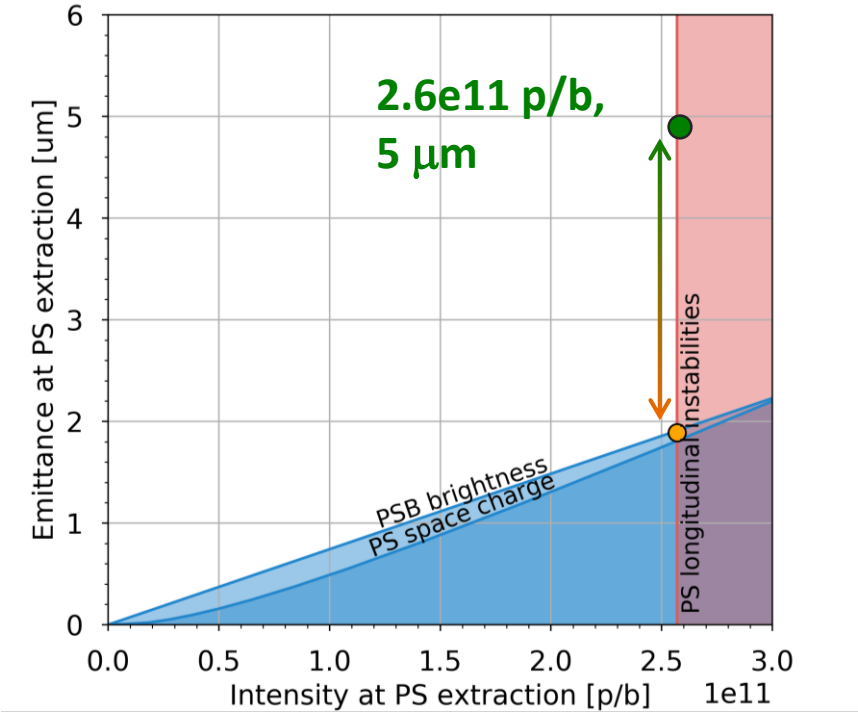
Run 3: LIU beam commissioning through the injector chain

Run 4: HL-LHC run with a period of 'luminosity learning'



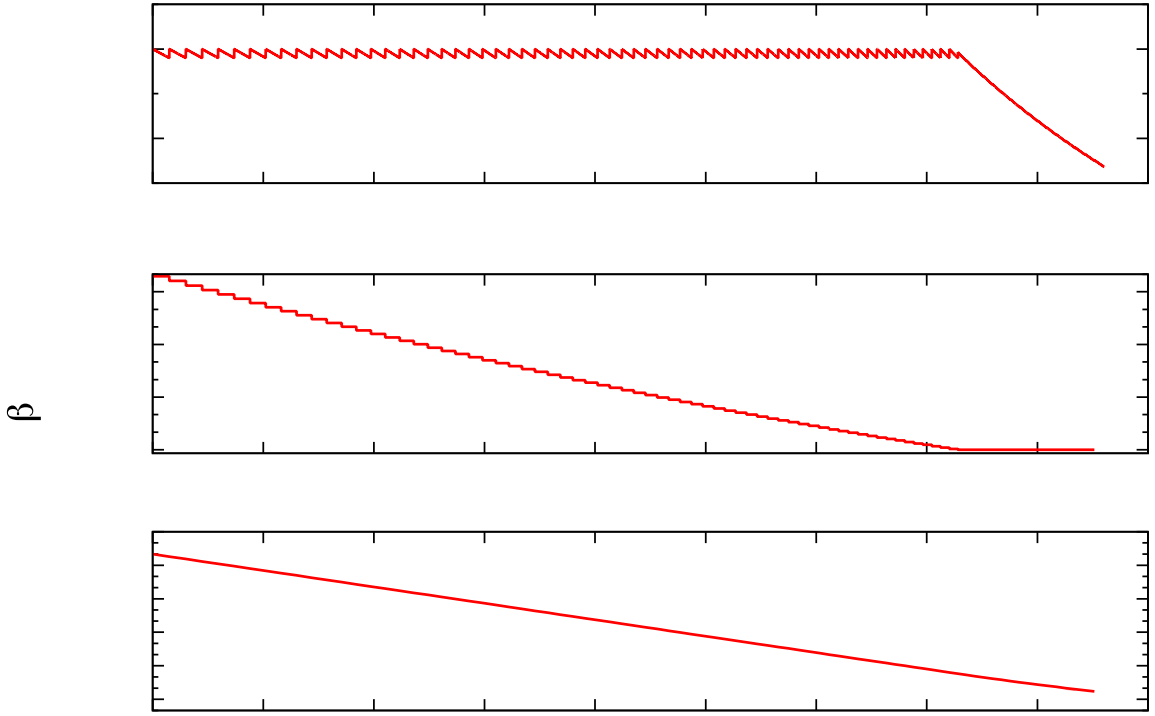
Lifting the PS intensity limitation

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years
- With transverse optimisation, beam is now stable up to **2.6e11 p/b**
- Goal in terms of **intensity out of the PS** reached!
- Brightness still pending Linac4 and space charge mitigation in PS



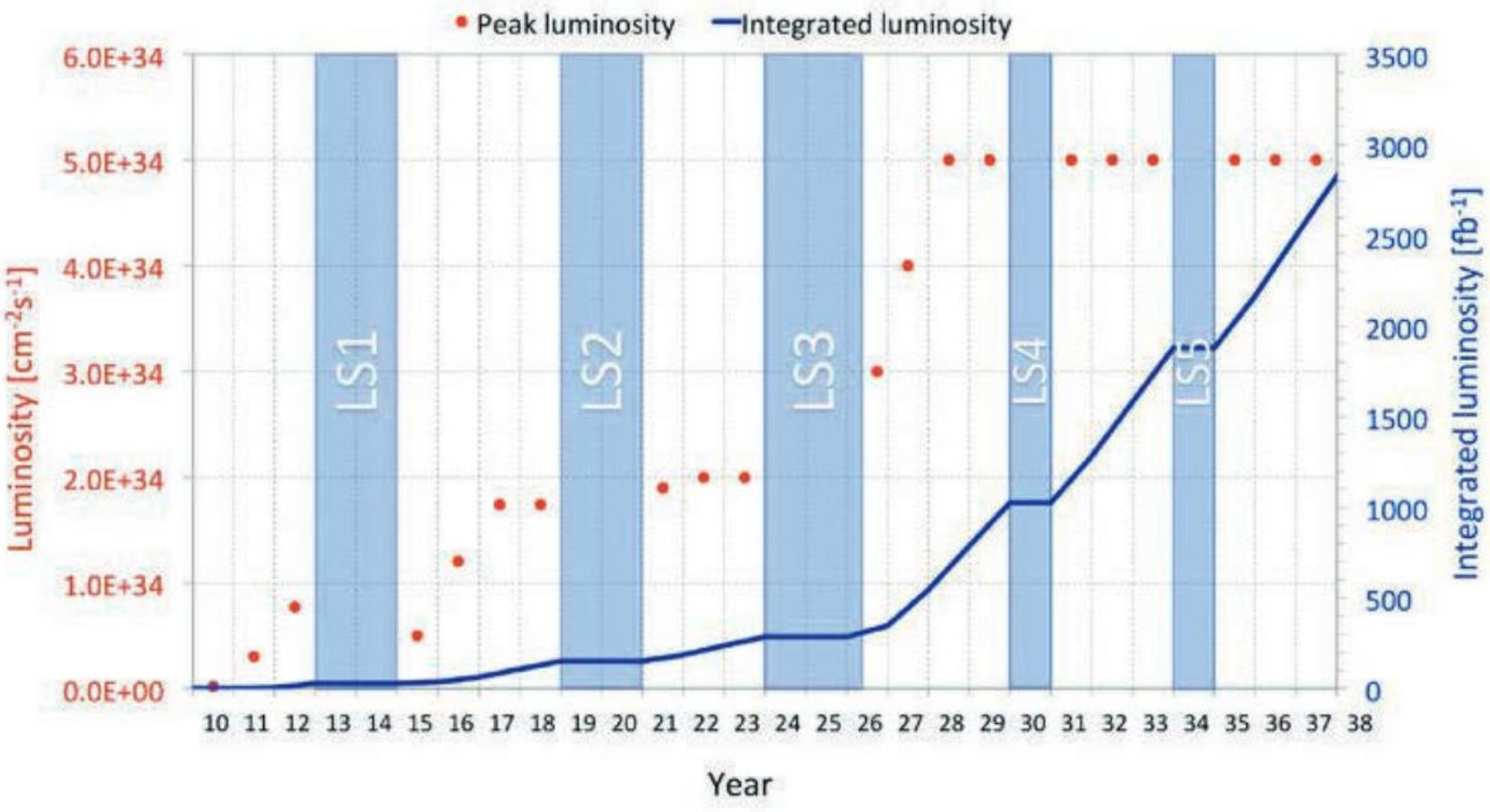
HL-LHC single particle dynamics

Simulated evolution of an **HL-LHC physics fill** with baseline parameters



- Strong effect of **linear and nonlinear errors** in IRs due to **large β** → **Low Dynamic Aperture** in absence of correction
- **Pre-computed corrections** from magnetic measurements needed even for basic optics measurements
- β^* levelling will require commissioning of a **large number of optical configurations** → Challenge for efficiency of the optics measurement and correction tools

Luminosity projection



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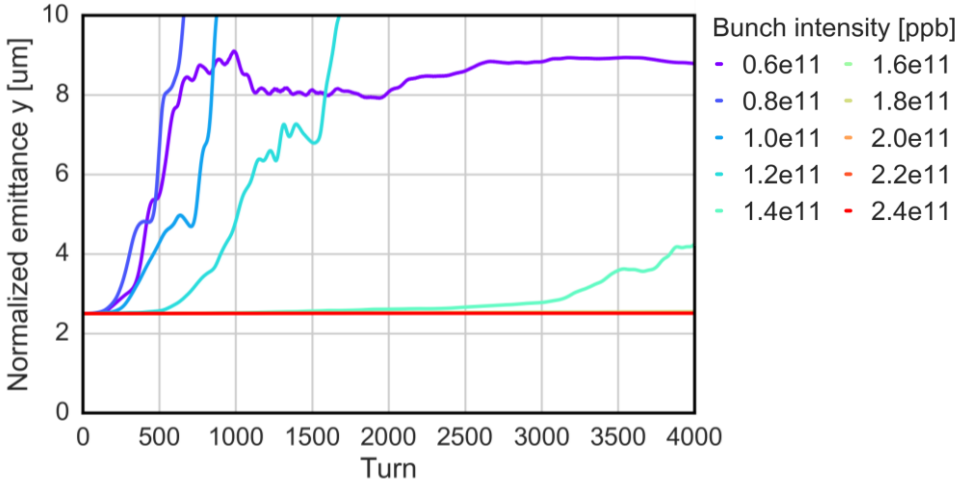
  - Caused mainly by electron cloud in quadrupoles
- Simulations predict more stability for HL-LHC

Instability simulations (450 GeV)
(e-cloud in the arc quadrupoles - SEY 1.3)



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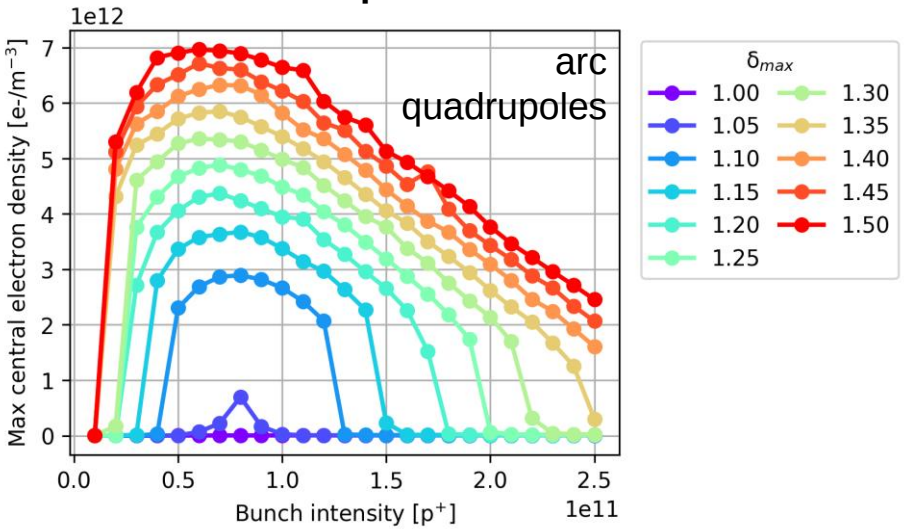
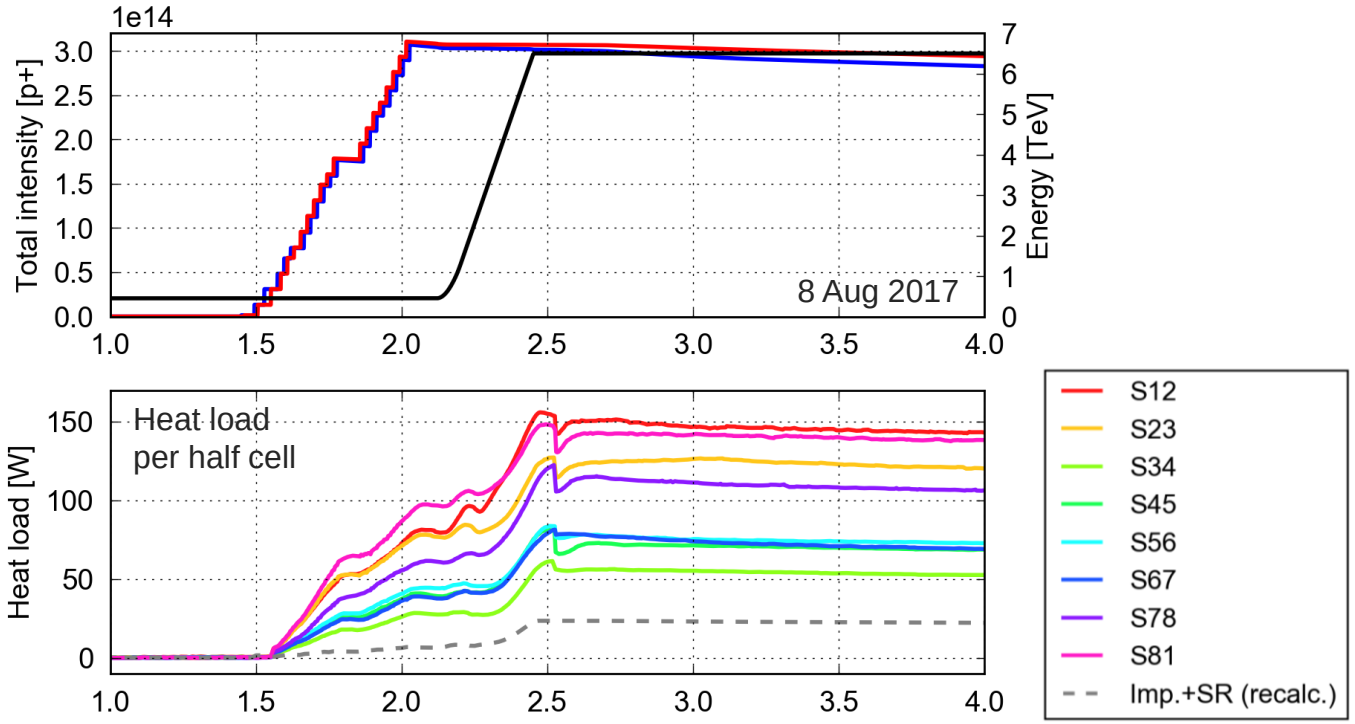


Beam induced heat load in LHC

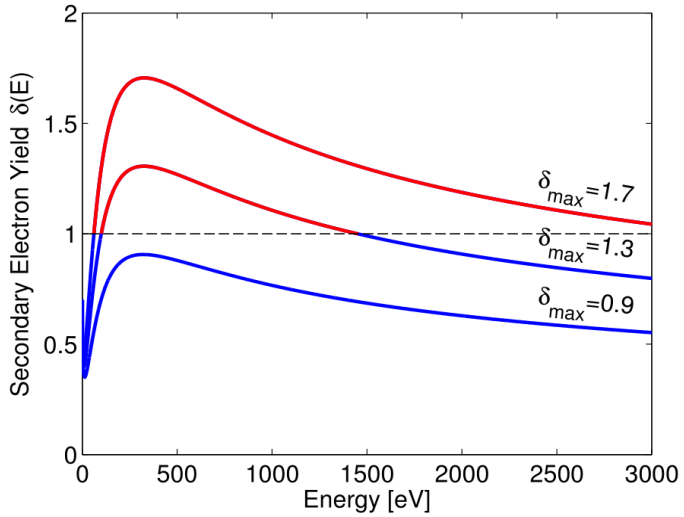


- High heat load on beam screen in cold regions (cryo limit 160 W/hc in the arcs)
  - With 25 ns beams
  - Much higher than calculation from impedance + synchrotron radiation
  - Different among arcs
- Most observations compatible with electron cloud, probably localised in some magnets (or even some parts of magnets)
  - Coating with a-C for triplet quadrupoles to decrease SEY

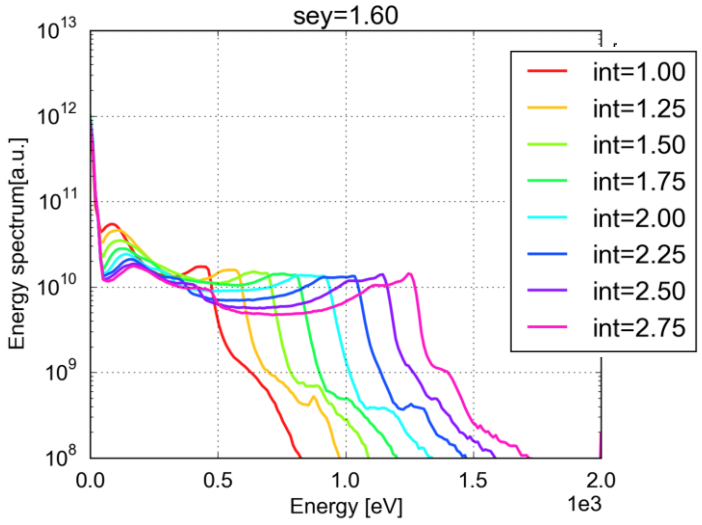
E-cloud build up with intensity

Underlying mechanism:

When the SEY decreases the **energy window for multipacting** becomes narrower

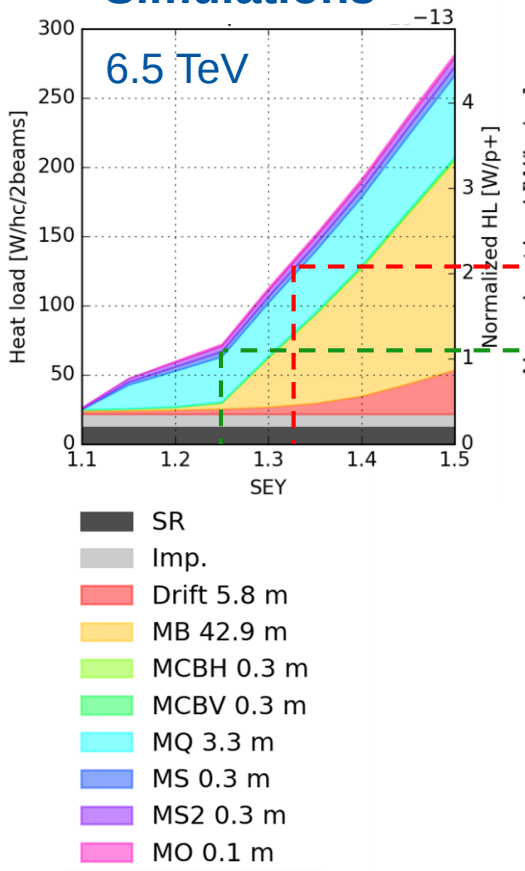


For high bunch intensity the e- spectrum drifts to higher energies and can move outside the most efficient region

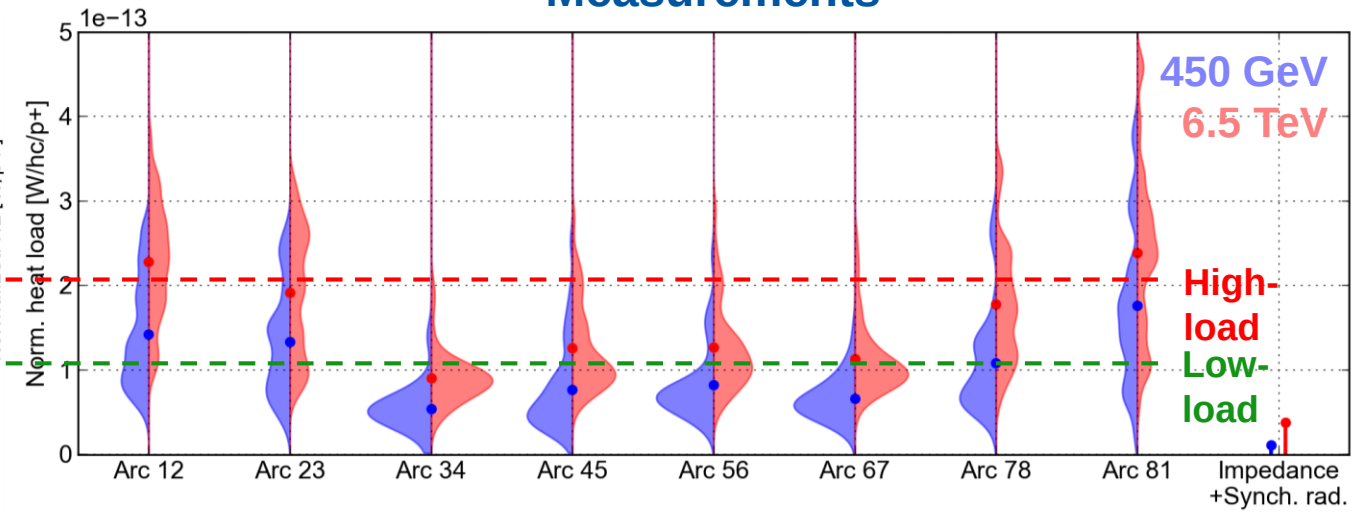


Inferring the average SEY

Simulations



Measurements



Fill	6674	6674
Started on	12 May 2018 02:35	12 May 2018 02:35
T_sample [h]	1.70	2.40
Energy [GeV]	450	6499
N_bunches (B1/B2)	2556/2556	2556/2556
Intensity (B1/B2) [p]	2.84e14/2.86e14	2.79e14/2.83e14
Bun.len. (B1/B2) [ns]	1.17/1.34	1.09/1.08
H.L. exp. imped. [W]	6.17	8.97
H.L. exp. synrad [W]	0.00	11.95
H.L. exp. imp.+SR [W/p+]	1.08e-14	3.72e-14
T_nobeam [h]	1.15	1.15

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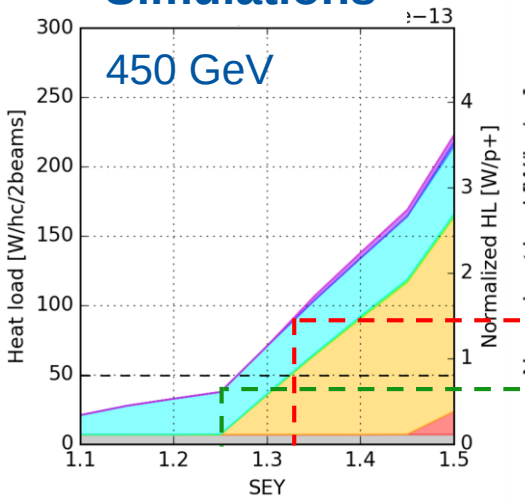

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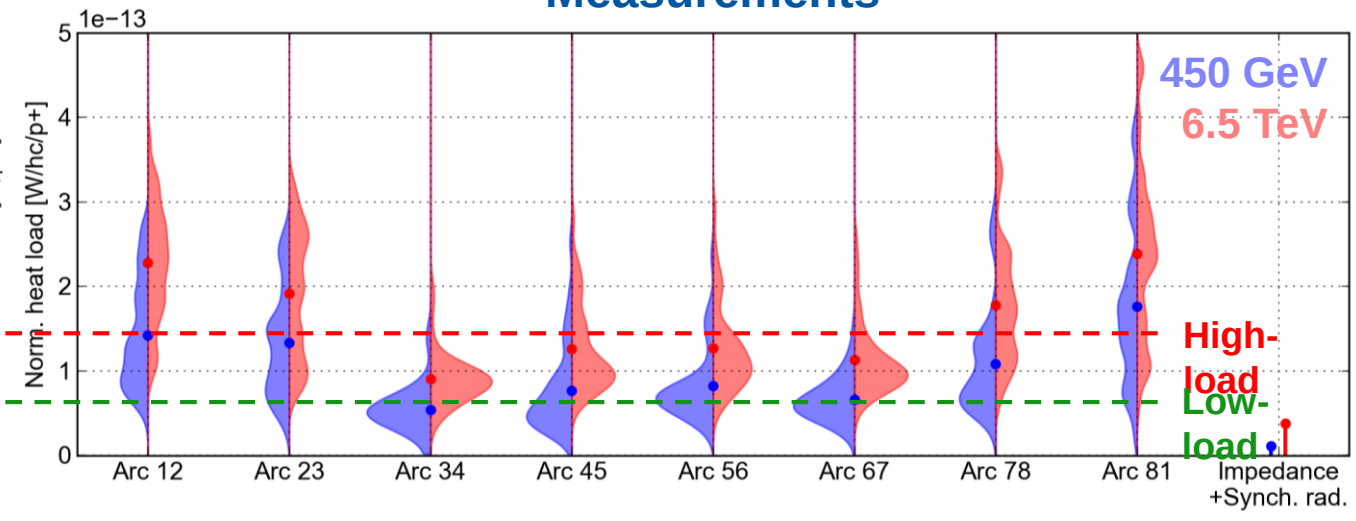

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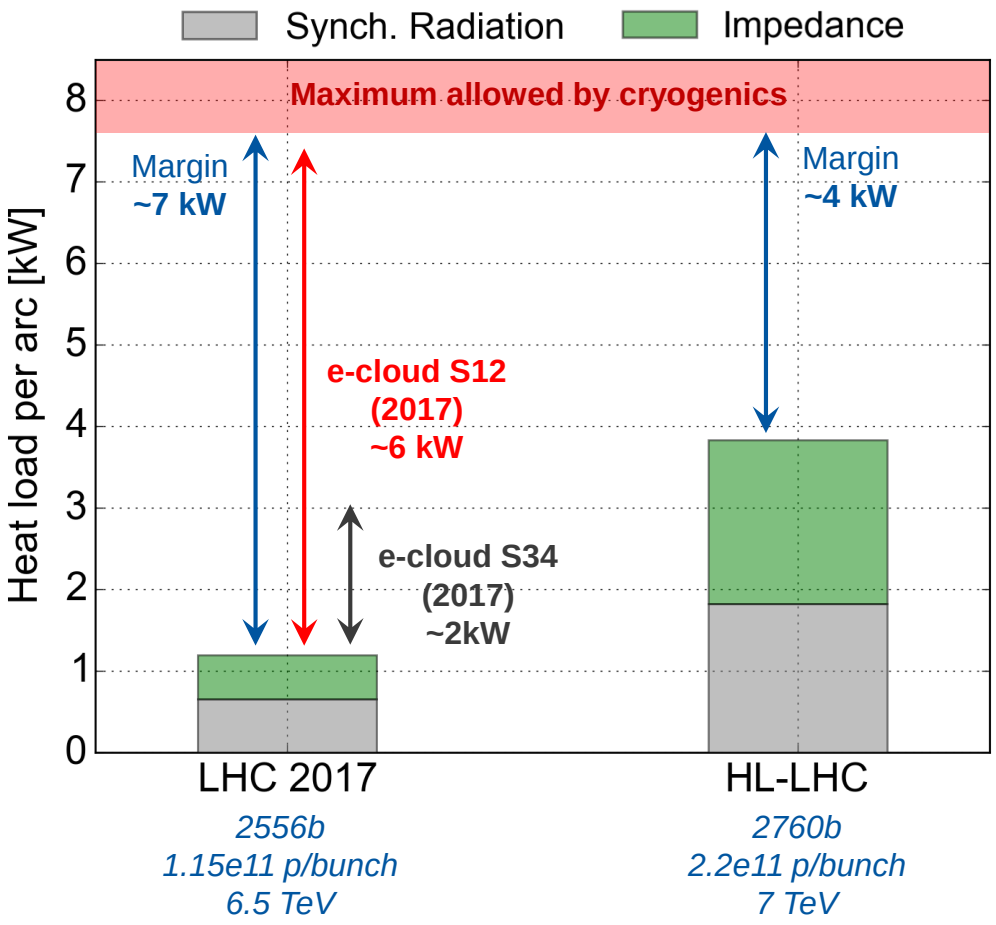
Beam induced heat load in LHC

- Two fold issue for HL-LHC
  - Less margin for cryostat with HL-LHC parameters (three-fold contribution from impedance and synchrotron radiation)
  - How does the additional load scale with bunch intensity? → We can make a prediction only if we assume it is caused by electron cloud



Some other challenges in LHC

- Beam-beam interaction
  - Head-on beam-beam tune shift limit (based on past experience) currently surpassed
  - Effect of the long-range → 6σ DA comfortably achieved during the whole levelling process, even including the chromaticity and octupole settings necessary for beam stability
- Incoherent emittance growth along the cycle
  - Larger than expected from Intra Beam Scattering (with margin), but impact de-facto mitigated by β^* levelling
  - Influence of noise → minimise sources by careful design of power converters, crab cavity controls, transverse damper upgrade (it might also benefit coherent instabilities)
- Beam halo active control for machine protection
  - Potentially large halo generation with HL-LHC beams, especially during commissioning
  - Cleaning techniques under study, option for Hollow Electron Lens

Some other challenges in LHC

- Beam-beam interaction
  - Head-on and long range (dynamic aperture during leveling), compensation techniques
- Incoherent emittance growth along the cycle
  - Sources to be understood, influence of noise
- Large beam halo generation with future beams
  - Halo active control for machine protection, cleaning techniques under consideration
- RF power and longitudinal stability
  - Power consumption for future injection voltage, transient beam loading, instabilities at flat bottom, longitudinal emittance blow up