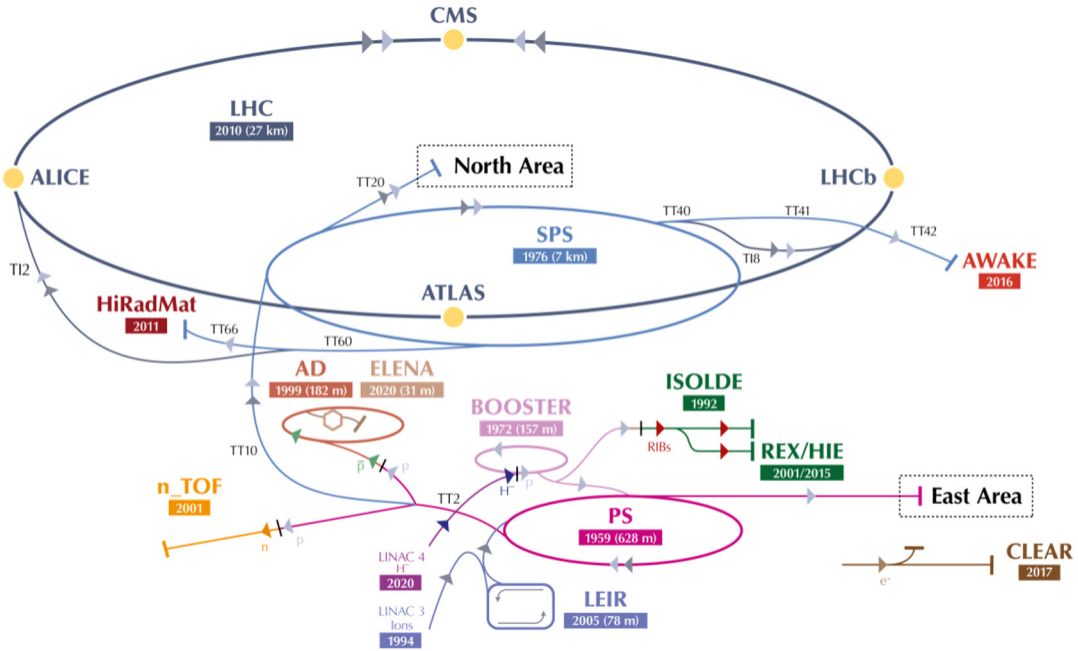
Achievements and Performance Prospects of the upgraded LHC Injectors

V. Kain, S. Albright, R. Alemany, M. E. Angoletta, F. Antoniou, T. Argyropoulos, F. Asvesta, B. Balhan, M. Barnes, D. Barrientos, H. Bartosik, P. Baudrenghien, G. Bellodi, N. Biancacci, A. Boccardi, J. Borburgh, C. Bracco, E. Carlier, J. Coupard, D. Cotte, H. Damerau, M. Fraser, A. Funken, G.P. di Giovanni, B. Goddard, G. Hagmann, K. Hanke, A. Huschauer, M. Jaussi, I. Karpov, T. Kovener, D. Kuchler, J.-B. Lallement, A. Lasheen, T. Levens, K. Li, A. Lombardi, N. Madysa, E. Mahner, M. Meddahi, L. Mether, B. Mikulec, J. Molendijk, E. Montesinos, D. Nisbet, F.-X. Nuiry, G. Papotti, K. Paraschou, F. Pedrosa, T. Prebibaj, S. Prodon, D. Quartullo E. Renner, F. Roncarolo, G. Rumolo, B. Salvant, M. Schenk, R. Scrivens, E. Shaposhnikova, P. Skowronski, A. Spierer, F. Tecker, D. Valuch, F. Velotti, R. Wegner, C. Zannini

IPAC'22 , Bangkok, Thailand, June 12-17 2022

CERN Accelerator Complex – LHC Injector Complex



+ Non-LHC Physics

ISOLDE: the radioactive ion beam facility
East Area: secondary beam lines fed by PS protons on 2 targets
nTOF: pulsed neutron source
AD/ELENA: low energy antiprotons
AWAKE: proton driven plasma wake field acceleration
HiRadMat: high intensity /brightness to material test facility
North Area: secondary beam lines fed by SPS protons/ions on 3 targets. Multiturn extraction (MTE) beam.

CERN's accelerator schedule for the years to come

- **Run 3: LHC started its final run**
  - 2022 - 2025
- **Next: installation of HL-LHC**
  - During Long Shutdown 3 (LS3)
- **One of main ingredients for HL-LHC: LHC Injector Upgrade (LIU)**
- **LIU installation 2019 – 2020 (LS2)**
  - **2021 first run of upgraded injector chain**

LHC Injector Upgrade for HL-LHC

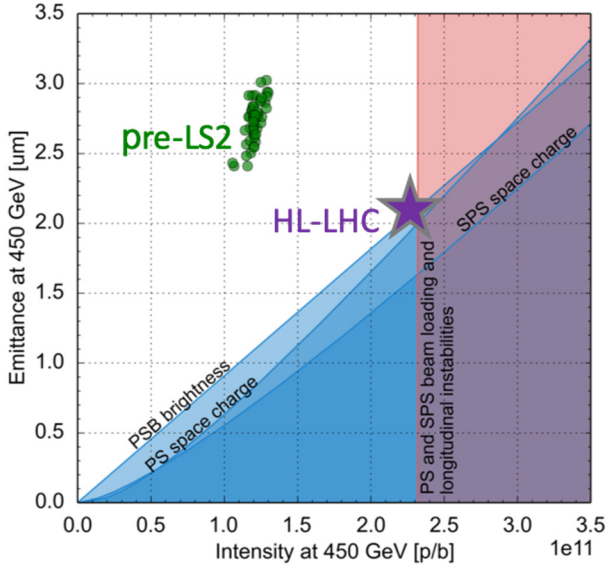
Increase intensity per p^+ bunch and brightness by factor 2

→ remove limitations along the chain in 2 year shutdown (2019–20)

HL-LHC parameters for protons and ions

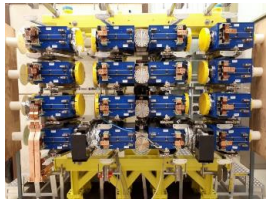
	N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	Bunches
HL-LHC	2.3	2.1	2760
Achieved	1.15	2.5	2760
	N (10^8 ions/b)	$\epsilon_{x,y}$ (μm)	Bunches
HL-LHC	1.9	1.5	1248
Achieved	2.0	1.5	648

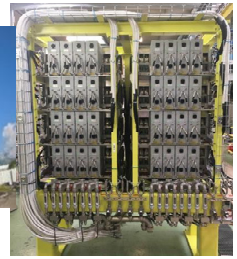
LHC injection: 288 bunches, 25 ns spacing

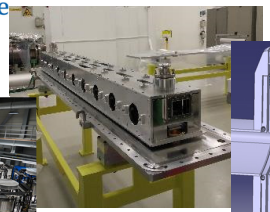


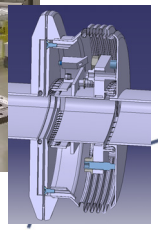
LIU in a nutshell

LHC Injectors Upgrade



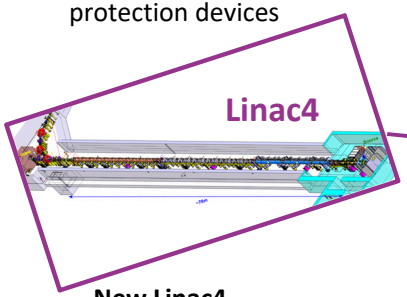






SPS
- Main **RF** system (200 MHz) upgrade
- Longitudinal **impedance** reduction & partial a-C coating
- New **beam dump,** collimators and protection devices

PSB
- **160 MeV** H^- charge exchange injection
- Acceleration to **2 GeV** with new main power supply and new RF systems



New Linac4
- Acceleration of 25 mA of H^- to **160 MeV**

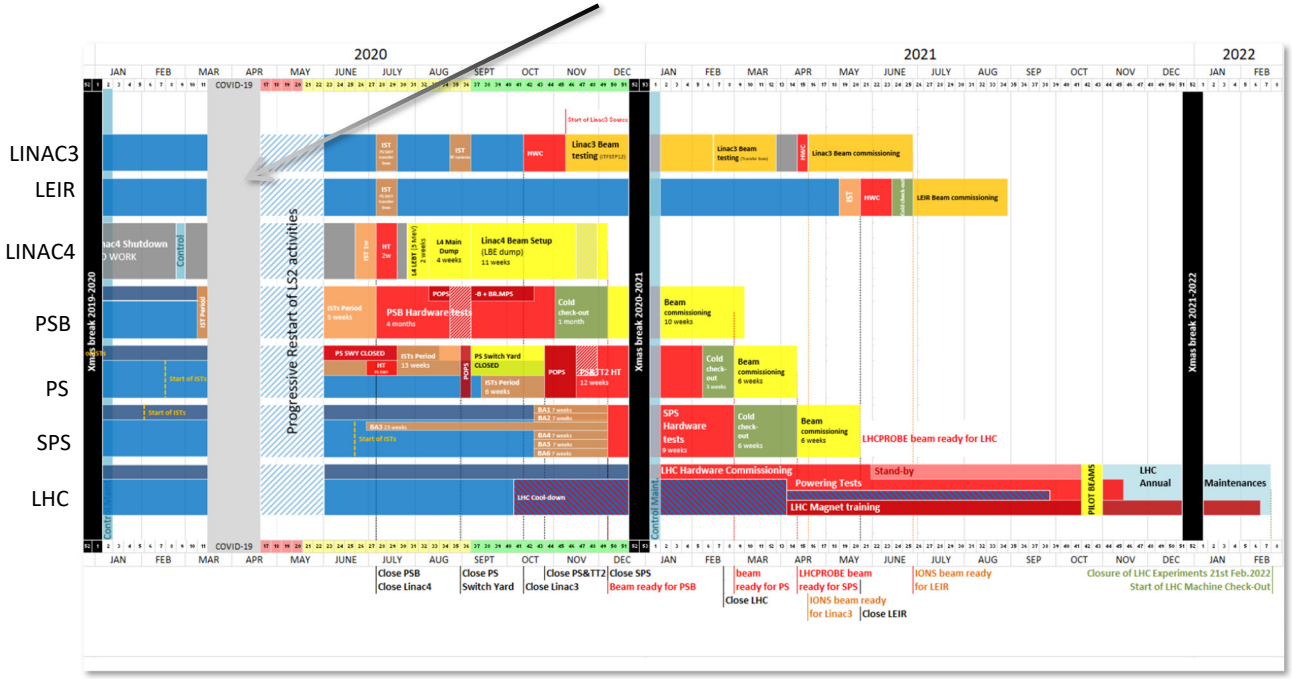
PS
- **2 GeV** injection
- New **RF** equipment including broad-band feedback

Achievements and Performance Prospects of the upgraded LHC Injectors

- **Strategy to**
  - Commission 6 accelerators post-LS2 and re-establish Fixed Target physics
  - Achieve:
    - 2018 parameters for LHC and Fixed Target beams
    - Demonstration of feasibility of momentum slip stacking in the SPS for Pb ions
- **Progress towards HL-LHC parameters**
- **Remaining Challenges during LHC Run 3**

Commissioning strategy 2020 - 2021

- 3-months shift due to COVID-19. No other changes to schedule



Prolonged commissioning period

Individual system tests (IST) end of shutdown

Hardware Commissioning from control room with operational tools

Standalone beam commissioning

First physics: ISOLDE 21 June

LHC: 2 weeks of pilot run in October

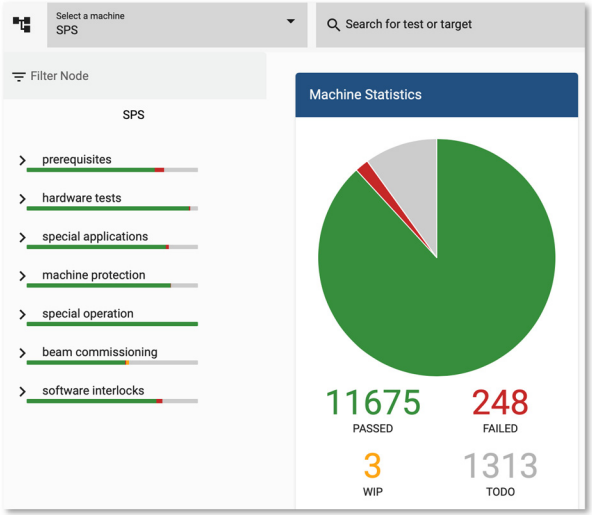
Commissioning coordination

- **Common coordination meeting for overall approach**
  - General controls infrastructure
  - Online check lists
  - Synergies
  - Common tools (reference measurement, performance tracking, …)

- **Dedicated commissioning teams per machine**
  - With dedicated coordination for beam dynamics, equipment,…

- **“Operational Readiness Analysis”**
  - Pre-beam reviews per machine to ensure consistency of approach
  - Identify missing components for operation or commissioning
  - Share expertise and experience and feed-forward to next machine

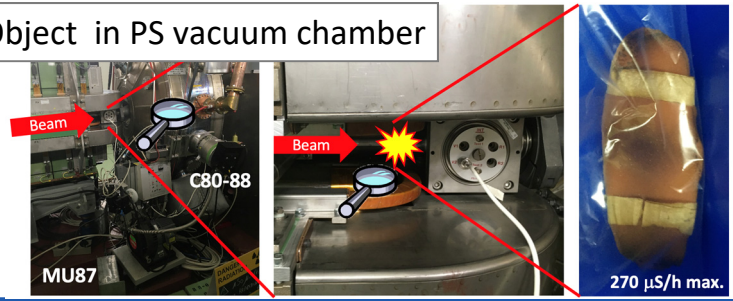
Online check lists



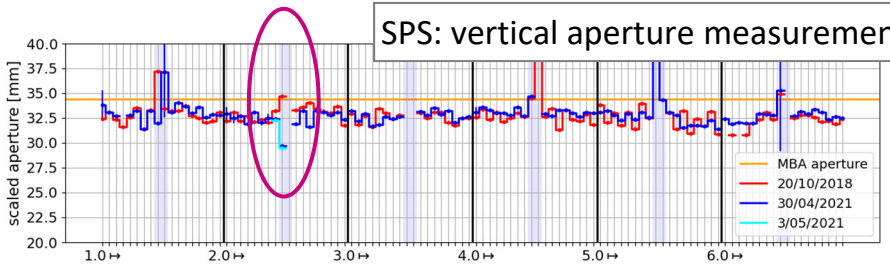
LIU commissioning strategy - Outcome

- **Overall result: re-commissioned all 6 accelerators and fulfilled 2021 program**
- **Lessons learned:**
  - **Software readiness** → global software coordinator and control room applications as part of system project definition
  - **Planning needs to include electronics, controls infrastructure**,… → in case of delays: clear priorities and potentially more frequent schedule updates
  - Build into design: capability for **easy aperture measurements** for every machine

Object in PS vacuum chamber



SPS: vertical aperture measurement

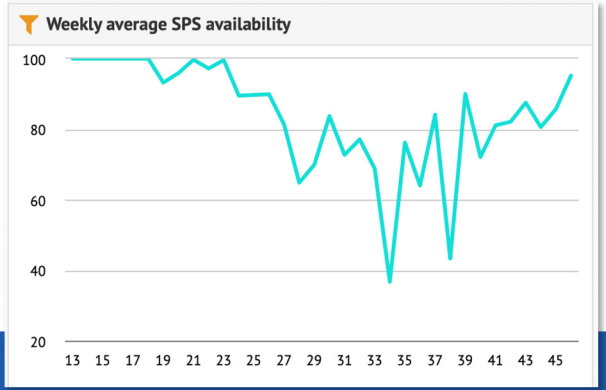


SPS: wrong transition piece in Long Straight Section 2

Availability – Hardware faults

- **Large number of systems installed during LS2 → long list of faults post-LS2**
  - Expected 'teething' effect: most faults were fixed rapidly
  - Some more serious persistent hardware problems (mainly in the SPS) limited the performance reach of injectors in 2021
  - Examples:
    - Non-radiation hard electronics in the tunnel for new SPS access system → upgraded during winter stop 2021-2022
    - Slow conditioning and many faults of 200 MHz RF cavities in the SPS: reduced available voltage

2623 faults in 2021
885.3 h of downtime



2021 availability of injectors

Accelerator	expected [%]	obtained 2021 [%]
LINAC4	95	97.4
PSB	90	94.5
PS	87	88.1
SPS	84	73.4

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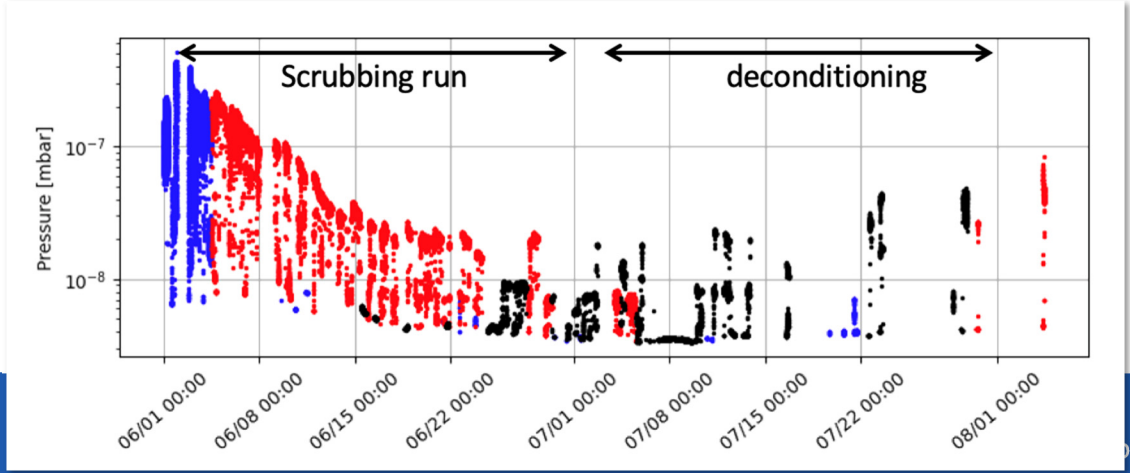
  - Expected ‘teething’ effect: most faults were fixed rapidly
  - Some more serious persistent hardware problems (mainly in the SPS) limited the performance reach of injectors in 2021
  - Examples:
    - Poor high voltage performance of 1 vertical dump kicker in the SPS → low vacuum thresholds; issue of vacuum deconditioning with time



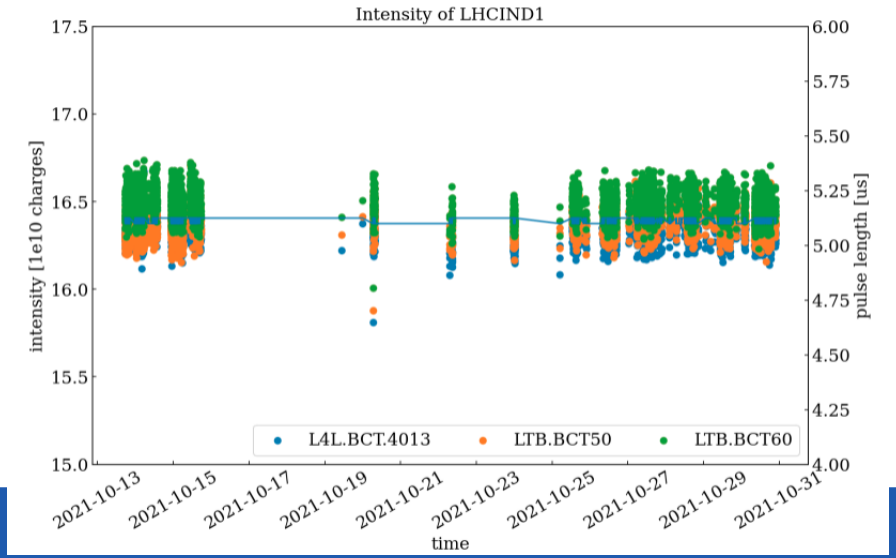
Limited overall performance with 25 ns beams in 2021

288 bunches of 1.2 x 10^{11} ppb for HiRadMat only possible with mini-scrubbing before each run

Progress towards HL-LHC parameters

Achieved 2021 performance in Linac4

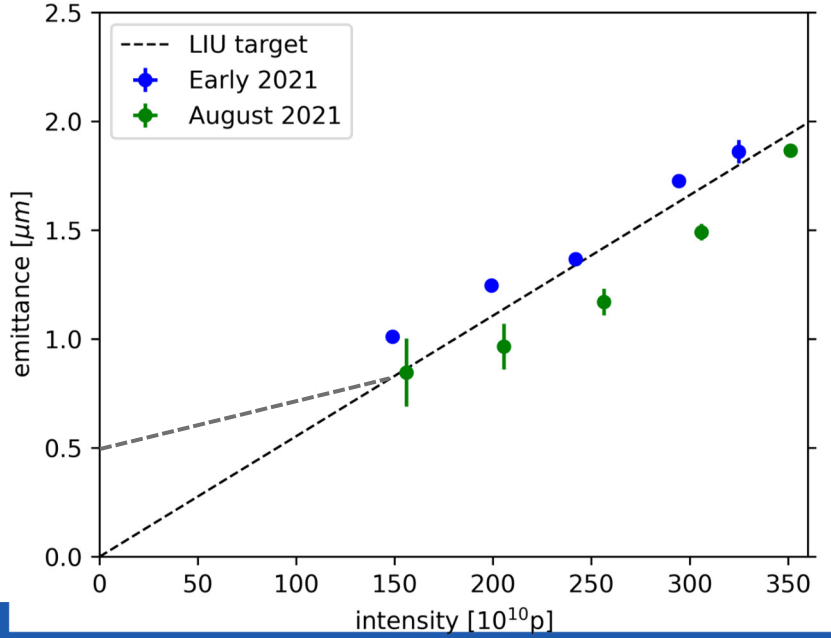
- **Remarkable performance of Linac4 during 2021**
  - No particular difficulties, **excellent RF stability**
  - Around **97% availability**
  - Example: LHC single bunch beam **intensity stability** ~0.4%
    - Very similar numbers for other LHC-type beams (~0.3 - 0.6%)



P. K. Skowronski *et al.*,
"Summary of the First Fully Operational Run of LINAC4 at CERN", MOPOST007

Achieved 2021 performance in the PSB

- **LHC 25 ns beam**
  - Already very close to the **LIU target** in the beginning of 2021 (**Early 2021**)
  - **Further improvement in brightness** by:
    - refining the **resonance compensation schemes**
    - **optimization** of the **working point** and
    - **optimization** of the injection chicane **beta beating correction** (**Aug. 2021**)
  - As expected, the emittance plateaus for lower intensities due to, e.g., scattering on the foil and injection errors
  - Now regularly exceeding LIU target

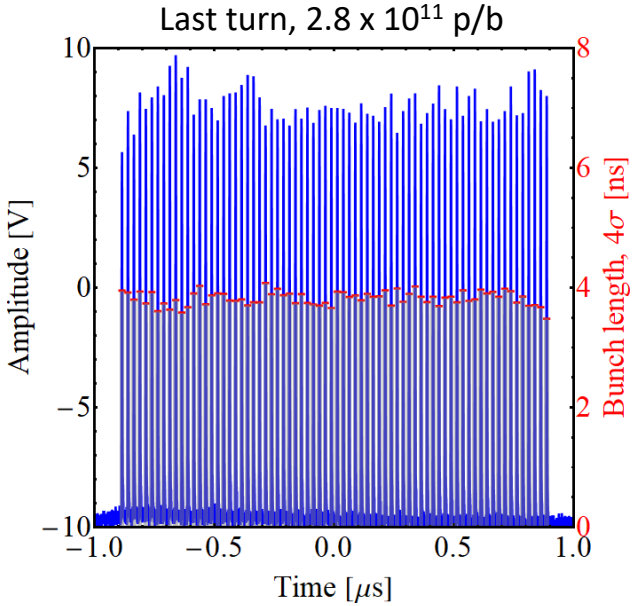


T. Prebibaj *et al.*, MOPOST007
S. Albright *et al.*, WEPOTK012
S. Albright *et al.*, WEPOTK013
D. Quartullo *et al.*, TUPOST006

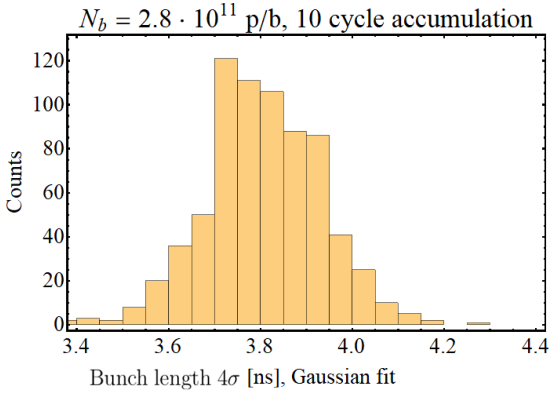
Achieved 2021 performance in the PS – standard 25 ns beam

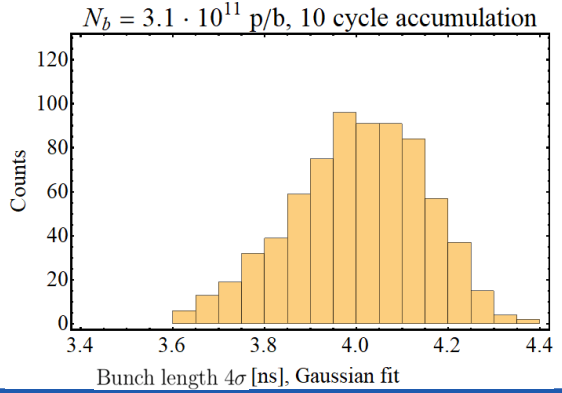
- **LIU bunch intensity of 2.6 x 10^{11} p/b recovered**
  - Little margin even up to 2.8 – 2.9 x 10^{11} p/b

- **At even higher intensity:**
  - Losses around transition crossing
  - Degradation of longitudinal parameters
  - Quadrupolar coupled-bunch instabilities during acceleration



H. Damerau *et al.*, WEPOTK046
S. Albright *et al.*, MOPOPT043



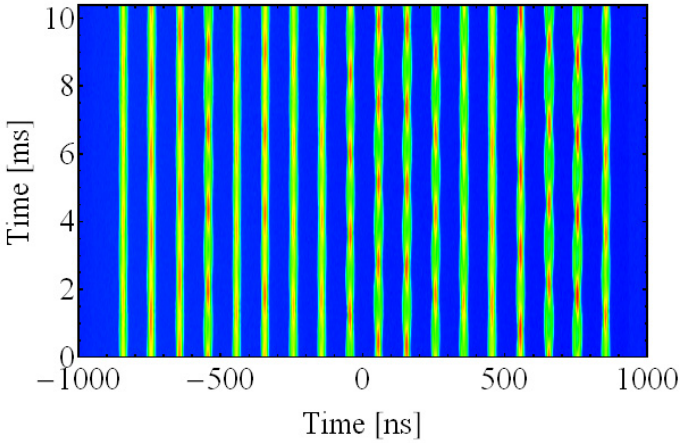


H. Damerau, A. Lasheen

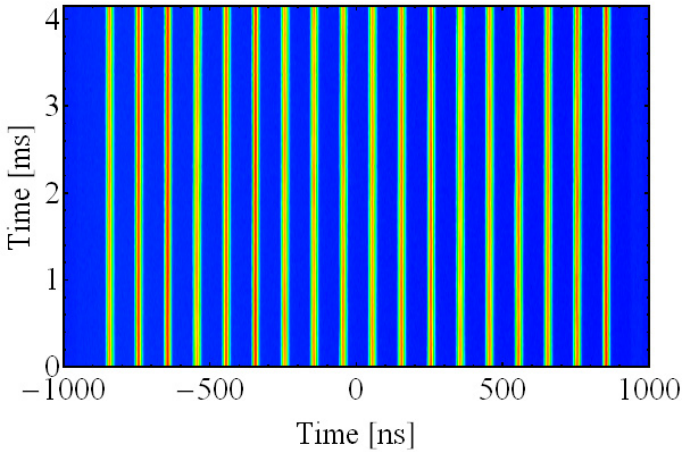
Achieved 2021 performance in the PS – standard 25 ns beam

- **Quadrupolar coupled-bunch instabilities at equivalent to ~3.1 · 10^{11} p/b at extraction**
  - **Higher threshold during acceleration** than before LS2, stronger instability at flat-top
  - **40 MHz RF system as Landau cavity** in bunch shortening mode (in phase)
    - Provides **sufficient damping even at highest intensities**

Single harmonic, 10 MHz

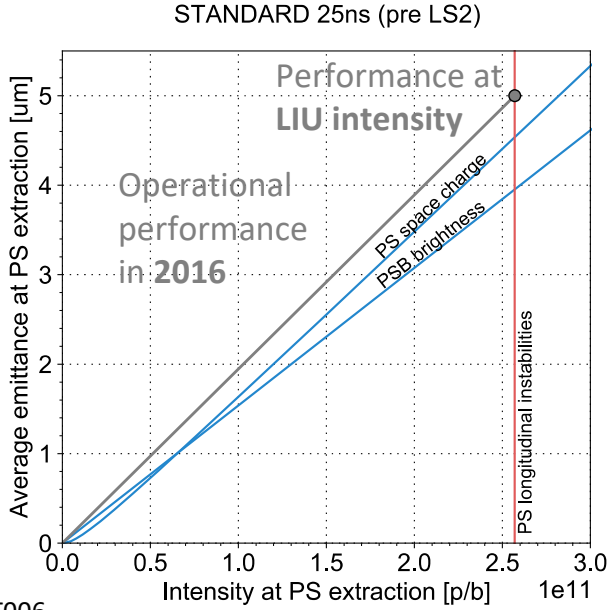


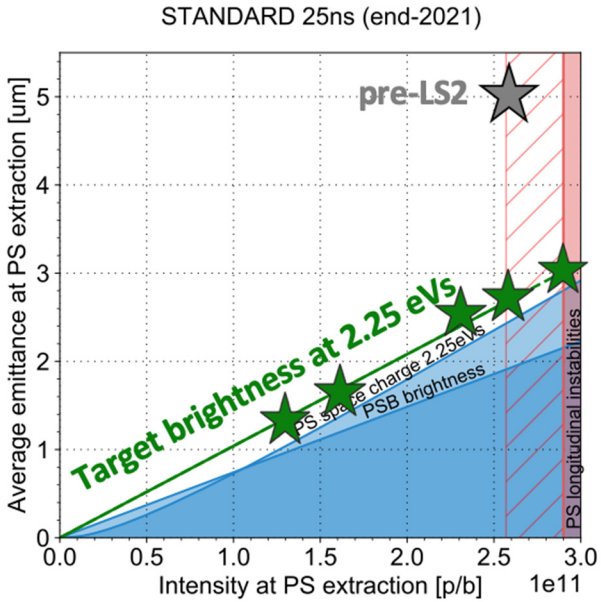
Bunch shortening mode
40/10 MHz voltage ratio 0.25



Achieved 2021 performance in the PS

- **Achievable brightness limited by space charge effects on the PS flat bottom**
  - Planned to follow a gradual brightness ramp-up
  - PSB to provide 2.0 – 2.25 eVs instead of HL-LHC 3 eVs in 2021
  - Emittance measurements follow constant brightness even at 2.9x10^{11} ppb

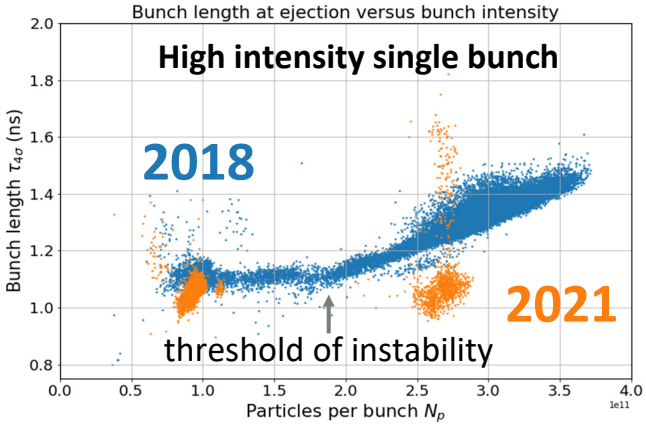


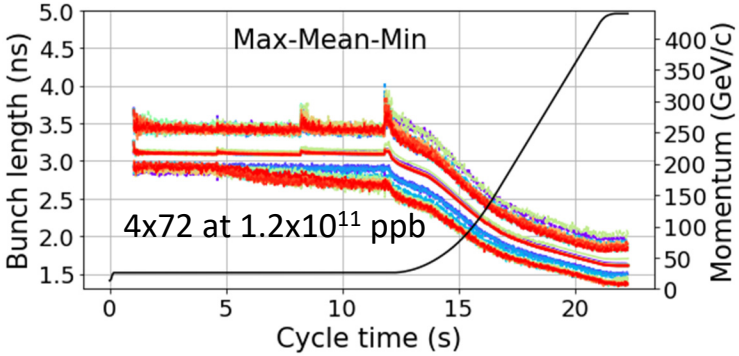


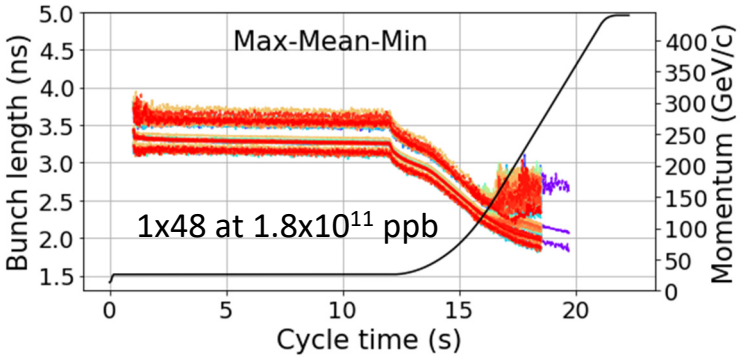
A.Huschauer *et al.*, "Beam Commissioning and Optimisation in the CERN Proton Synchrotron after the Upgrade of the LHC Injectors", MOPOST006

Achieved 2021 performance in the SPS

- **Success of impedance reduction campaign is confirmed by**
  - Suppression of microwave instability for high intensity single bunches
  - Measurements with long bunches (peak at 1.4 GHz disappeared)
- **Stable beams with 4x72b at 1.2x10^{11} ppb**
  - thanks to optimization of RF voltage programs (200 MHz + 800 MHz), blow-up settings, energy matching, and use of longitudinal damper
  - 2021: 1x48b at 1.8x10^{11} unstable during the ramp due to lack of RF power
- **Accelerated for the first time 1.6x10^{11} ppb in 72b to flat top**

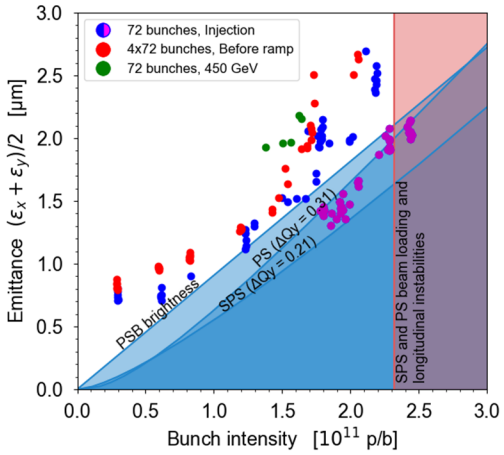


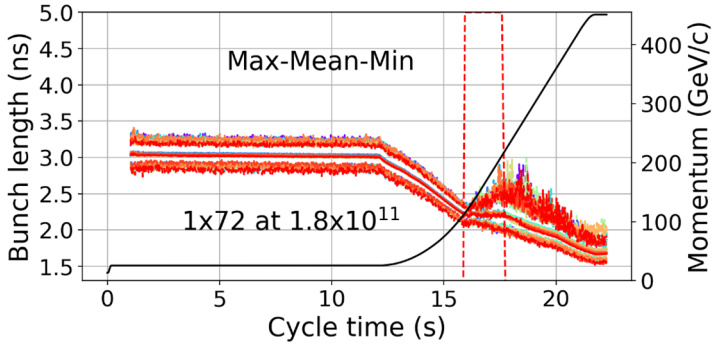




Achieved performance in the SPS since 2021

- **Replacement of problematic vertical dump kicker during winter stop 2021-2022**
  - → 4 week scrubbing run for conditioning early 2021
- **More RF voltage, better voltage calibration, optimized longitudinal blow-up**
  - 1.8 x 10^{11} p/b in 72 bunches @ 450 GeV with correct longitudinal parameters
  - Longitudinal emittance of 3 eVs between PSB and PS → brightness margin at injection in the SPS (purple dots in figure)





Remaining challenges:
- Vacuum spikes **horizontal dump kicker**
- Heating of **injection kicker** limits study time

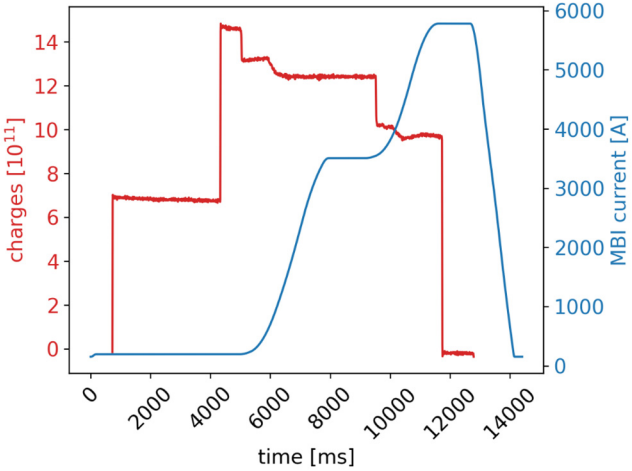
LHC required injection bunch length (1.65 ns) @ exit of injectors **achieved**

A. Spierer *et al.*, TUPOST021
G. Hagmann *et al.*, TUPOST023
I. Karpov *et al.*, WEPOMS008
D. Quartullo *et al.*, TUPOST005
N. Bruchon *et al.*, TUPOST042
D. Quartullo *et al.*, WEPOMS009

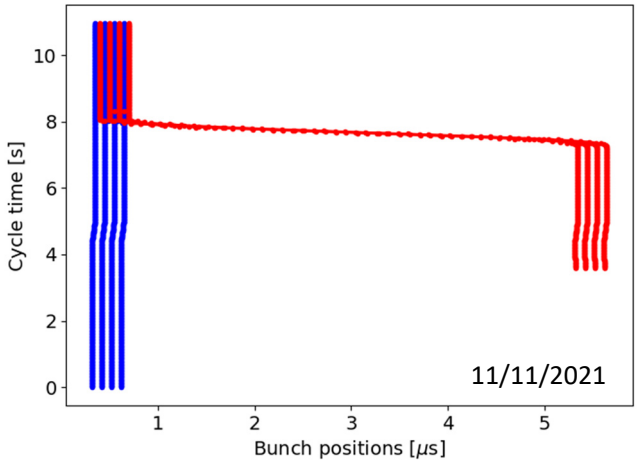
Pb ion beams

Achieved 2021 performance in the SPS

- **HL-LHC bunch parameters already achieved in 2018**
  - But with 100 ns spacing. Outstanding: 50 ns bunch spacing with slip stacking
- **Major 2021 achievement in SPS → beam commissioning of slip stacking RF gymnastics**



2 x 4 bunches @ 100 ns → 8 bunches @ 50 ns



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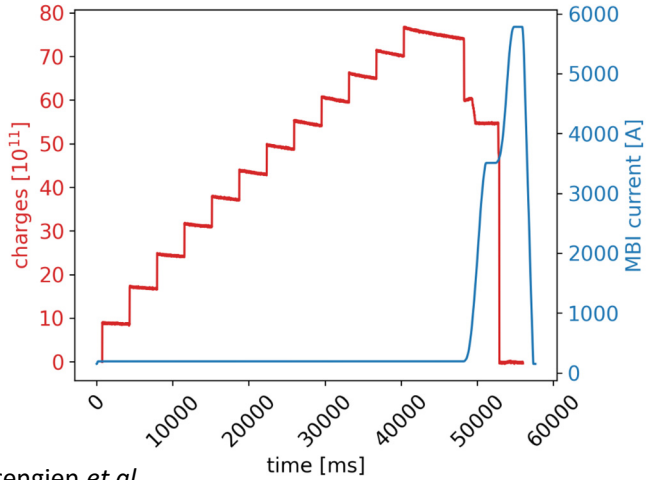


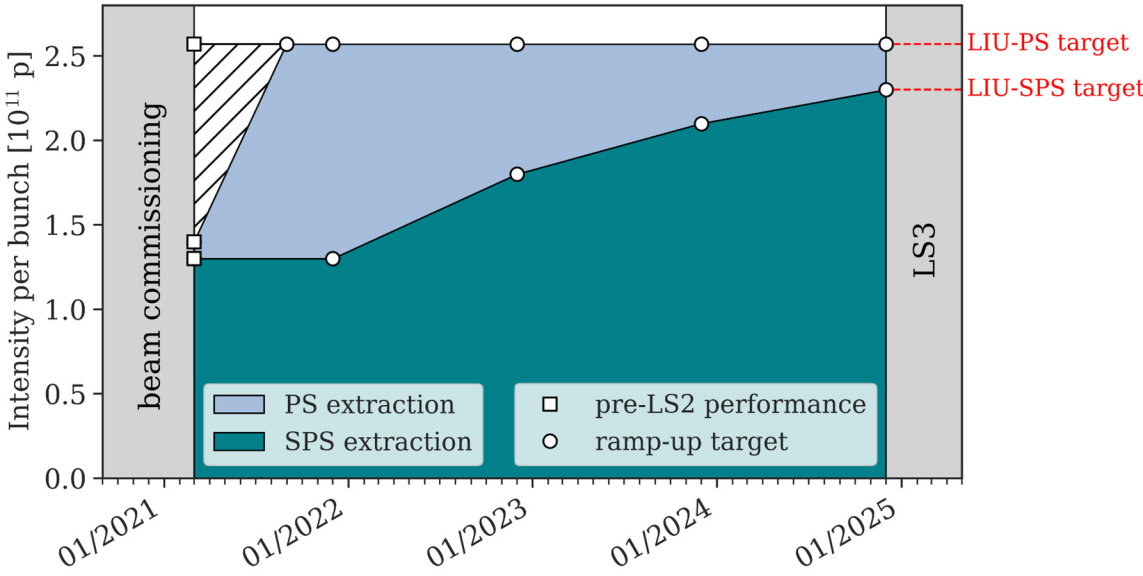
P. Baudhrengien *et al.*,
"The CERN SPS Low Level RF: Lead Ions Acceleration", TUPOST022

P. Baudrenghien et al.

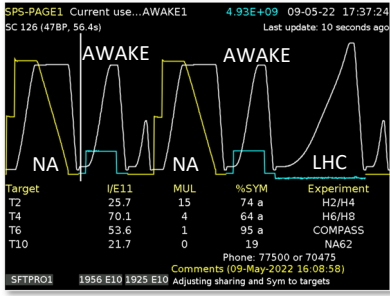
Remaining challenges during Run 3

Parameter ramp-up during LHC Run 3

- **Remaining challenges for HL-LHC parameters from the injectors are in the SPS**
  - Working point @ injection, horizontal dump kicker vacuum behavior, transmission, reproducibility,…
- **Defined goals for longitudinal and transverse emittance per year**
  - E.g. 2 eVs for PSB-PS transfer in 2021
- **Expect to provide trains with 1.8 x 10^{11} p/b in 288 bunches at SPS extraction as of 2023**
- **Ions 2022: HL-LHC performance**

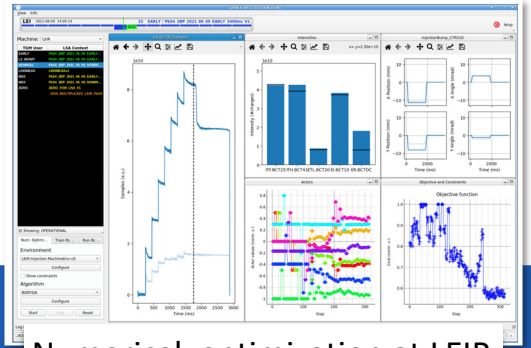


Efficiency and Reproducibility Challenges



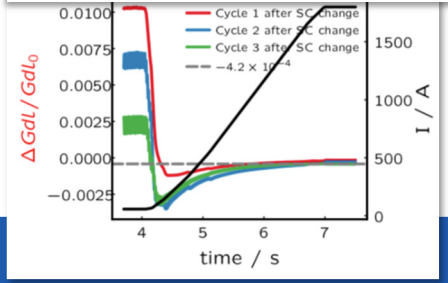
- **Shorten LHC turn-around time, with least impact on other physics**
  - Dedicated “LHC filling”
- **LHC beam to be re-tuned whenever taken**
- **→ global effort to increase efficiency and stability of CERN accelerator complex**
- **Machine learning and numerical optimization as toolkit to**
  - Replace manual tuning
  - Model eddy currents, hysteresis and other effects

F. Velotti *et al.*, TUPOST045
N. Madysa *et al.*, TUPOST040

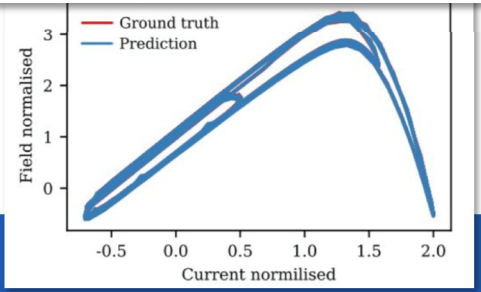


Numerical optimization at LEIR

main quadrupole field change



Predicting field as function of history



Conclusion

- **The equipment and software upgrade of the LHC injector chain to reach HL-LHC parameters was successfully completed in 2019-2020**

- **Goal of the 2021 run was to re-establish pre-shutdown LHC and fixed target physics parameters**
  - PSB and PS have already reached HL-LHC parameters

- **Remaining challenges are now in the SPS**
  - Commissioning limited by slow conditioning of the 200 MHz cavities and various kicker systems

- **Reproducibility and efficiency remain a concern with beams at edge of stability**
  - Automation and machine learning algorithms being developed to optimize performance