CERN

ACCELERATOR SEMINAR

Giovanni Rumolo
CERN

Thursday, 29. April 2021 at 4 pm

Online-Seminar via Zoom
(ID: 989 8482 9760/ PW: 266183)

LHC Injectors Upgrade

Accelerator physics challenges of the LHC Injectors Upgrade (LIU) Project

Giovanni Rumolo and Malika Meddahi,
R. Alemany, H. Bartosik, G. Bellodi, J. Coupard, H. Damerau, G.P. Di Giovanni, A. Funken, B. Goddard, K. Hanke, A. Huschauer, V. Kain, A. Lombardi, B. Mikulec, F. Pedrosa, S. Prodon, R. Scrivens, E. Shaposhnikova

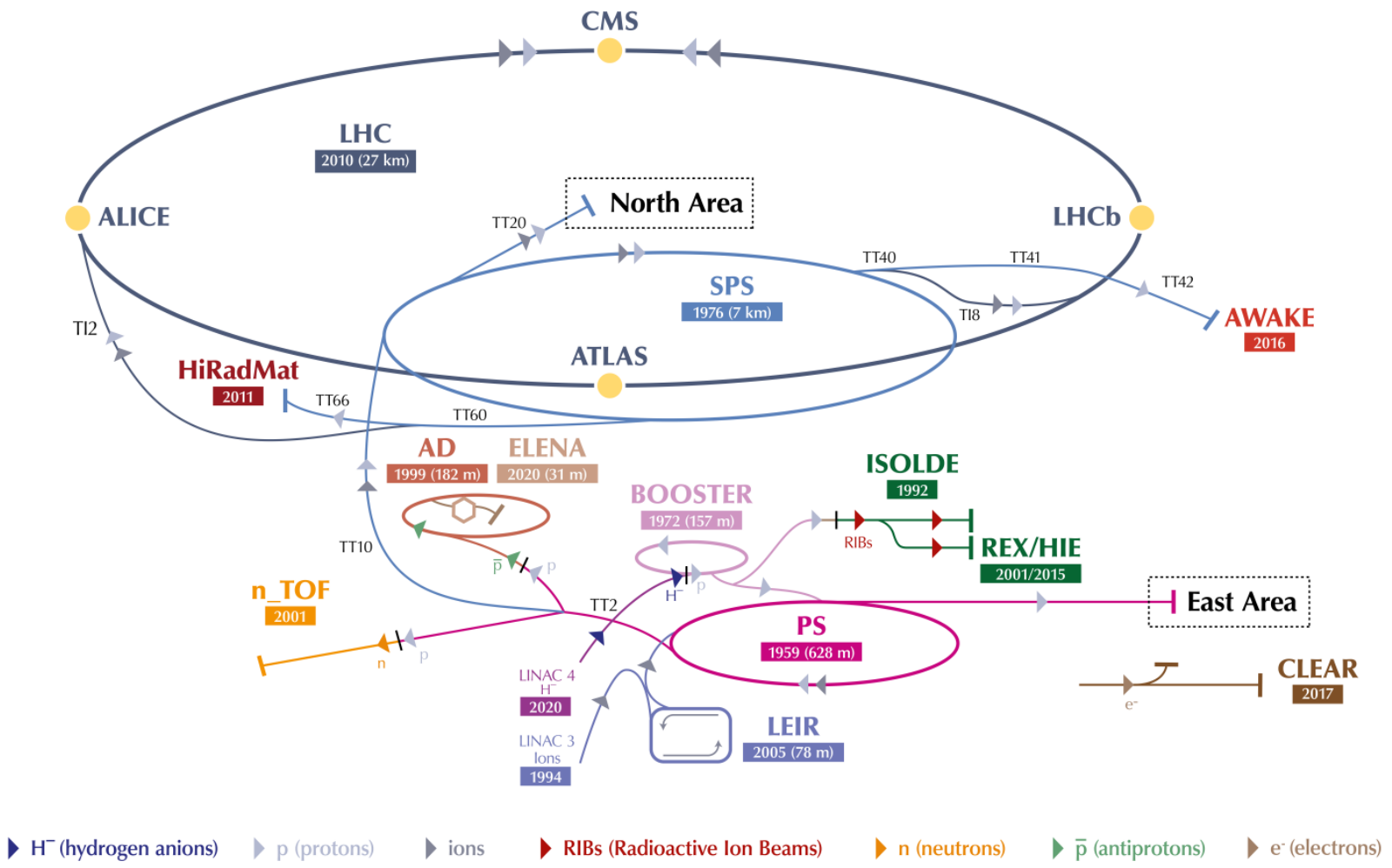
Outline

LHC Injectors Upgrade

- The CERN injectors complex
  - Production scheme of the proton beams for LHC
- The LHC Injectors Upgrade (LIU) project
  - Goals and means of LIU
  - Expected beam performance vs. current performance
  - Highlights of accelerator physics studies
- The LIU project execution
  - Overview on timeline
  - Return to operation and beam performance ramp-up after LIU installation
  - Some first results from beam commissioning
- Conclusions

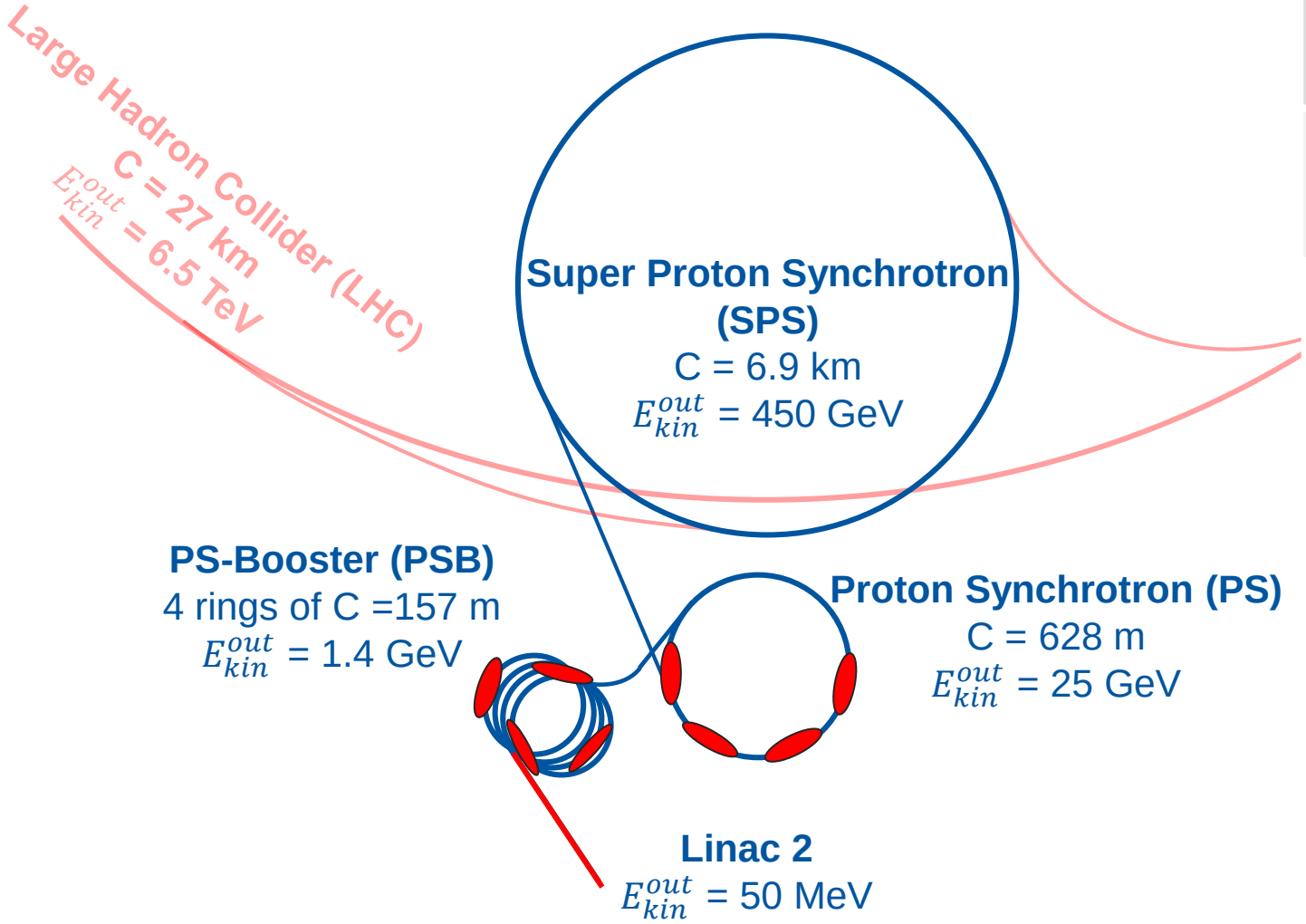
The CERN accelerator complex

LHC Injectors Upgrade



Production scheme of LHC beams before LIU

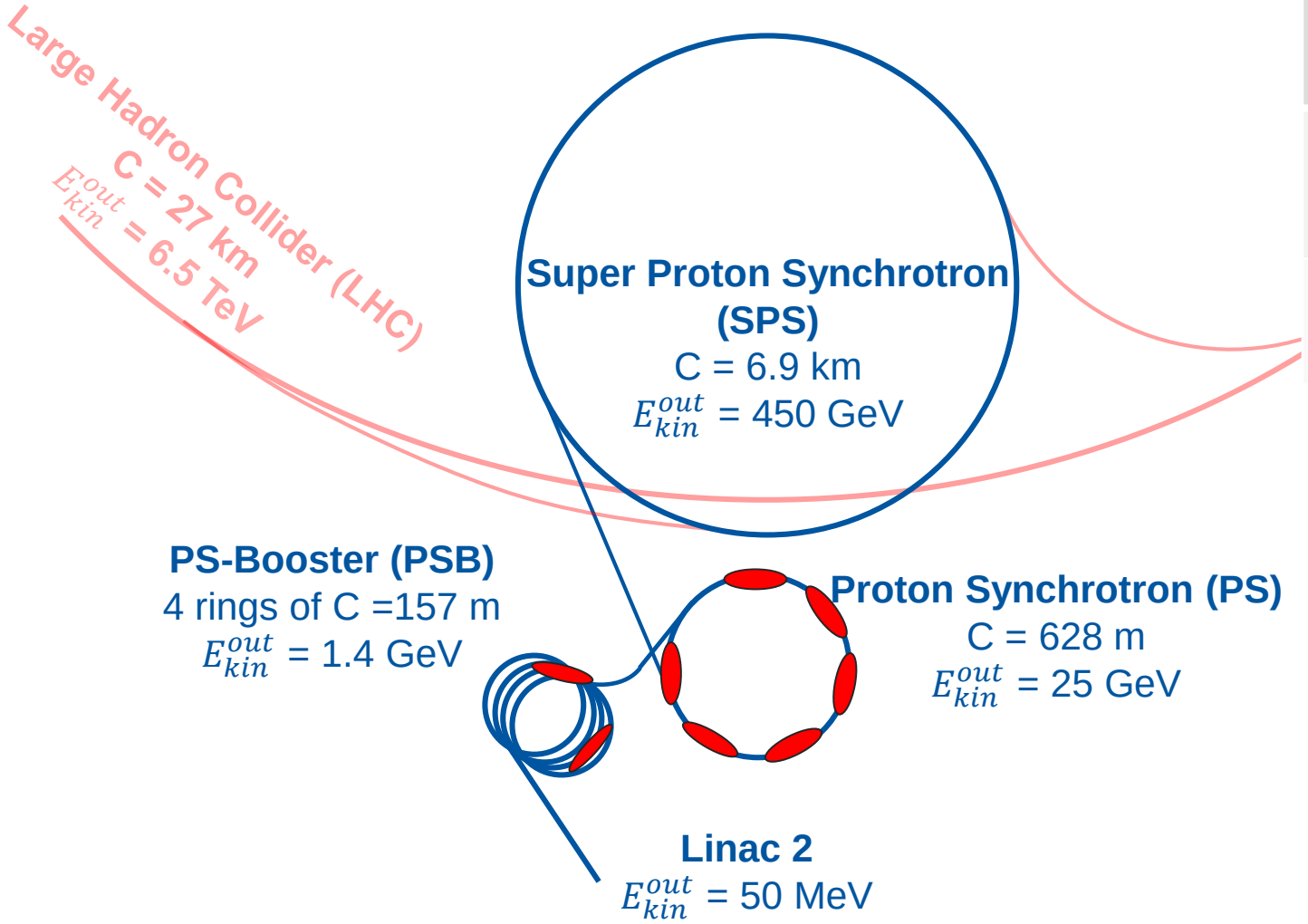
LHC Injectors Upgrade



Beam transfer	Number of bunches	Bunch spacing (ns)
Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–

Production scheme of LHC beams before LIU

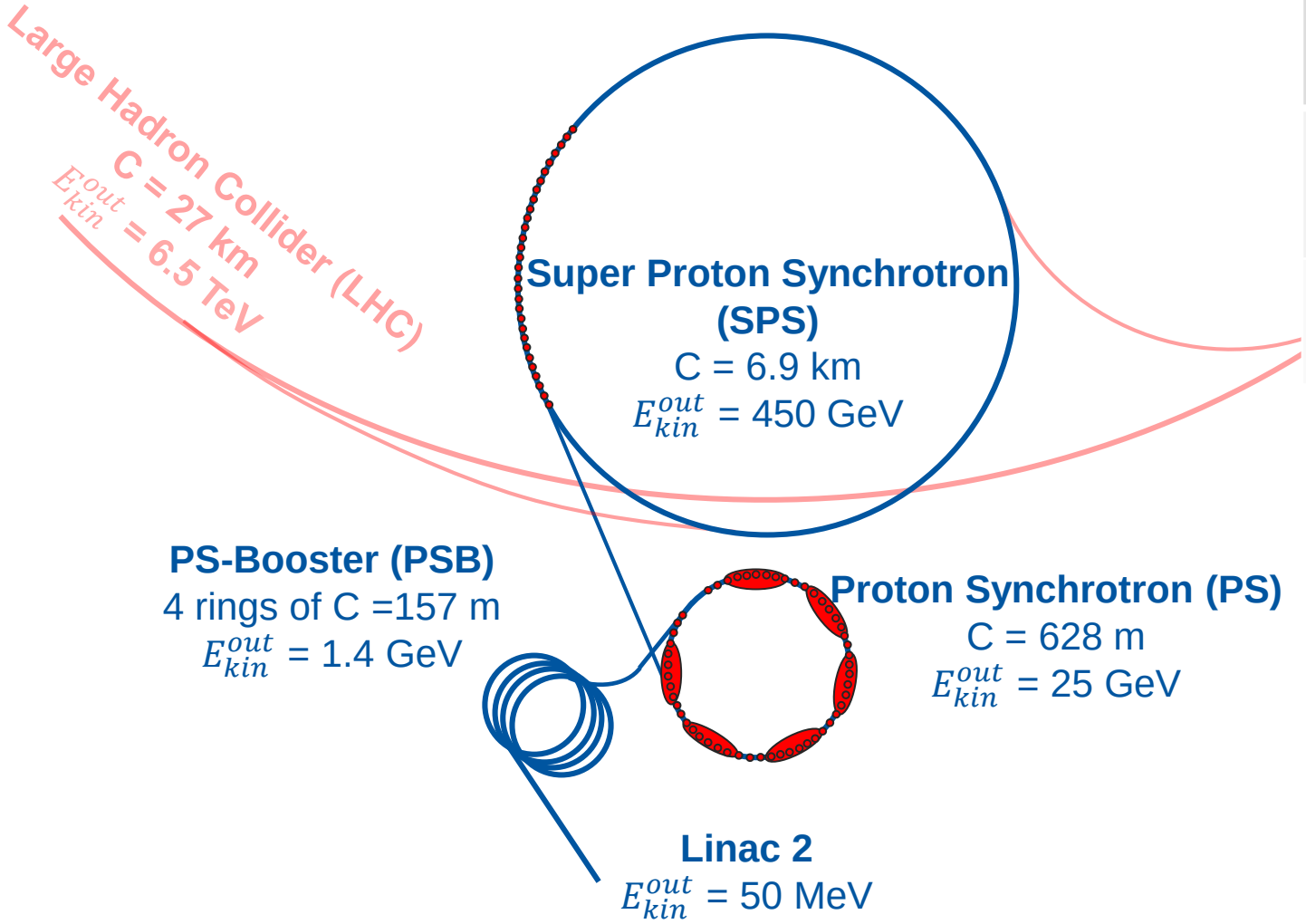
LHC Injectors Upgrade



Beam transfer	Number of bunches	Bunch spacing (ns)
Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272

Production scheme of LHC beams before LIU

LHC Injectors Upgrade

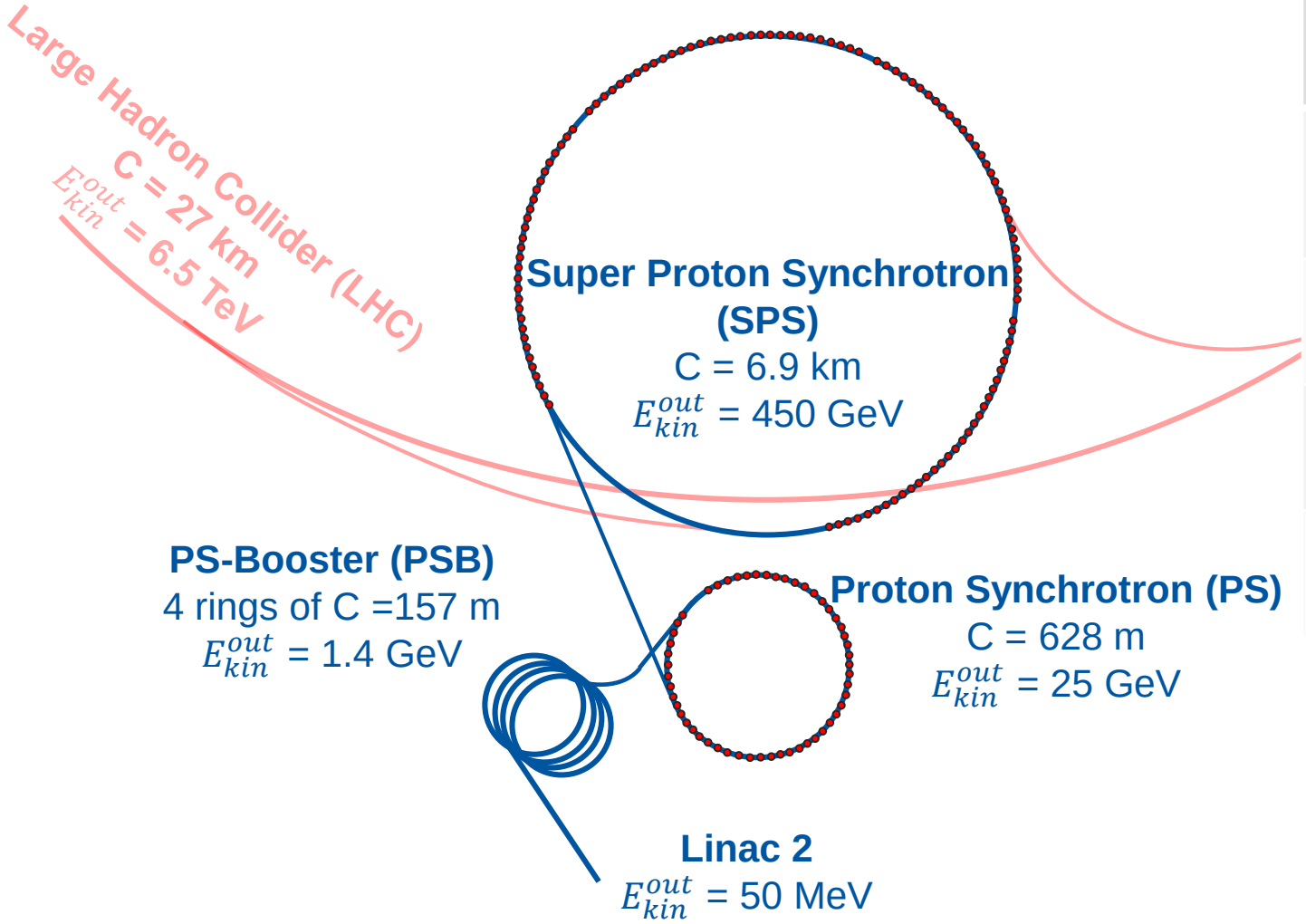


Beam transfer	Number of bunches	Bunch spacing (ns)
Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272

One triple bunch splitting and two double bunch splittings in the PS

Production scheme of LHC beams before LIU

LHC Injectors Upgrade



Beam transfer	Number of bunches	Bunch spacing (ns)
Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272
PS → SPS E_{kin}^{out} = 25 GeV	72	25

Four injections into the SPS

Goals of CERN upgrades in a nutshell (HL-LHC)

LHC Injectors Upgrade

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

Goals of CERN upgrades in a nutshell (LIU)

LHC Injectors Upgrade

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

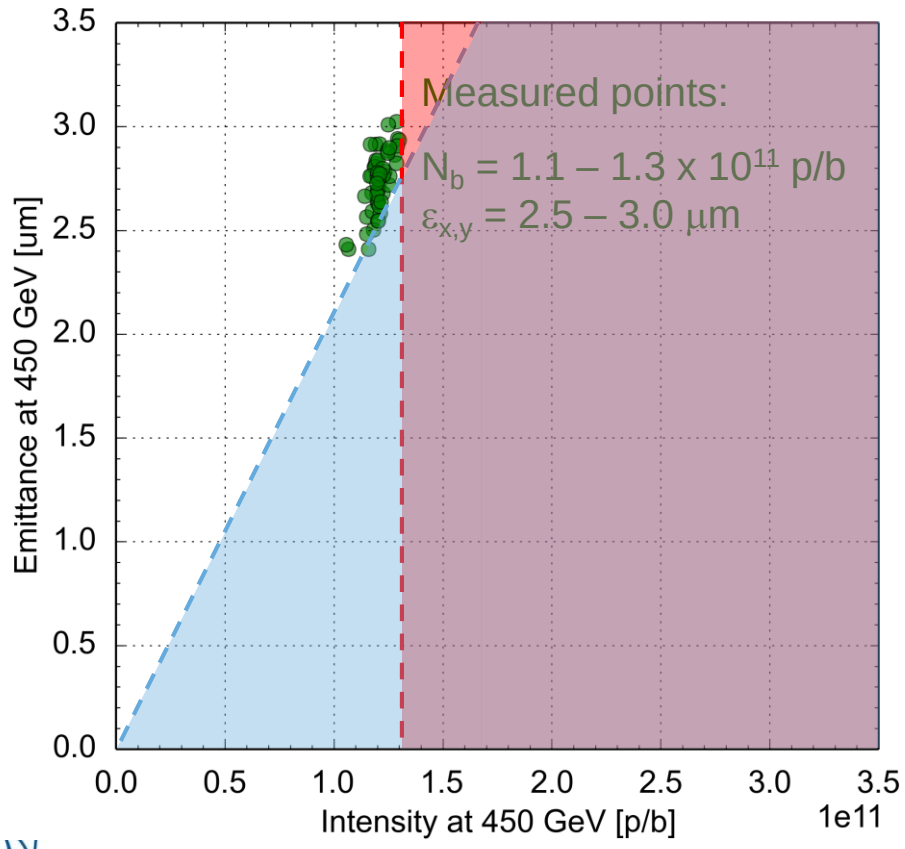
The **LHC Injectors Upgrade (LIU)**

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

LHC beam limitation diagrams

LHC Injectors Upgrade

- Intensity and brightness of the LHC beams at the **SPS extraction (450 GeV)** result from intensity and brightness limitations of all injectors in the chain



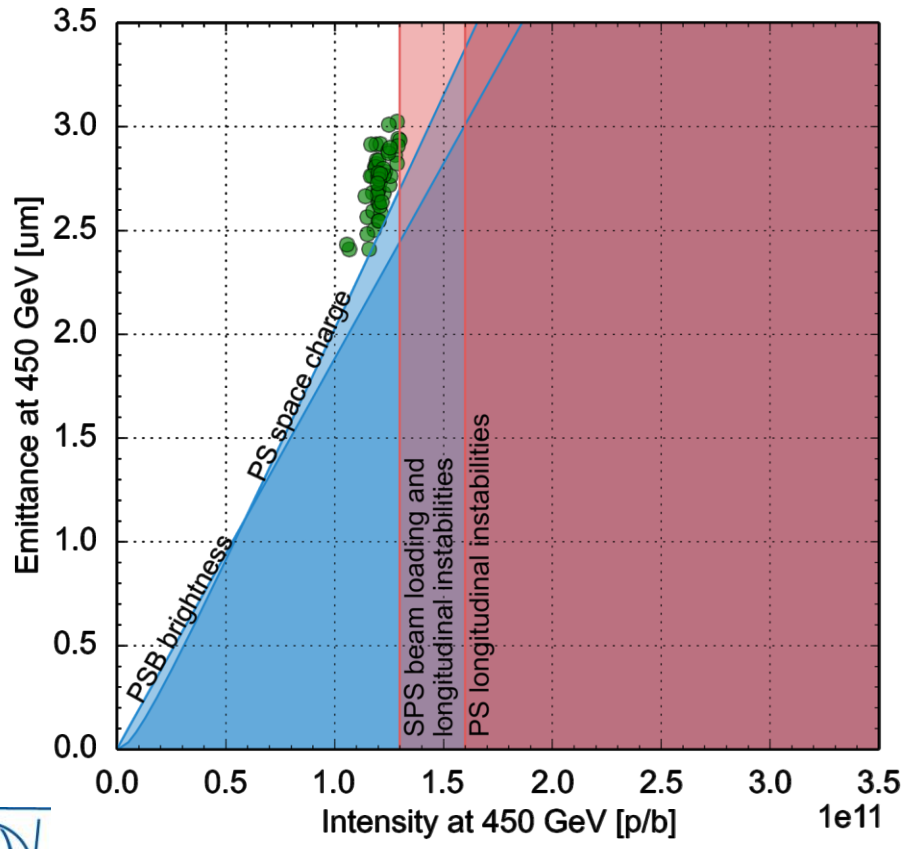
- Coherent instabilities, electron cloud, beam induced heating, beam losses typically limit the achievable **intensity**

$$N_b < N_{\max}$$

LHC beam performance before upgrade

LHC Injectors Upgrade

- LHC beam parameters at the **SPS extraction (450 GeV)** result from intensity and brightness limitations of all injectors in the chain



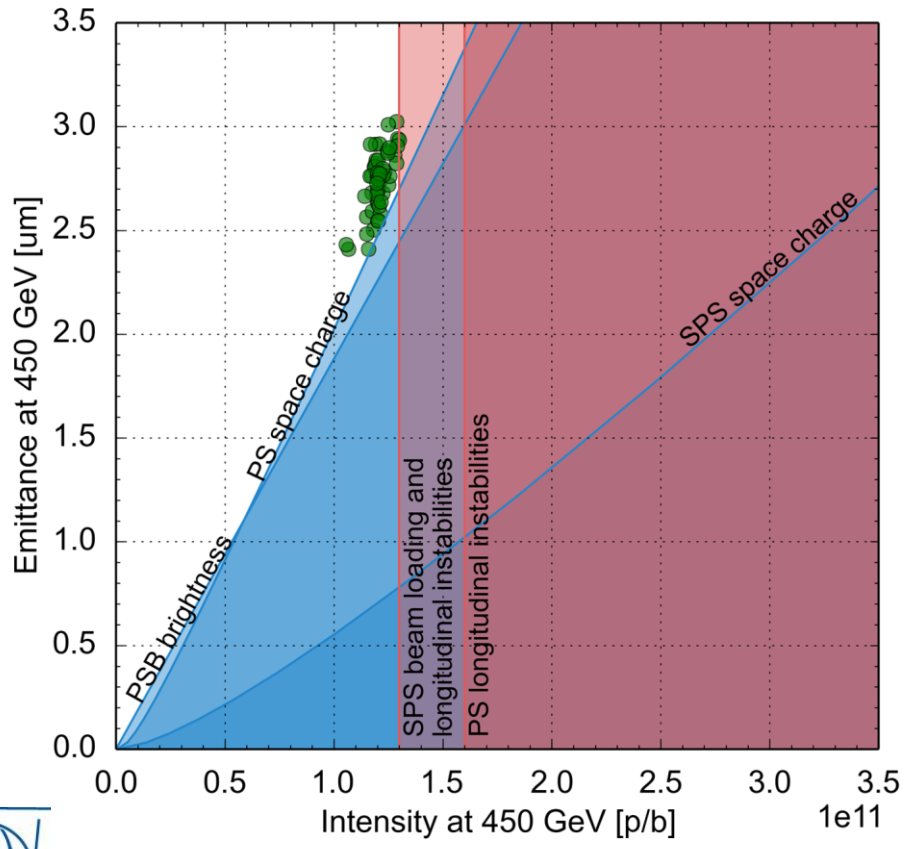
- **Brightness**
  - PSB brightness determined by space charge at injection
  - Limit for PS space charge at injection $\Delta Q_y < 0.31$

- **Intensity**
  - SPS is limited by beam loading and longitudinal instabilities on the ramp and flat top
  - PS is limited by longitudinal coupled bunch instability on the ramp and flat top

LHC beam performance before upgrade

LHC Injectors Upgrade

- LHC beam parameters at the **SPS extraction (450 GeV)** result from intensity and brightness limitations of all injectors in the chain

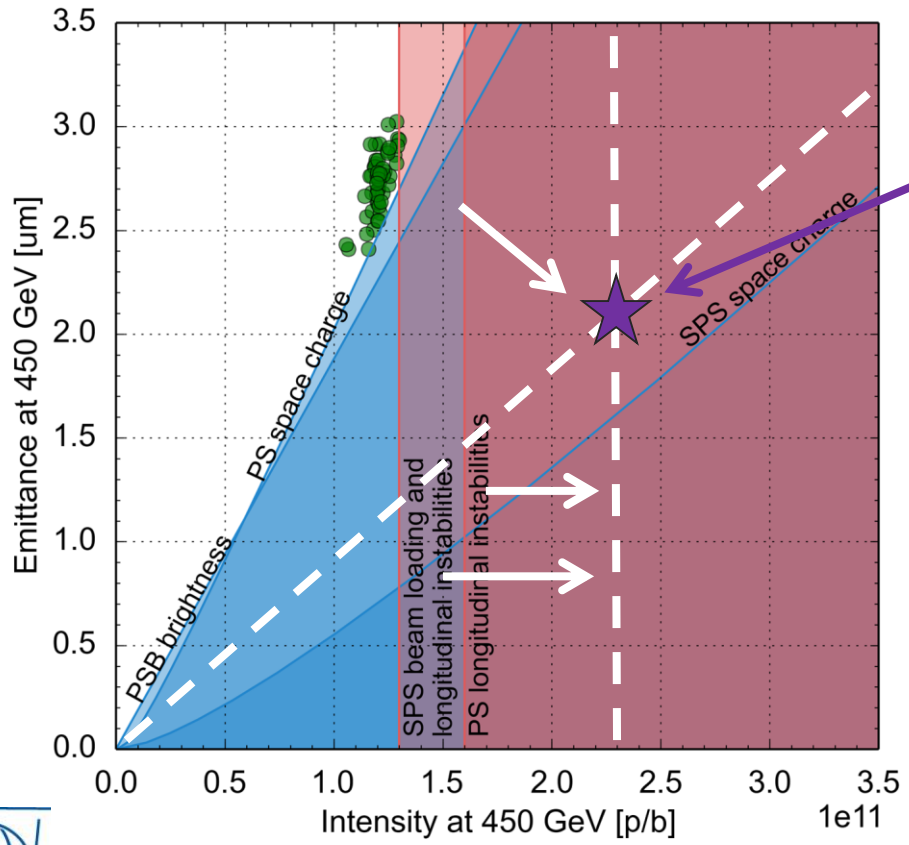


- **Brightness**
  - PSB brightness determined by space charge at injection
  - Limit for PS space charge at injection $\Delta Q_y < 0.31$
  - ✓ *Space charge in SPS not a limit for LHC beams*
- **Intensity**
  - SPS is limited by beam loading and longitudinal instabilities on the ramp and flat top
  - PS is limited by longitudinal coupled bunch instability on the ramp and flat top
  - ✓ *PSB intensity limit well above displayed range*

The LHC Injectors Upgrade (LIU) project

LHC Injectors Upgrade

- **Performance goal** → Match the beam parameters at **SPS extraction** to the **High Luminosity LHC (HL-LHC) target**



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

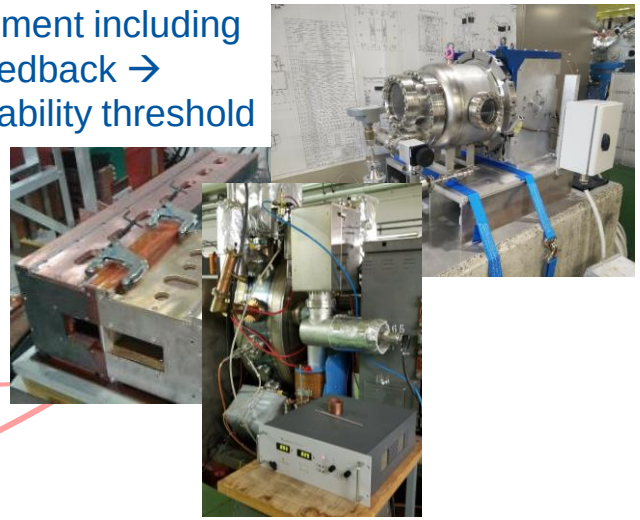
- **LIU strategy**
  - →Identify the sources of the performance limitations in each of the injectors impeding the achievement of the HL-LHC target parameters
  - →Define and deploy the necessary upgrade items to overcome these limitations

A quick overview on the LIU project

LHC Injectors Upgrade

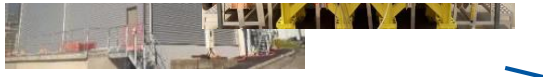
- Main **RF** system (200 MHz) upgrade → Increased RF power and improved controls
- Longitudinal **impedance** reduction & partial a-C coating → Increased instability thresholds
- New **beam dump** and protection devices

- **2 GeV** injection → Reduced space charge at PS injection
- New **RF** equipment including broad-band feedback → Increased instability threshold



Super Proton Synchrotron (SPS)
C = 6.9 km
E_{kin}^{out} = 450 GeV

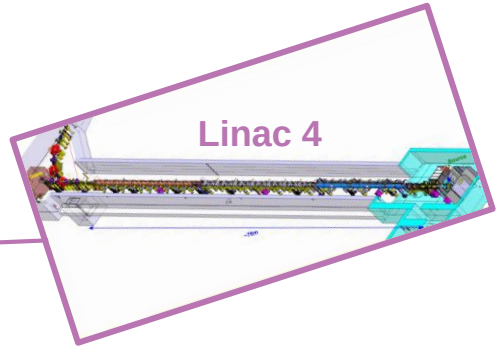
PS-Booster (PSB)
4 rings of C =157 m
E_{kin}^{out} = 2.0 GeV



- **160 MeV** H⁻ charge exchange injection → Reduced space charge at PSB injection
- Acceleration to **2 GeV** with new main power supply and new RF systems

- Acceleration of H⁻ to **160 MeV**
- Target 25 mA within 0.3 μm

Proton Synchrotron (PS)
C = 628 m
E_{kin}^{out} = 25 GeV

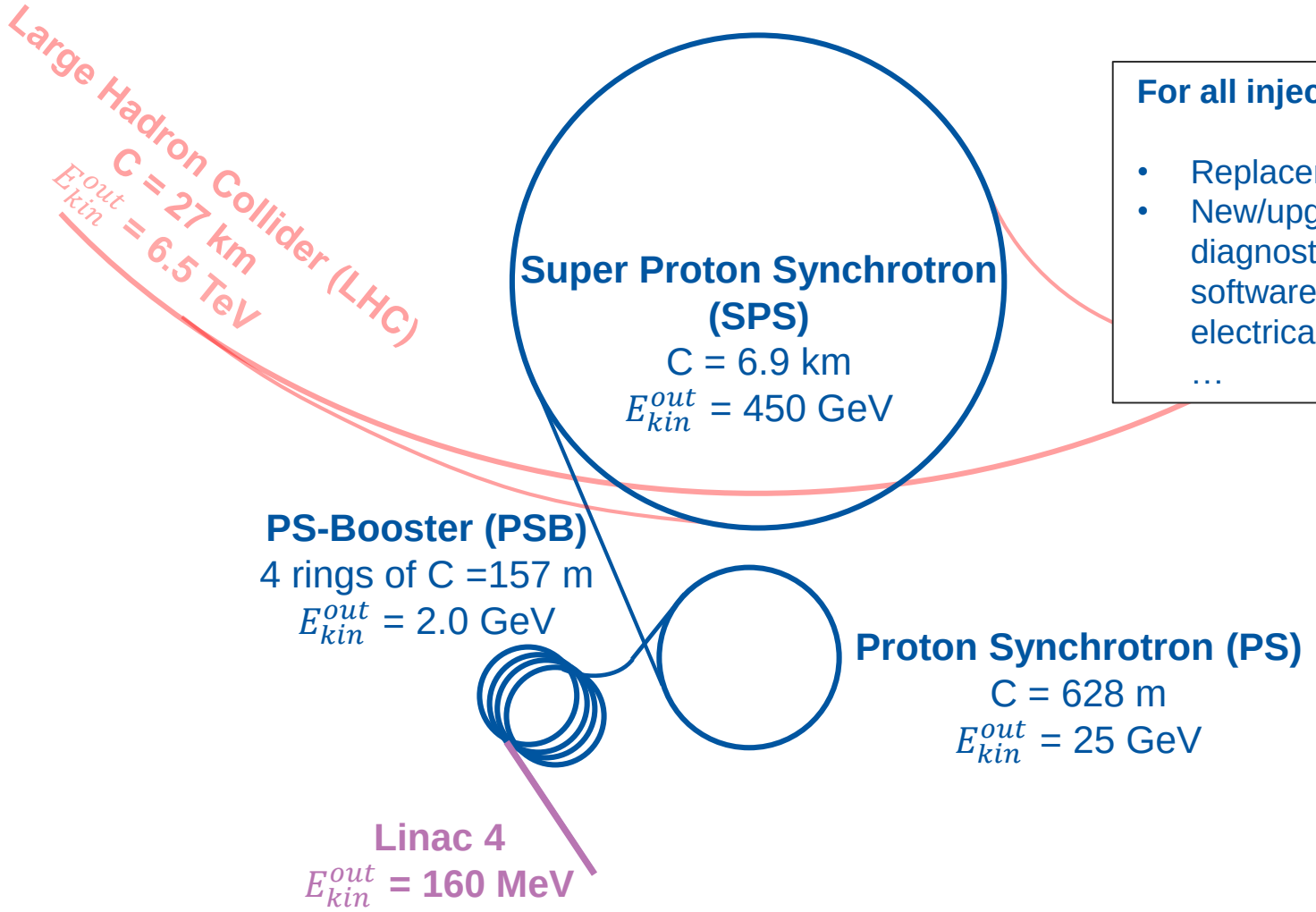


Linac 4
E_{kin}^{out} = 160 MeV

Linac 2
E_{kin}^{out} = 50 MeV

A quick overview on the LIU project

LHC Injectors Upgrade



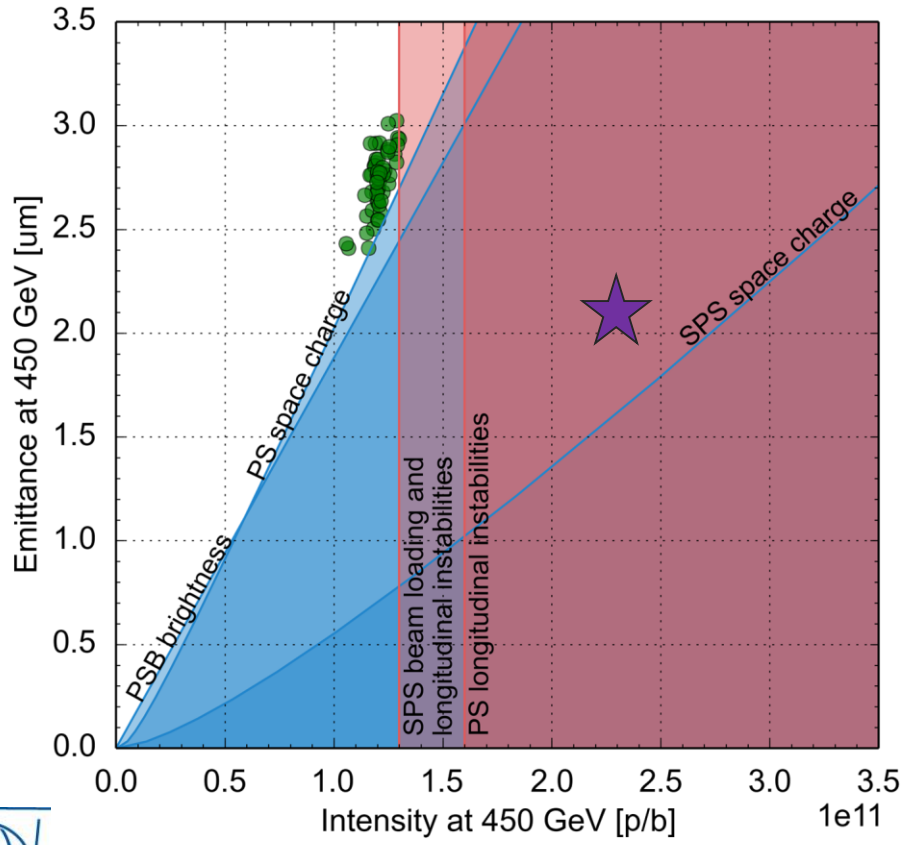
For all injectors :

- Replacement of ageing/sensitive hardware
- New/upgraded beam instrumentation and diagnostics devices, vacuum systems, software tools, machine protection, electrical services, cooling and ventilation …

Beam performance with LIU upgrades

LHC Injectors Upgrade

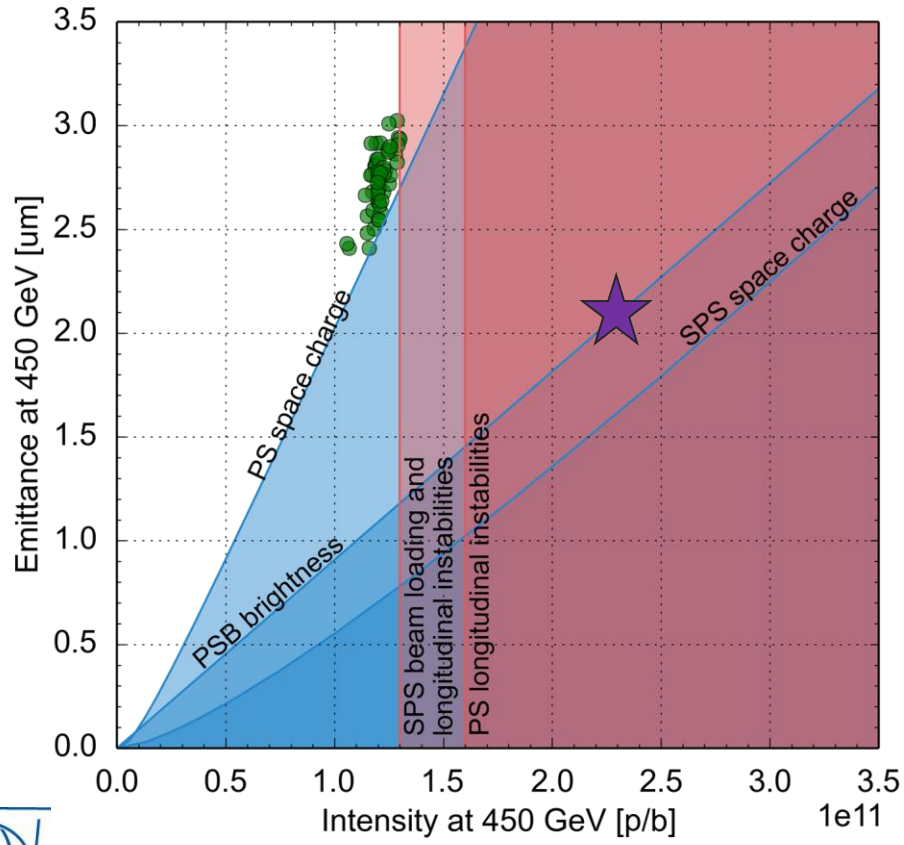
- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



Beam performance with LIU upgrades

LHC Injectors Upgrade

- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance

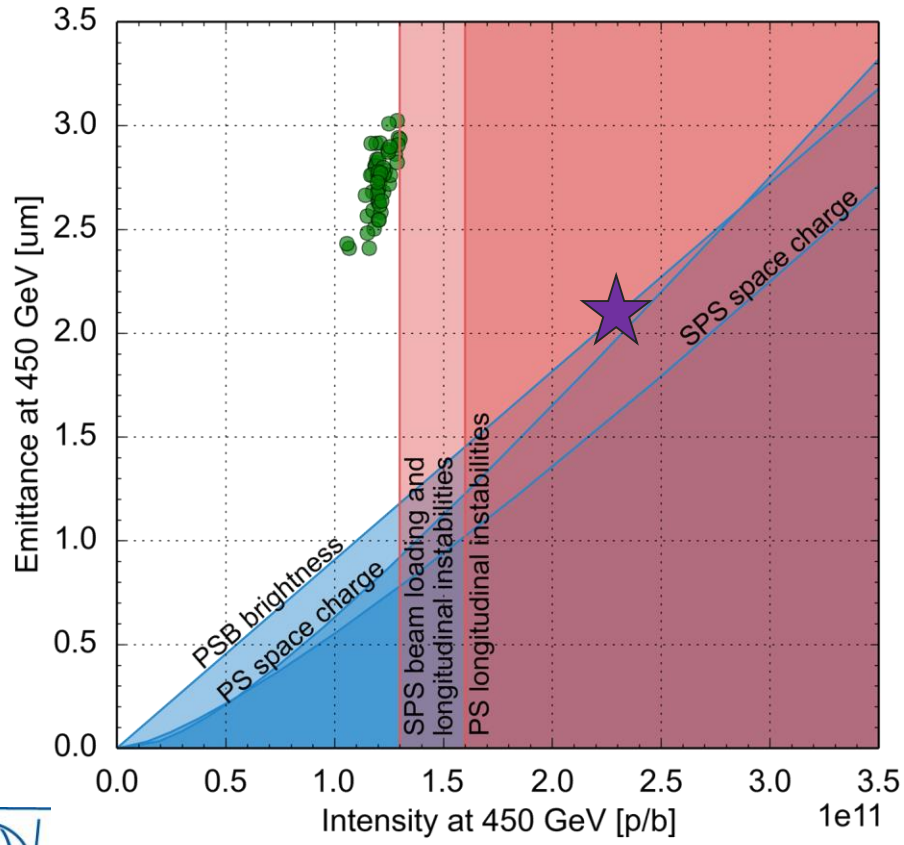


- **Connection of PSB to Linac4**
  - Linac4 providing 25 mA within 0.4 um
  - Charge exchange H^- injection at 160 MeV into PSB

Beam performance with LIU upgrades

LHC Injectors Upgrade

- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance

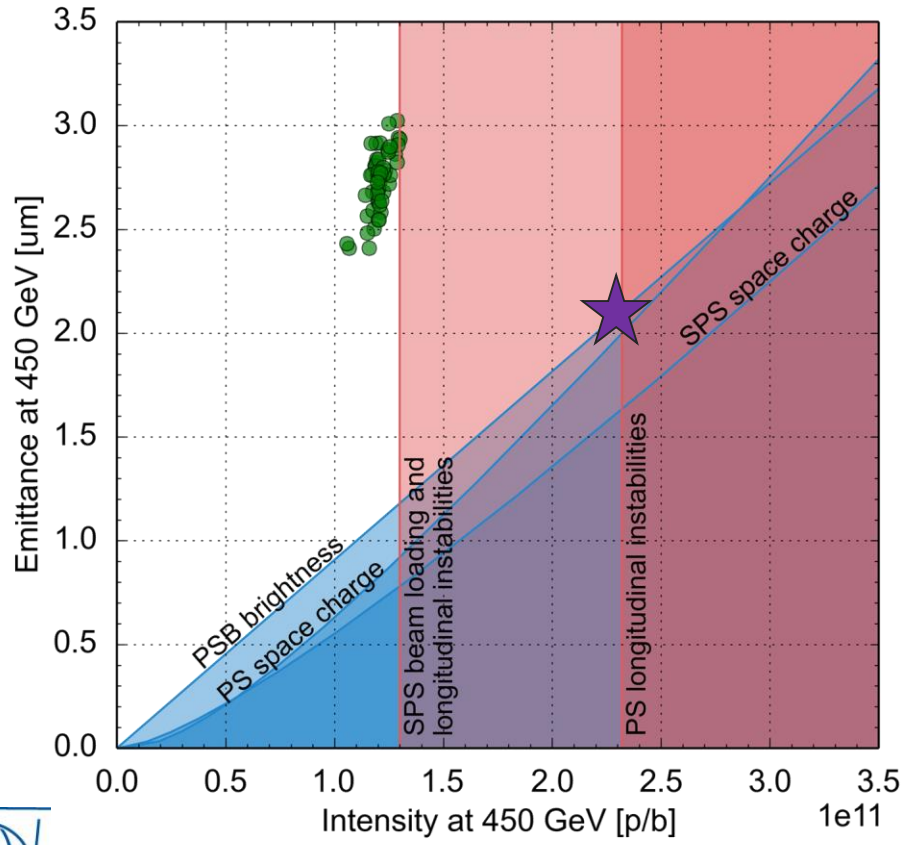


- Connection of PSB to Linac4
- **PSB acceleration to 2 GeV**
  - New main power supply and RF system in PSB
  - New injection region in PS

Beam performance with LIU upgrades

LHC Injectors Upgrade

- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance

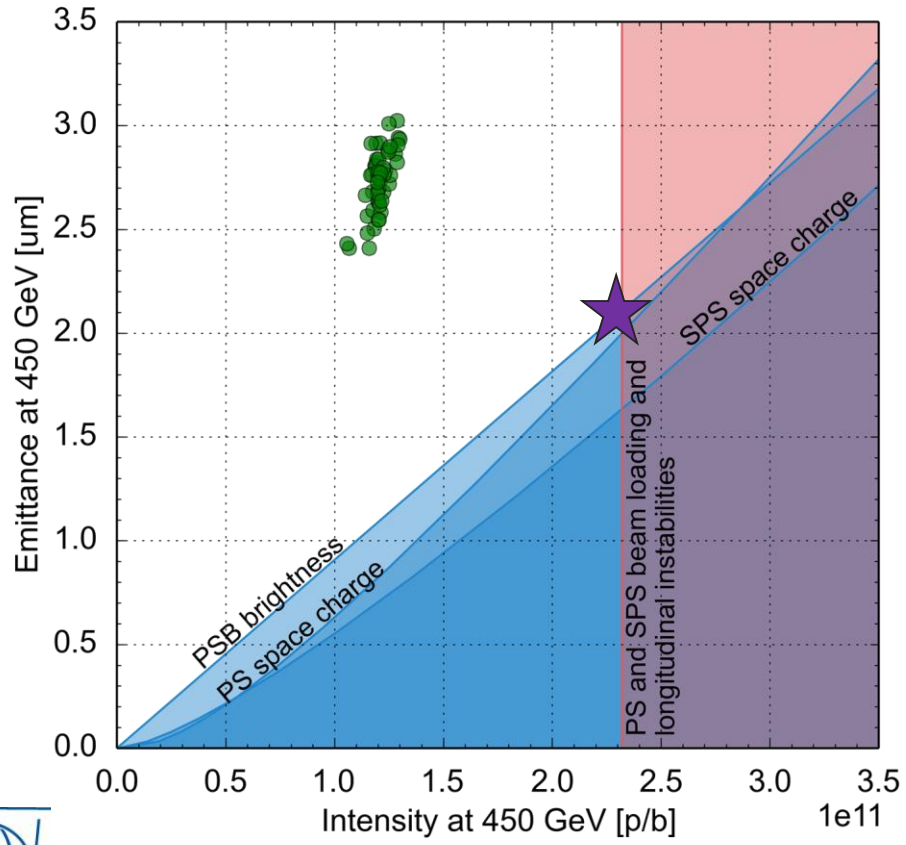


- Connection of PSB to Linac4
- PSB acceleration to 2 GeV
- **PS RF upgrades, e.g.**
  - New broadband cavity for longitudinal feedback system against instabilities
  - Impedance reduction of RF systems

Beam performance with LIU upgrades

LHC Injectors Upgrade

- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance

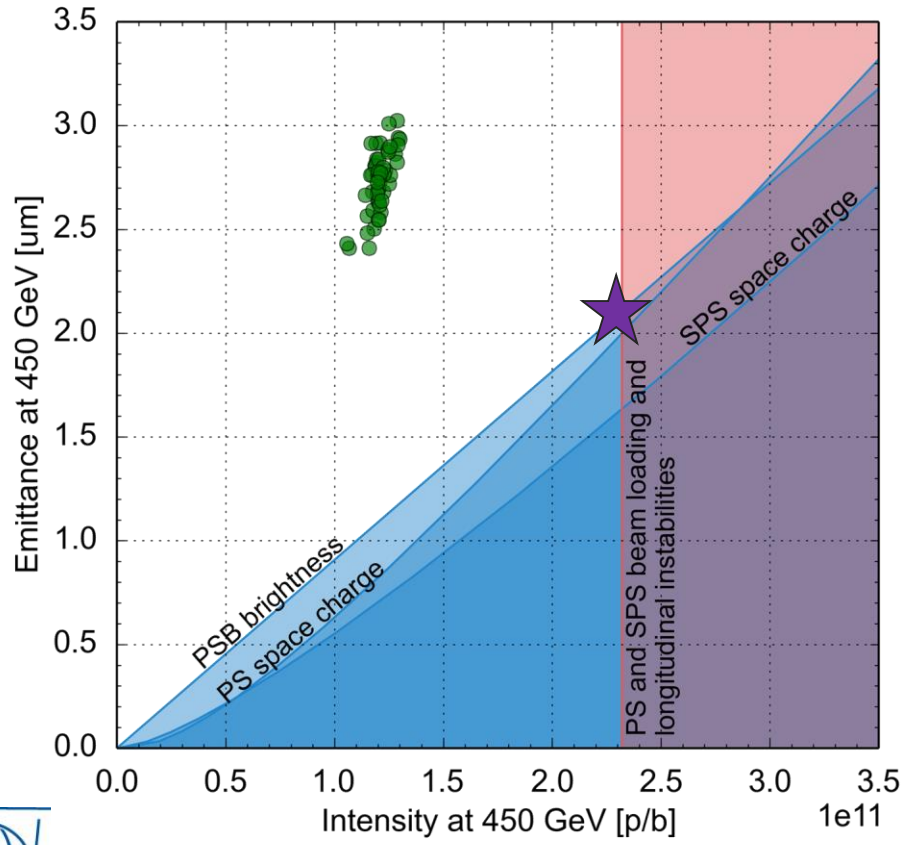


- Connection of PSB to Linac4
- PSB acceleration to 2 GeV
- PS RF upgrades
- **SPS upgrade**
  - Power and LLRF upgrade of 200 MHz RF system
  - Longitudinal impedance reduction
  - a-C coating of focusing quadrupole chambers
  - Deployment of low γ_t optics
  - Upgrade of beam dump and protection devices

Beam performance with LIU upgrades

LHC Injectors Upgrade

- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



✓ Connection of PSB to Linac4

✓ PSB acceleration to 2 GeV

✓ PS RF upgrades

✓ SPS upgrade

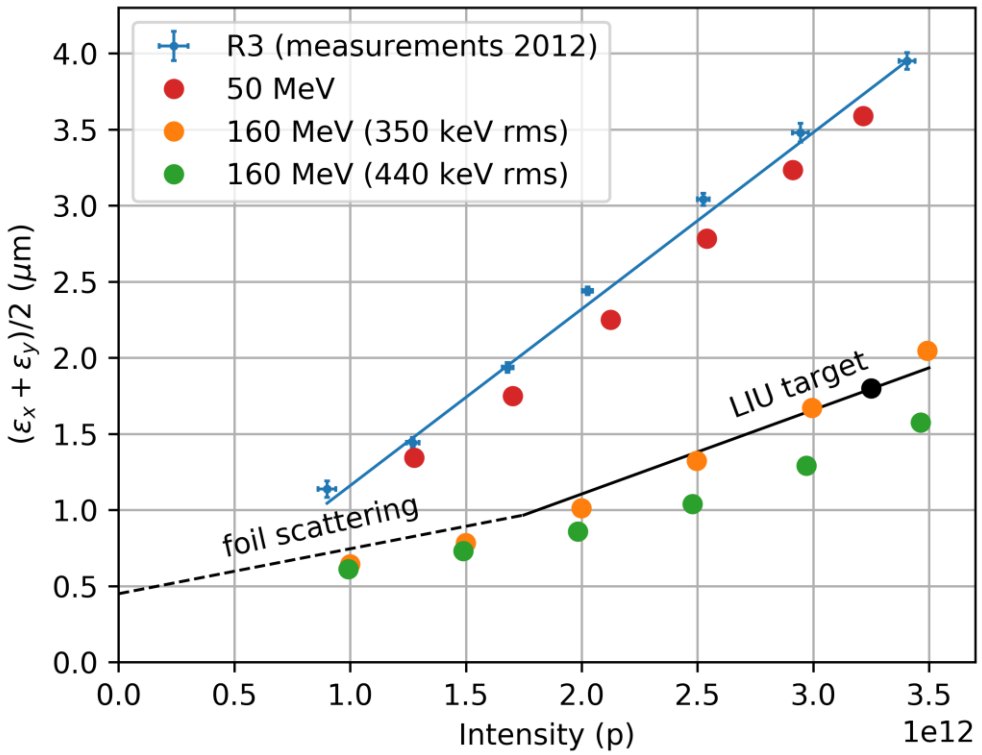
⇒ **LIU parameter reach for proton beams matches the HL-LHC target within baseline**

Some examples of studies that guided definition of LIU parameter reach or LIU baseline choices

(1) Connection of PSB to Linac4

LHC Injectors Upgrade

- The achievable beam brightness with multiturn injection at 50 MeV (Linac2) is inherently limited by the injection process and space charge
  - Linear increase of transverse emittance with increase of injected intensity
  - Simulations could closely reproduce measured slope
- Brightness can be doubled by moving to **H- injection at 160 MeV** (~twice $\beta\gamma^2$)
  - Simulations show that indeed brightness can be improved by factor 2, and even beyond by optimizing injection parameters (e.g., incoming energy spread)
  - Limit coming from Linac4 emittance and scattering against stripping foil for low intensity

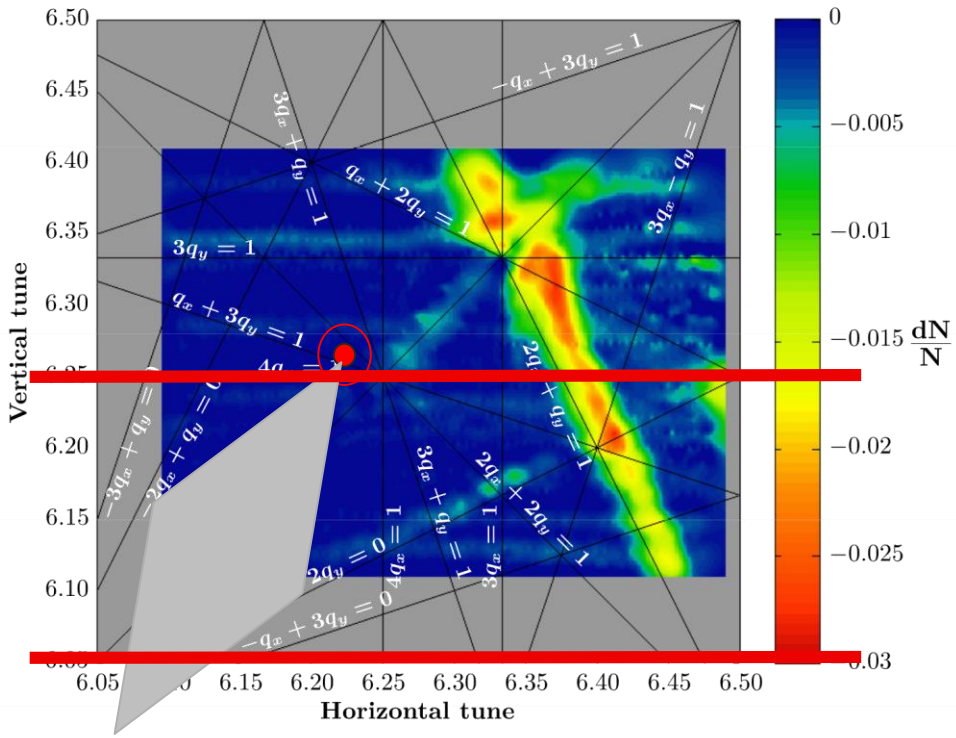


(2) PS space charge

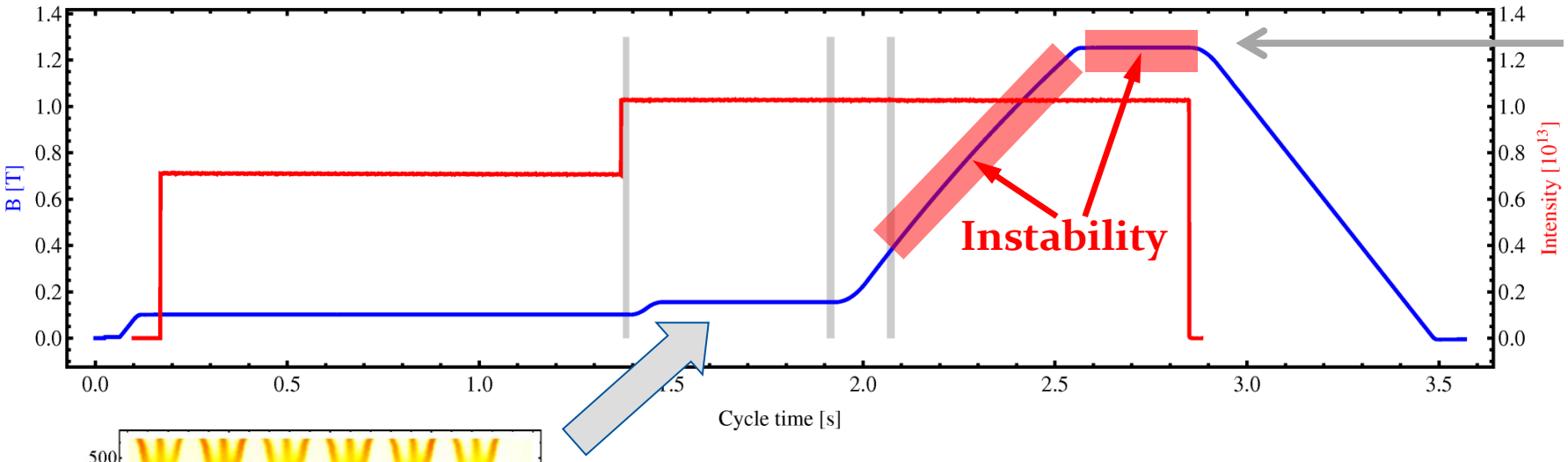
LHC Injectors Upgrade

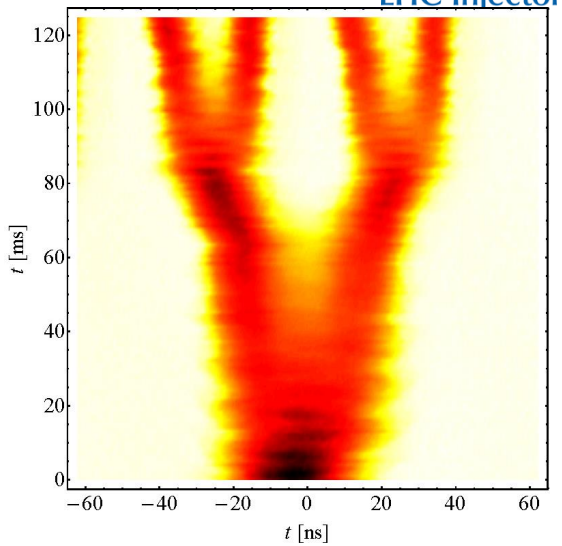
- Space charge plays a crucial role at the PS injection
  - 4 PSB bunches with large tune spread sit at injection energy for 1.2 s
  - Tune spread needs to be accommodated between integer resonance and space charge driven structural resonance 8Qy=50 during 1.2 sec flat bottom

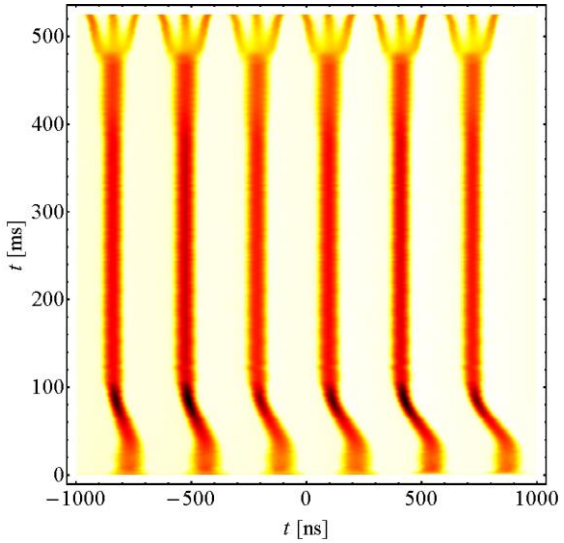
- In order to keep the pre-LIU tune spread at injection with double intensity in the same transverse ε
  - Increase of injection energy to **2 GeV** (63% gain in $\beta\gamma^2$)
  - **Larger longitudinal emittance** at PSB-PS transfer to allow for longer bunches and larger δp/p



(3) PS intensity limitation





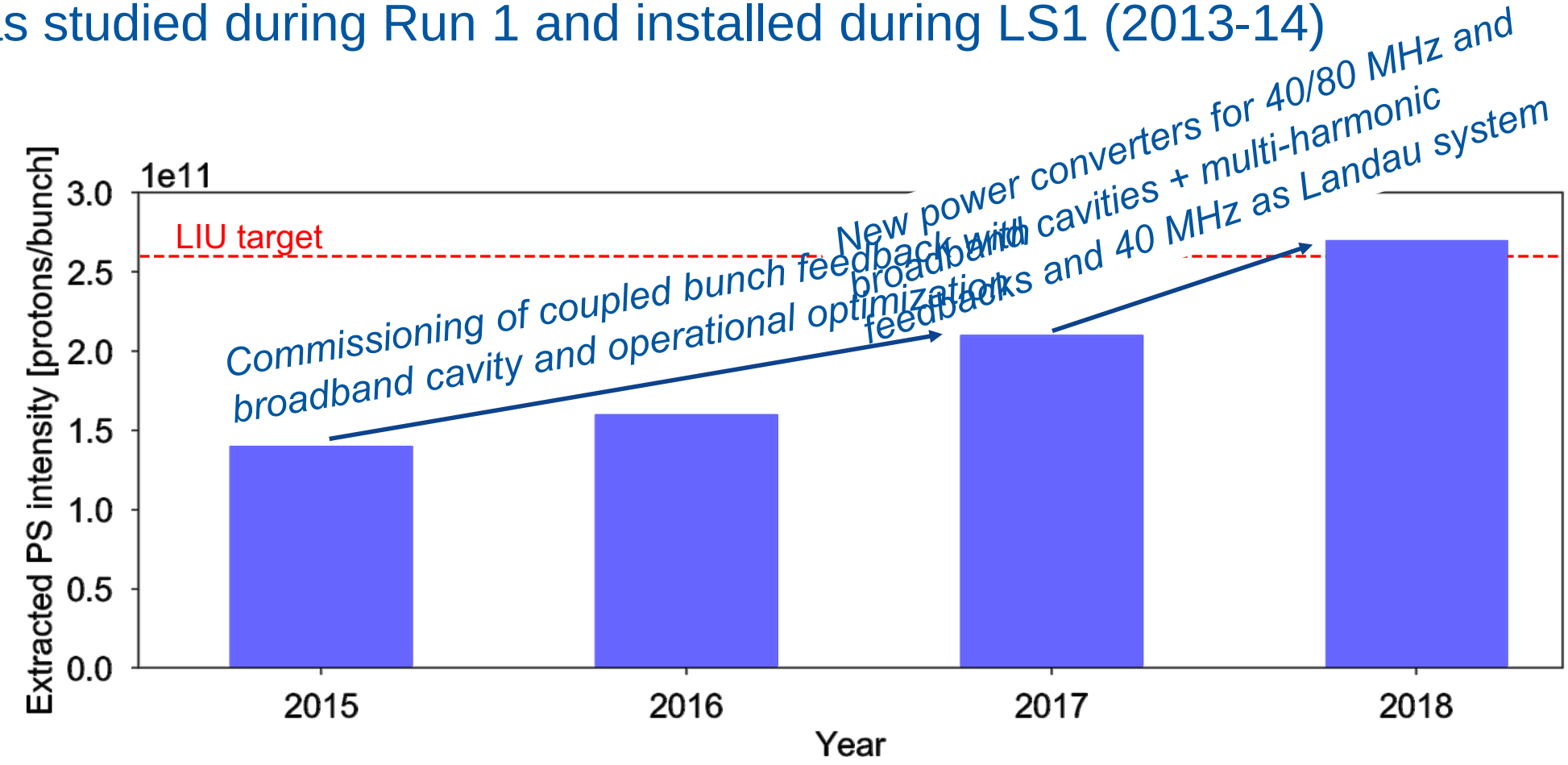


- Bunch current limited to **1.5e11 p/b at extraction**
- Above 1.5e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top
  - Simulations show it is a dipolar oscillation mainly driven by **10 MHz RF system impedance**
- Need **broad-band feedback system** to counteract this instability

(3) PS intensity limitation

LHC Injectors Upgrade

- Broadband cavity to act as **kicker for longitudinal feedback system in PS** was studied during Run 1 and installed during LS1 (2013-14)



(3) PS intensity limitation

LHC Injectors Upgrade

- Broadband cavity to act as **kicker for longitudinal feedback system in PS** was studied during Run 1 and installed during LS1 (2013-14)

✓ Thanks to operational deployment + further RF improvements, **LIU target intensity at PS extraction could be already achieved with margin**

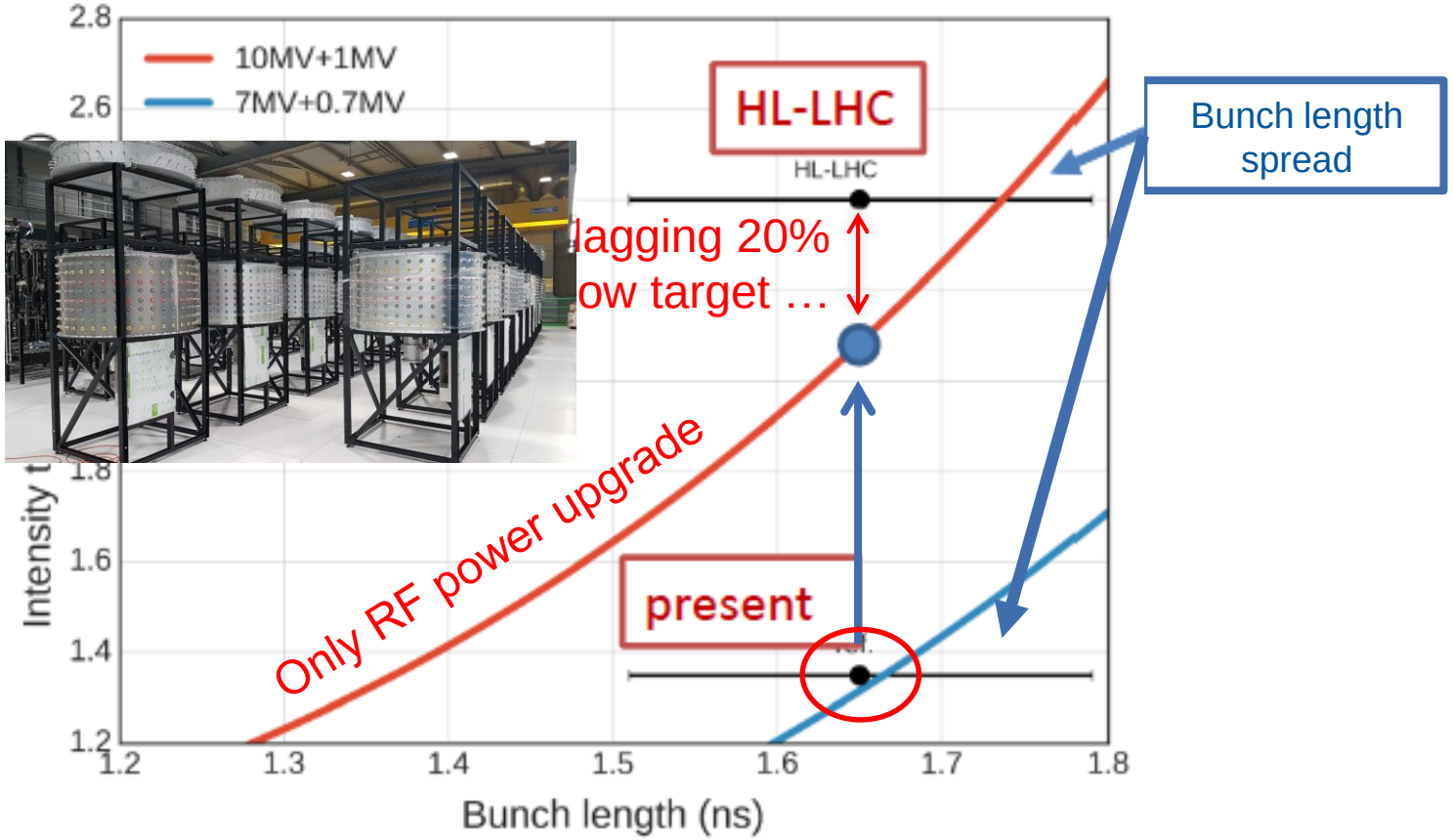
- Disclaimer: LIU brightness only available with Linac4 and 2 GeV PSB upgrade

- **Lesson learnt** → Full exploitation of new hardware, i.e. up to delivery of the benefits anticipated on paper, requires time and extensive machine studies

(4) SPS intensity limitation (longitudinal)

LHC Injectors Upgrade

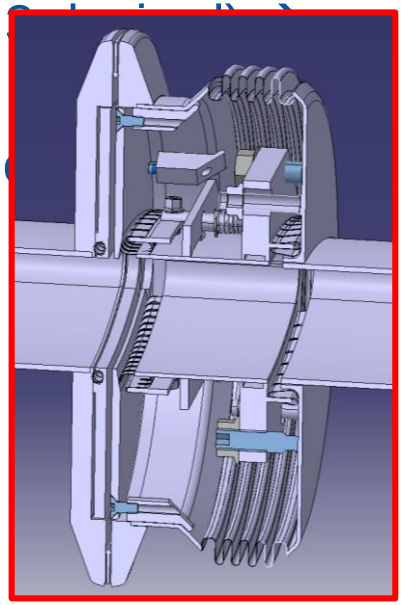
- **SPS intensity limitations**
  - **Beam loading** in the present 200 MHz TW RF system
  - **Longitudinal instabilities** during ramp with very low threshold currently cured by
    - 800 MHz RF system in bunch shortening mode
    - Controlled emittance blow-up (with constraint of 1.7 ns bunch length at extraction)
- Globally, intensity limited to about **1.3e11 p/b** at extraction

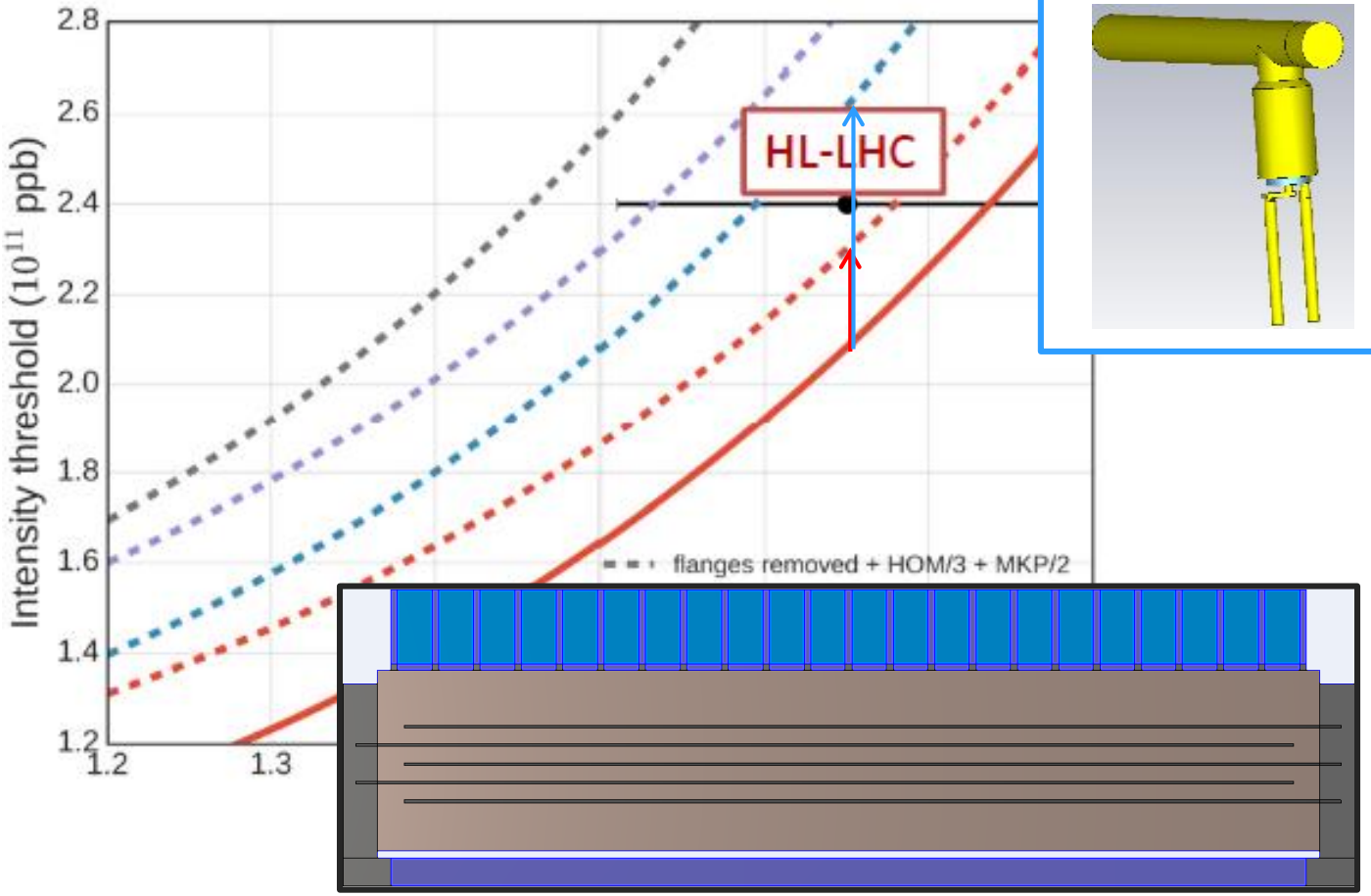


(4) SPS intensity limitation (longitudinal)

LHC Injectors Upgrade

- **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



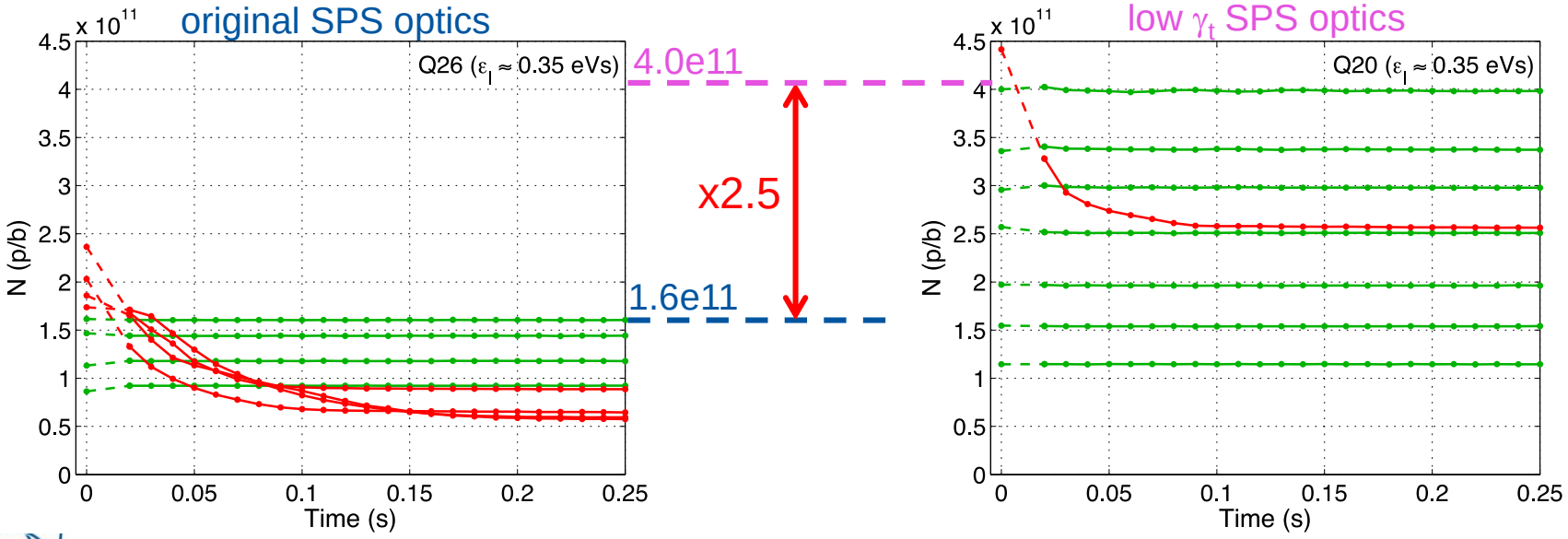


new HOM coupler

(5) SPS intensity limitation (transverse)

LHC Injectors Upgrade

- **Transverse Mode Coupling Instability (TMCI)** threshold was **1.6e11 p/b** with the original Q26 optics (integer part of the tune 26)
- Simulations showed that it could be raised to 4e11 p/b using a low gamma transition (γ_t) optics (Q20)

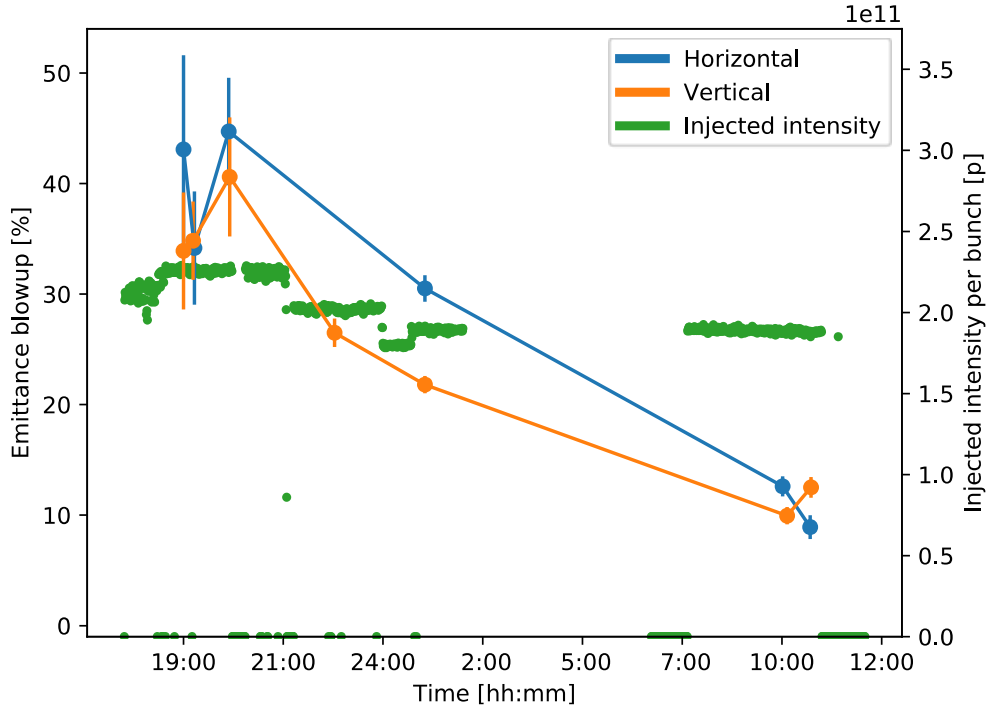


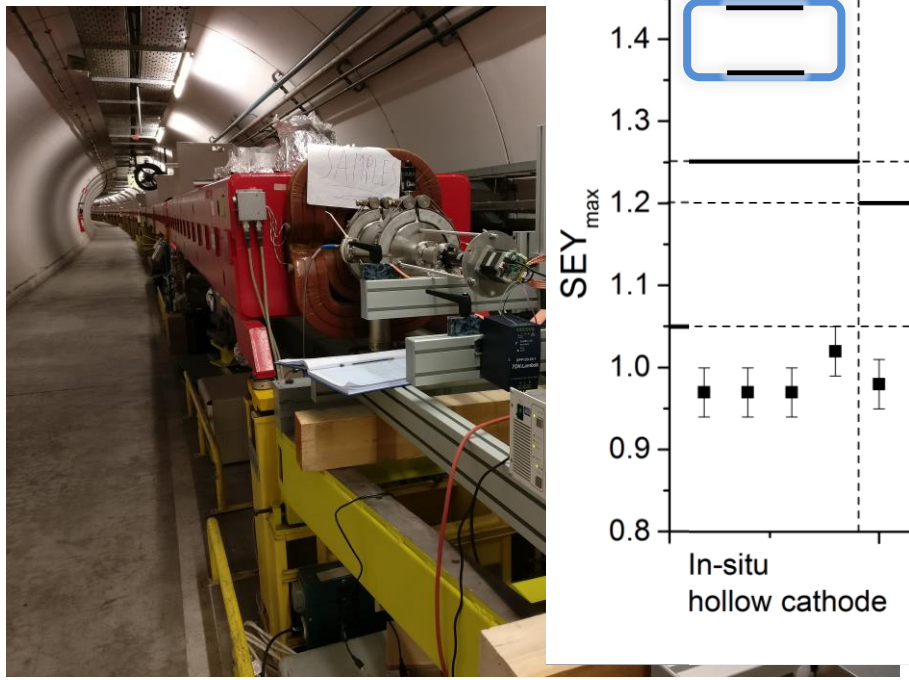
- **Measurements confirmed this 2.5 times higher threshold!**
- **The Q20 optics has been made operational for LHC beams**

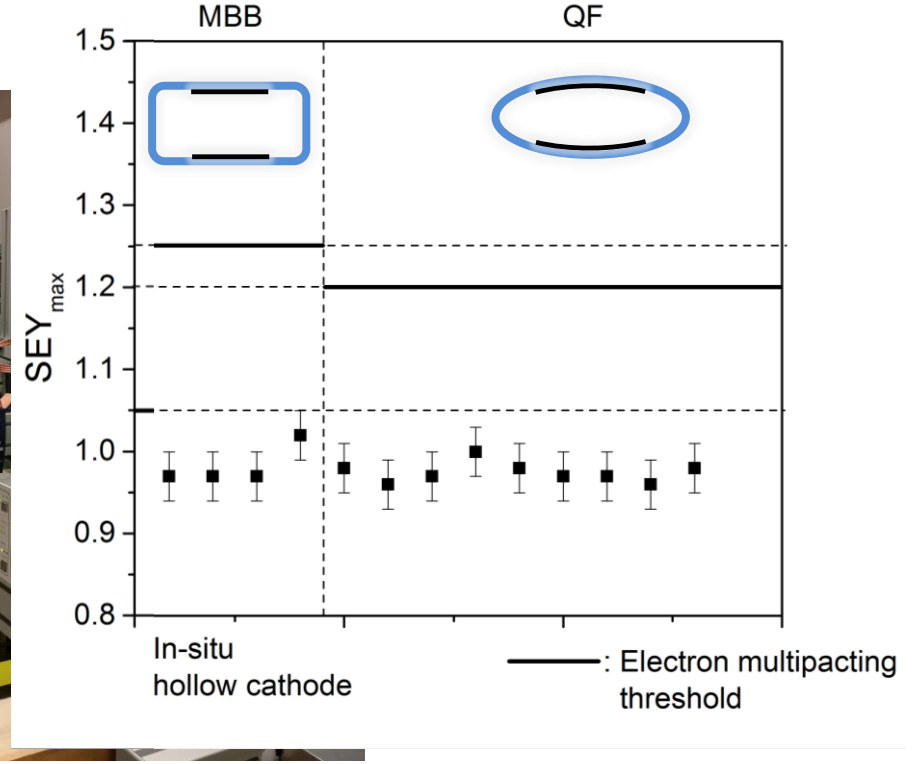
(6) SPS electron cloud

LHC Injectors Upgrade

- **Electron cloud mitigation** relies mainly on
  - Beam induced scrubbing
  - Coating with a-C the chambers of the focusing quadrupoles and adjacent drift chambers







A quick overview on the timeline of the LIU project and where we are standing now

2010

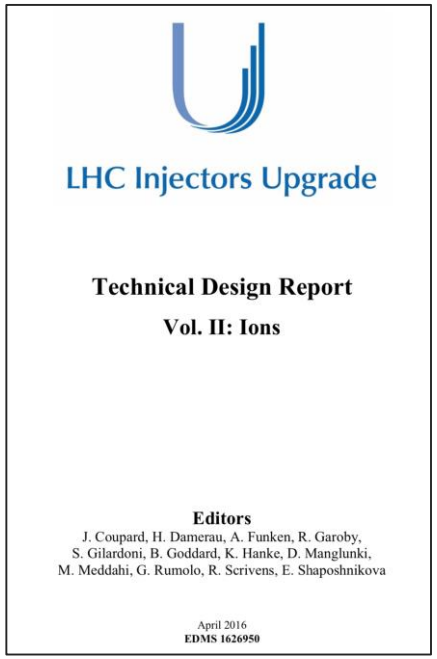
2018

2020

2024

Run 1 + Long Shutdown 1 + Run 2 (2010 – 2018)
Preparation, prototyping, testing, production

- **Start of LIU project (November 2010)**
- Beam studies (machine development and simulations) to refine existing models and fix project baseline
- Advanced installation and testing during LS1 and End-of-Year stops
- Civil engineering, surface work, cabling, decabling, …
- **Linac4** commissioning and quality/reliability runs



August 25, 2017 – Beam parameters at injection of each accelerator

PSB (H^- injection from Linac4)

		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Achieved	Standard	17.73	2.14	0.05	1.0	1100	2.4	(0.51, 0.59)
	BCMS	8.48	1.15	0.05	0.9	1000	2.2	(0.46, 0.56)
LIU target	Standard	34.21	1.72	0.16	1.4	650	1.8	(0.58, 0.69)
	BCMS	17.11	1.36	0.16	1.4	650	1.8	(0.35, 0.43)

PS (Standard: 4b+2b – BCMS: 2× 4b)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Achieved	Standard	16.84	2.25	1.4	1.2	180	0.9	(0.25, 0.30)
	BCMS	8.05	1.20	1.4	0.9	150	0.8	(0.24, 0.31)
LIU target	Standard	32.50	1.80	2.0	3.00	205	1.5	(0.18, 0.30)
	BCMS	16.25	1.43	2.0	1.48	135	1.1	(0.20, 0.31)

SPS (Standard: 4 × 72b – BCMS: 5 × 48b)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Achieved	Standard	1.33	2.36	26	0.35	4.0 (3.0)	0.9 (1.5)	(0.05, 0.07)
	BCMS	1.27	1.27	26	0.35	4.0 (3.0)	0.9 (1.5)	(0.07, 0.12)
LIU target	Standard	2.57	1.89	26	0.35	4.0 (3.0)	0.9 (1.5)	(0.10, 0.17)
	BCMS	2.57	1.50	26	0.35	4.0 (3.0)	0.9 (1.5)	(0.12, 0.21)

LHC (≈10 injections)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
Achieved	Standard	1.20	2.60	450	0.47 (0.48)	1.65 (1.21)	288
	BCMS	1.15	1.39	450	0.40 (0.41)	1.50 (1.13)	96
LIU target	Standard	2.32	2.08	450	0.56 (0.58)	1.65 (1.24)	288
	BCMS	2.32	1.65	450	0.56 (0.58)	1.65 (1.24)	240

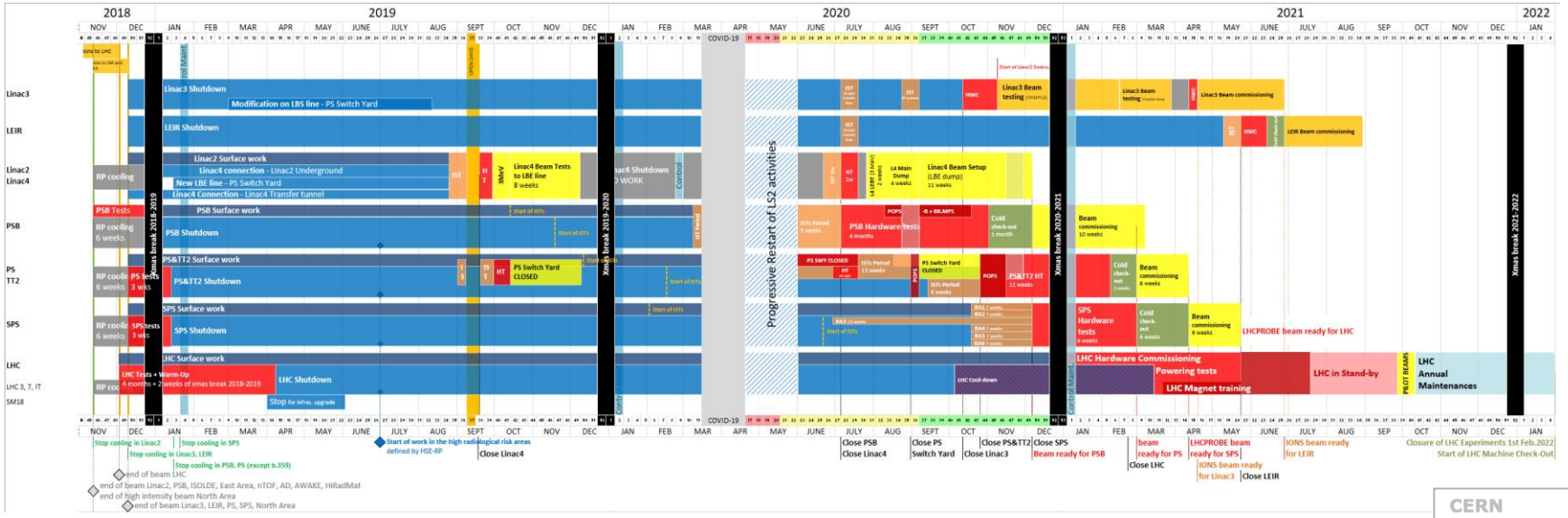
LHC Injectors Upgrade

2010

2018

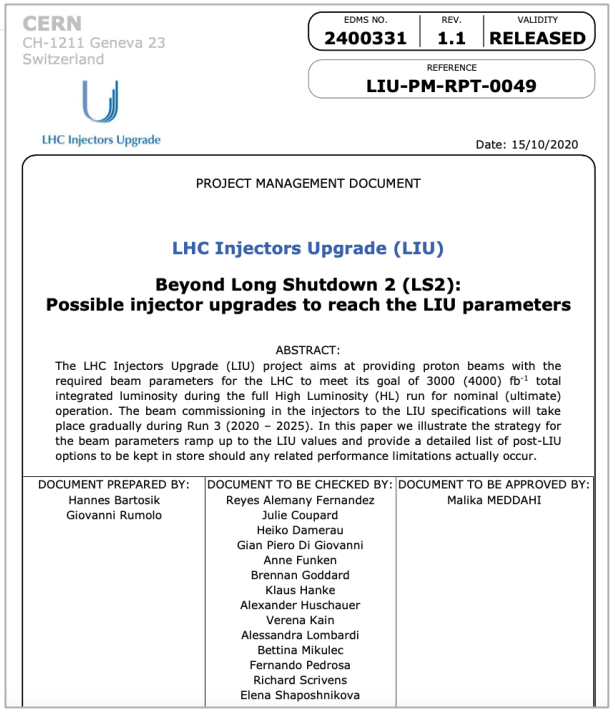
2020

2024



Long Shutdown 2 (2018 – 2020)
Peak of LIU installation phase

- Final phases of LIU equipment production
- **LIU equipment installation** across all injectors
- Preparation of operational scenarios – tools, performance ramp-up, back-up options



CERN
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

2010

2020 – 2021 → 2022 → 2023 → 2024

Ramp up to HL-LHC intensity of 2.1e11, then to 2.3e11 p/b within desired brightness and loss budgets for post-LS3 readiness

- Intensity and brightness ramp up to 1.8e11 p/b and 1.7 um at SPS exit within desired loss budgets
- Commissioning of the LIU ion beams for HL operation

2018

- Recovery of pre-Long Shutdown proton beams with Linac4 and newly installed LIU equipment
- Beginning of commissioning of LIU ion beams for High Luminosity (HL) operation in 2022

2020

Run 3 (2020 – 2024)

- **Recommissioning** of upgraded injectors
- **End of LIU project on 30 June 2021!**

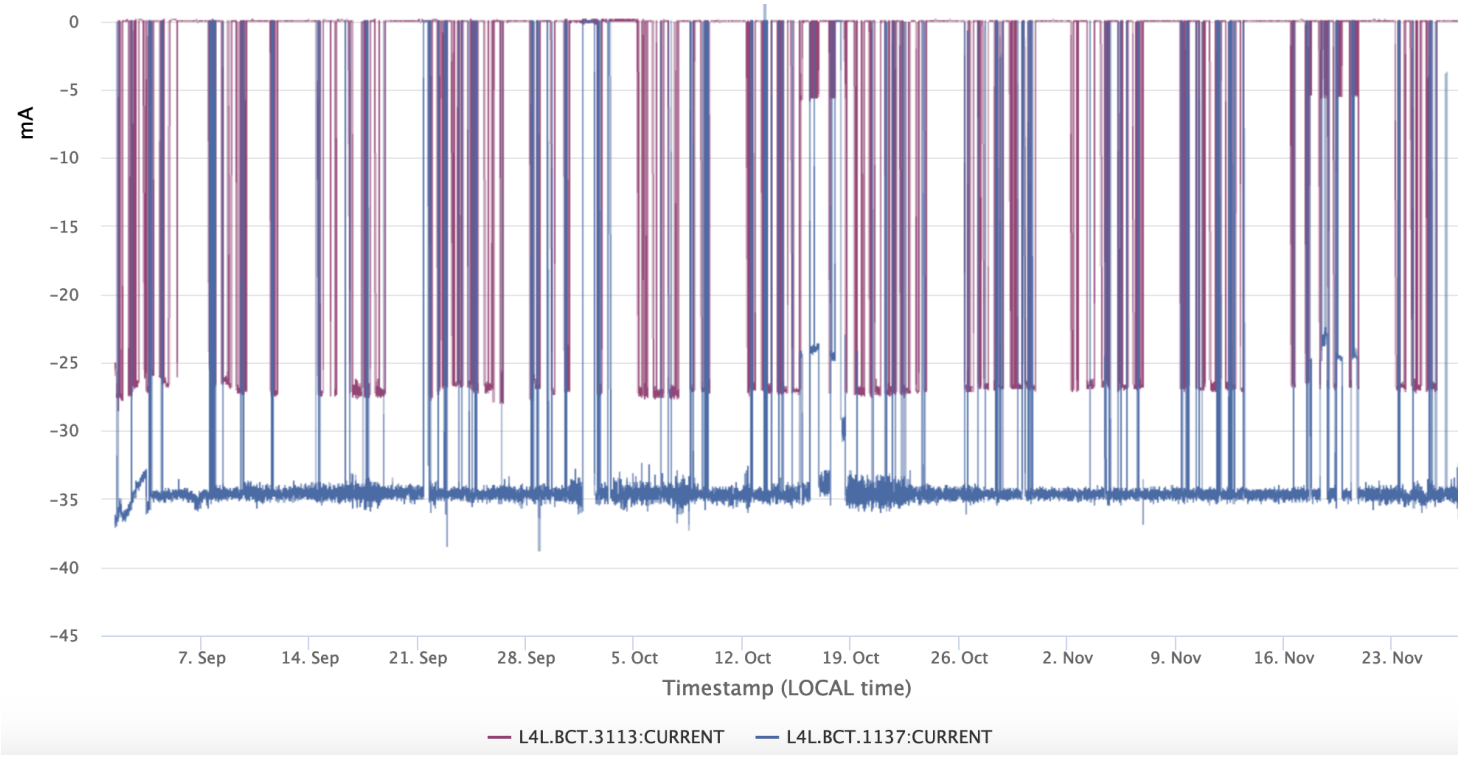
→ Beam commissioning to **LIU specifications** throughout Run 3

2024

Where we are standing now (Linac4)

LHC Injectors Upgrade

- **Linac4** has been in operation since July 2020 and is currently working as injector for the PSB
- Excellent **source stability** thanks to continuous caesiation and autopilot



~27 mA after RFQ

~35 mA at source exit

Where we are standing now (Linac4)

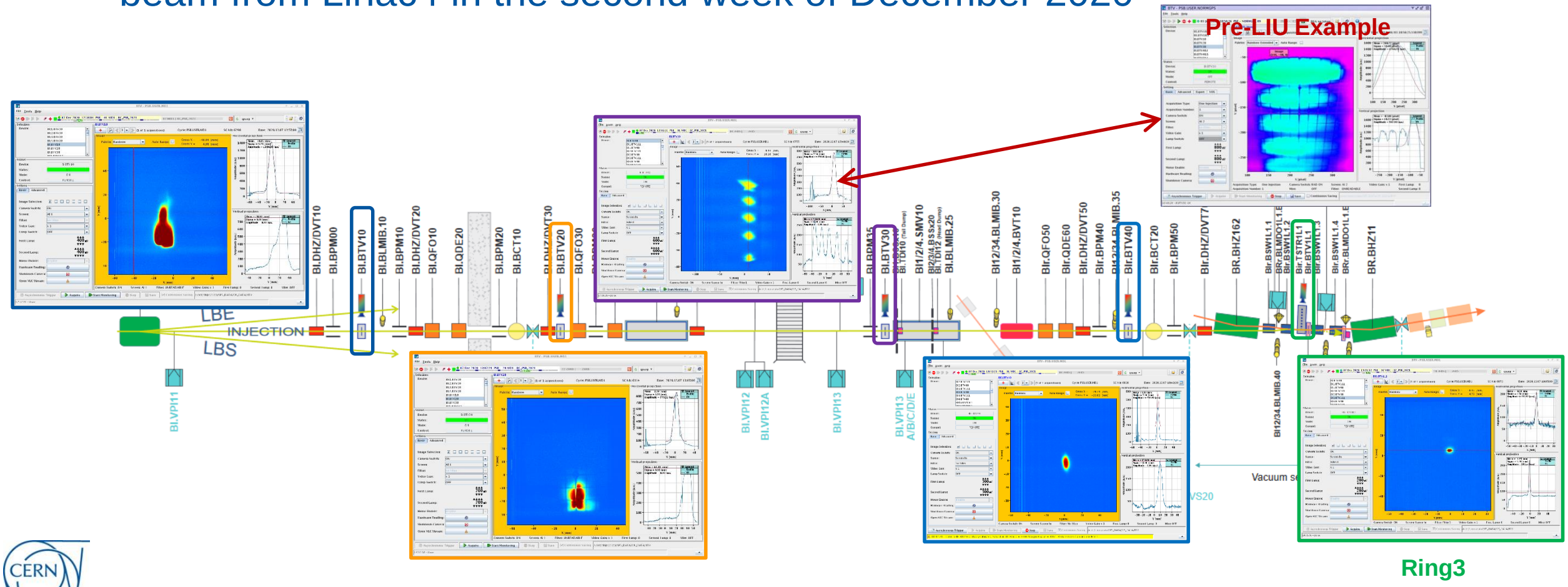
LHC Injectors Upgrade

- **Linac4** has been in operation since July 2020 and is currently working as injector for the PSB
- Excellent **source stability** thanks to continuous caesiation and autopilot
- Different **transfer line optics** applied to different PSB production schemes
  - New high-level controls to link debuncher settings to optics settings
- Weekly **availability** up to 100%, and in average well above 97%

Where we are standing now (PSB)

LHC Injectors Upgrade

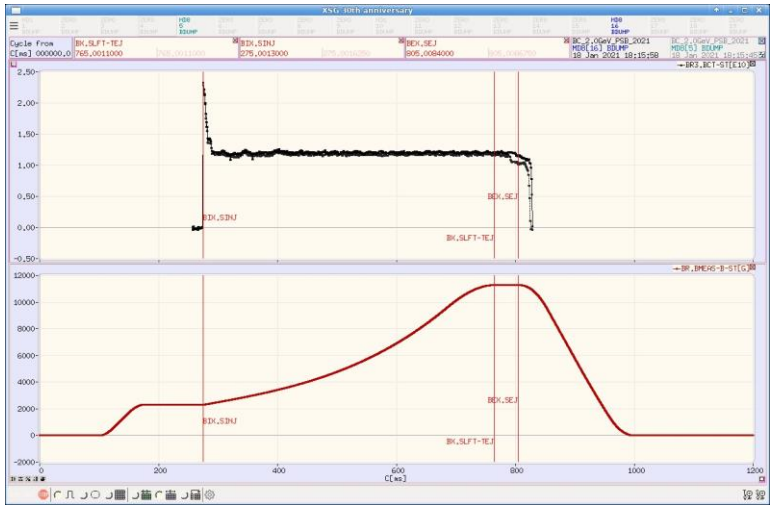
- After four months of hardware commissioning, the PSB has taken its first beam from Linac4 in the second week of December 2020



Where we are standing now (PSB)

LHC Injectors Upgrade

- After four months of hardware commissioning, the PSB has taken its first beam from Linac4 in the second week of December 2020
- By the end of 2020 the new injection system was fully commissioned and the beam was captured in the new RF system and circulated at 160 MeV
- By end of January 2021 the beam could be accelerated to 2 GeV and extracted to the dump in the transfer line

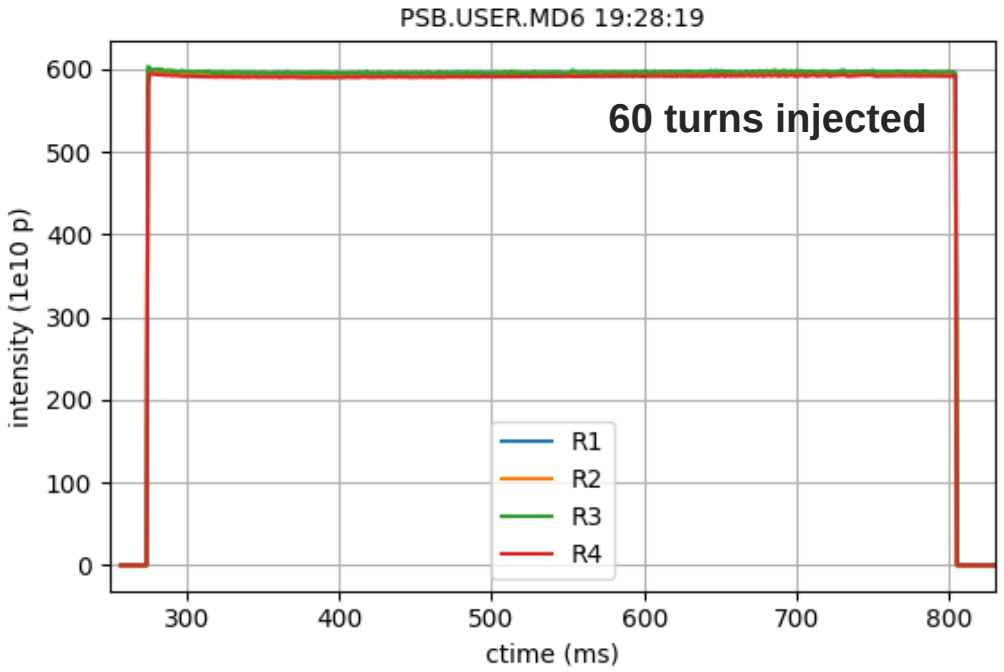


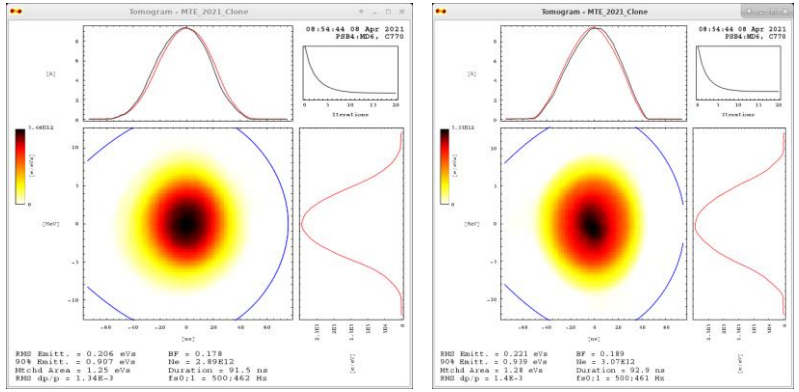
First beam accelerated to 2 GeV on 18th of January 2021

Where we are standing now (PSB)

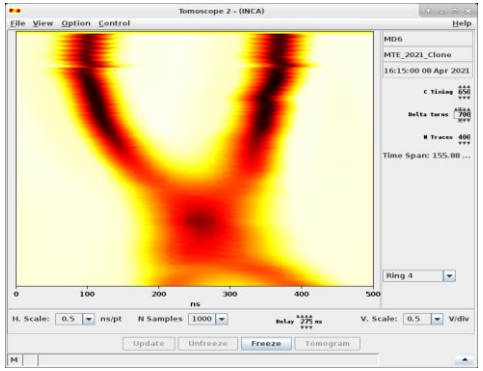
LHC Injectors Upgrade

- The whole zoo of beams for Fixed Target users are quickly being produced to serve physics users as they gradually come back online
  - E.g. SPS FT beam with excellent transmission, controlled longitudinal emittance blow up, bunch splitting





ε_z = 1.2 eVs



Where we are standing now (PSB)

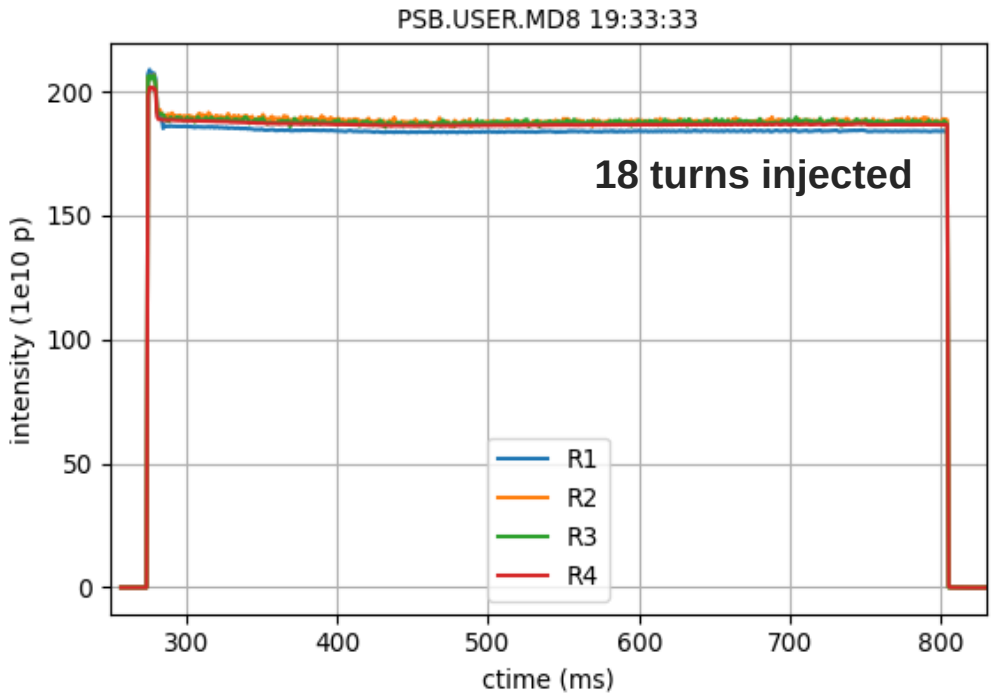
LHC Injectors Upgrade

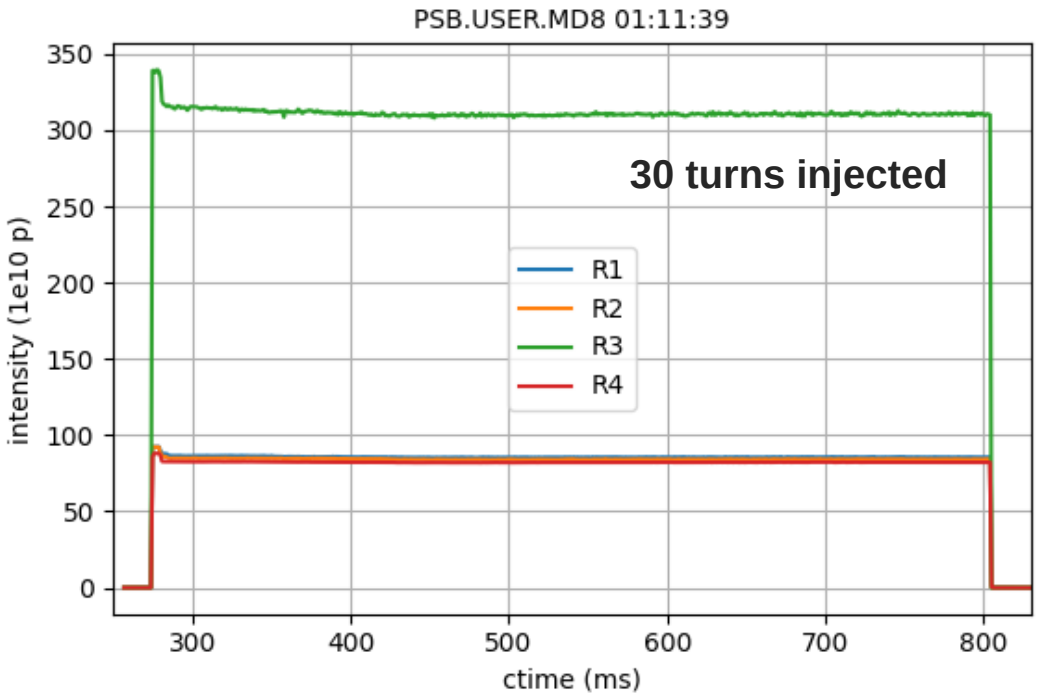
- LHC beam is being also carefully prepared
  - Intensity spanning from pre-LIU to LIU values
  - Lots of optimization ongoing but already in very good shape
    - Injection with no painting and large energy spread from Linac4 (around 450 keV)
    - Working point still ramped over a reduced range
    - Capture in double harmonic with a little longitudinal shaving and (for the moment) no intentional longitudinal emittance blow-up along the ramp
    - Resonance compensation scheme implemented to suppress/reduce losses upon resonance crossing along the cycle

Where we are standing now (PSB)

LHC Injectors Upgrade

- LHC beam is being also carefully prepared
  - Intensity spanning from pre-LIU to LIU values

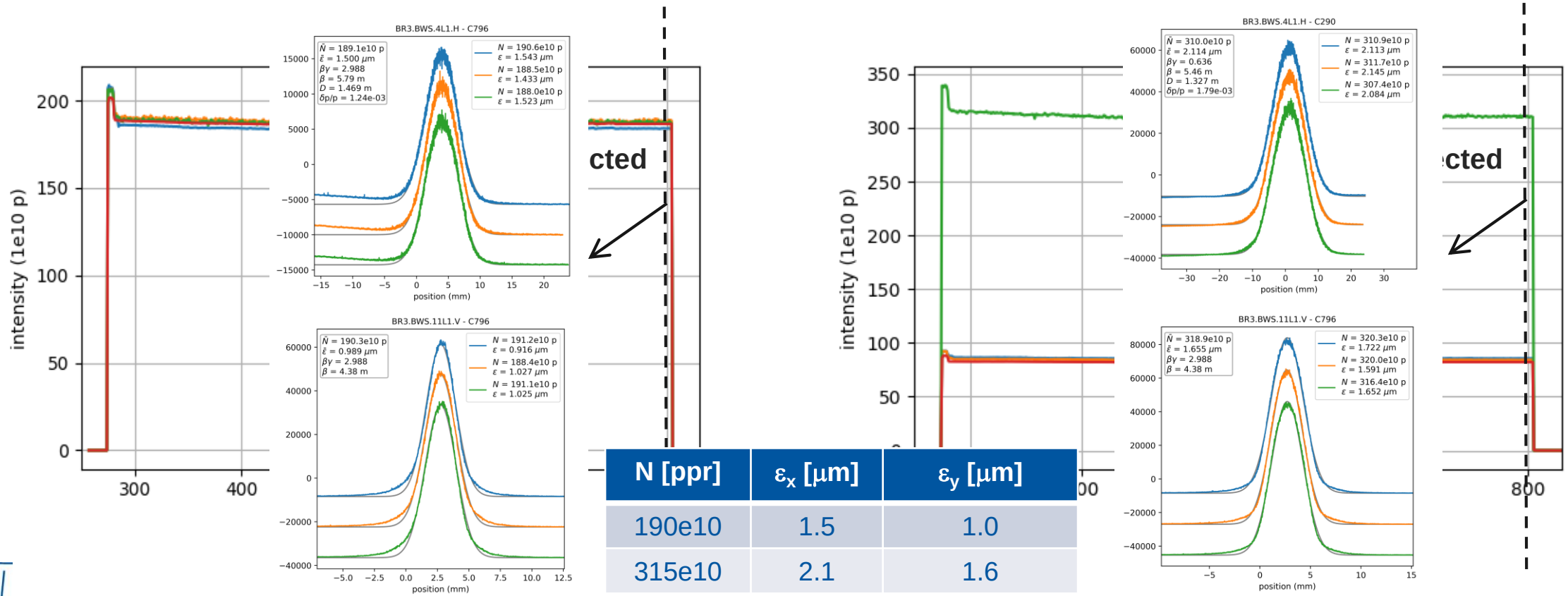




Where we are standing now (PSB)

LHC Injectors Upgrade

- LHC beam is being also carefully prepared
  - Intensity spanning from pre-LIU to LIU values

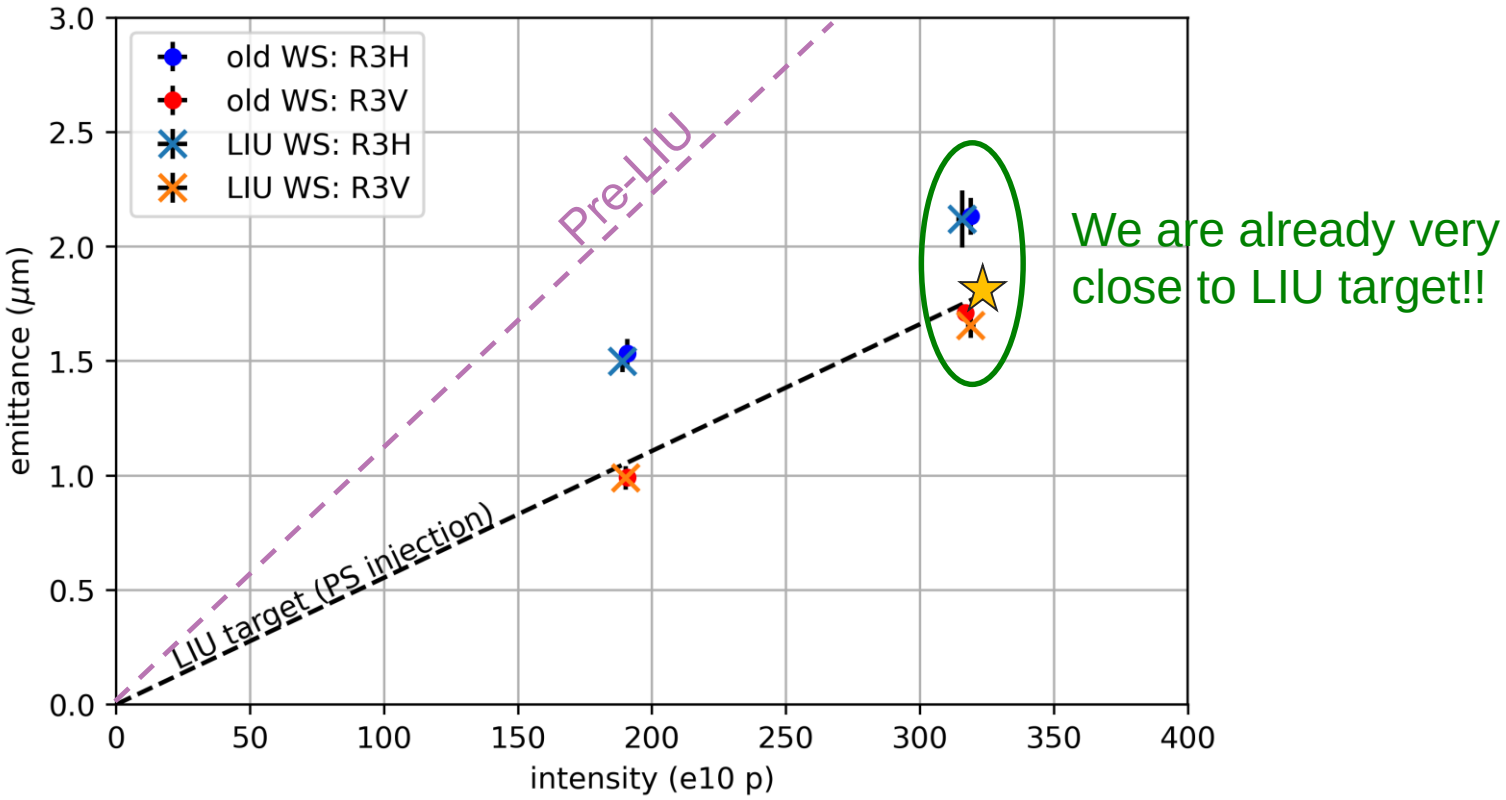


N [ppr]	ε_x [μm]	ε_y [μm]
190e10	1.5	1.0
315e10	2.1	1.6

Where we are standing now (PSB)

LHC Injectors Upgrade

- LHC beam is being also carefully prepared
  - First measured points on PSB brightness line

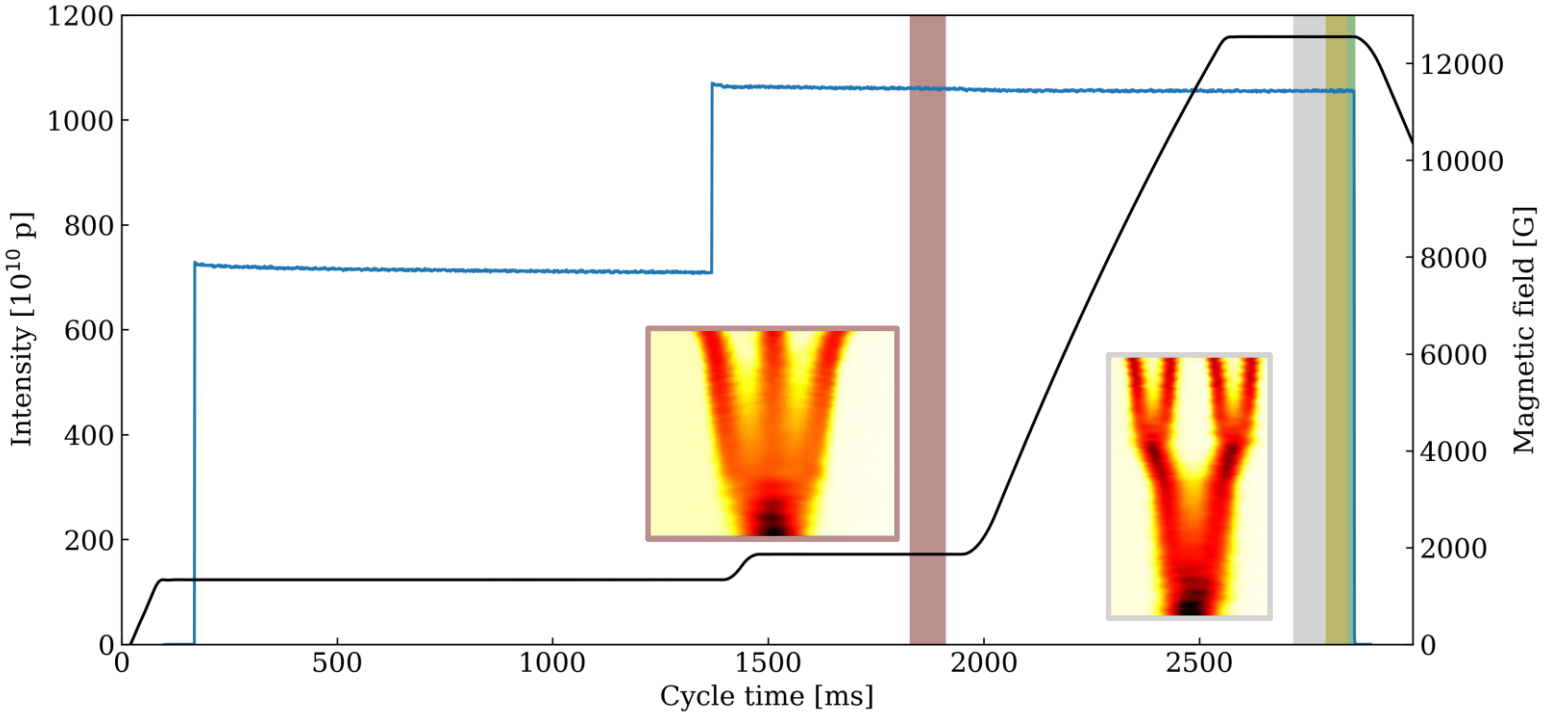


We are already very close to LIU target!!

Where we are standing now (PS)

LHC Injectors Upgrade

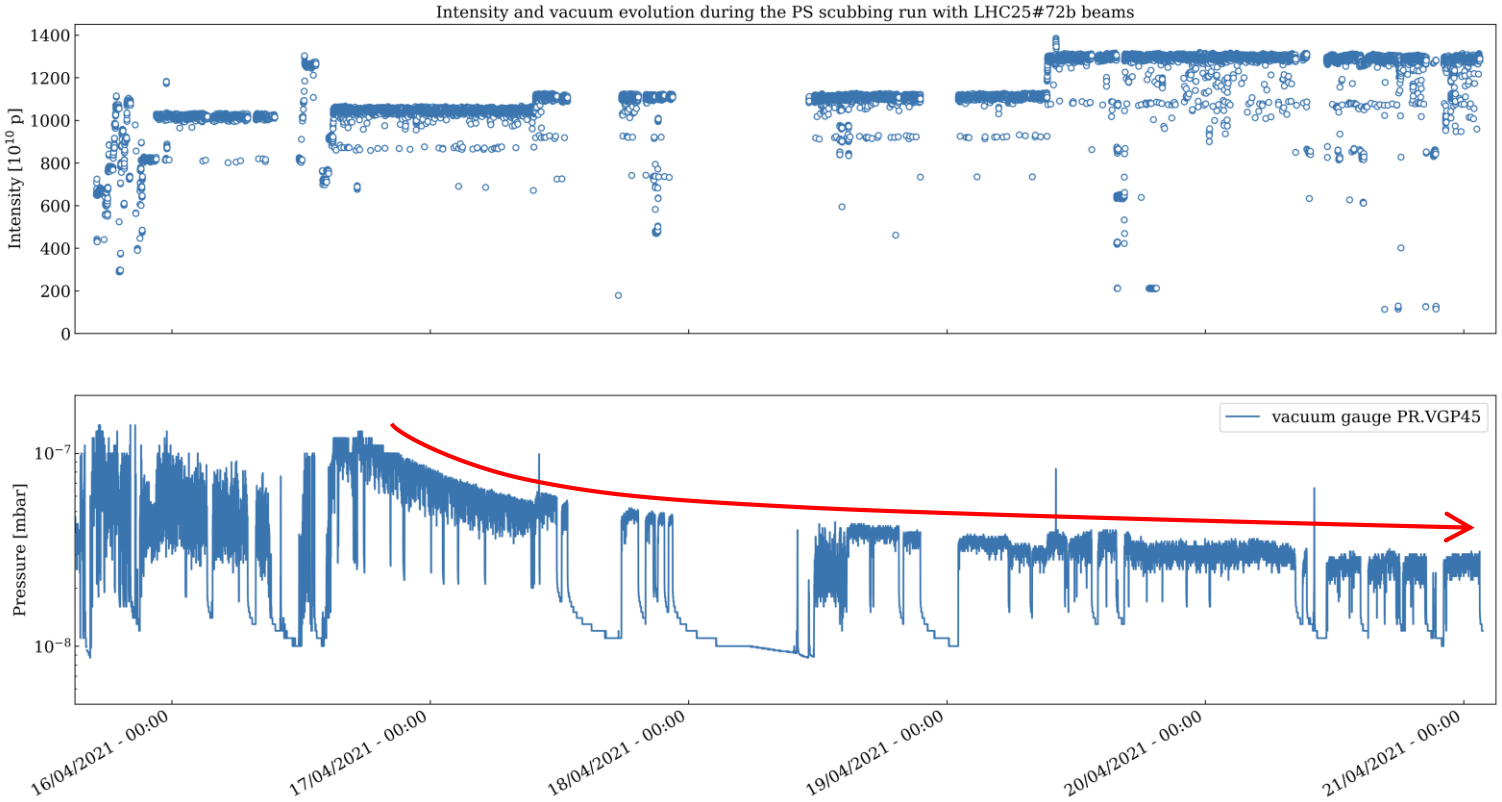
- The PS has been taking beam since beginning of March
  - LHC beam already restored up to 1.8e11 p/b extracted
  - Excellent transmission, emittance preservation needs to be studied



Where we are standing now (PS)

LHC Injectors Upgrade

- The PS has been taking beam since beginning of March
  - Electron cloud formation after last bunch splitting had to be overcome with a scrubbing run to avoid vacuum interlock



Where we are standing now (SPS)

LHC Injectors Upgrade

- The SPS has started taking beam on Friday 23 April
  - Commissioning of new orbit measurement system
  - Operational deployment of new dump system
  - First capture of single bunch in upgraded RF system

Conclusions

LHC Injectors Upgrade

- **LIU project baseline** was built to fulfil the HL-LHC target parameters
  - An advanced modeling of the LHC injectors and a close analysis of their performance limitations have constantly guided the process
  - Main phase of **installation** has lasted **two years of long shutdown (LS2)**
  - Injectors back to operation in cascade since July 2020

- LIU project currently in its **closing phase**
  - Linac4, PSB and PS are in advanced stage of beam commissioning or even operation
  - SPS is just starting beam commissioning
  - Project will officially finish at the end of June 2020

- First promising results from beam commissioning (PSB brightness line, PS e-cloud mitigation and high intensity production), however still a long way to the full demonstration of the LIU beam parameters across the whole injectors chain

www.cern.ch

THANK YOU FOR YOUR ATTENTION