CERN

Performance with the Upgraded LHC Injectors

Malika Meddahi and Giovanni Rumolo

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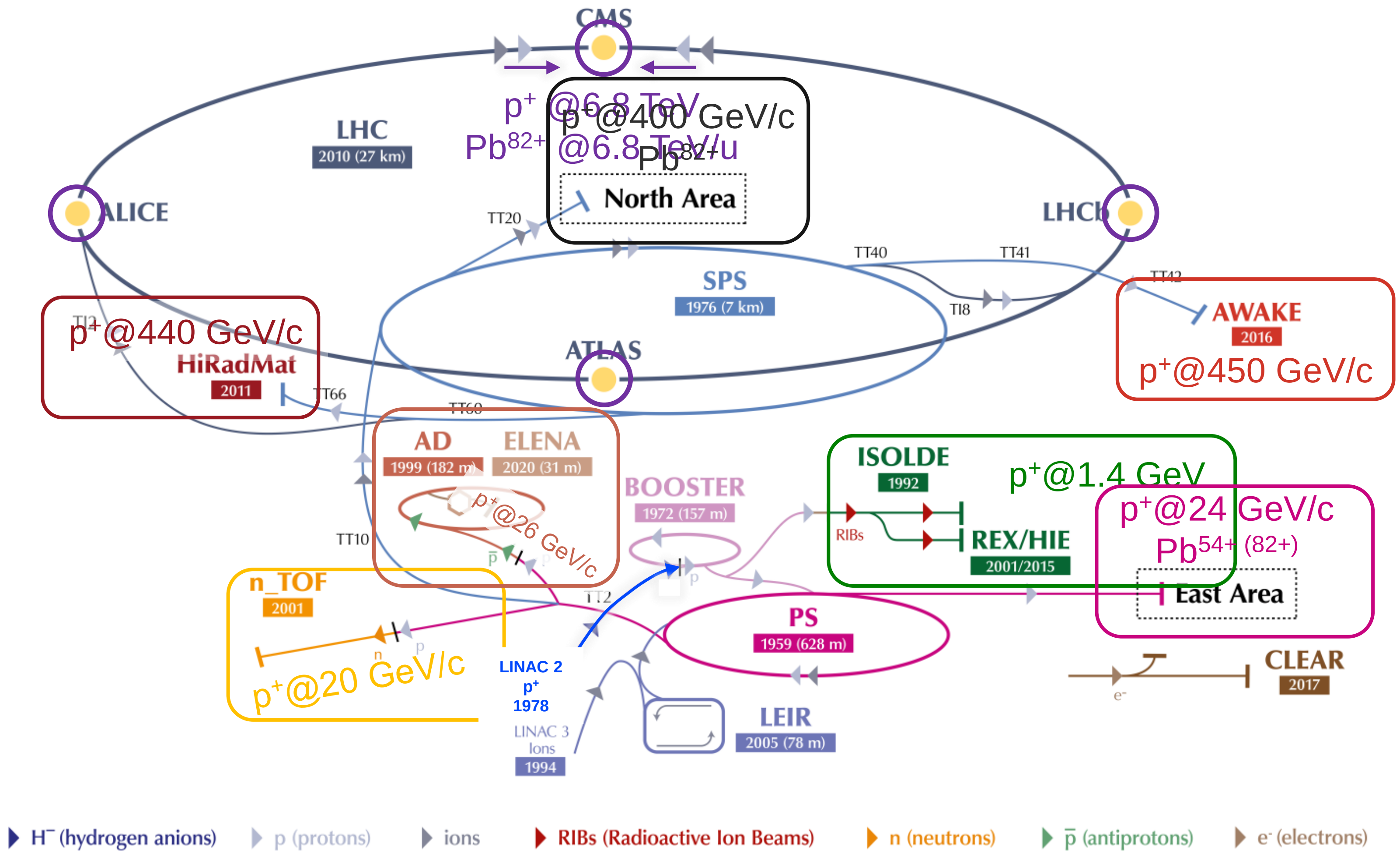
Outline

LHC Injectors Upgrade

- The CERN injectors complex and its recent upgrade
  - Overview accelerator complex
  - Goals and rationale of the LHC Injectors Upgrade (LIU) project
  - Organisation, execution and legacy of LIU
- Beam performance ramp-up after LIU installation
  - Beam commissioning, tuning and operational use
  - Achievements, by-products and ongoing studies
- Summary and outlook

The CERN accelerator complex

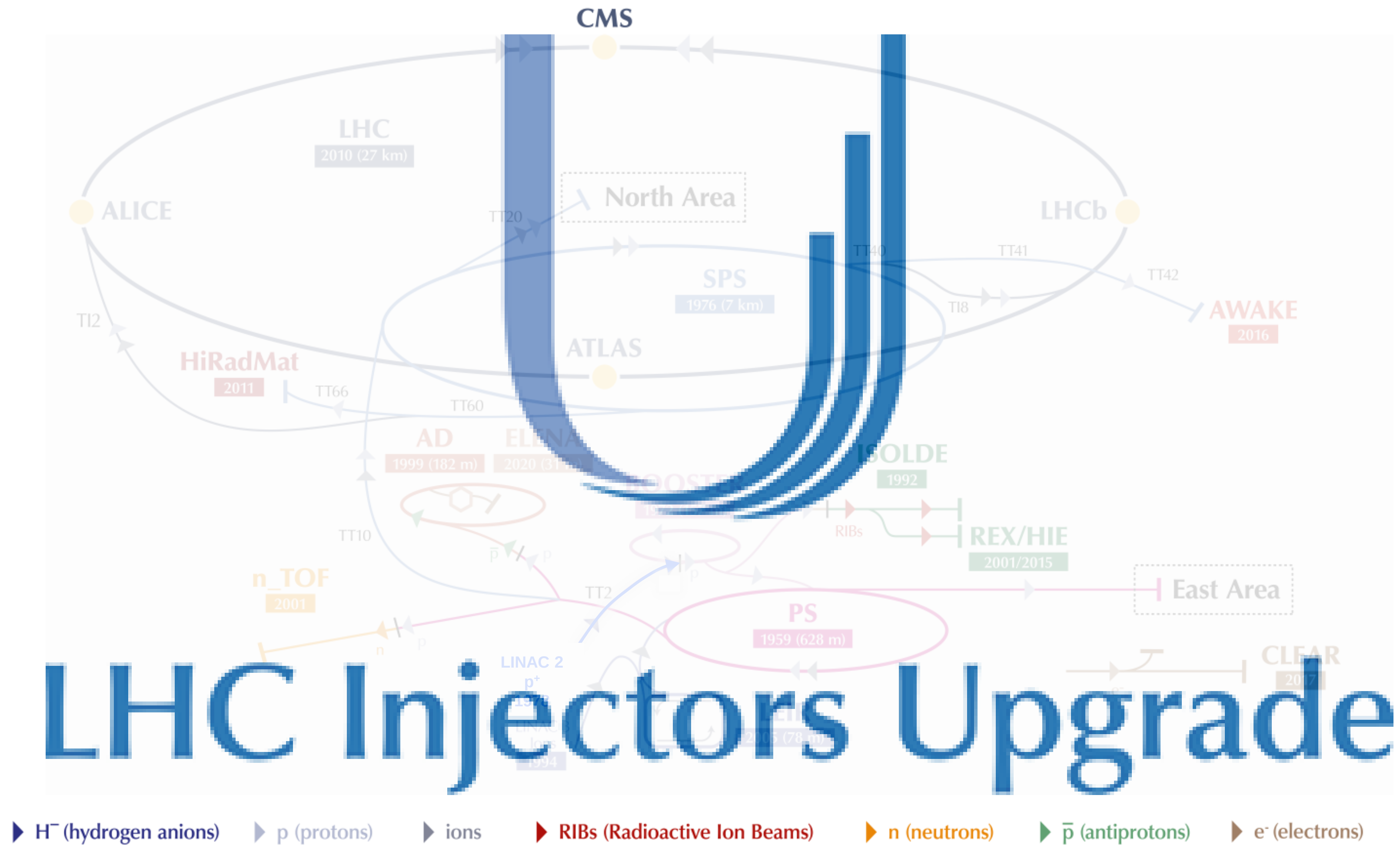
LHC Injectors Upgrade



- Chain of linear and circular accelerators to serve:
  - The four LHC experiments
  - A variety of Fixed Target experiments/facilities at the different energy stages reached along the chain
- Before 2020 **LINAC 2** was injecting protons into PSB
- In the Long Shutdown 2 (2019-20) a big revamp of the injectors took place …

The CERN accelerator complex

LHC Injectors Upgrade



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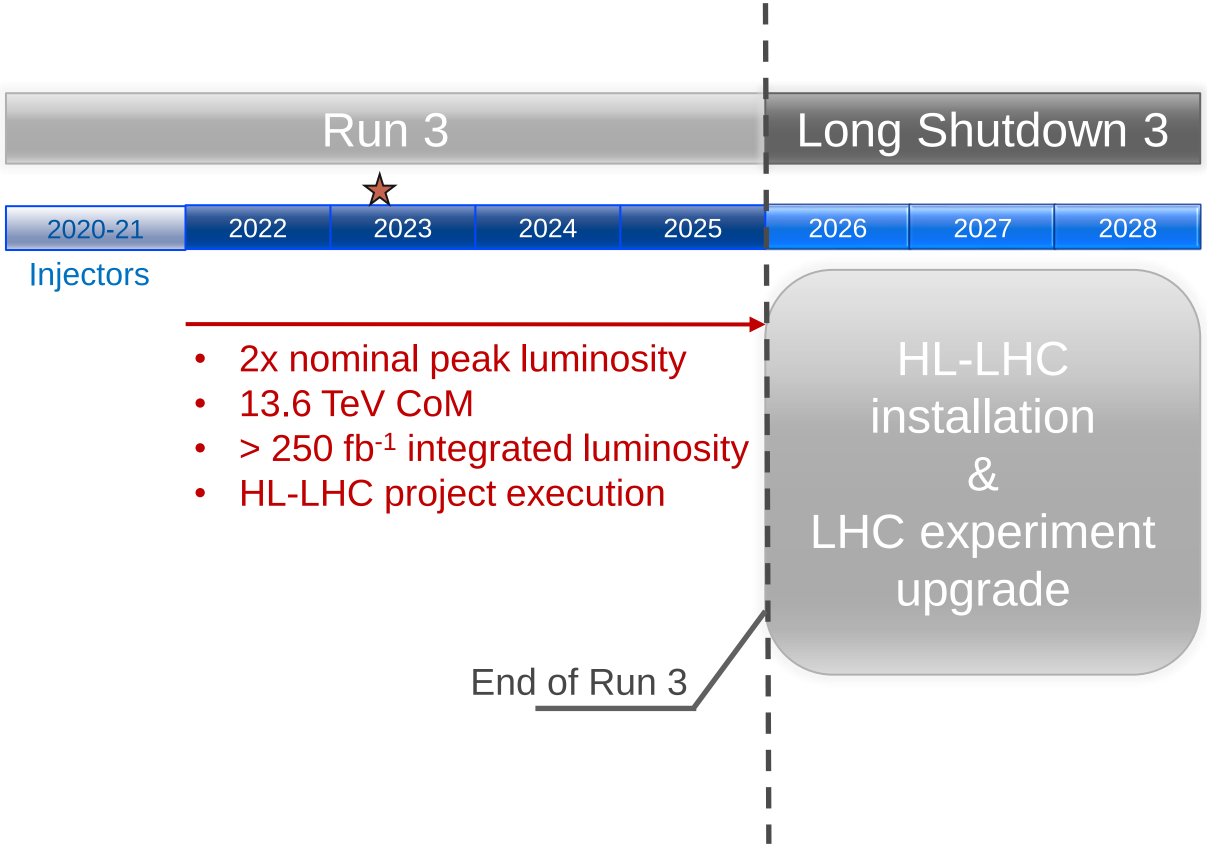
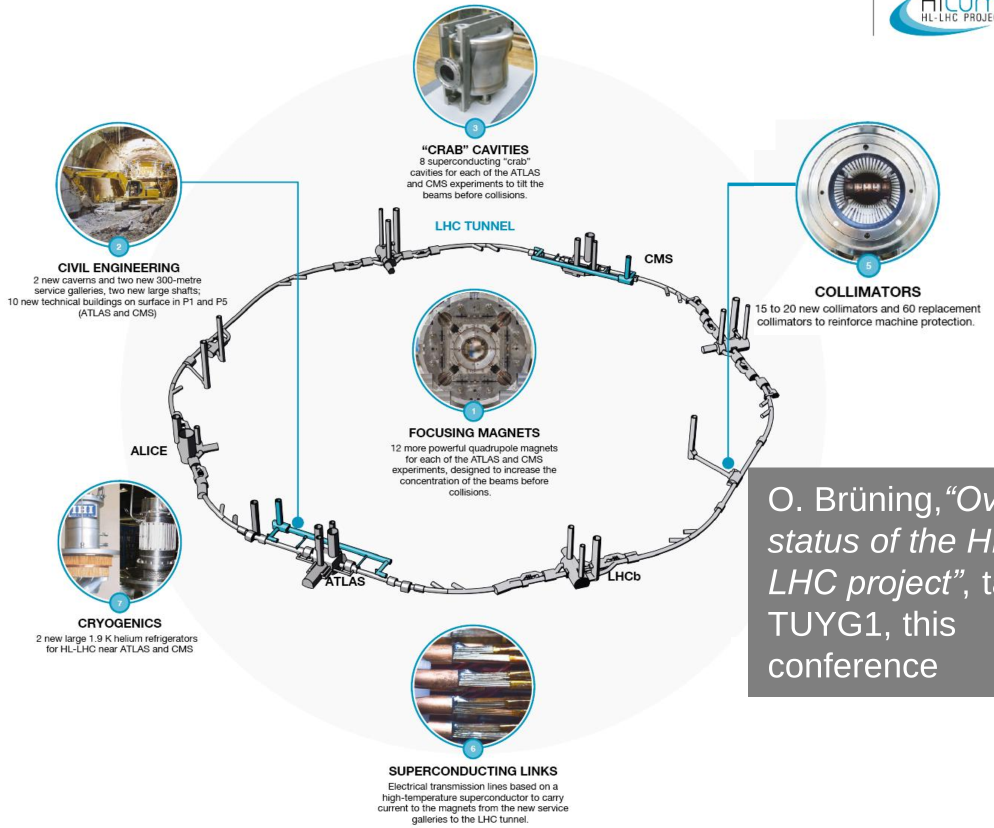
Goals and rationale: High Luminosity LHC

LHC Injectors Upgrade

- Where we are, where we are going, what we need …



HiLumi HL-LHC PROJECT



O. Brüning, *"Overall status of the HL-LHC project"*, talk TUYG1, this conference

Goals and rationale: High Luminosity LHC

LHC Injectors Upgrade

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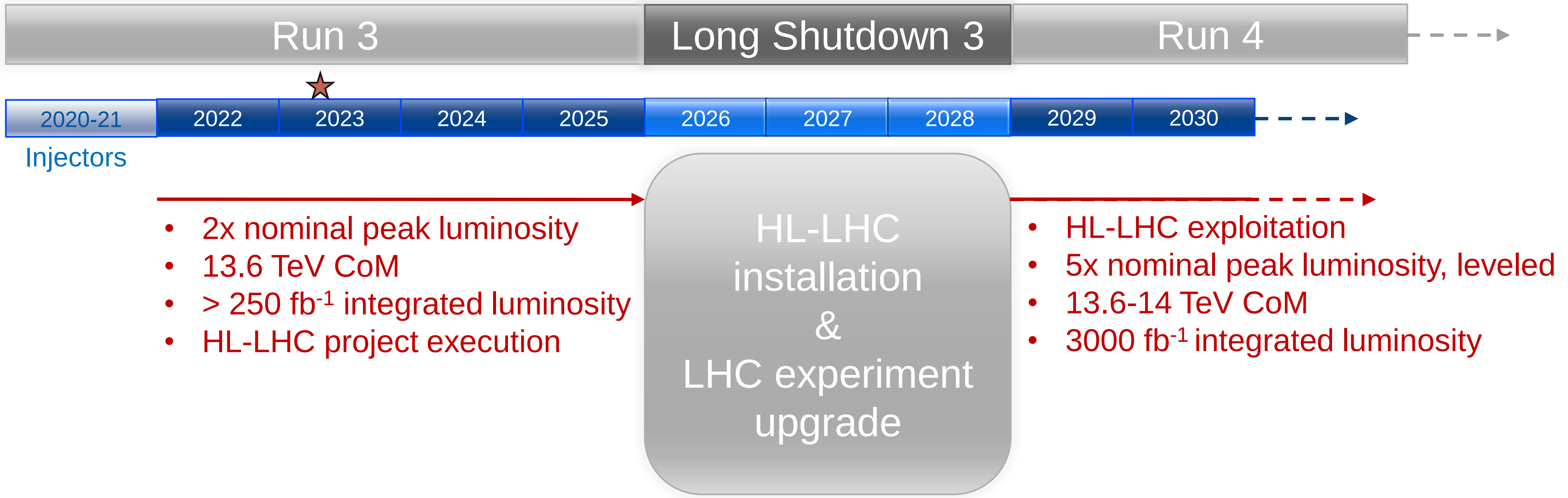

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LHC Injectors Upgrade

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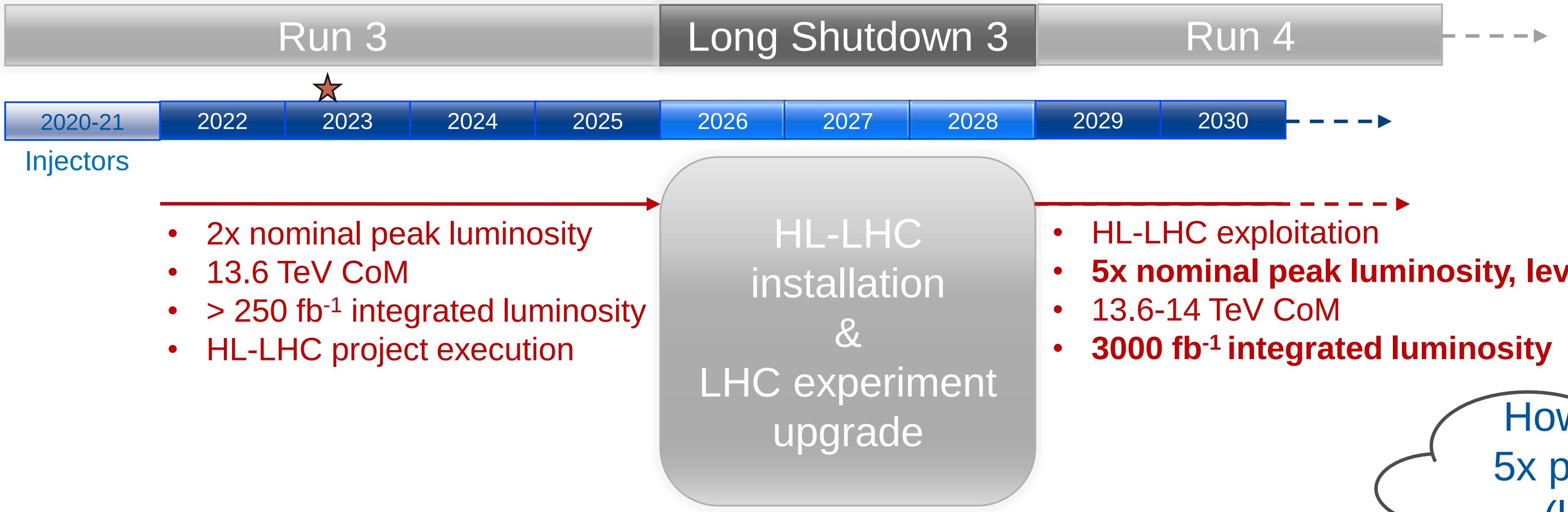

- 2x nominal peak luminosity
- 13.6 TeV CoM
- > 250 fb^{-1} integrated luminosity
- HL-LHC project execution

- HL-LHC exploitation
- **5x nominal peak luminosity, leveled**
- 13.6-14 TeV CoM
- **3000 fb^{-1} integrated luminosity**

How do we reach 5x peak luminosity (leveled) and 3000 fb^{-1}??

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

Goals and rationale: High Luminosity LHC

LHC Injectors Upgrade

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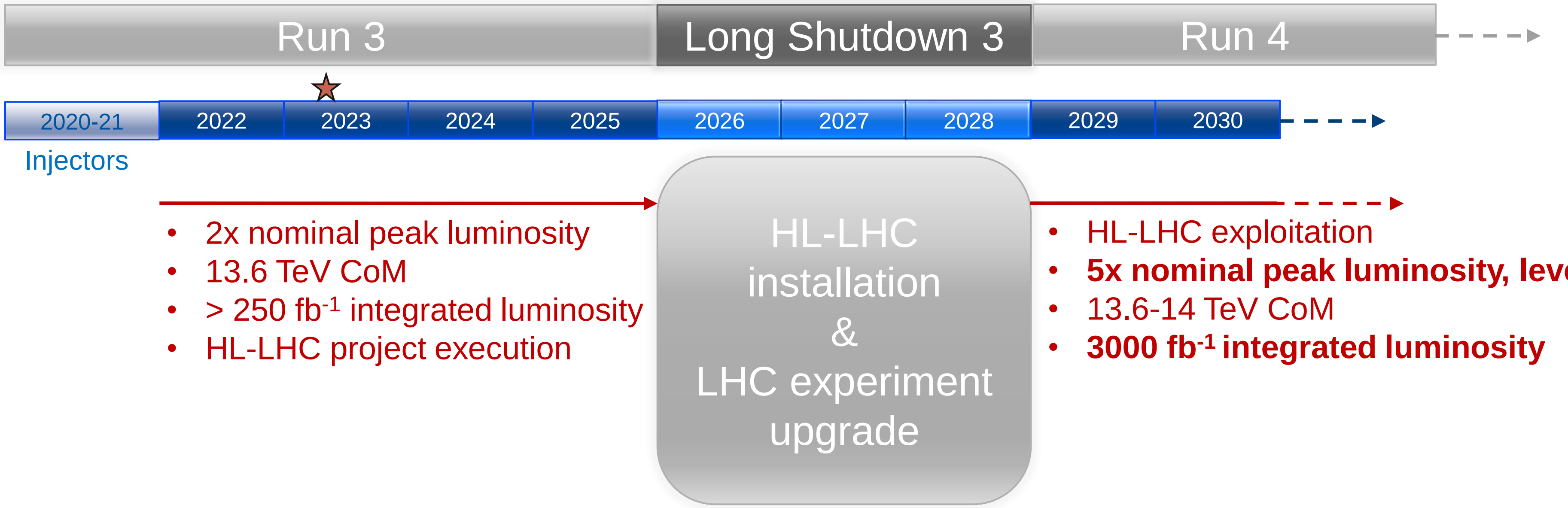

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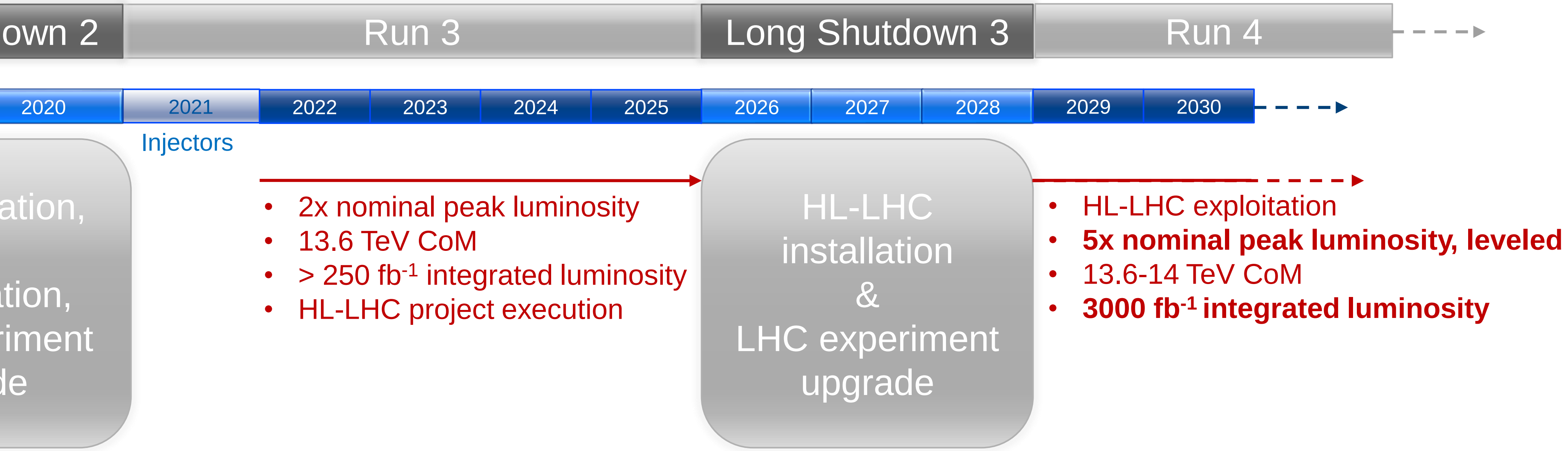
Goals and rationale: High Luminosity LHC → LIU

LHC Injectors Upgrade

- A leap back in time …



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Goals and rationale: High Luminosity LHC → LIU

LHC Injectors Upgrade

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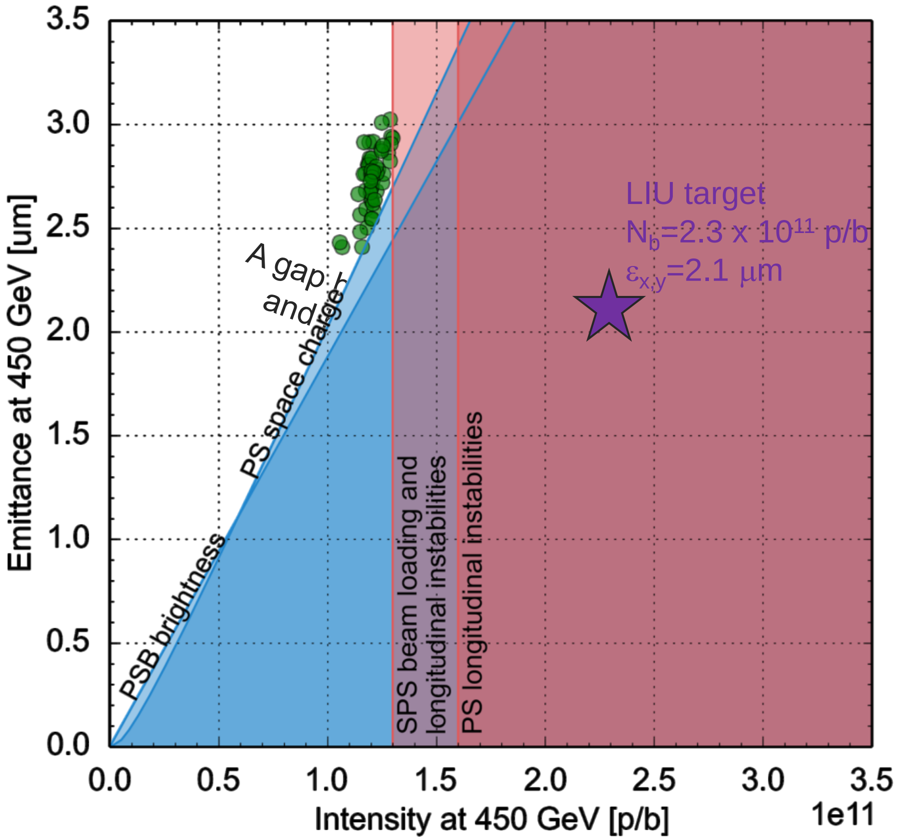

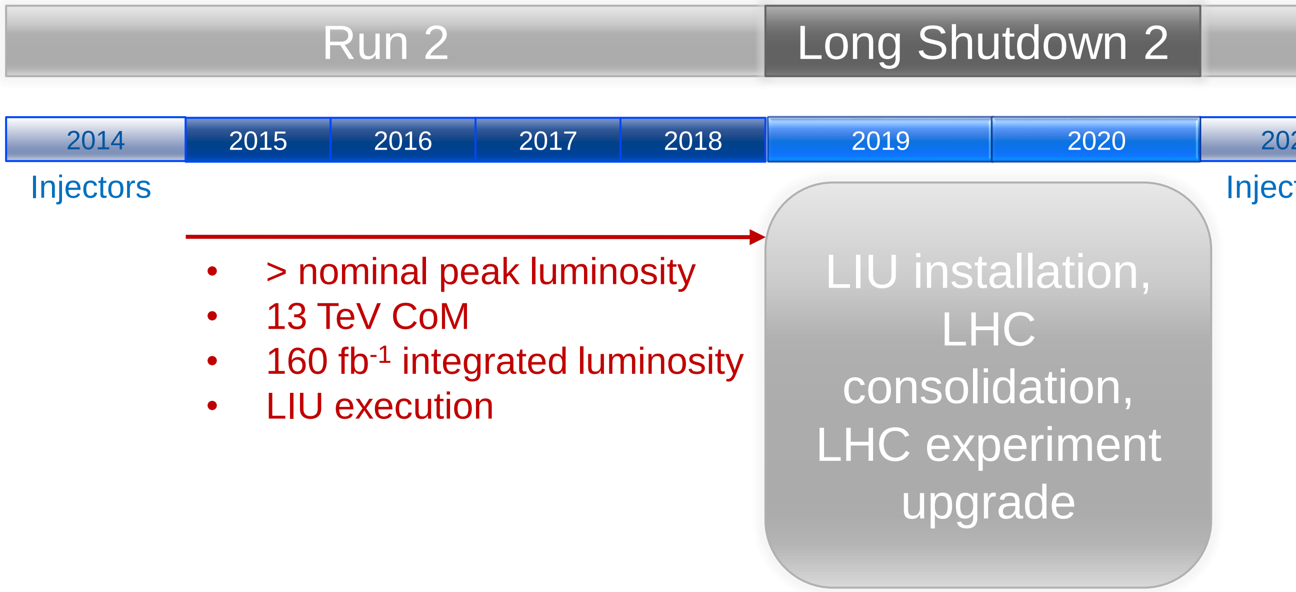

Goals and rationale: High Luminosity LHC → LIU

LHC Injectors Upgrade

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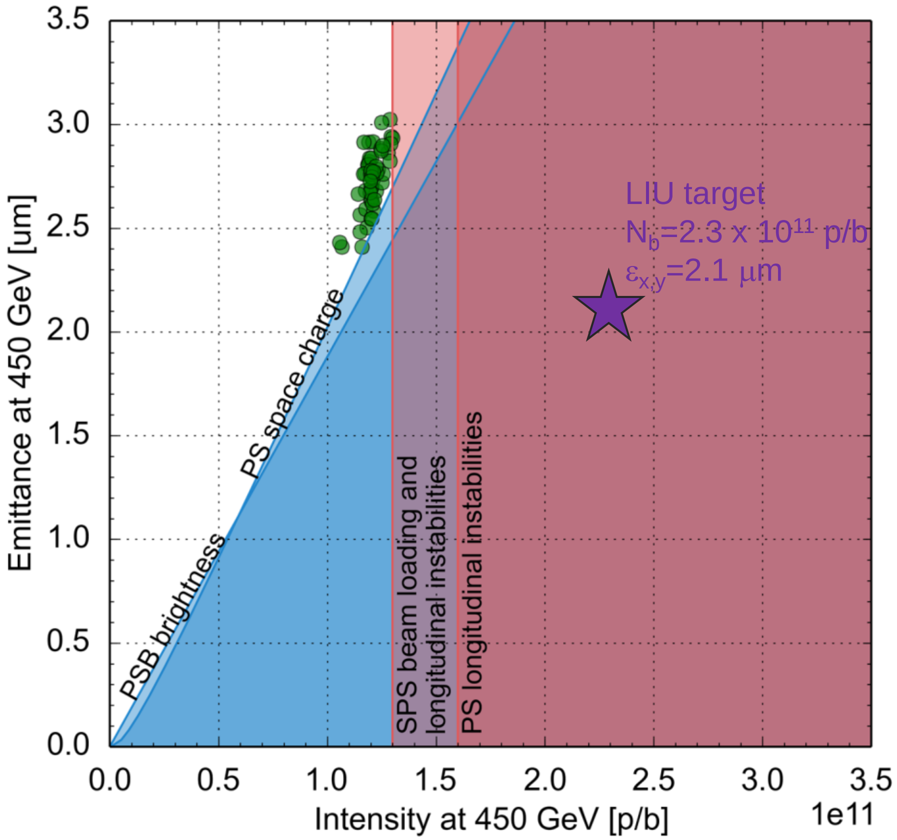
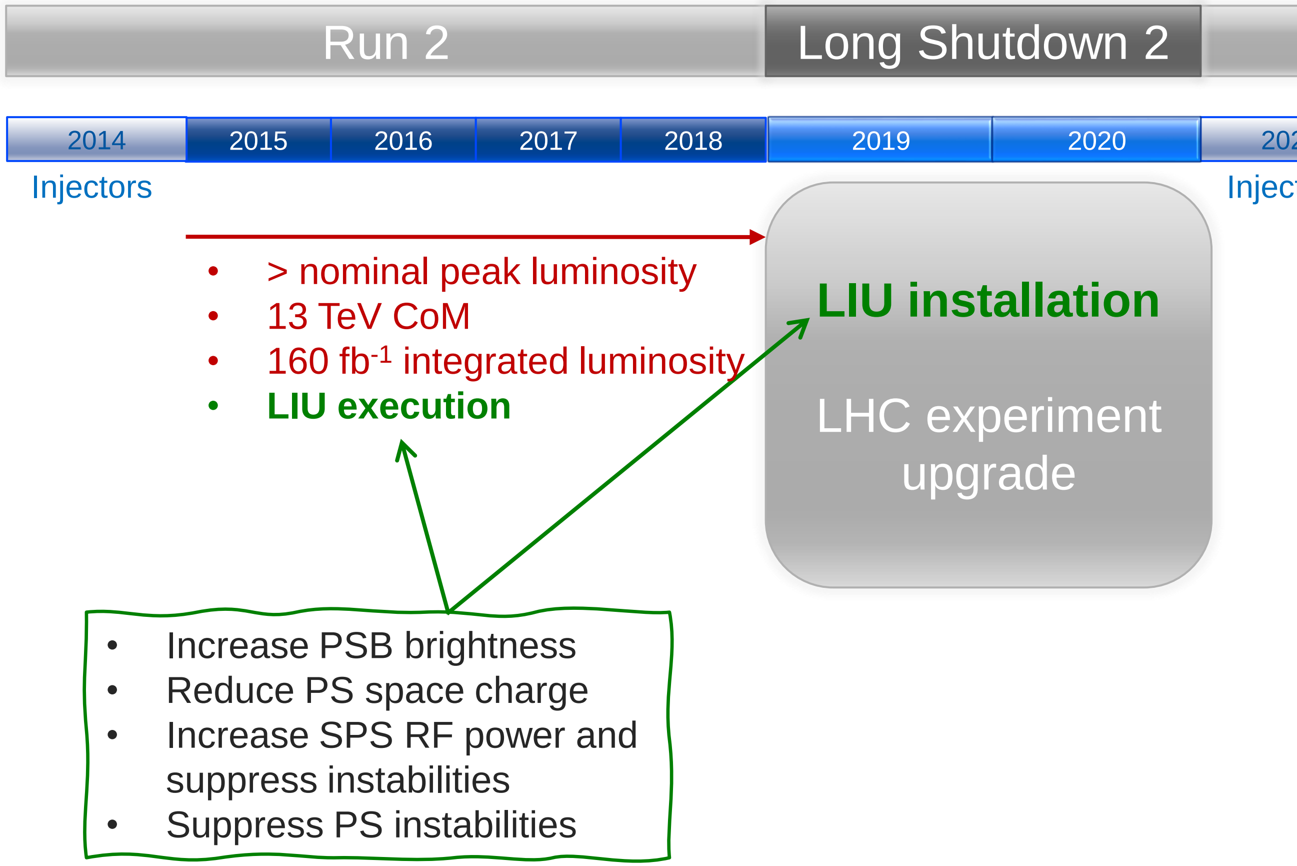
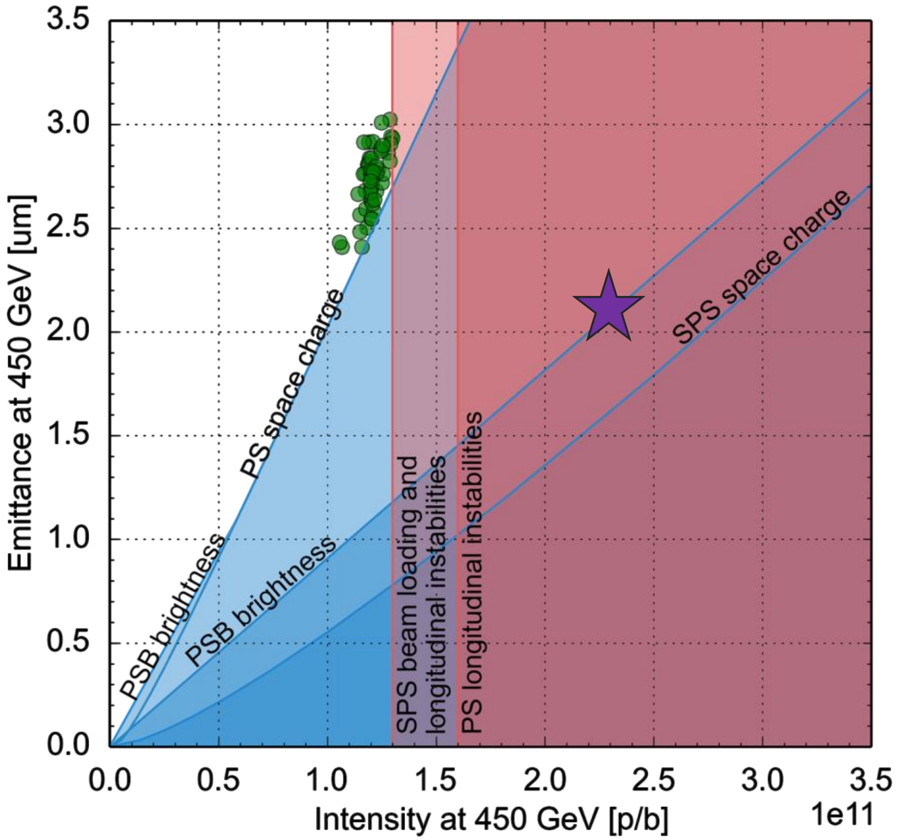




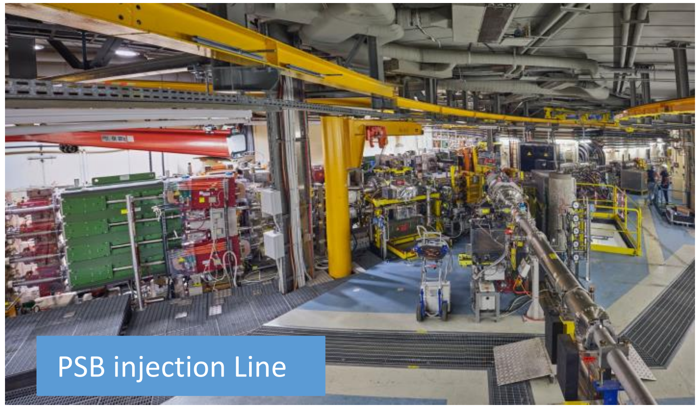
Main LIU installations

LHC Injectors Upgrade

- Expected impact on performance of LIU hardware modifications



- **Connection of PSB to Linac4**
  - Linac4 providing 25 mA within 0.4 μm
  - Charge exchange H^- injection at E_{kin} = 160 MeV into PSB



Main LIU installations

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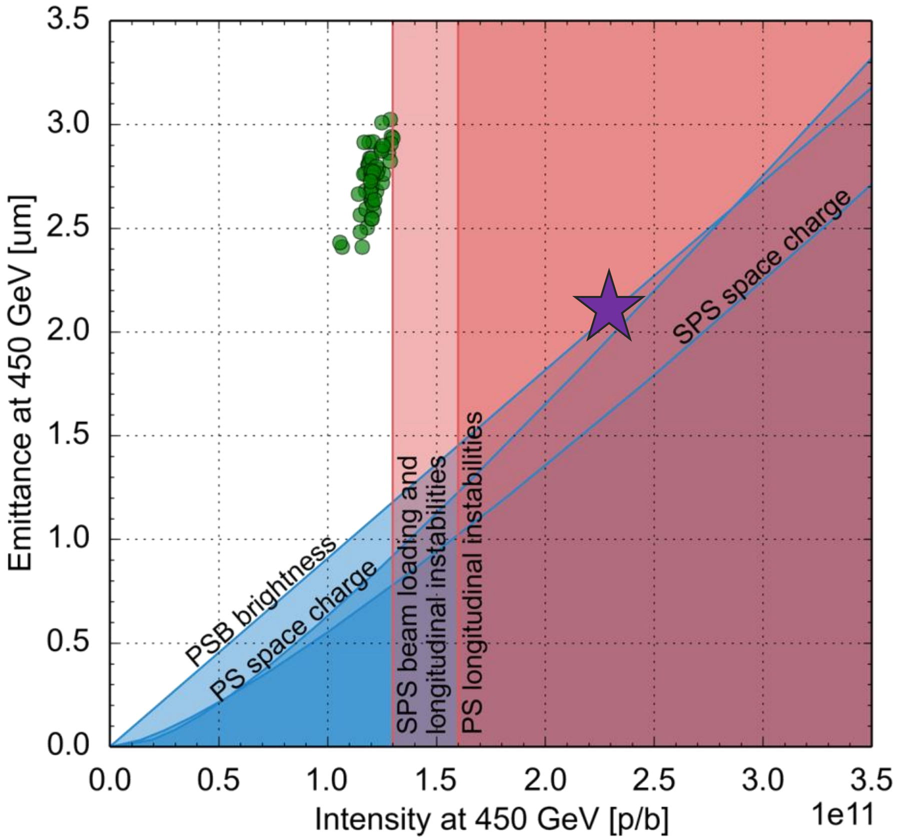


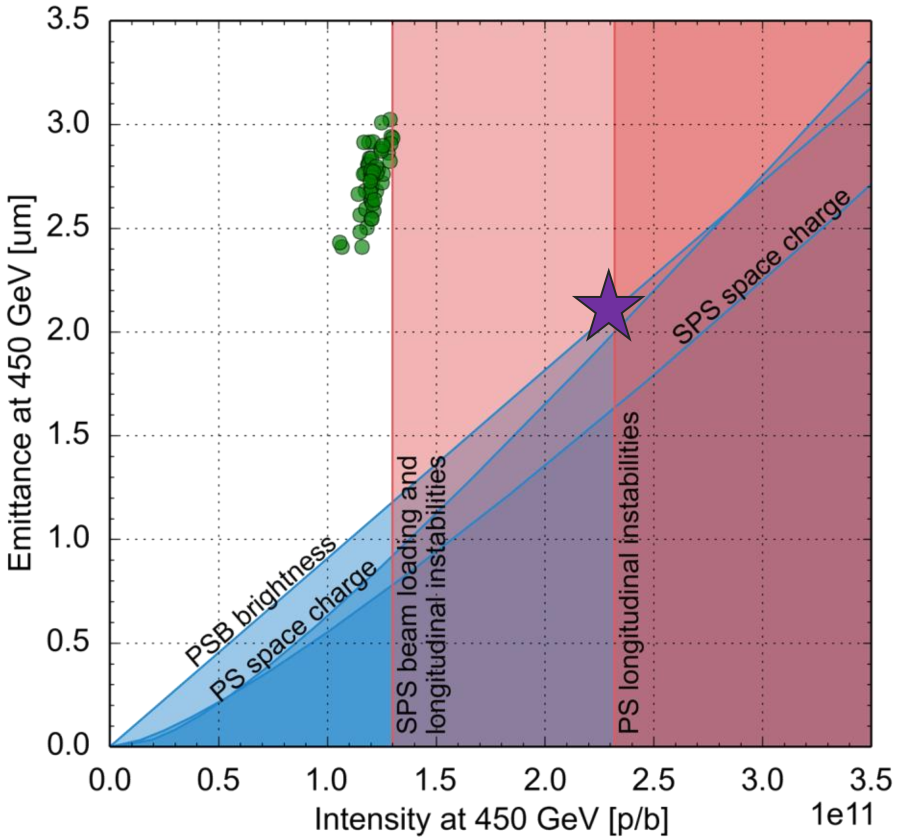
- **PSB acceleration to E_{kin} = 2 GeV**
  - New main power supply and RF system in PSB
  - New injection region in PS


PSB new RF modules

PSB new power supply building

Main LIU installations

- Expected impact on performance of LIU hardware modifications



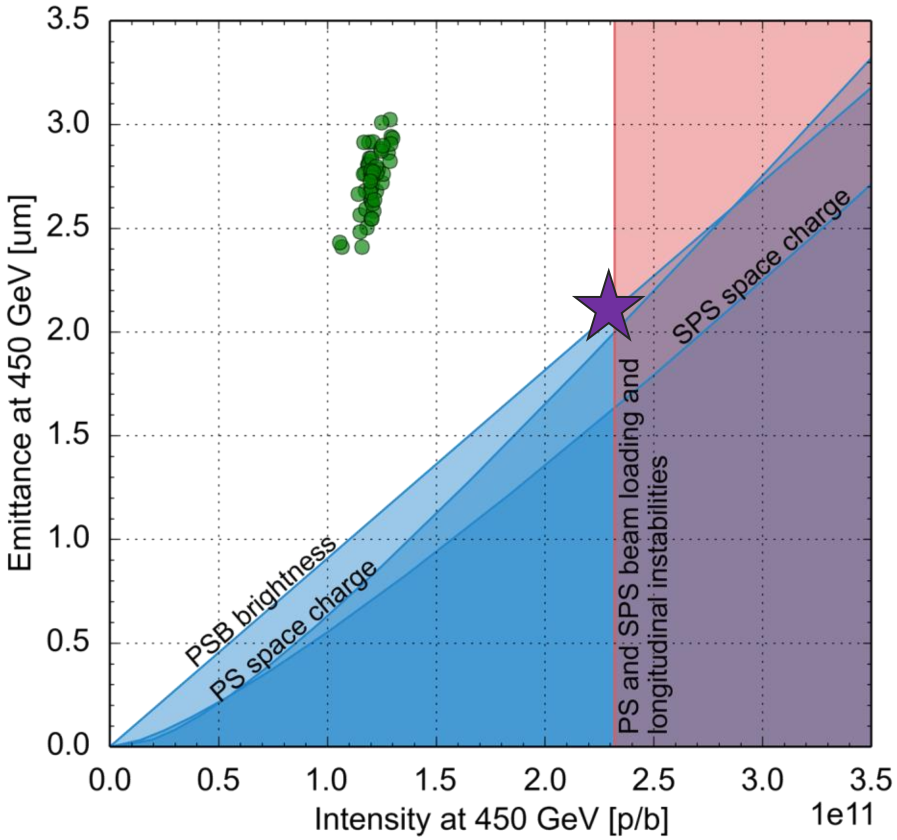
- **PS RF upgrades, e.g.**
  - New broadband cavity as kicker for longitudinal feedback system against instabilities
  - Impedance reduction of RF systems

Longitudinal damper

10 MHz amplifiers

Main LIU installations

- Expected impact on performance of LIU hardware modifications



- **SPS upgrade**
  - Power and control upgrade of 200 MHz RF system
  - Longitudinal impedance reduction
  - Amourphous-Carbon coating of selected vacuum chambers


New RF amplifier towers

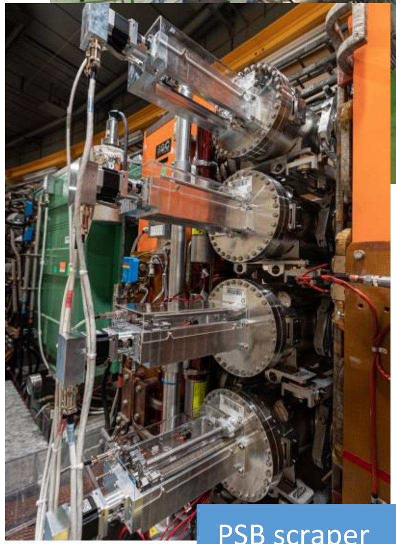

Low-impedance flanges

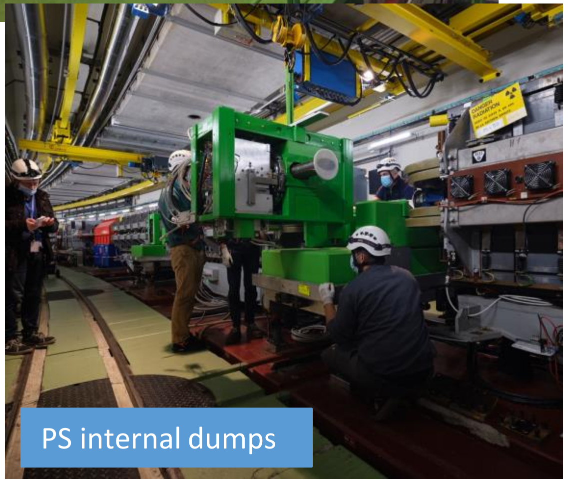
Main LIU installations

LHC Injectors Upgrade

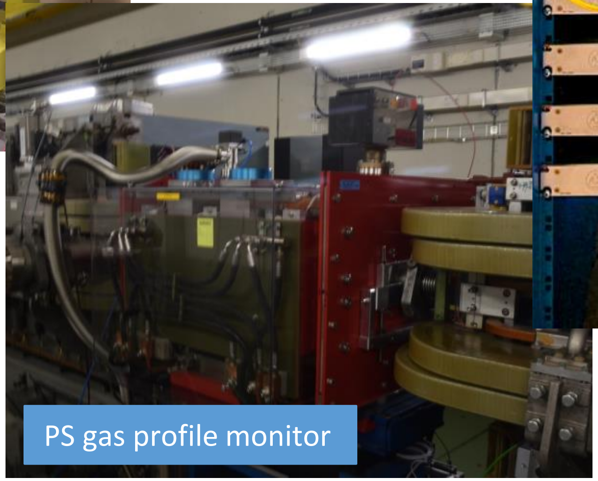
- In addition:

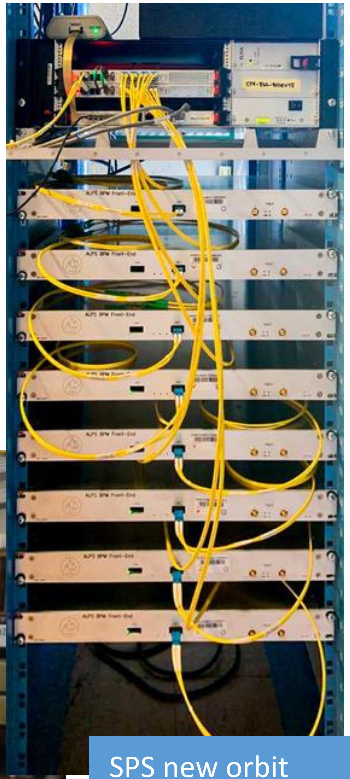

New SPS beam dump


PSB scraper


PS internal dumps


PSB wire scanners


PS gas profile monitor


SPS new orbit measurement system

The evolution of the LIU project

LHC Injectors Upgrade

- A **10-years** long and **180 M€** worth project rich of progress and milestones

- **Mandate**

"The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC. This includes LINAC4, the PS booster, the PS, the SPS, as well as the heavy ion chain."

of baseline items
- Planning & budgeting
- Exploratory beam studies
- Begin prototyping & testing

Review of all CERN upgrade plans

LHC Injectors Upgrade

⇒ The **most** performance improving upgrades MUST be **done as soon as technically possible**

S. Myers RLIUP Pre-summary 6

The evolution of the LIU project

LHC Injectors Upgrade

- A **10-years** long and **180 M€** worth project rich of progress and milestones

Run 1	Long Shutdown 1	Run 2	Long Shutdown 2	Run 3

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Injectors (2014) — Injectors (2021)

Inauguration of Linac4

Peak execution time of the project:
LIU hardware installation

Beam quality and reliability runs to prepare Linac4 connection to PSB and operation

- Study & refine models
- Prototype, build, test, install when possible

The evolution of the LIU project

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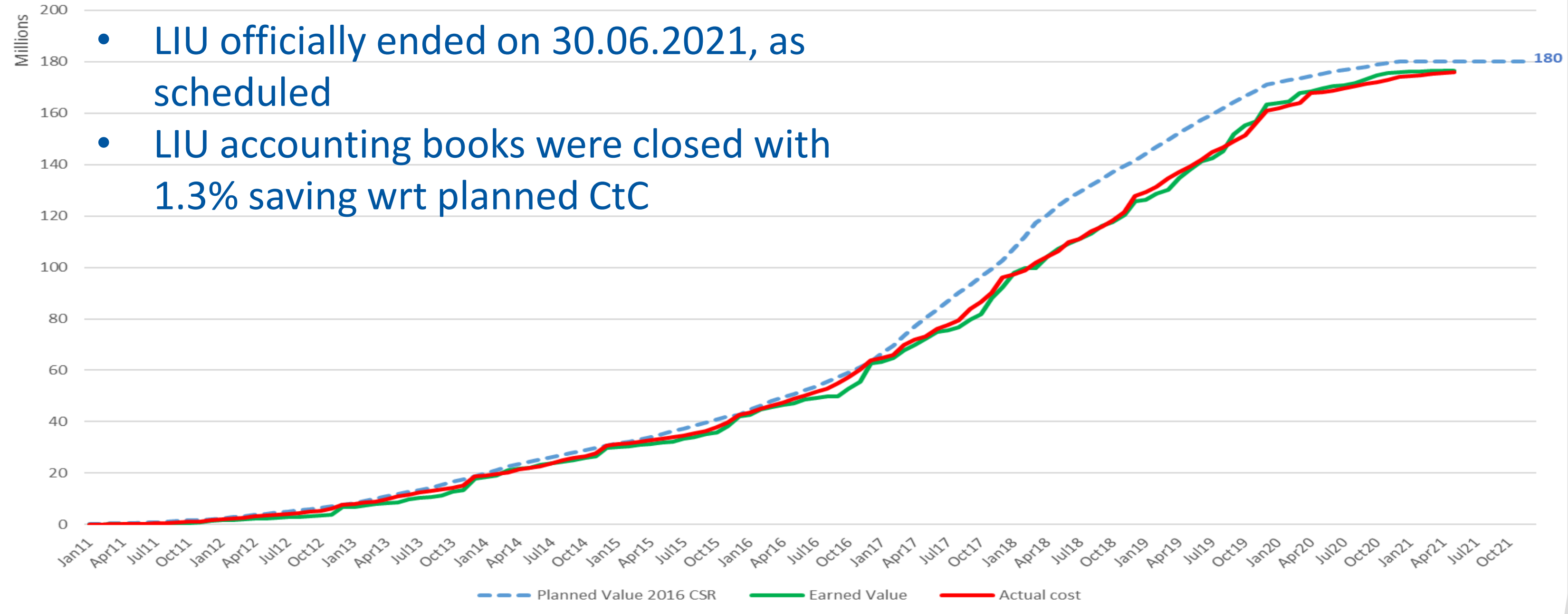
Run 1 | Long Shutdown 1 | Run 2 | Long Shutdown 2 | Run 3

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

Injectors | Injectors

- LIU officially ended on 30.06.2021, as scheduled
- LIU accounting books were closed with 1.3% saving wrt planned CtC



The evolution of the LIU project

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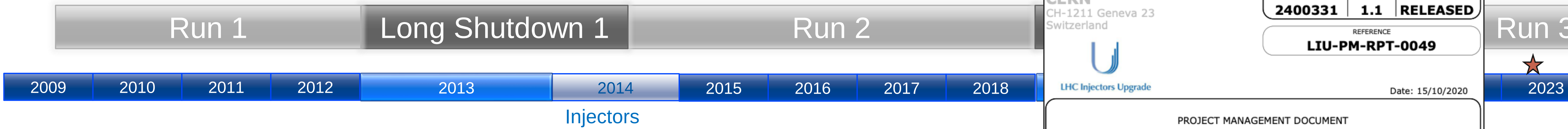


LIU legacy:

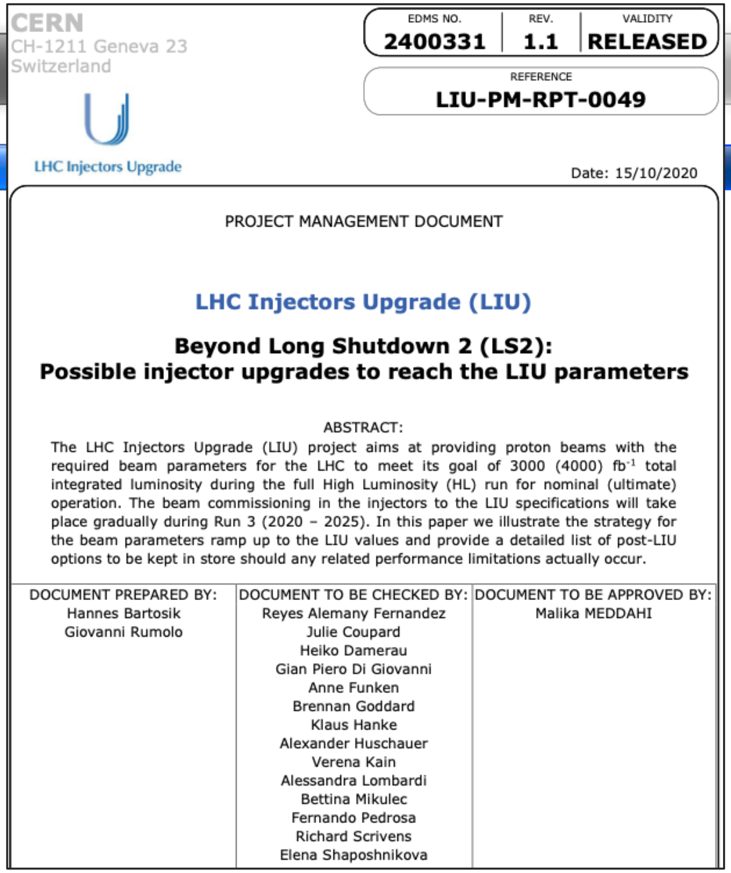
- A robust plan for LIU beam ramp-up over Run 3
- A risk register listing beyond-LIU items to be installed for possible shortcomings

2020-21 Commissioning of pre-LS2 beams + commissioning of LIU Pb ion beams

2022 Commissioning of 1.8 10^{11} p/b with desired brightness and degradation budgets

2023 Commissioning of 2.1 10^{11} p/b with desired brightness and degradation budgets

2024 Commissioning of 2.3 10^{11} p/b with desired brightness and degradation budgets



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CH-1211 Geneva 23
Switzerland

LHC Injectors Upgrade

EDMS NO.	REV.	VALIDITY
2400331	1.1	RELEASED

REFERENCE
LIU-PM-RPT-0049

Date: 15/10/2020

PROJECT MANAGEMENT DOCUMENT

LHC Injectors Upgrade (LIU)

Beyond Long Shutdown 2 (LS2):
Possible injector upgrades to reach the LIU parameters

ABSTRACT:
The LHC Injectors Upgrade (LIU) project aims at providing proton beams with the required beam parameters for the LHC to meet its goal of 3000 (4000) fb^{-1} total integrated luminosity during the full High Luminosity (HL) run for nominal (ultimate) operation. The beam commissioning in the injectors to the LIU specifications will take place gradually during Run 3 (2020 – 2025). In this paper we illustrate the strategy for the beam parameters ramp up to the LIU values and provide a detailed list of post-LIU options to be kept in store should any related performance limitations actually occur.

DOCUMENT PREPARED BY:	DOCUMENT TO BE CHECKED BY:	DOCUMENT TO BE APPROVED BY:
Hannes Bartosik Giovanni Rumolo	Reyes Alemany Fernandez Julie Coupard Heiko Damerau Gian Piero Di Giovanni Anne Funken Brennan Goddard Klaus Hanke Alexander Huschauer Verena Kain Alessandra Lombardi Bettina Mikulec Fernando Pedrosa Richard Scrivens Elena Shaposhnikova	Malika MEDDAHI

The evolution of the LIU project

LHC Injectors Upgrade

- A **10-years** long and **180 M€** worth project rich of progress and milestones

Run 1				Long Shutdown 1		Run 2				Long Shutdown 2		Run 3		
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023 ☆
					Injectors							Injectors		


***LIU project team** @End-of-LIU event, 28.06.2021*

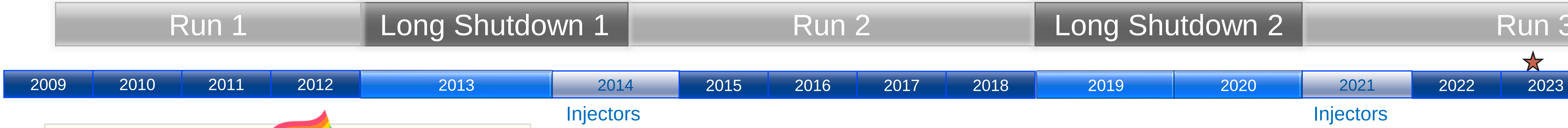
A key to LIU success?

Teamwork &

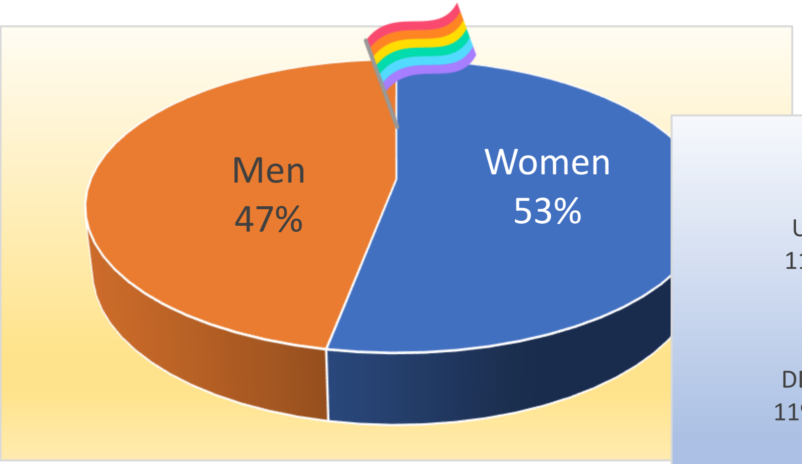
The evolution of the LIU project

LHC Injectors Upgrade

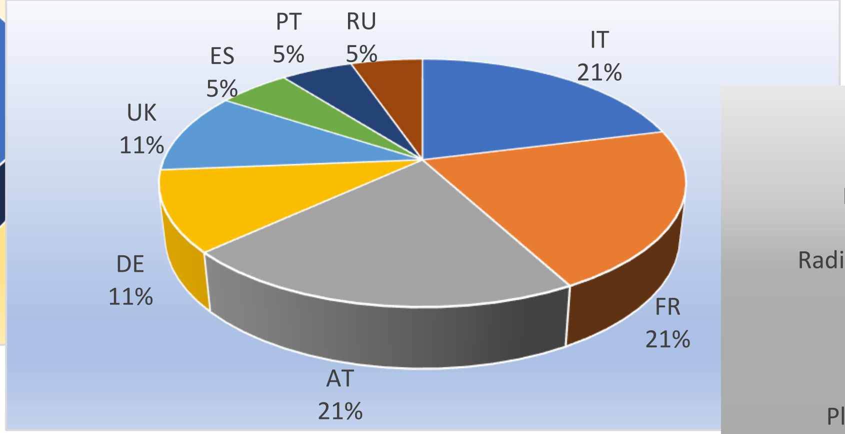
- A **10-years** long and **180 M€** worth project rich of progress and milestones



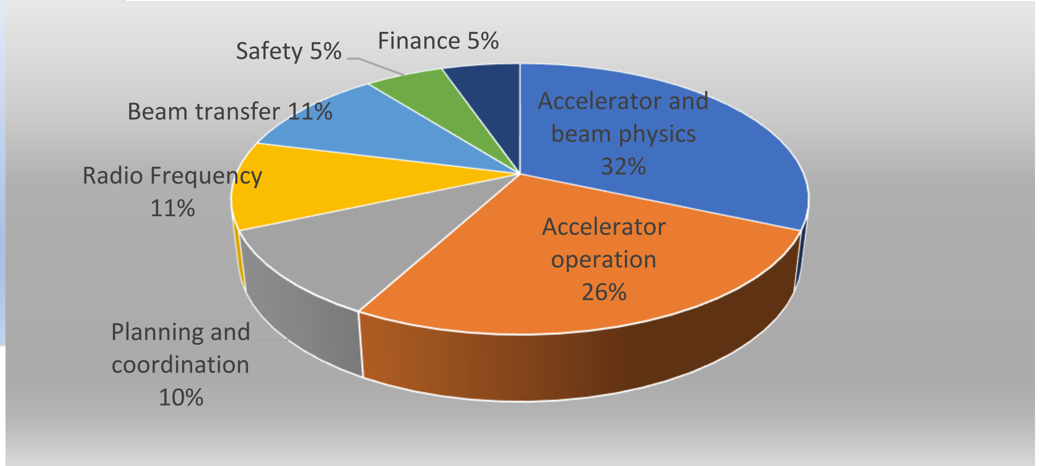
A key to LIU success?



Diversity in gender …



… in nationality …

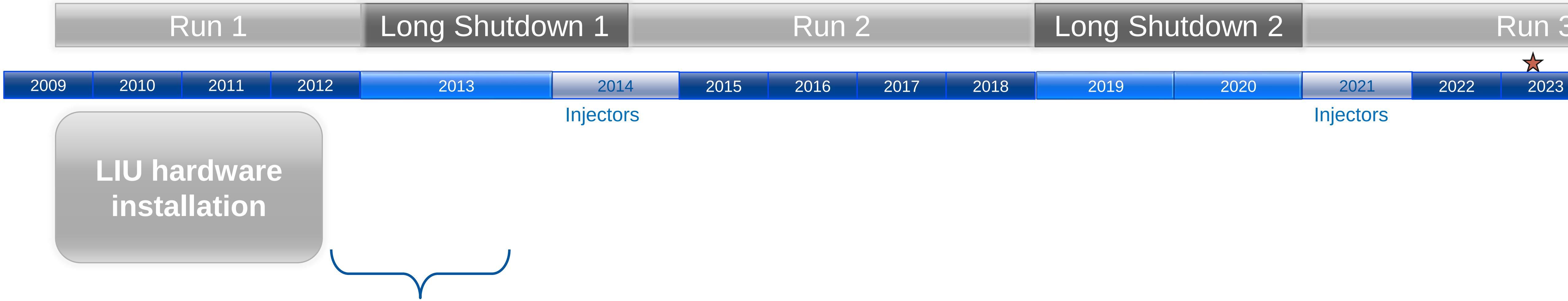


… in domain of competence …

Beam performance with upgraded injectors

LHC Injectors Upgrade

- Now we close the loop and get back to where we are …

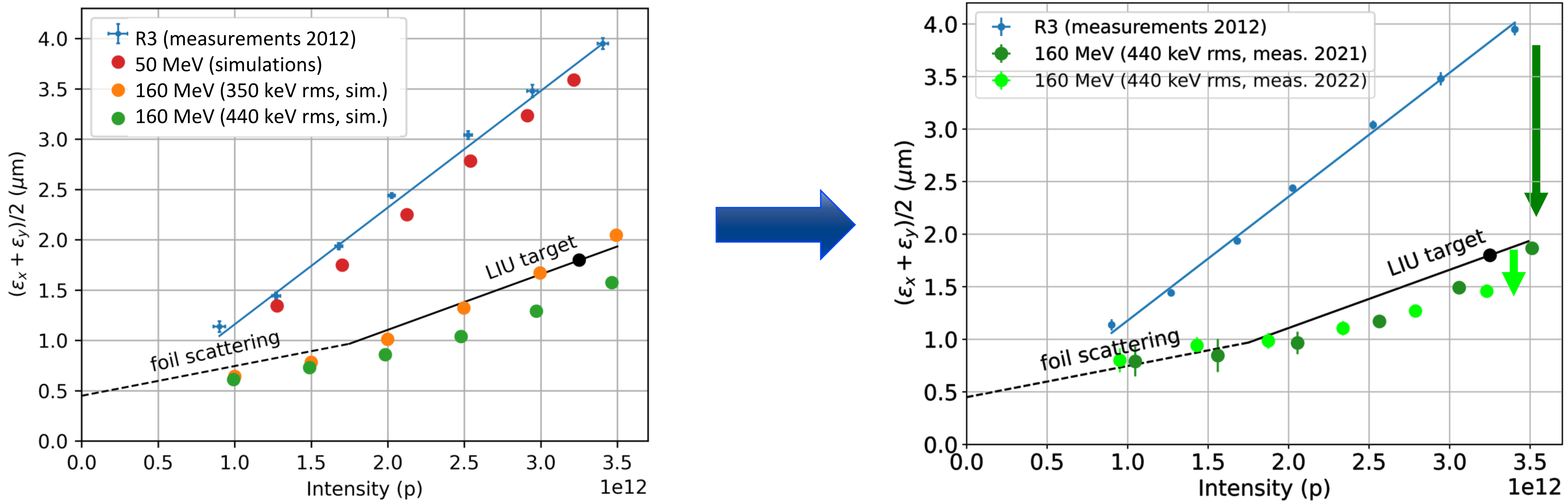


- 2 years with beam
- How many of the LIU promises have been fulfilled?
- What issues have we discovered?

PSB 2021-22

LHC Injectors Upgrade

- **PSB brightness line after connection with Linac4**



LIU predictions fulfilled?

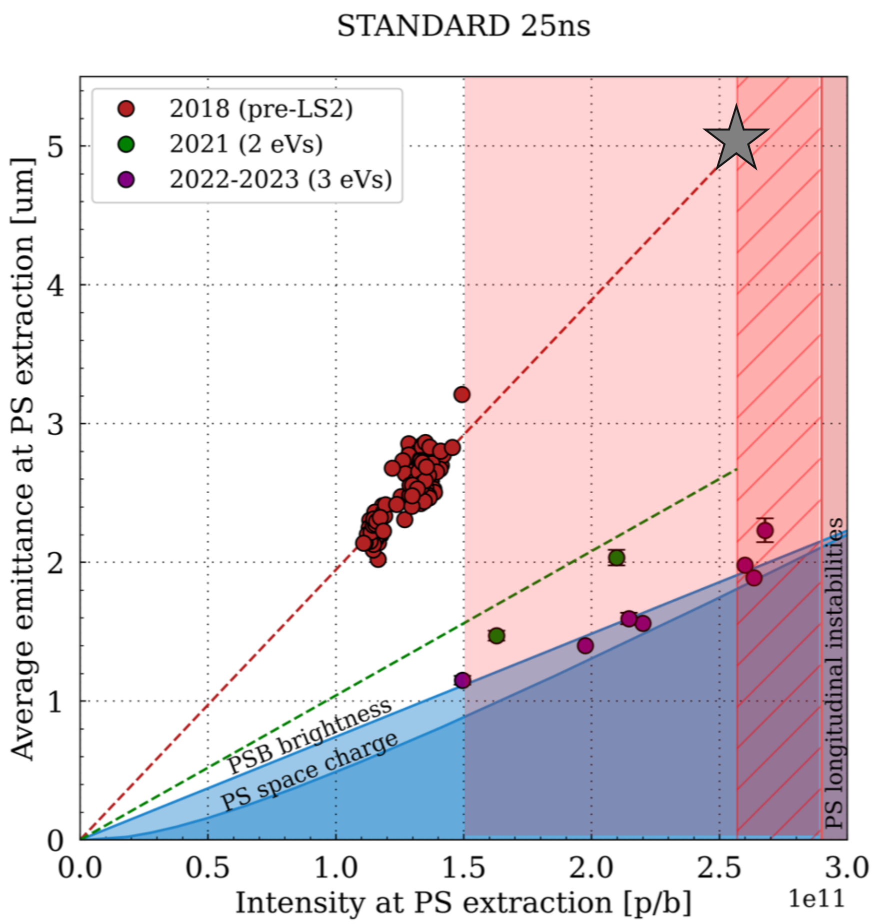
LHC Injectors Upgrade

- **Double brightness for PSB beams after connection with Linac4** ✓
  - Achieved with margin

PS 2021-22

LHC Injectors Upgrade

- LIU intensity and brightness achieved and exceeded in 2022 in the PS

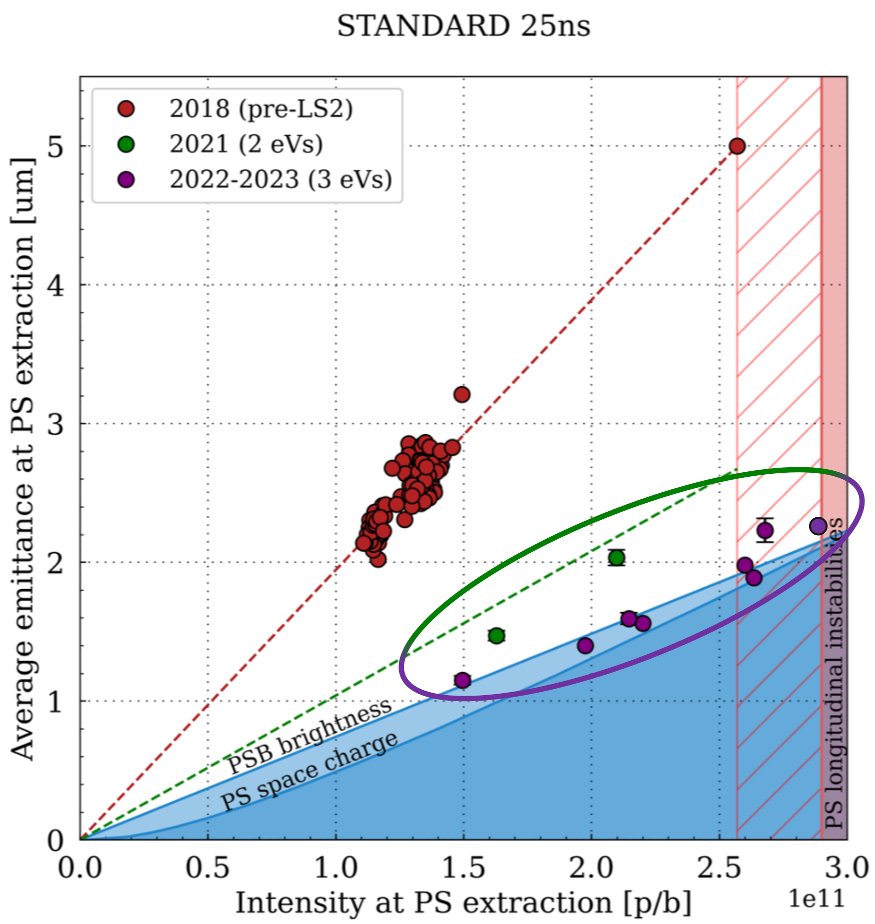


- Intensity demonstrated already in 2018 thanks to LIU longitudinal feedback prototype installed in 2014

PS 2021-22

LHC Injectors Upgrade

- LIU intensity and brightness achieved and exceeded in 2022 in the PS



- Intensity demonstrated already in 2018
- First step of brightness ramp-up (2021) with 2 GeV and 2 eVs injection
- Full PS performance achieved in 2022 thanks to 3 eVs injection
- Actually 2.9 • 10^{11} p/b successfully achieved out of the PS

LIU predictions fulfilled?

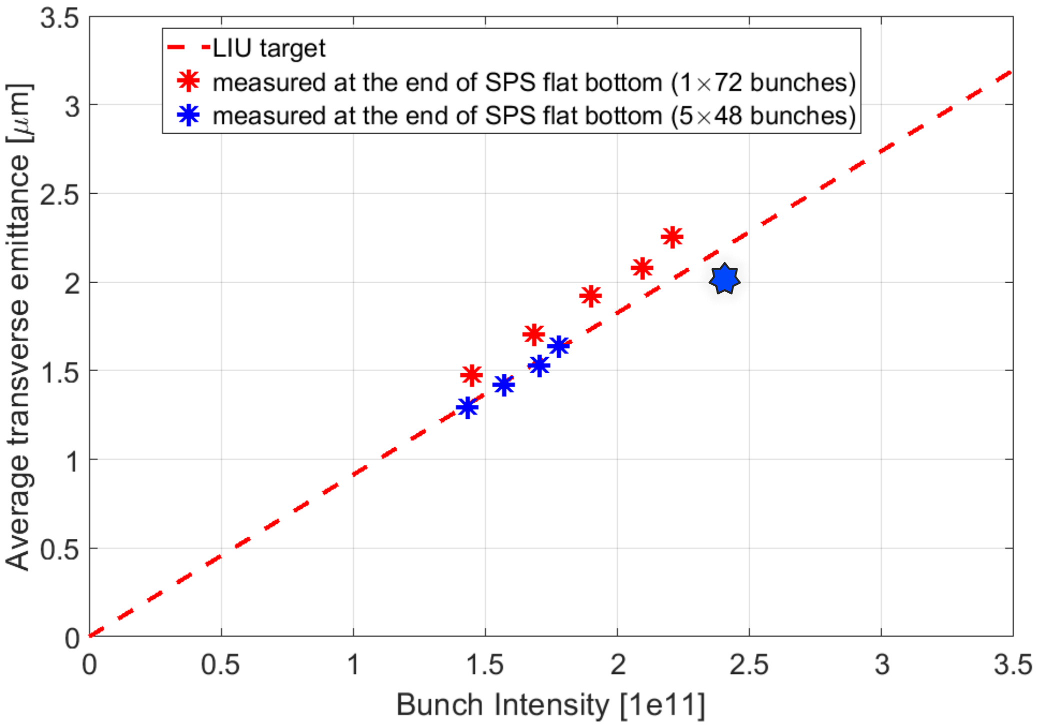
LHC Injectors Upgrade

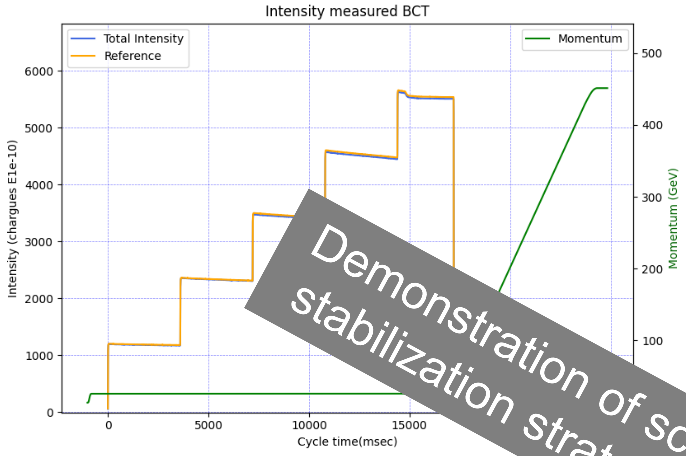
- **Double brightness for PSB beams after connection with Linac4** ✓
- **Preservation of PSB brightness in PS thanks to space charge reduction at 2 GeV injection** ✓
- **Stabilisation of PS longitudinal instabilities to extract 2.6 • 10^{11} p/b** ✓
  - Even reached 2.9 • 10^{11} p/b

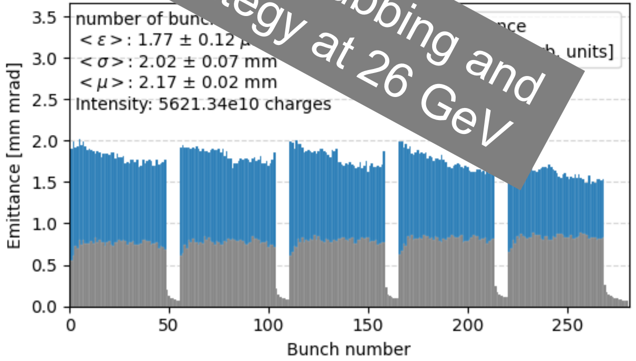
SPS 2021-22

LHC Injectors Upgrade

- The SPS recovered all pre-LS2 beams in 2021 and had a successful intensity & brightness ramp-up at injection (26 GeV/c) in 2022







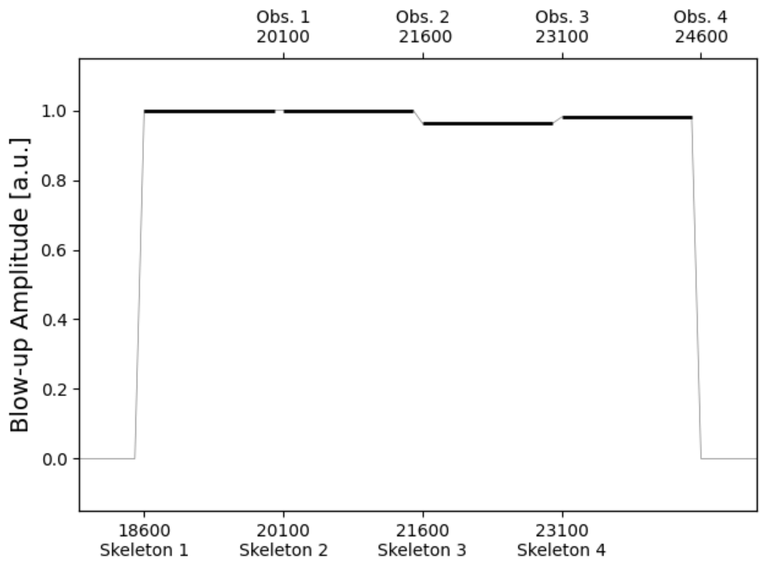
Demonstration of scrubbing and stabilization strategy at 26 GeV

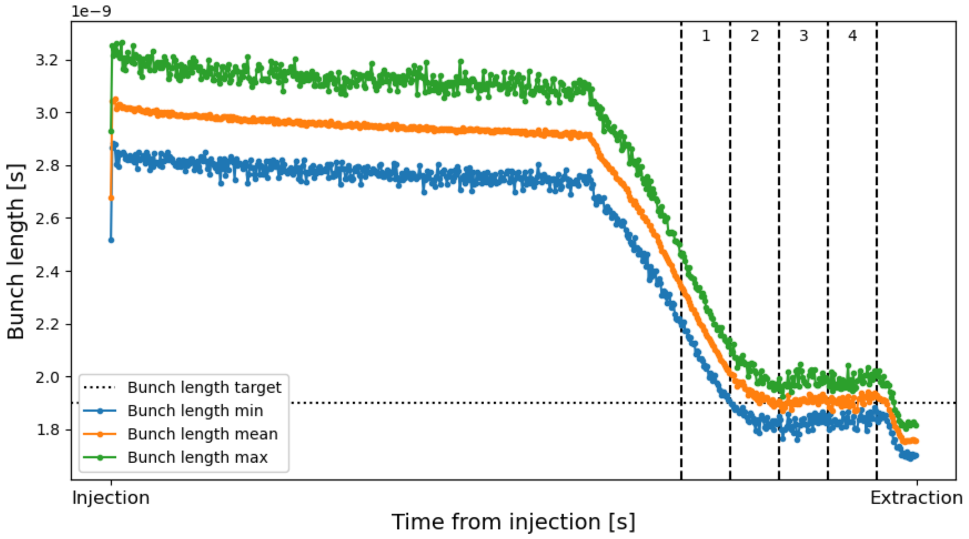
5 trains of 48 bunches with 95% transmission and stable beam across injection plateau

SPS 2021-22

LHC Injectors Upgrade

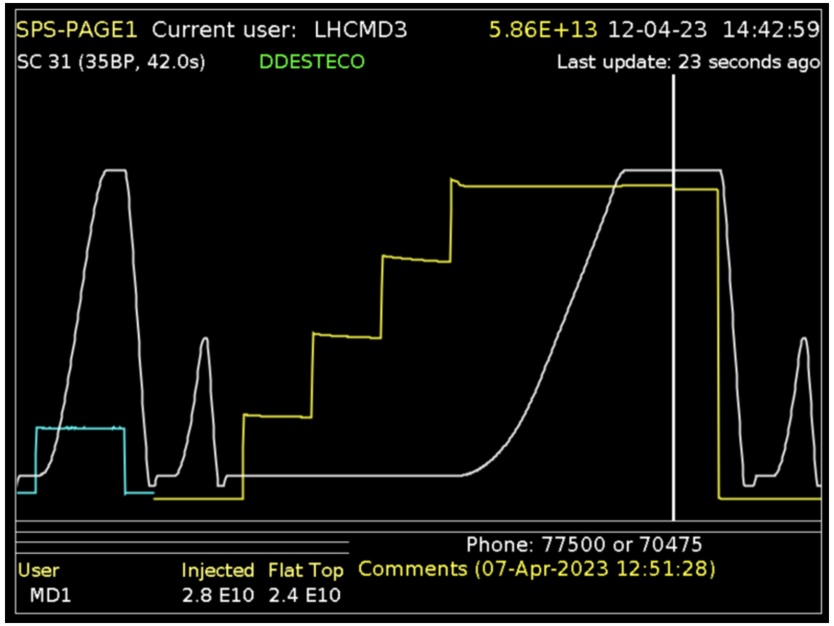
- The SPS recovered all pre-LS2 beams in 2021 and had a successful intensity & brightness ramp-up at injection (26 GeV/c) in 2022
- Longitudinal stability on the ramp achieved by **deployment of automatized longitudinal emittance blow-up** with target bunch length (2022)

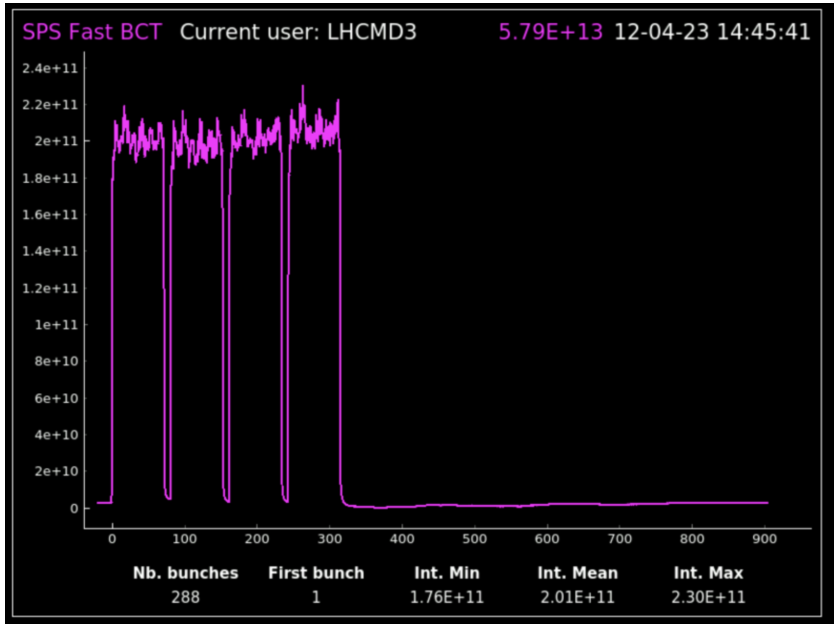




SPS 2023: Sneak a peek …

- Reached **2 • 10^{11} p/b with 4 trains of 72 bunches** at SPS extraction and even **2.2 • 10^{11} p/b in single train**





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LHC Injectors Upgrade

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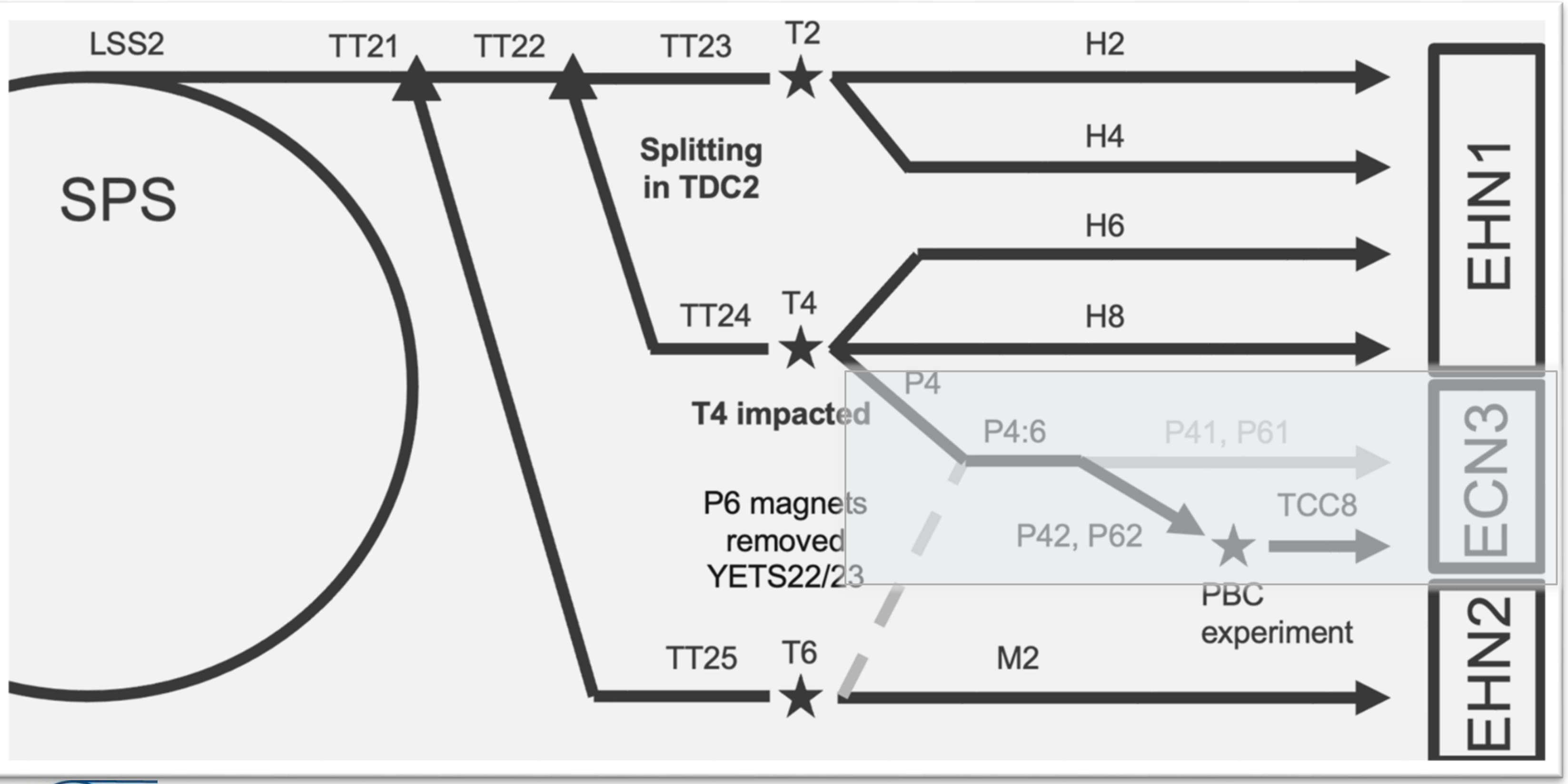
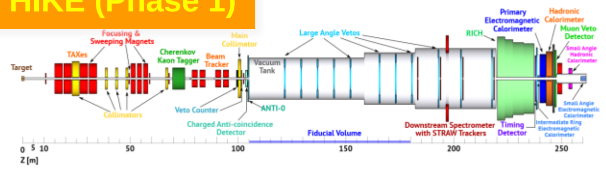
- **Preservation of PSB brightness in PS thanks to space charge reduction at 2 GeV injection** ✓
- **Stabilisation of PS longitudinal instabilities to extract 2.6 • 10^{11} p/b** ✓
- **SPS scrubbing and stabilization strategies in transverse and longitudinal planes** ✓
- **Acceleration of LIU beams in the SPS** ✓
  - Achieved 2.0 • 10^{11} p/b at extraction in 4 trains of 72 bunches (consistent with ramp-up plan)

LIU for fixed target physics …

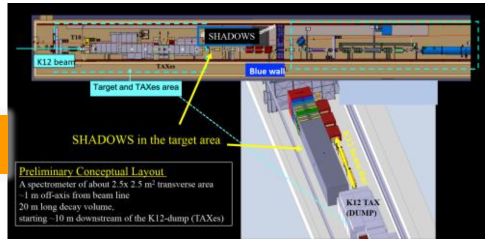
- **Beam delivery to SPS North Area (NA) with potential future users within the Physics Beyond Colliders (PBC) program**



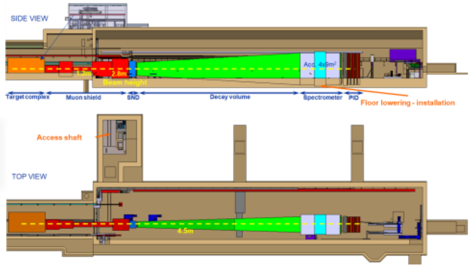
HIKE (Phase 1)



SHADOWS

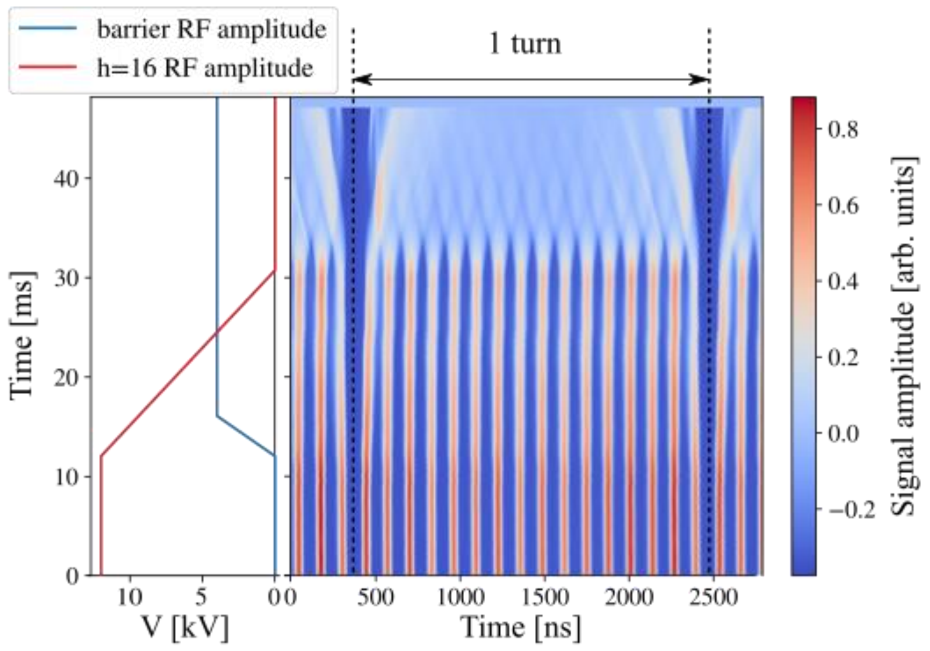


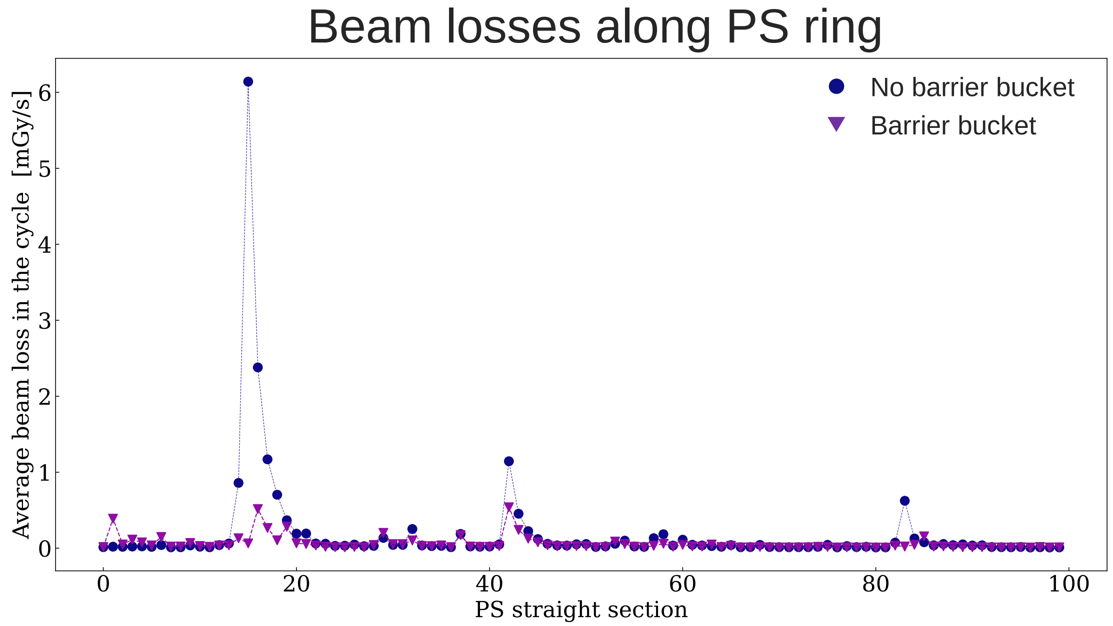
SHiP@ECN3



LIU for fixed target physics …

- **Beam delivery to SPS North Area (NA) with potential future users within the Physics Beyond Colliders (PBC) program**
- **Barrier bucket PS-to-SPS transfer thanks to LIU broadband cavity**
  - Important loss (and activation) reduction at PS extraction, now operational

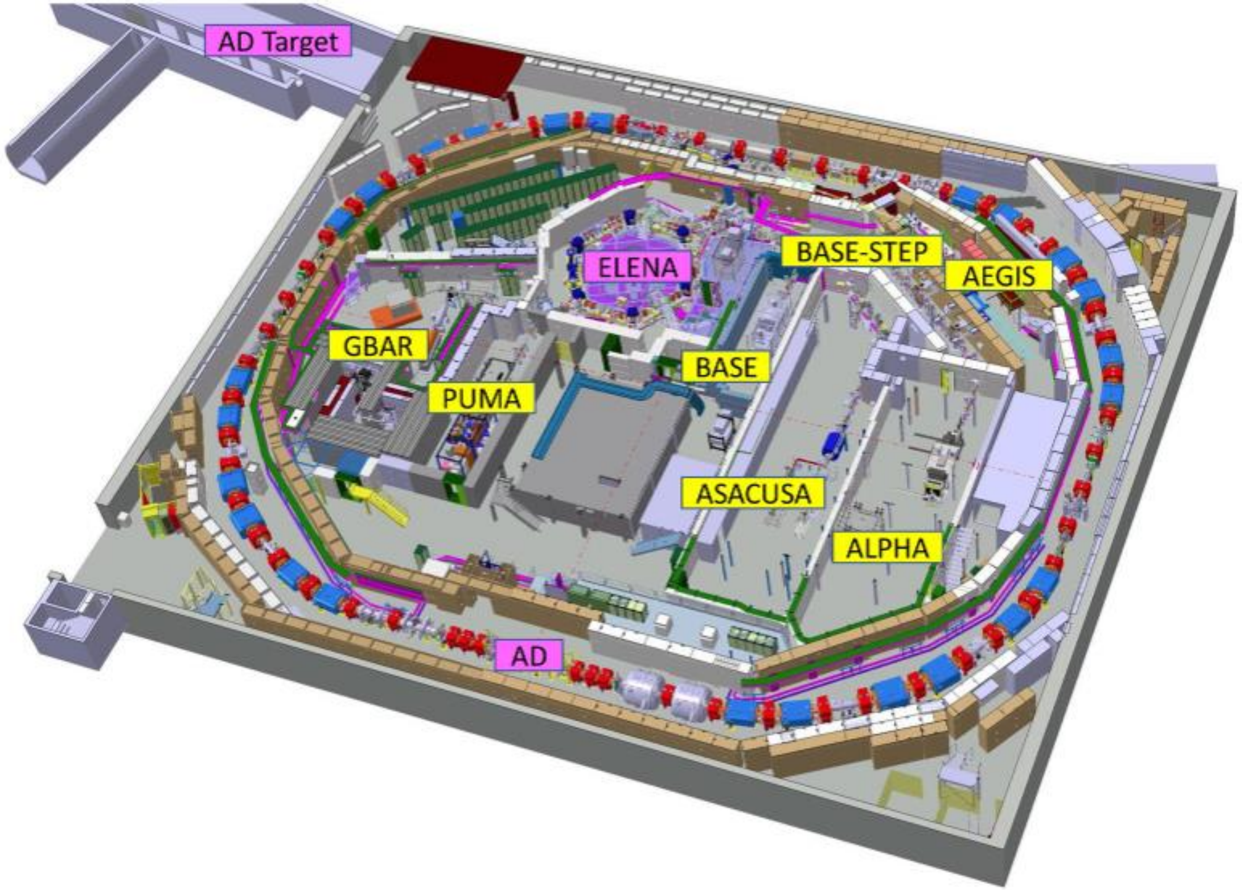




… and antiproton production …

LHC Injectors Upgrade

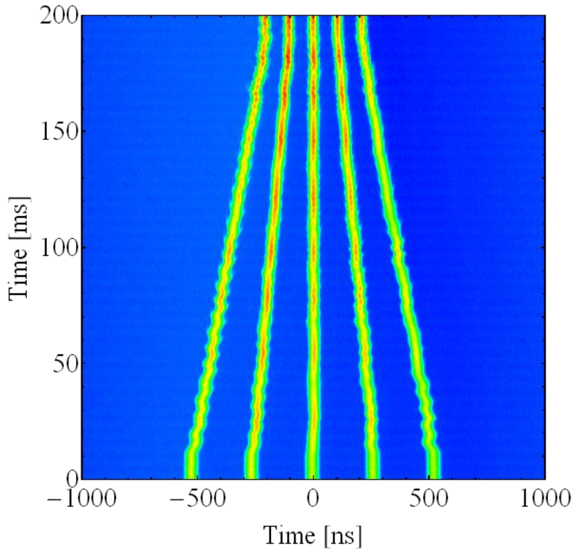
- **Seven experiments receiving 100 keV pbar from Antiproton Decelerator (AD) / ELENA**

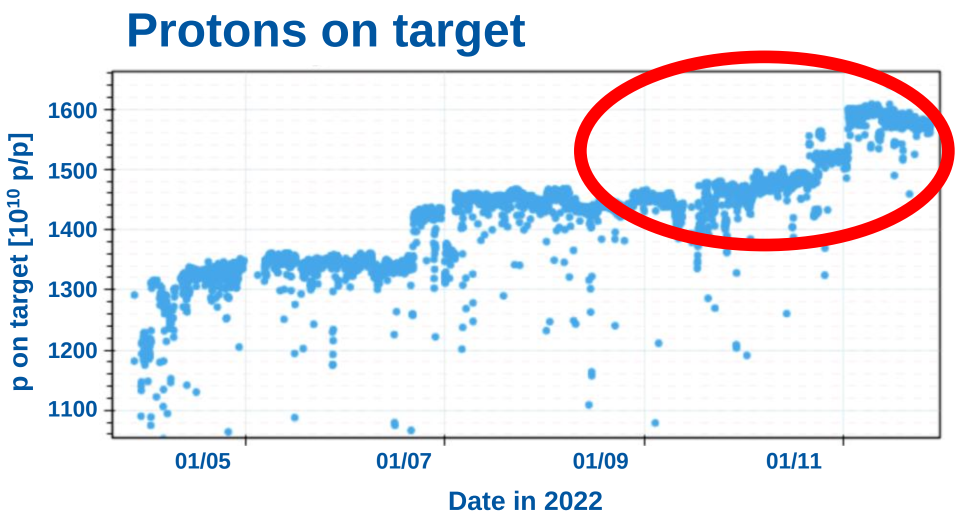


… and antiproton production …

LHC Injectors Upgrade

- **Seven experiments receiving 100 keV pbar from Antiproton Decelerator (AD) / ELENA**
- **Intensity increase on AD target**
  - PSB/PS can send 5 bunches to AD target thanks to lower LIU emittances
  - First increase by >10% end 2022, further 30% increase possible





And much more …

LHC Injectors Upgrade

- **The future has more in store …**
  The case for post HL-LHC colliders is strong and well developed – several choices are on the table and decisions will be taken by the end of this decade

- **The LHC injectors are gearing up for the new era challenges …**
  - Achieve better efficiency and automation of operation
  - Continue minimising environmental impact - CERN energy management and accelerator sustainability panels
  - Play a key role for next generation machines

Summary and outlook

LHC Injectors Upgrade

- **LIU project** was conceived to fulfil the HL-LHC target parameters
  - Completed on time and budget
  - Injectors sequentially back to operation since July 2020
  - Teamwork, diversity and competences were the project strength

- **LIU beam commissioning on schedule**
  - PSB and PS already fulfilled and exceeded LIU targets
  - SPS also in line with ramp-up plan and excellent results already achieved
  - LIU has benefited beams **beyond standard LHC-type**, opening paths for high intensity Fixed Target beams in all injectors

- **Throughout 2023 and 2024 the beam optimization will continue to open a new era of high brightness beam facilities**

IPAC contributions relevant to this talk

LHC Injectors Upgrade

Presenter	Title	IPAC reference
O. Brüning	*Overall status of the HL-LHC project*	**TUYG1**
L. Mether	*Electron cloud observations and mitigation for the LHC Run 3*	**WEPA091**
A. Huschauer	*Beam performance and operational efficiency at the CERN Proton Synchrotron*	**TUPA158**
C. Zannini	*Transverse instabilities at injection energy in the CERN-SPS: Lessons learned during high intensity studies*	**WEPL156**
C. Zannini	*Beam induced heating mitigation of the SPS kickers: A crucial upgrade to move towards HL-LHC beam intensities*	**WEPL157**
G. Papotti	*Experimental confirmation of the impedance reduction campaign in the CERN SPS*	**TUODA2**
A. Lasheen	*Improved antiproton production beam at CERN*	**TUPM075**
A. Lasheen	*Investigations of losses on the CERN SPS flat bottom with HL-LHC type beams*	**TUPA153**
G. Papotti	*An Improved Procedure for Energy Matching between PS and SPS at CERN*	**TUPA156**
G. Papotti	*SPS fixed target spill quality improvements in the longitudinal plane*	**TUPA157**
S. Joly	*Overview of transverse instabilities in the CERN Proton Synchrotron*	**WEPL148**

IPAC contributions relevant to this talk

LHC Injectors Upgrade

Presenter	Title	IPAC reference
S. Joly	*Impedance-induced beam observables in the CERN Proton Synchrotron*	**WEPL149**
M. Neroni	*Characterization of the longitudinal beam coupling impedance and mitigation strategy for the fast extraction kicker KFA79 in the CERN PS*	**WEPL150**
C. Zannini	*Transverse beam coupling impedance studies at the CERN Proton Synchrotron Booster after the LHC Injectors Upgrade*	**WEPL154**
C. Zannini	*Head-Tail Mode Zero Instability Growth Rate Studies in the CERN SPS*	**WEPL155**
C. Zannini	*“Characterization of Transverse Profiles Along the LHC Injector Chain at CERN”, paper*	**WEPL158**
G. Hagmann	*The CERN SPS Low Level RF feedback with amplitude and frequency modulation*	**THPA092**
M. E. Angoletta	*Operation and New Capabilities of CERN's Digital LLRF Family for Injectors*	**THPA094**
P. Baudrenghien	*Beam loading compensation in the CERN SPS 200 MHz cavities. Measurements and comparison with expectations*	**THPA096**
L. Intelisano	*Measurements of longitudinal loss of Landau damping in the CERN Proton Synchrotron*	**WEPA012**

IPAC contributions relevant to this talk

LHC Injectors Upgrade

Presenter	Title	IPAC reference
L. Intelisano	*Longitudinal loss of Landau damping in the CERN Super Proton Synchrotron at 200 GeV*	**WEPA013**
B. Karlsen-Bæck	*Validation of control loop modelling for power limitation studies with beams for HL-LHC*	**TUPA160**
E. Vinten	*Longitudinal microwave instability with long bunches in the CERN Proton Synchrotron*	**WEPA011**
R. Borner	*SPS bunch-by-bunch phase measurement in the CERN SPS Low Level RF*	**THPA093**
J. Egli	*The CERN SPS Low Level RF: Embedded acquisition system for the Cavity-Controller and Beam-Control commissioning and diagnostics*	**THPA095**

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