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HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

HGS-HIRe Lecture Week on Accelerator Physics & Technology
June 2019 - Laubach

CERN LHC Injectors Upgrade (LIU) Project: Beam dynamics aspects & solutions

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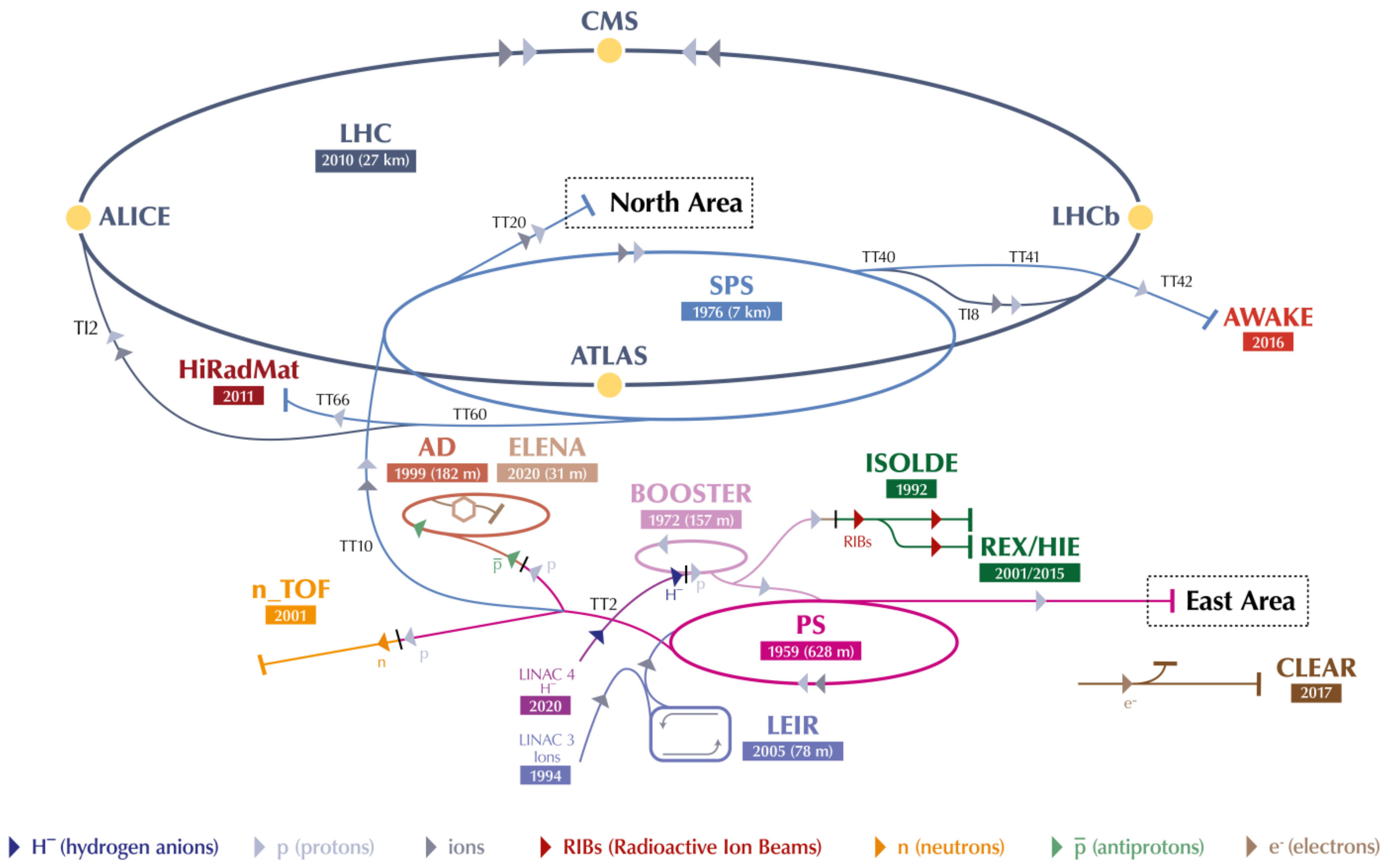
Outline

- 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. pre-LIU performance
  - How advanced beam dynamics steered the project baseline
- The LIU project execution and legacy
  - Overview on timeline
  - Beam performance ramp-up after LIU installation
- Summary

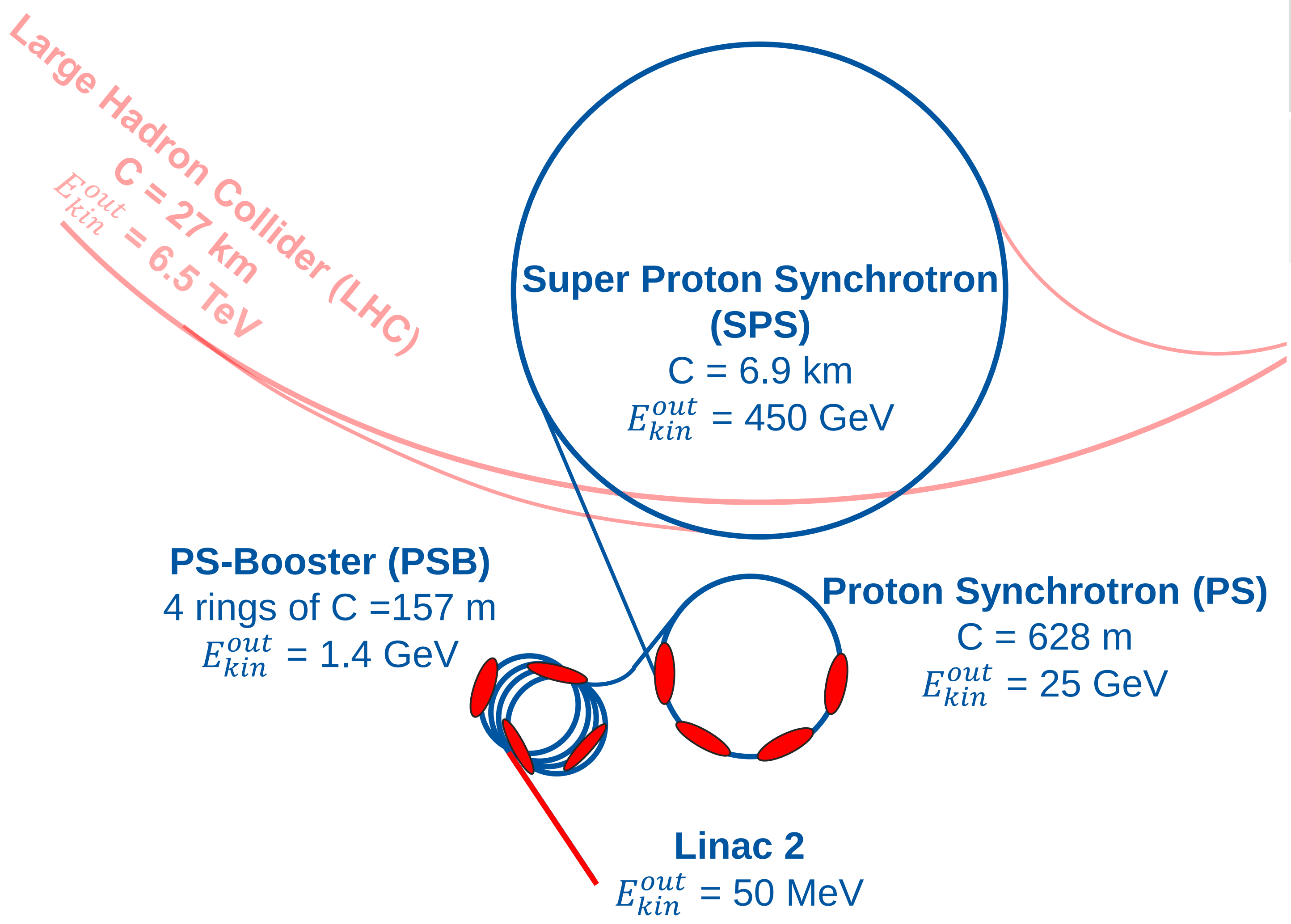
The CERN accelerator complex

LHC Injectors Upgrade



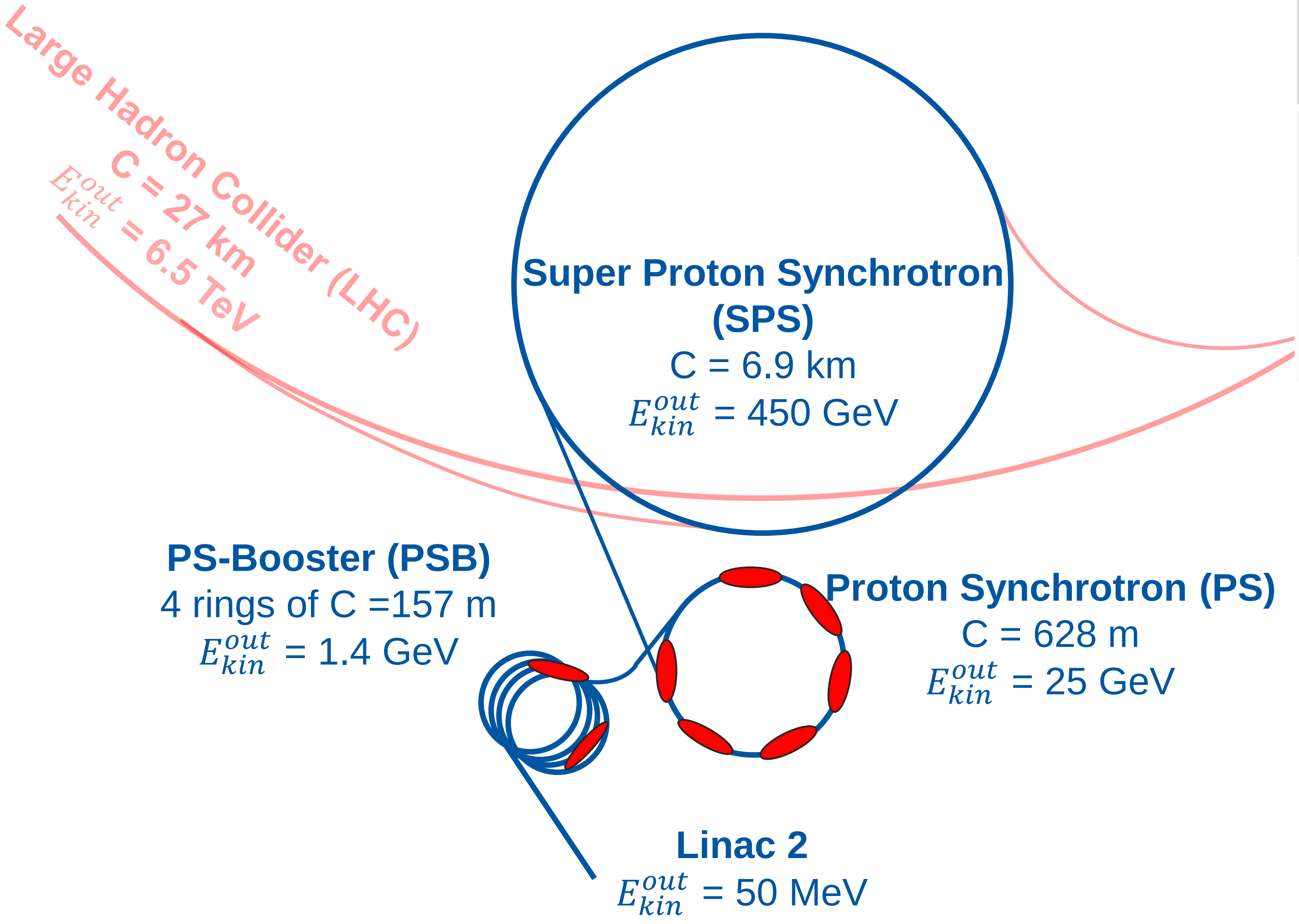
Production scheme of LHC beams before LIU

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



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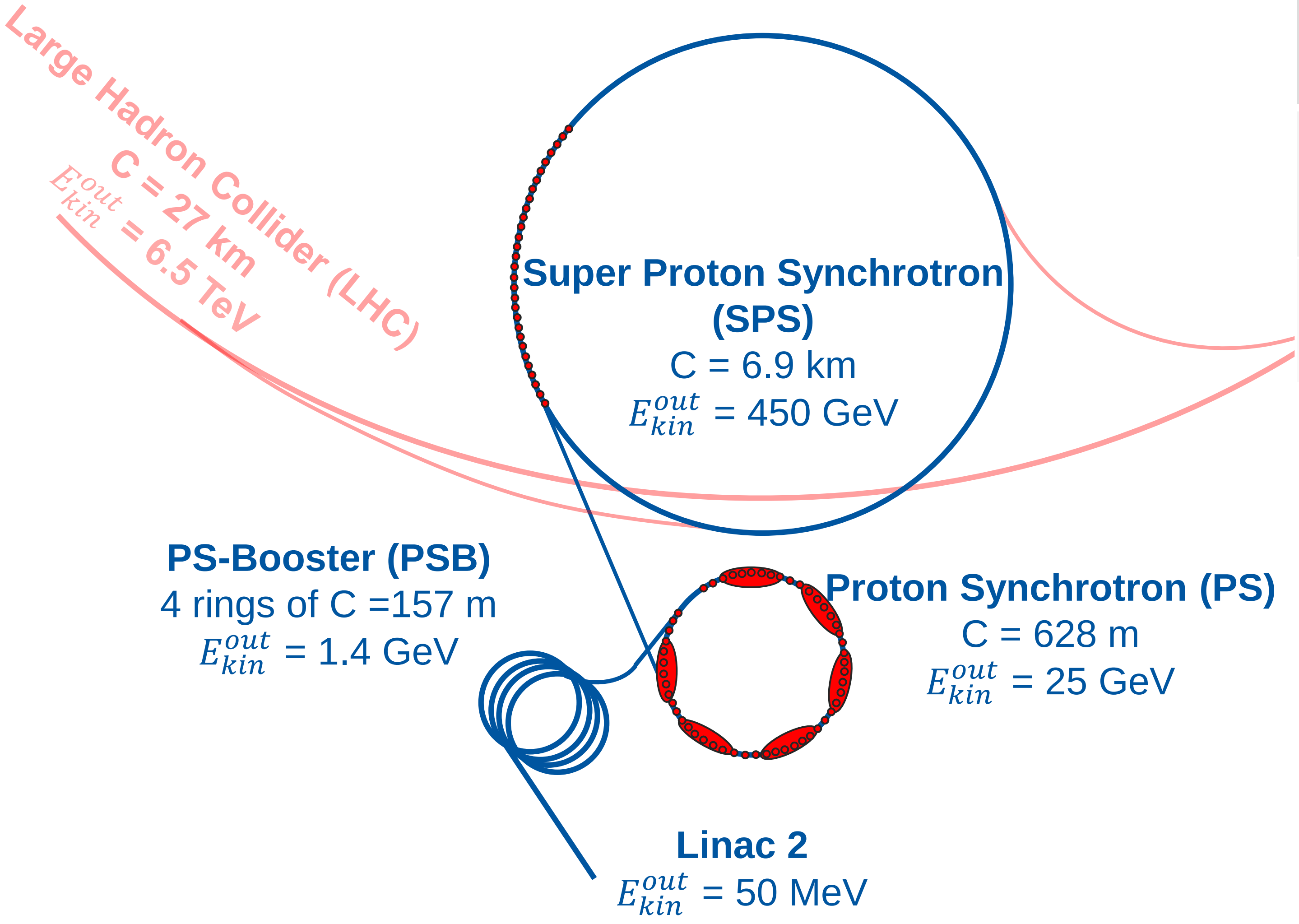
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272

Production scheme of LHC beams before LIU



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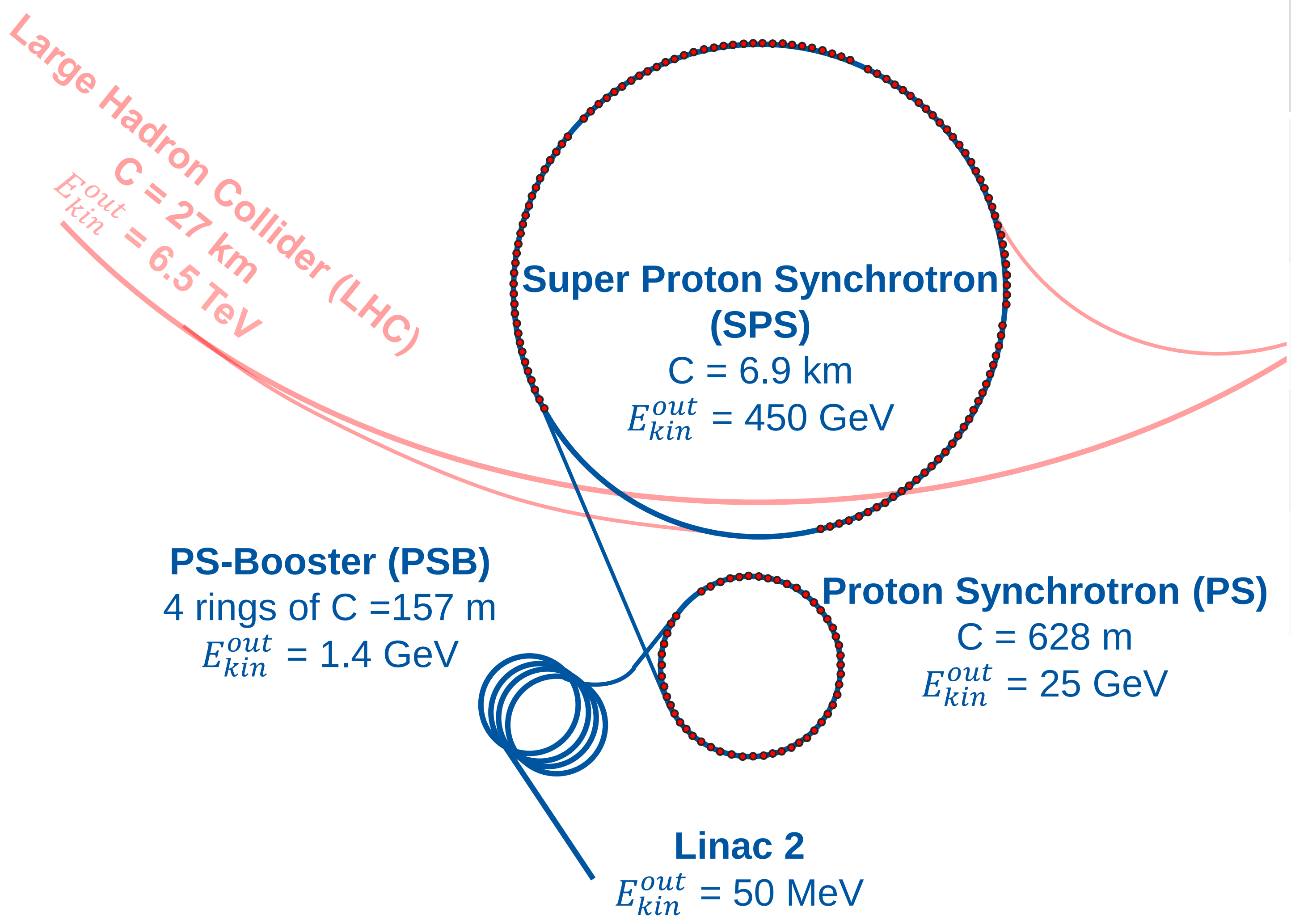
One triple bunch splitting and two double bunch splittings in the PS

Production scheme of LHC beams before LIU

LHC Injectors Upgrade



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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 (2029 – 2040+)
- Based on operation at levelled luminosity of **5 (7.5) $\times 10^{34}$ $cm^{-2}s^{-1}$** 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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	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**
Pre-LIU	1.3	2.7	25 ns	4x72 per injection

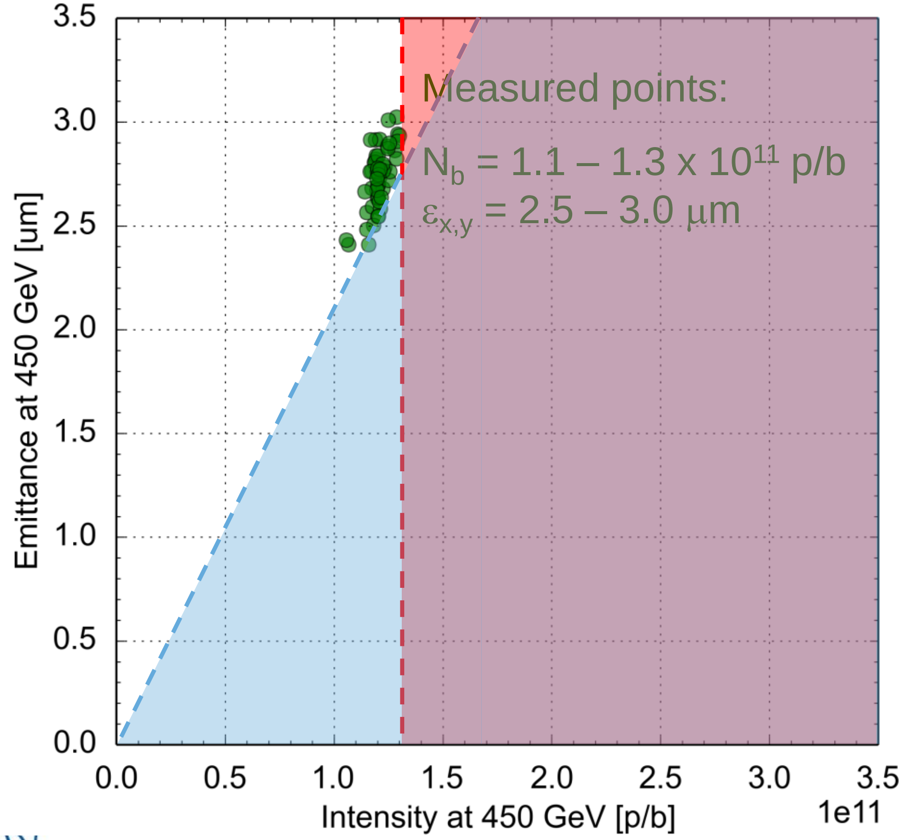
The **LHC Injectors Upgrade (LIU)**

- 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



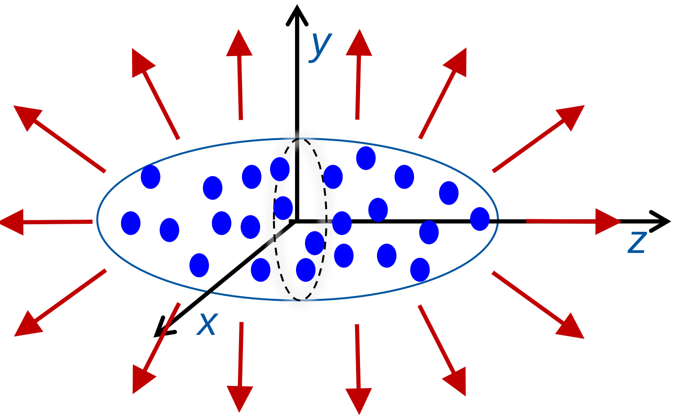
- Coherent instabilities, electron cloud, beam induced heating, beam losses typically limit the achievable **intensity**

$$N_b < N_{\max}$$

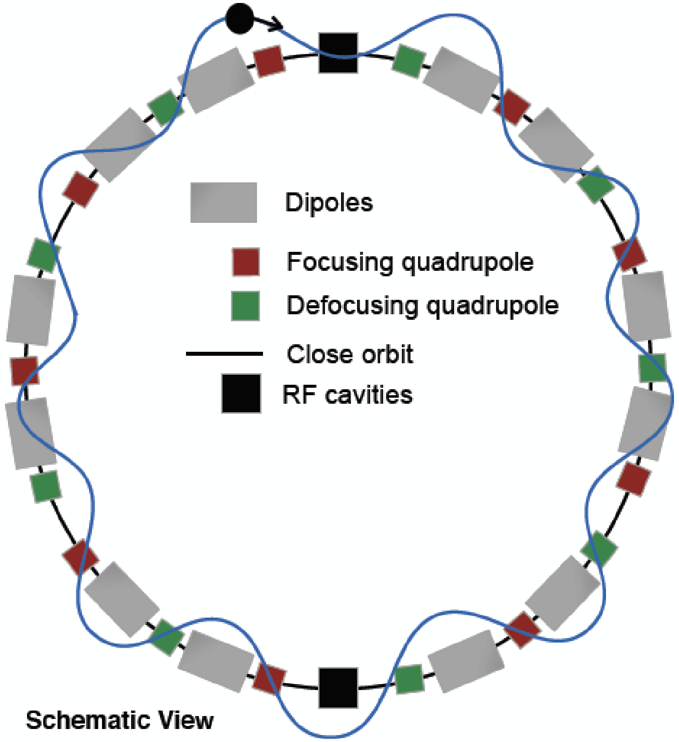
Brightness limitations: **space charge**

LHC Injectors Upgrade

- Particles within a bunch moving at speed lower than speed of light generate a **repulsive force** acting on each particle

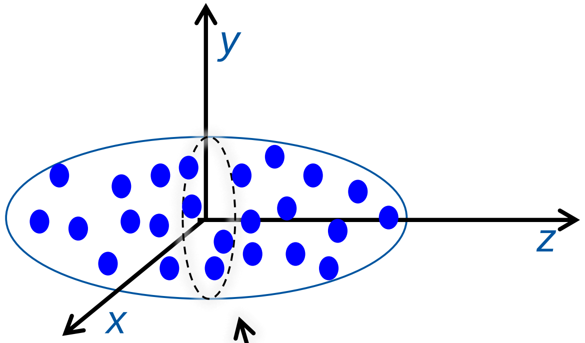


- This is an additional defocusing force on single particles, whose oscillation frequencies around the accelerator (**tunes**) consequently decrease
- Furthermore, particles feel different space charge defocusing forces according to their positions → Spread of tunes within the bunch

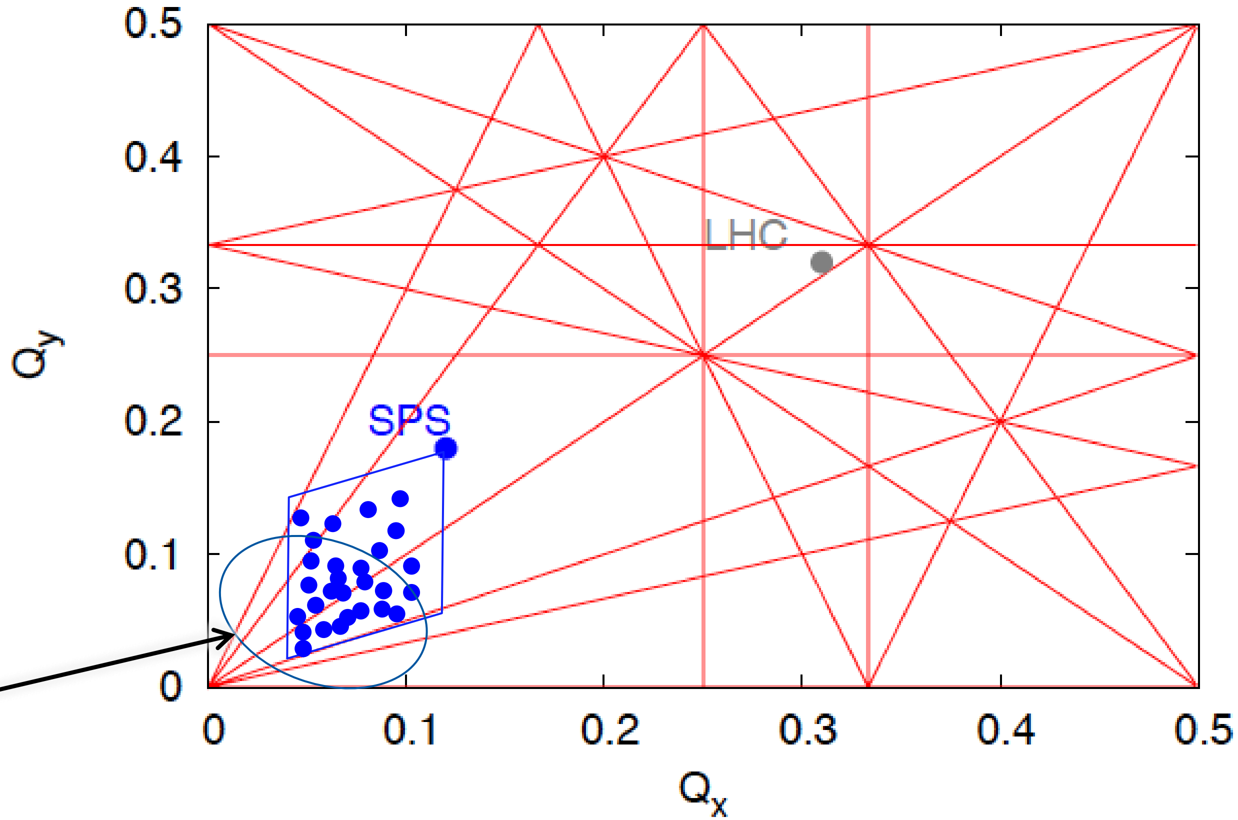


Brightness limitations: **space charge**

- In the tune plane (Q_x, Q_y), the nominal tunes are placed in areas free from resonance lines (i.e. combinations of tunes leading to orbit instability)
- Space charge shifts the tunes of the single particles, which may then hit the resonance lines!



Particles oscillating close to the bunch peak density



Brightness limitations: **space charge**

LHC Injectors Upgrade

- In the tune plane (Q_x, Q_y), the nominal tunes are placed in areas free from resonance lines (i.e. combinations of tunes leading to trajectory instability)
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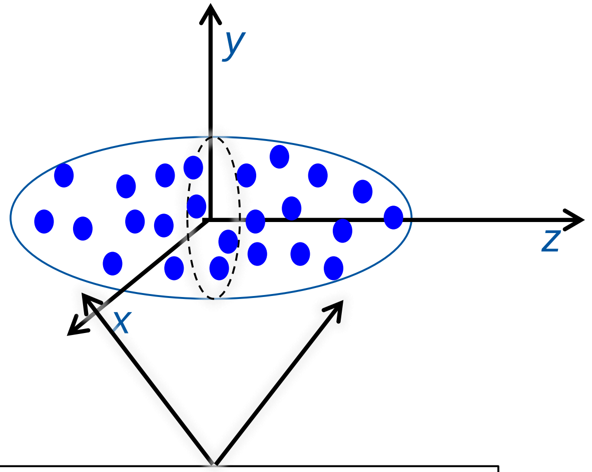
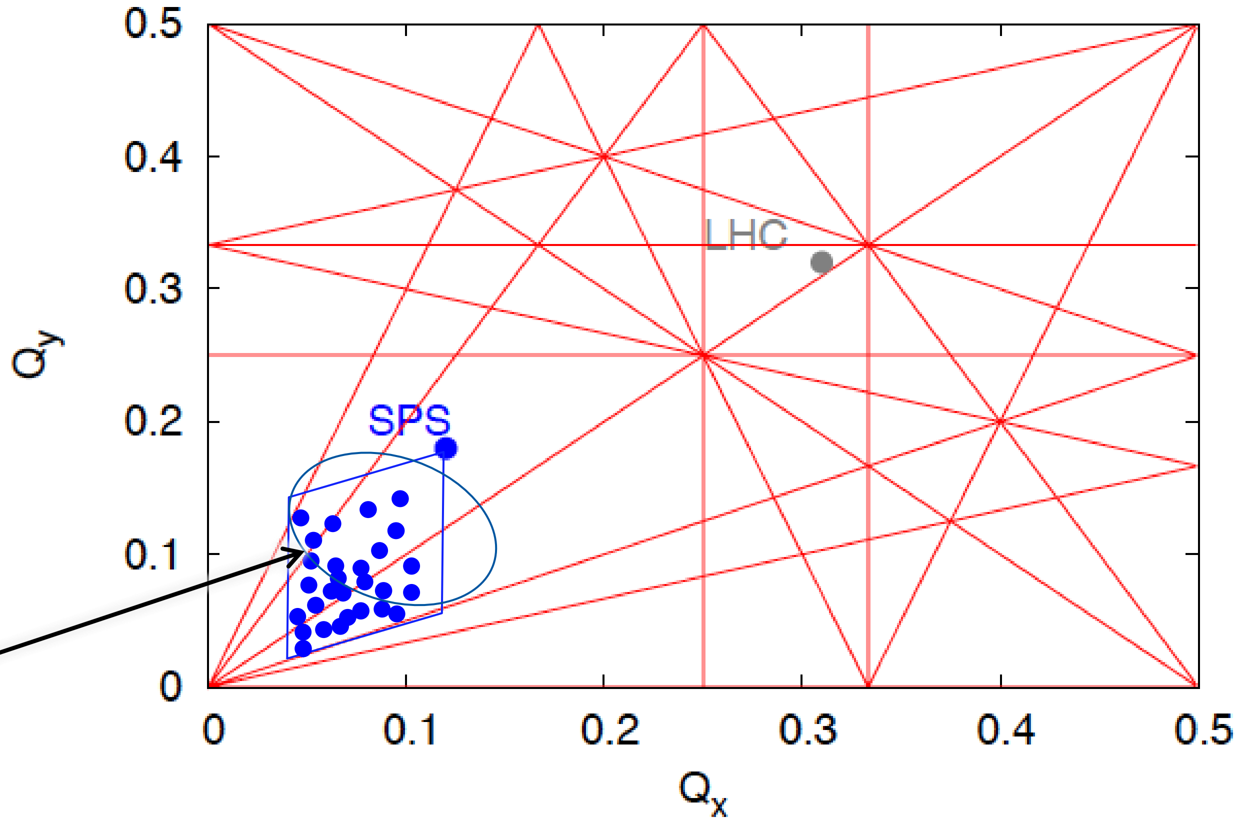


Particles at the tails of the longitudinal distribution



Brightness limitations: **space charge**

LHC Injectors Upgrade

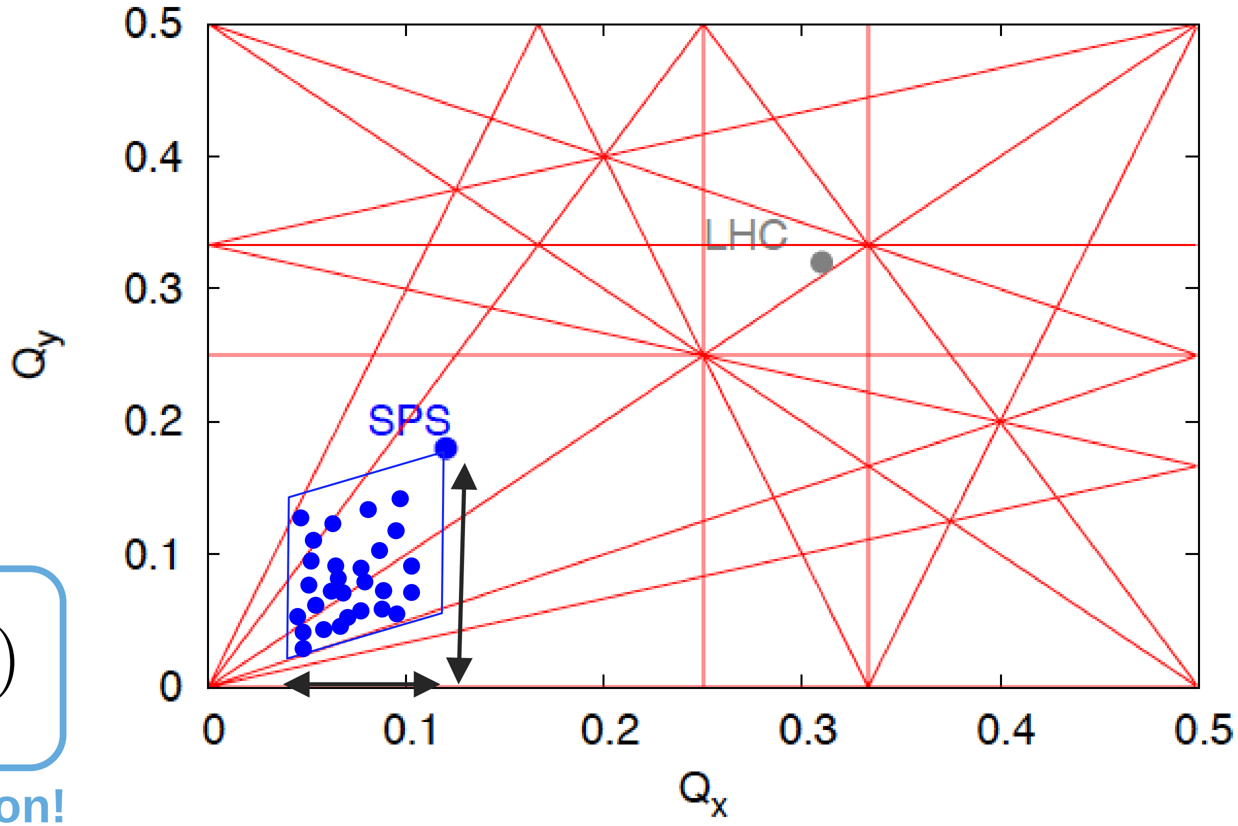
- Due to their shifted tunes, some of the trajectories of the single particles can
  - Grow to large amplitudes and get stabilised → **emittance growth**
  - Become unstable and hit the machine aperture → **beam loss**

$$\Delta Q_{x,y}^{\max} = -\frac{r_0 R N_b C}{2\pi e \beta \gamma^2 \epsilon_{x,y} \sigma_z}$$

$$\Delta Q_{x,y}^{\max} < \Delta Q_{x,y}^{\mathrm{thr}} \quad \Rightarrow$$

$$\frac{\epsilon_{x,y}}{N_b} > b_{\max}(\sigma_z, C, \gamma, \ldots)$$

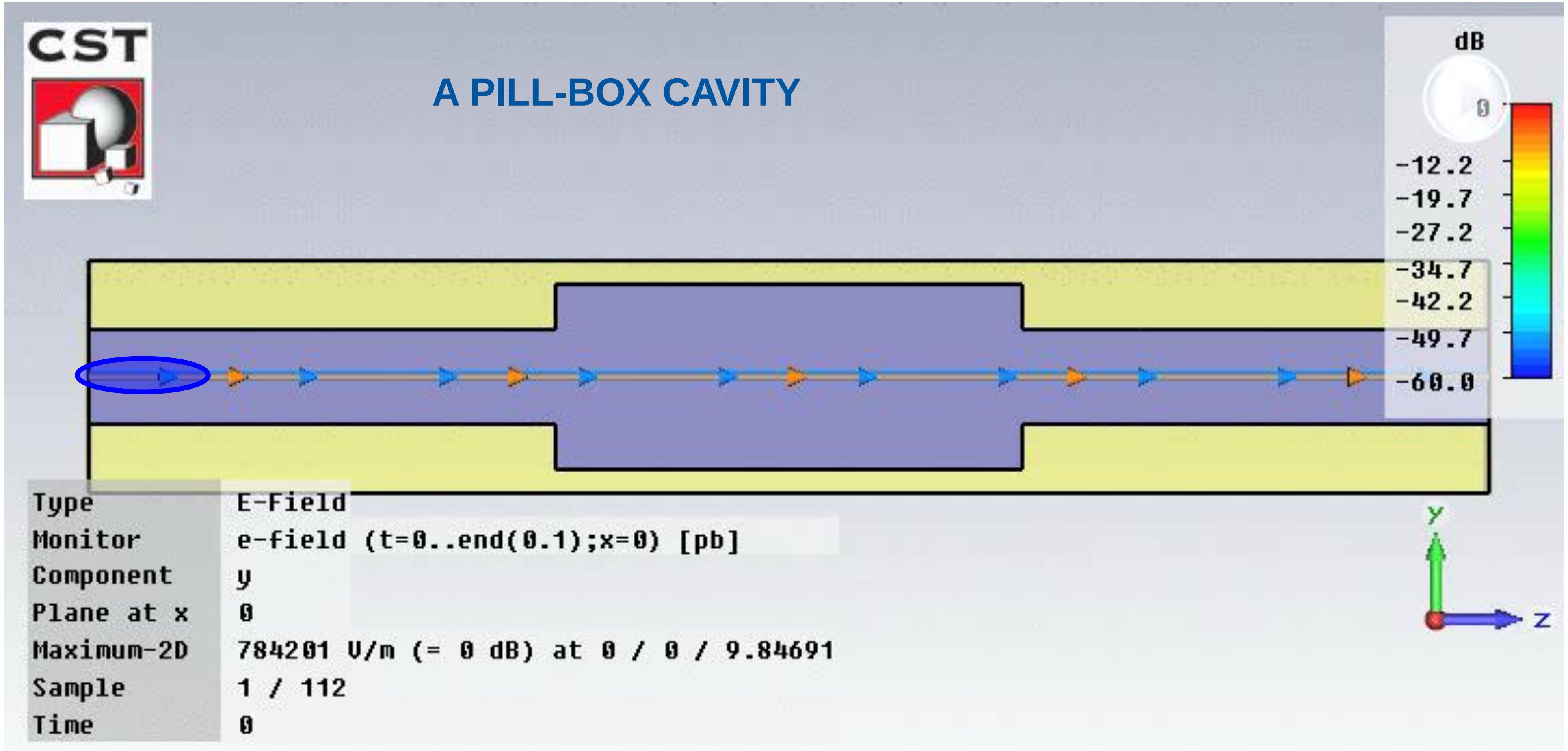
Brightness limitation!



Intensity limitations: **Impedance**

LHC Injectors Upgrade

- Particle bunches propagating in an accelerator interact electromagnetically with all the structures and devices they traverse



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Intensity limitations: **Impedance**

LHC Injectors Upgrade

- Particle bunches propagating in an accelerator interact electromagnetically with all the structures and devices they traverse
- This electromagnetic interaction is described by means of **wake functions** and **beam coupling impedances**
  - **Wake function** in time domain → Integrated force felt by a witness particle following at a distance z a source particle while traversing the device

$$W(z) = -\frac{1}{e^2}\int_0^L F(s,z)ds$$

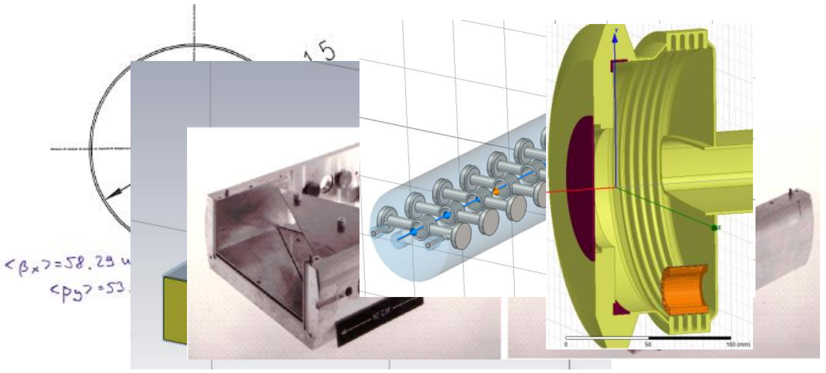
  - **Beam coupling impedance** in frequency domain → The Fourier transform of the wake function

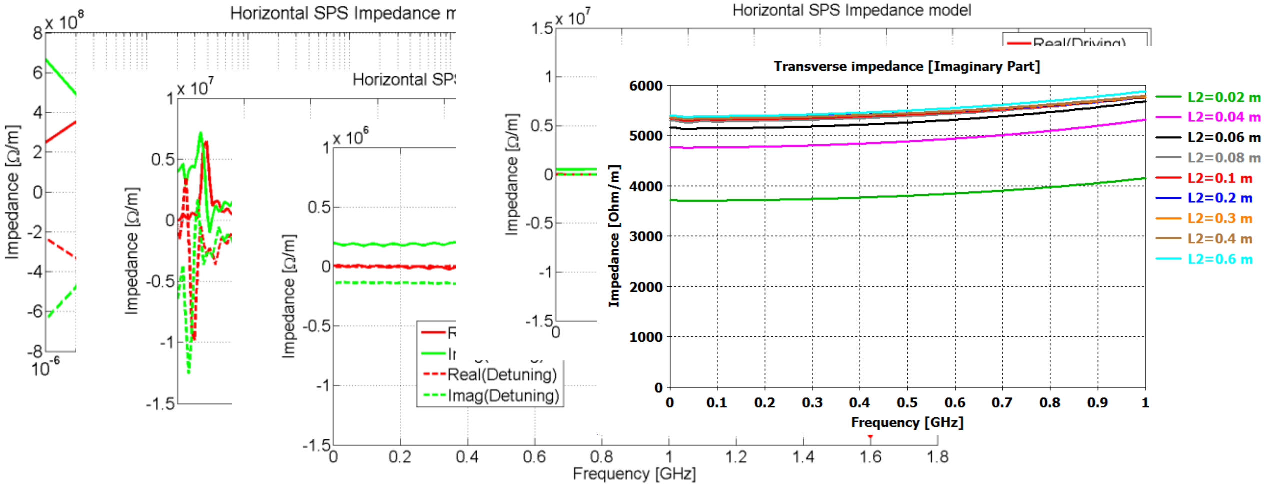
$$Z(\omega) = \int_{-\infty}^{\infty} W(z) \exp\left(-\frac{i\omega z}{c}\right)\frac{dz}{c}$$

Intensity limitations: **Impedance**

LHC Injectors Upgrade

- Particle bunches propagating in an accelerator interact electromagnetically with all the structures and devices they traverse
- This electromagnetic interaction is described by means of **wake functions** and **beam coupling impedances**
- Wake functions and impedances are calculated for every single accelerator device and then have to be summed up to calculate their global effect on the particle beam



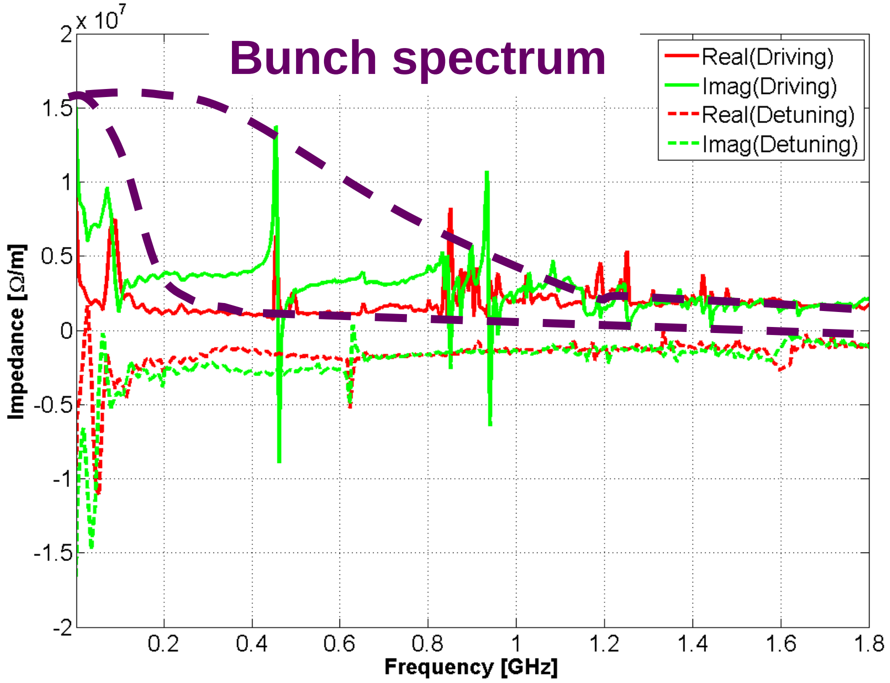


Intensity limitations: **Impedance**

LHC Injectors Upgrade

- Particle bunches propagating in an accelerator interact electromagnetically with all the structures and devices they traverse
- The global interaction leads to significant **energy loss** and **beam instability** if the impedance spectrum overlaps significantly with the bunch spectrum

$$Z_{\perp,||}(\omega) = \frac{1}{\langle\beta\rangle}\sum_i \beta^i_{\perp,||} Z^i_{\perp,||}(\omega)$$



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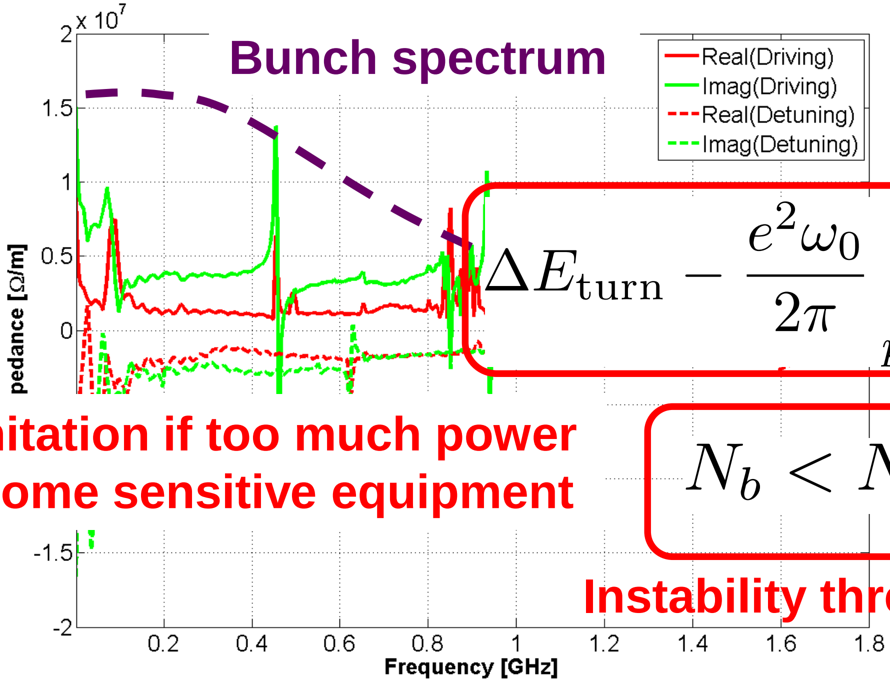


$$\Delta E_{\rm turn} - \frac{e^2\omega_0}{2\pi}\sum_{p=-\infty}^{\infty} |\tilde{\lambda}(p\omega_0)|^2 \cdot {\rm Re}[Z_{||}(p\omega_0)]$$

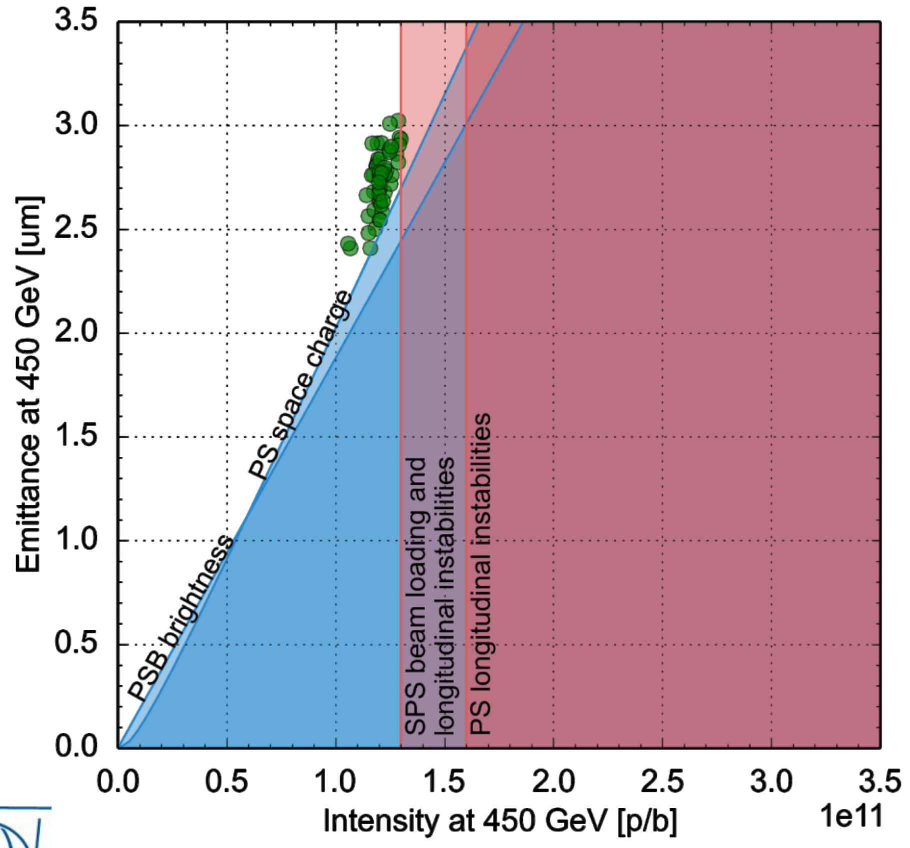
Also intensity limitation if too much power is deposited on some sensitive equipment

$$N_b < N_{\rm max}(Z_{\perp,||}, Q_s, \gamma, \ldots)$$

Instability threshold → Intensity limitation!

LHC beam performance before 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

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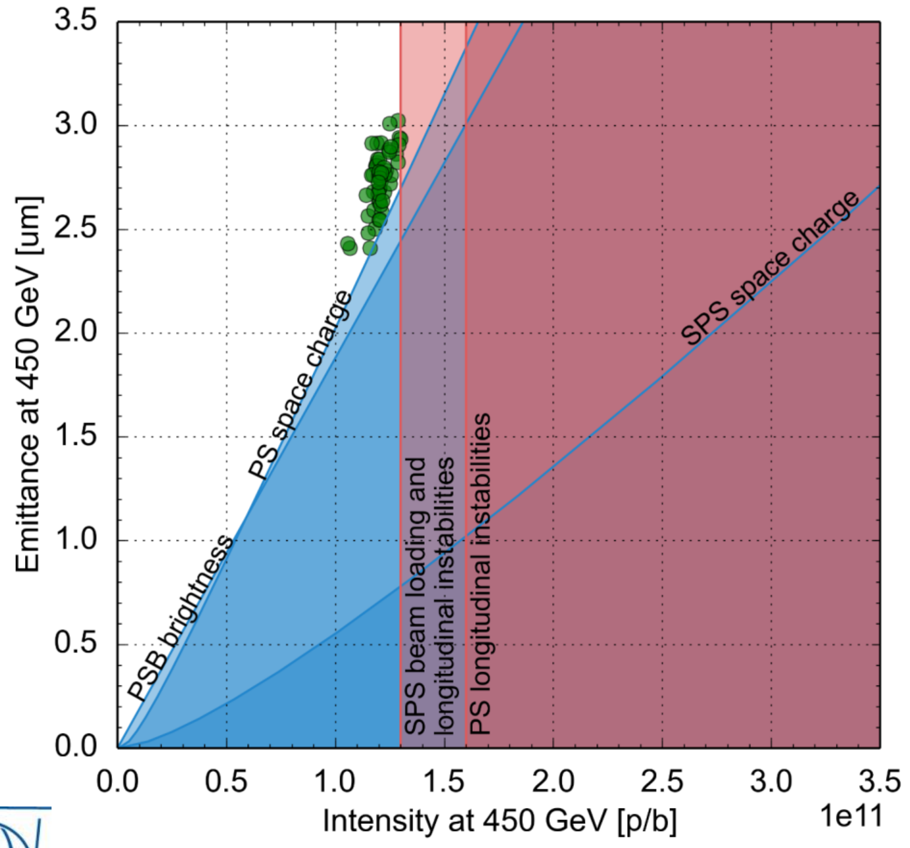
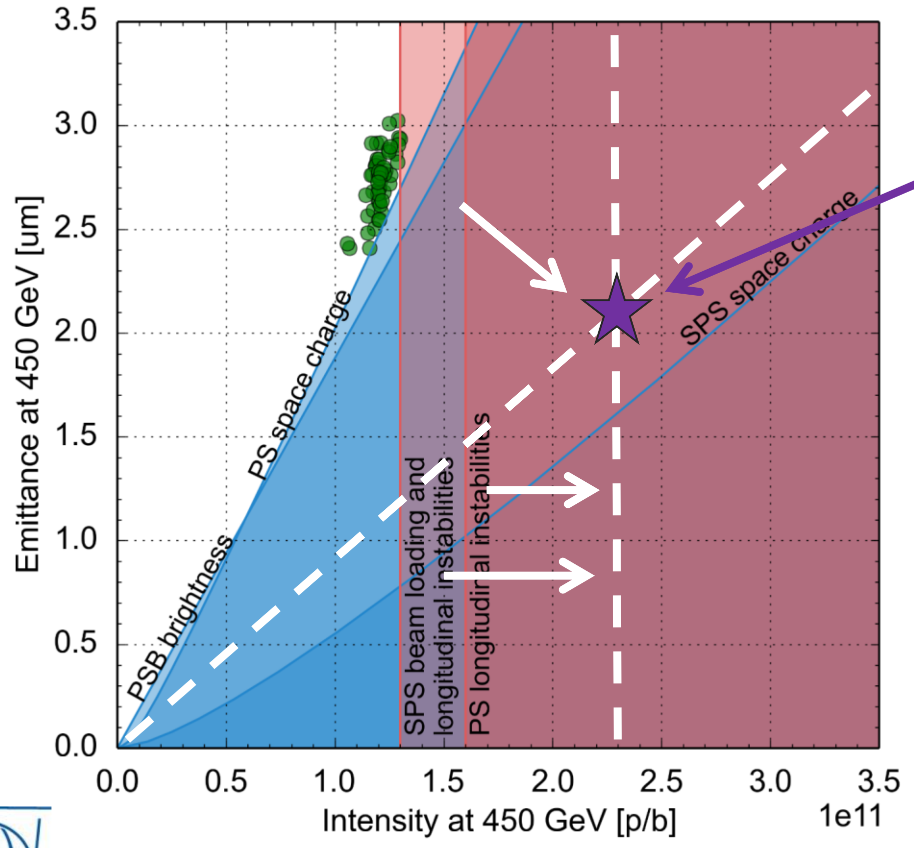


- **Brightness**
  - PSB brightness determined by space charge at injection
  - Limit for PS space charge at injection $\Delta Q_y < 0.31$
  - ✓ *Space charge in SPS not a limit for LHC beams*
- **Intensity**
  - SPS is limited by beam loading and longitudinal instabilities on the ramp and flat top
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

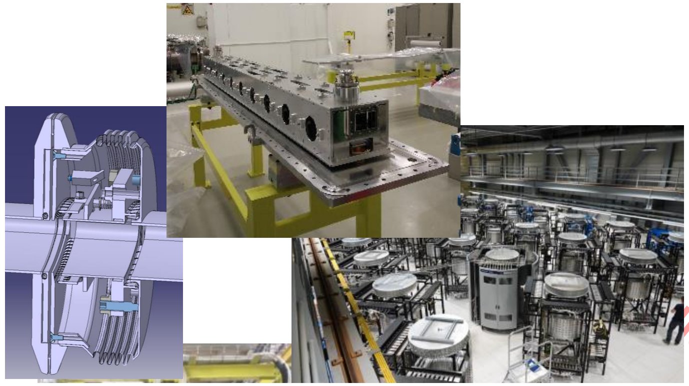


	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	2.3	2.1
Before upgrades	1.3	2.7

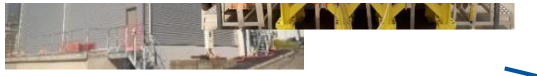
- **LIU strategy**
  → Identify the sources of the performance limitations in each of the injectors impeding the achievement of the HL-LHC target parameters
  → Define and deploy the necessary upgrade items to overcome these limitations

A quick overview on the LIU project

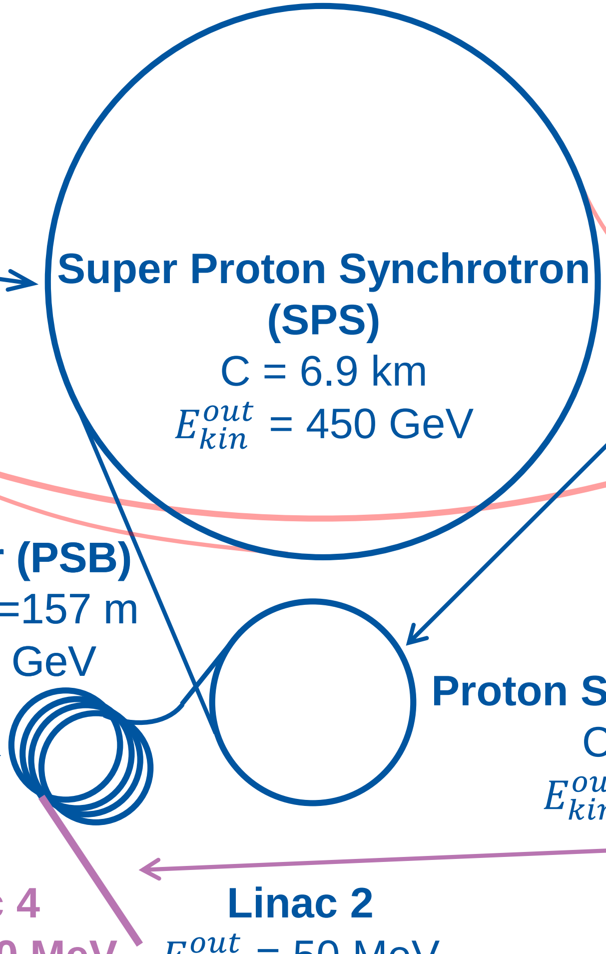
LHC Injectors Upgrade



- 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



- **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



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

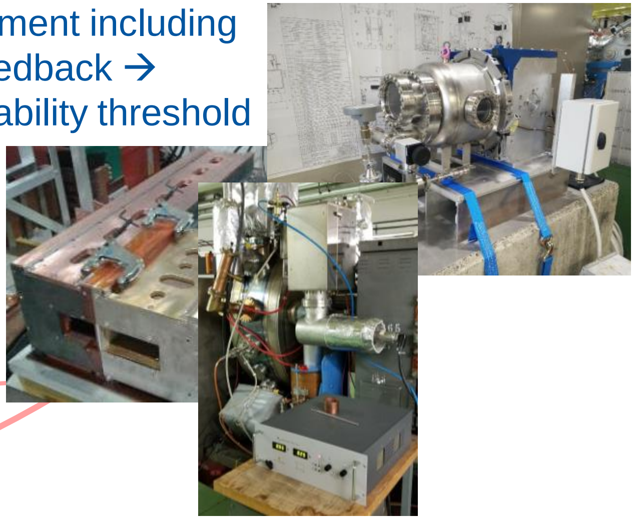
PS-Booster (PSB)
4 rings of C =157 m
E_{kin}^{out} = 1.4 / 2.0 GeV

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

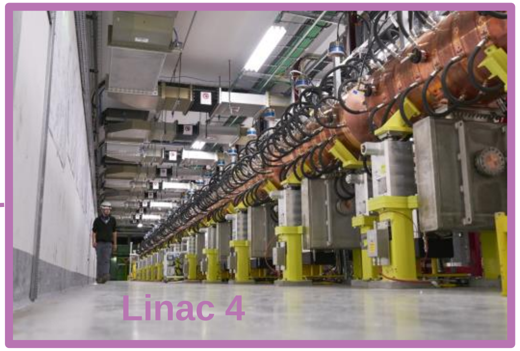
Linac 4
E_{kin}^{out} = **160 MeV**

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

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

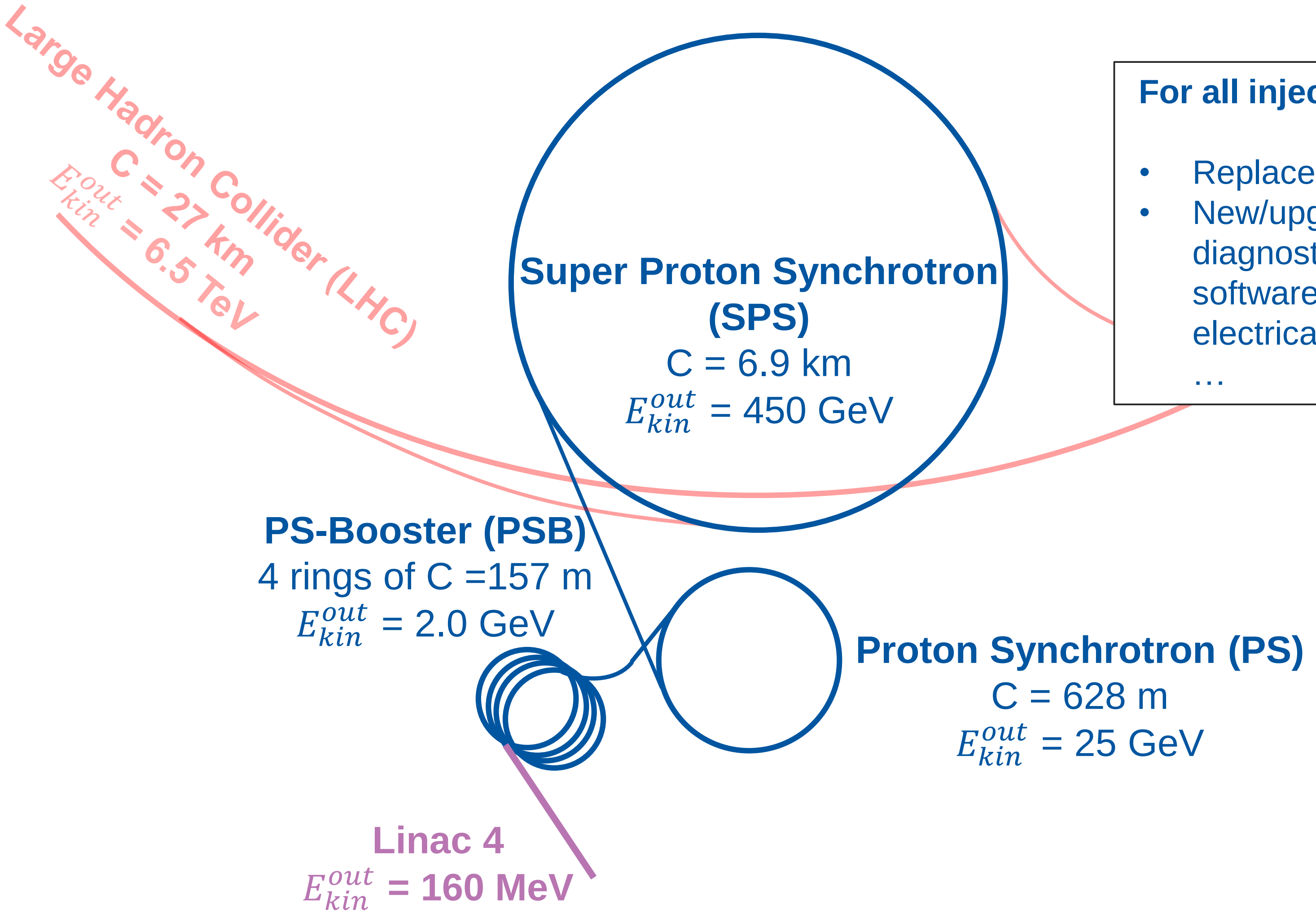


- Acceleration of H^- to **160 MeV**
- Up to 40 mA within 0.3 μm



A quick overview on the LIU project

LHC Injectors Upgrade



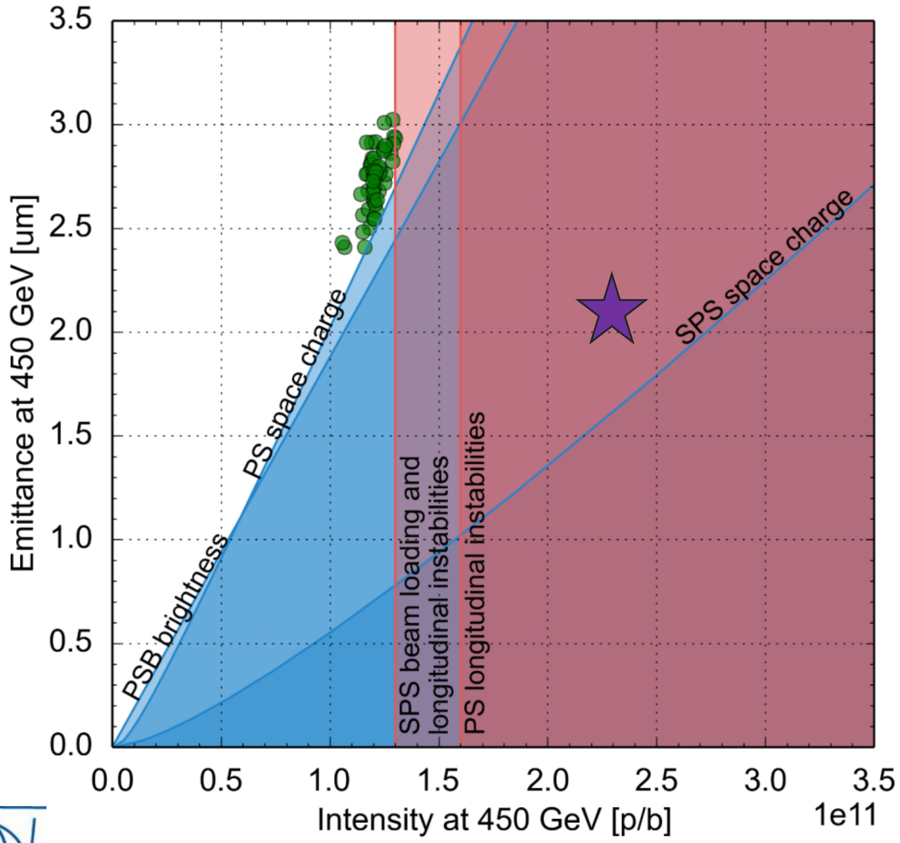
For all injectors :

- 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



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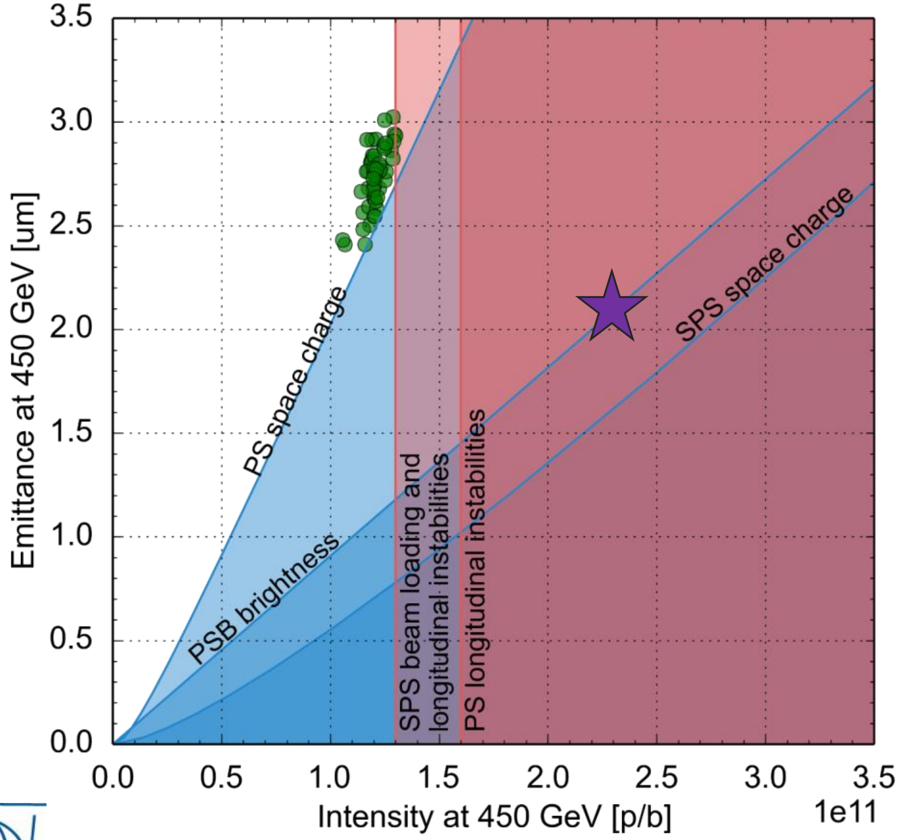
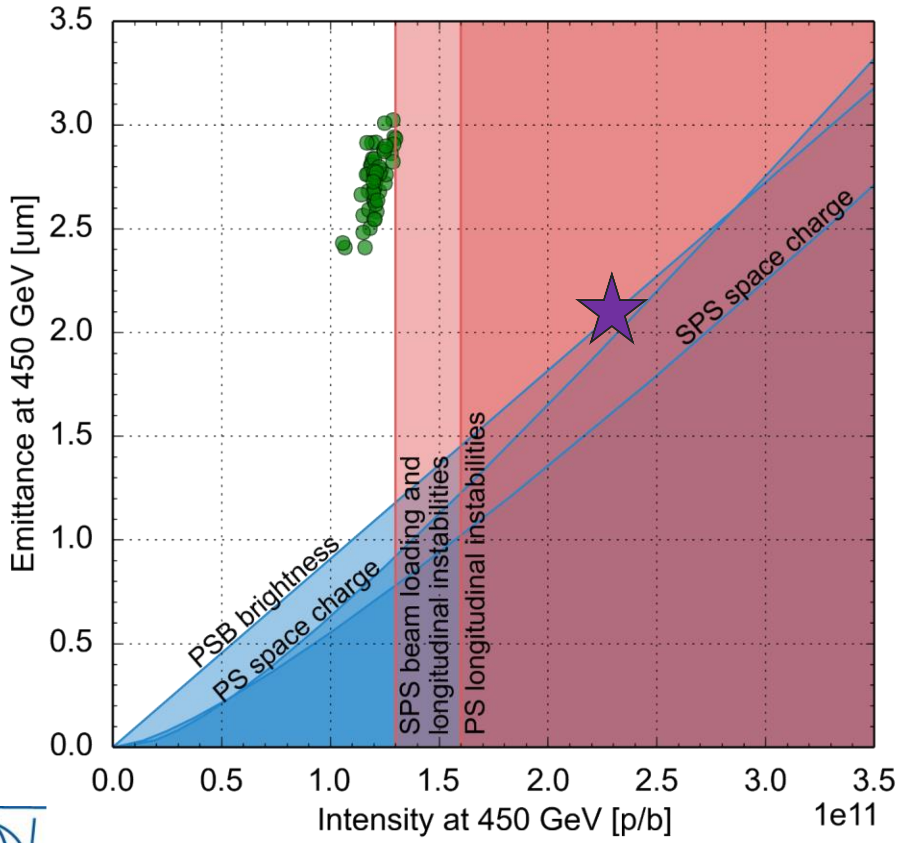


- **Connection of PSB to Linac4**
  - Linac4 providing 25 mA within 0.4 um
  - Charge exchange H^- injection at 160 MeV into PSB

Beam performance with LIU upgrades

LHC Injectors Upgrade

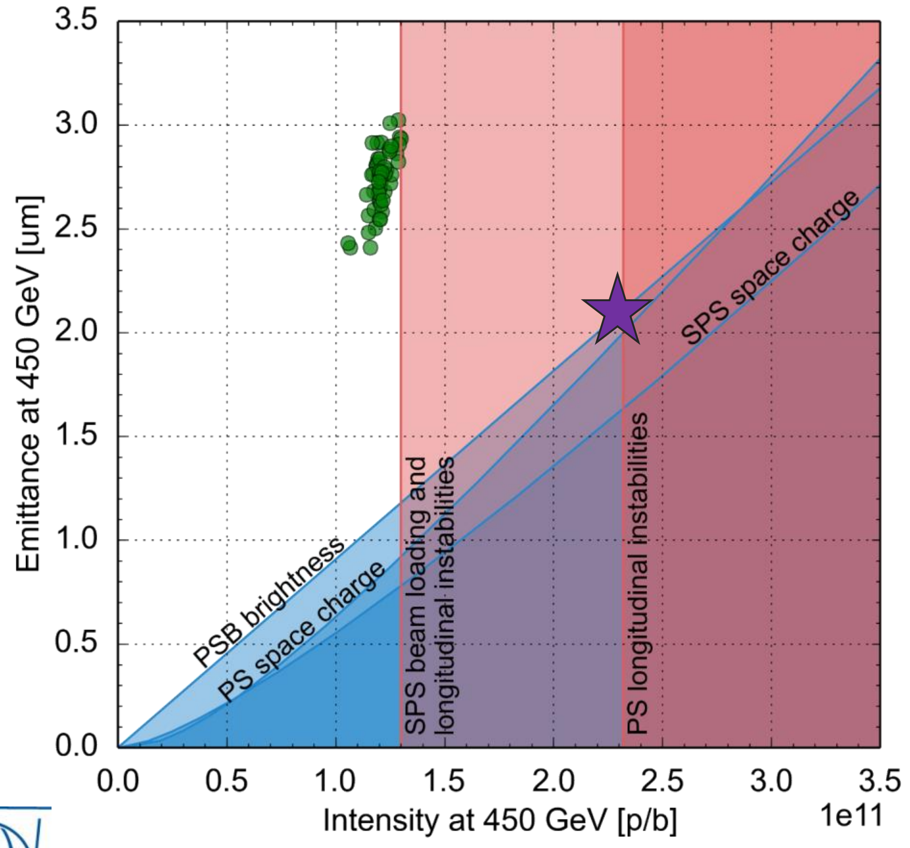
- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



- 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

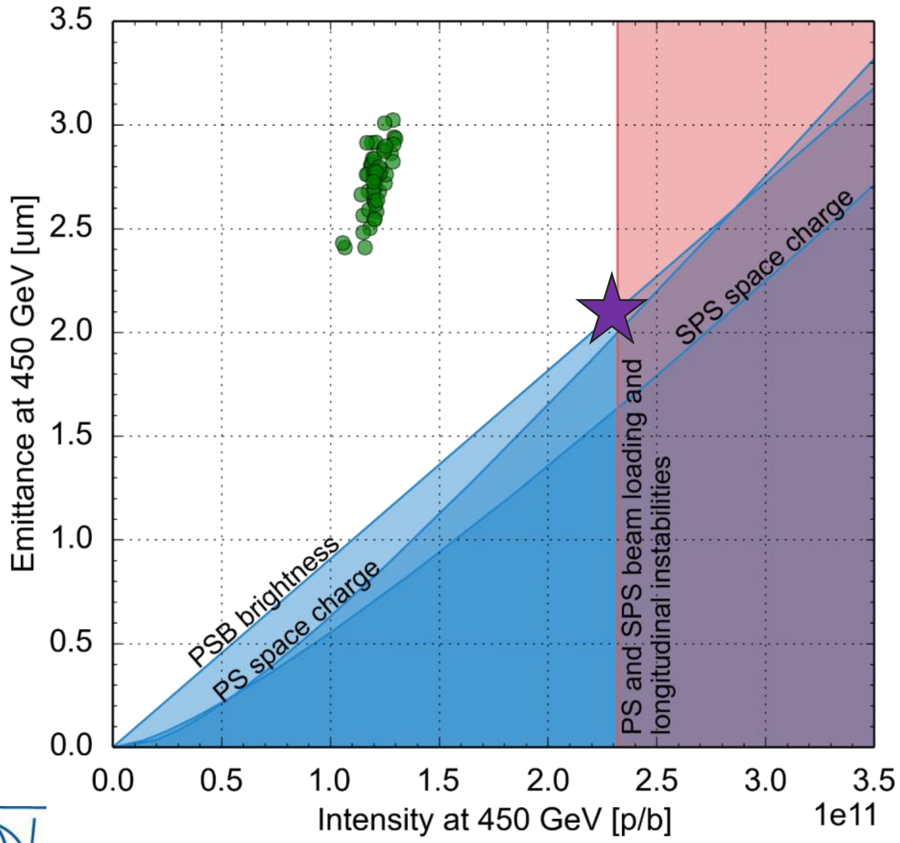
- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



- 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

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

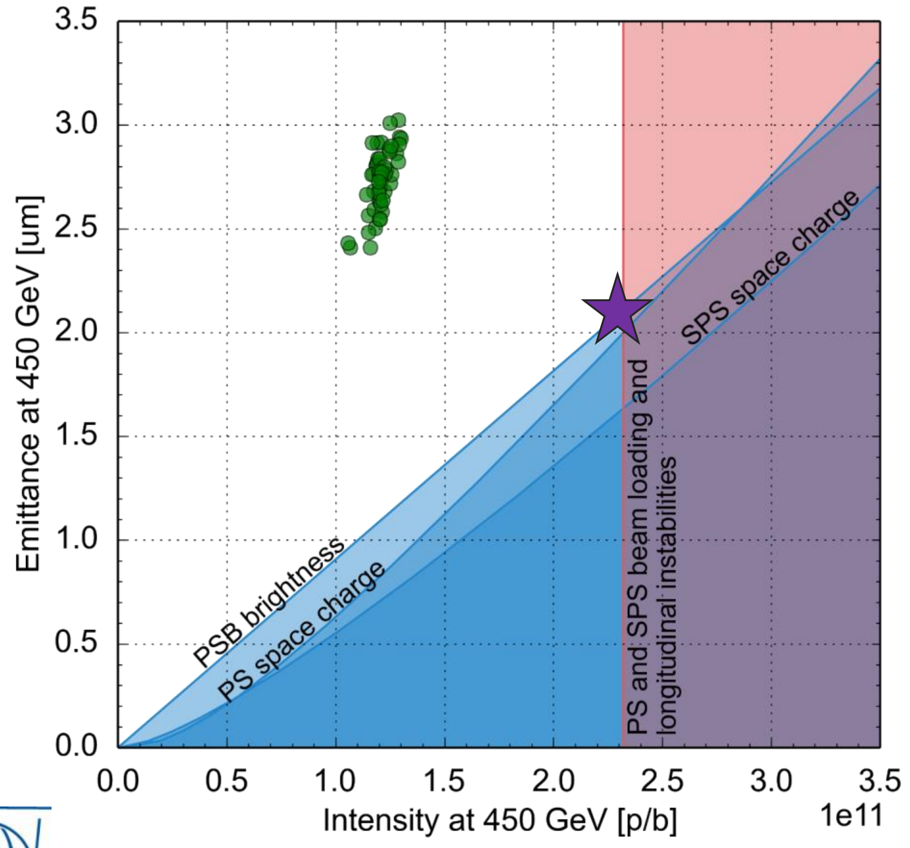


- Connection of PSB to Linac4
- PSB acceleration to 2 GeV
- PS RF upgrades
- **SPS upgrade**
  - Power and LLRF upgrade of 200 MHz RF system
  - Longitudinal impedance reduction
  - a-C coating of focusing quadrupole chambers
  - Deployment of low γ_t optics
  - Upgrade of beam dump and protection devices

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

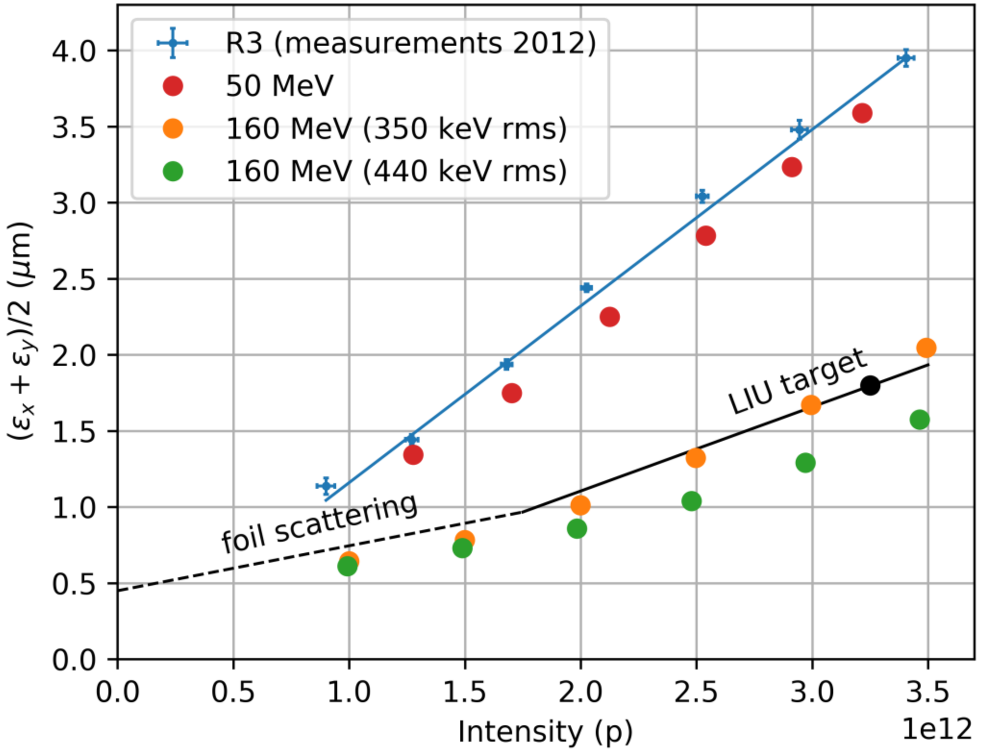
⇒ **LIU parameter reach for proton beams matches the HL-LHC target within baseline**

Some examples of beam dynamics studies that guided definition of LIU parameter reach and, consequently, the LIU baseline choices

(1) Connection of PSB to Linac4

LHC Injectors Upgrade

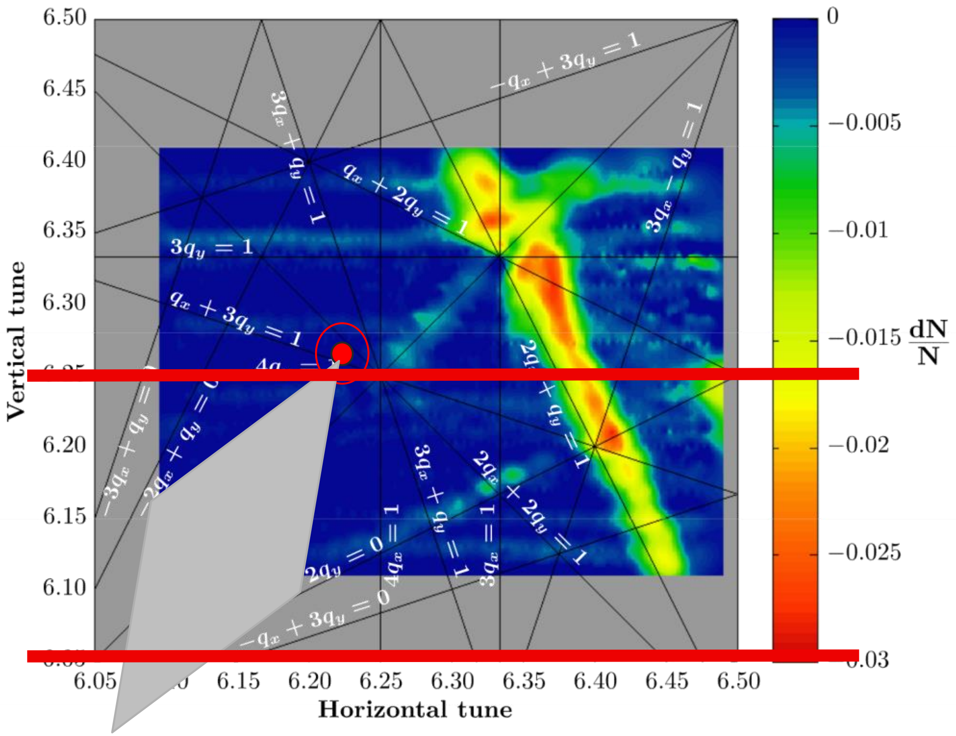
- The achievable beam brightness with multiturn injection at 50 MeV (Linac2) is inherently limited by the injection process and space charge
  - Linear increase of transverse emittance with increase of injected intensity
  - Simulations could closely reproduce measured slope
- Brightness can be doubled 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

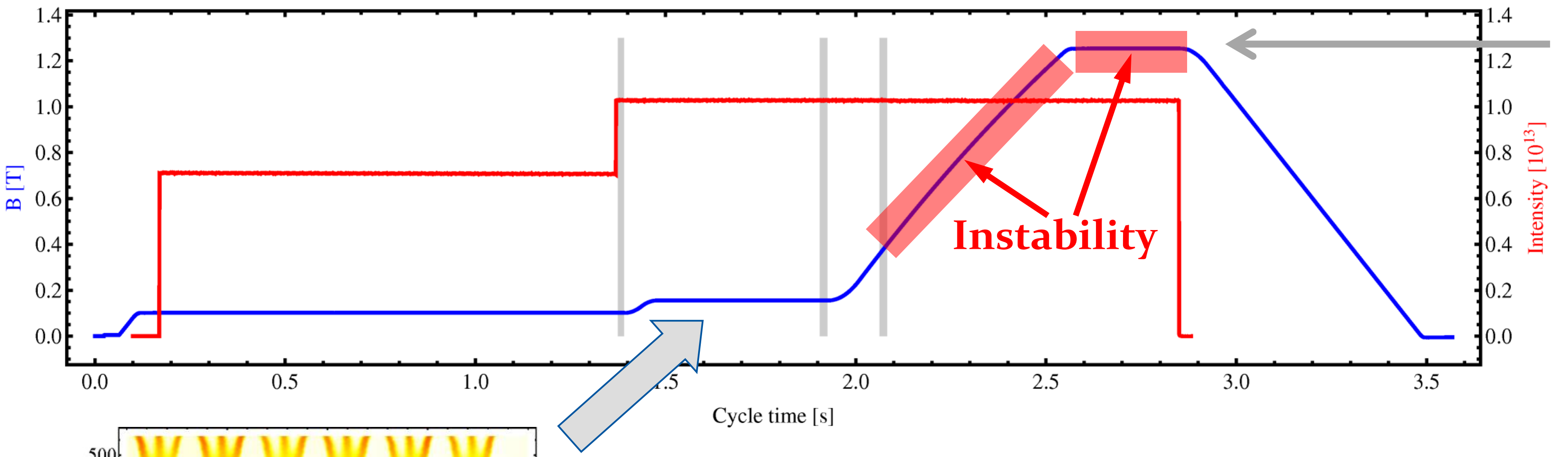
LHC Injectors Upgrade

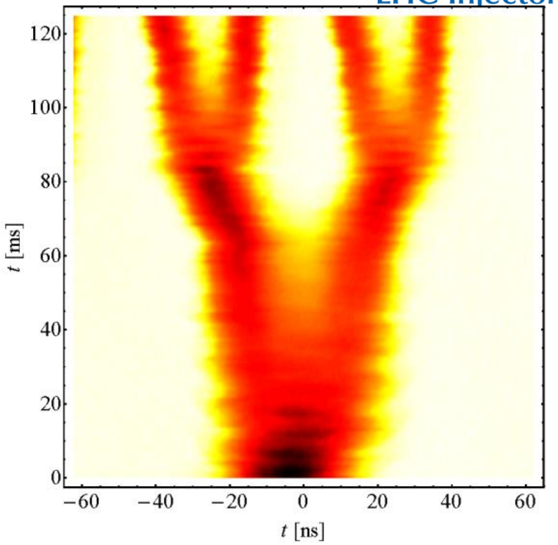
- Space charge plays a crucial role at the PS injection
  - 4 PSB bunches with large tune spread sit at injection energy for 1.2 s
  - Tune spread needs to be accommodated between integer resonance and space charge driven structural resonance 8Qy=50 during 1.2 sec flat bottom

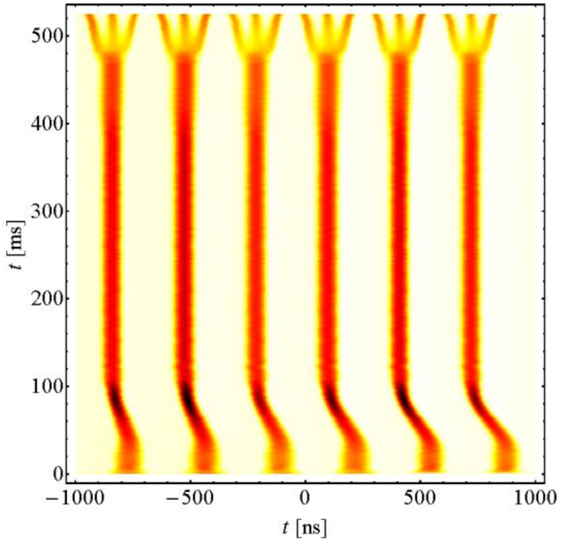


- In order to keep the pre-LIU tune spread at injection with double intensity in the same transverse ε
  - Increase of injection energy to **2 GeV** (63% gain in $\beta\gamma^2$)
  - **Larger longitudinal emittance** at PSB-PS transfer to allow for longer bunches and larger δp/p

(3) PS intensity limitation



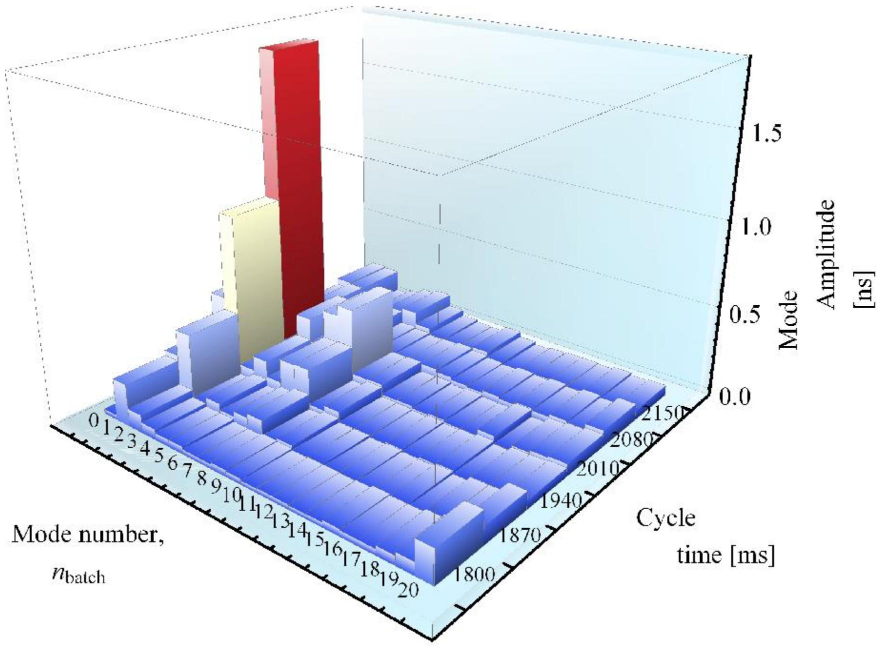




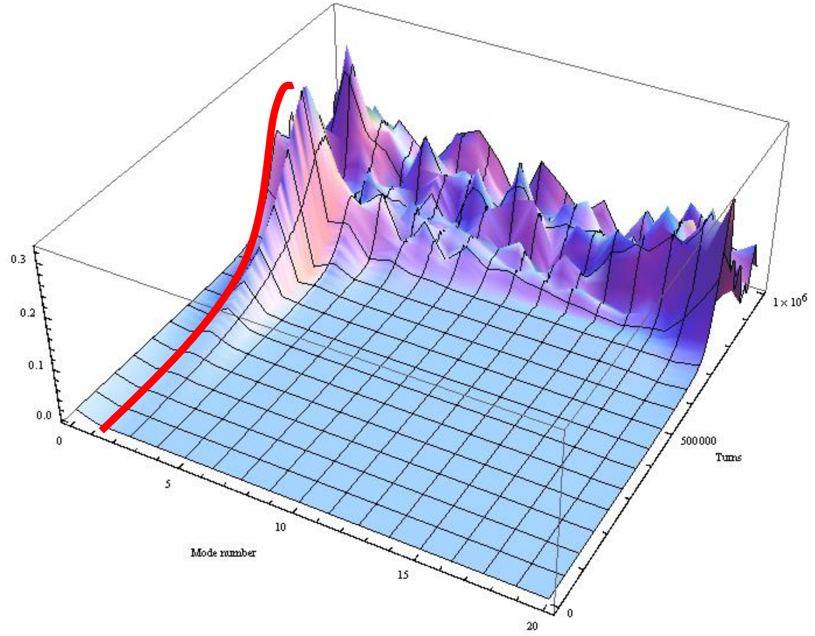
- Bunch current limited to **1.5e11 p/b at extraction**
- Above 1.5e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top
  - Simulations show it is a dipolar oscillation mainly driven by **10 MHz RF system impedance**

(3) PS intensity limitation

Measured mode spectra



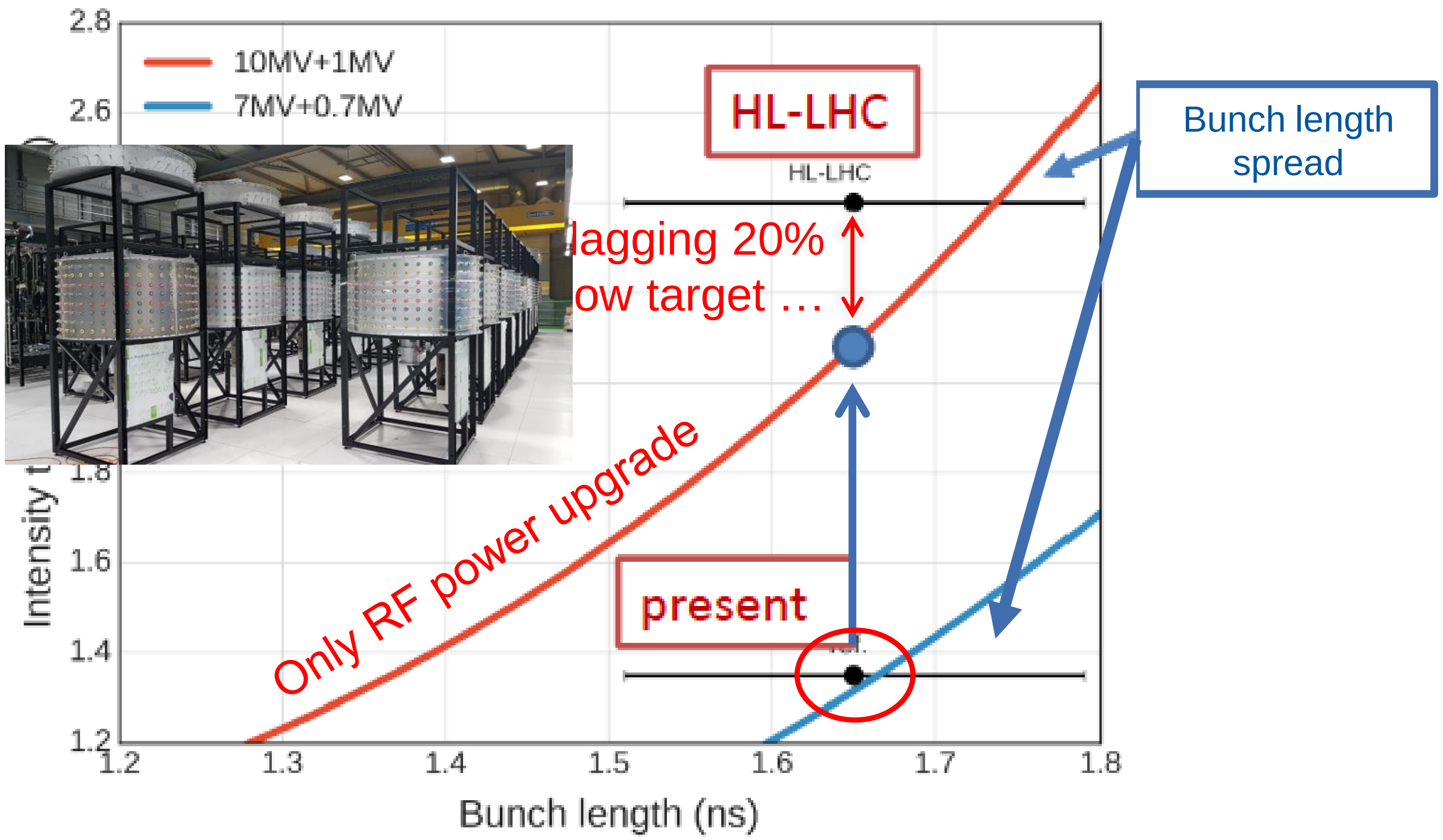
Simulations with 10 MHz cavities + Finemet cavity impedance model



- Instability successfully reproduced in simulations (mode n=2)
- **Broad-band feedback system demonstrated** to counteract this instability in simulations

(4) SPS intensity limitation (longitudinal)

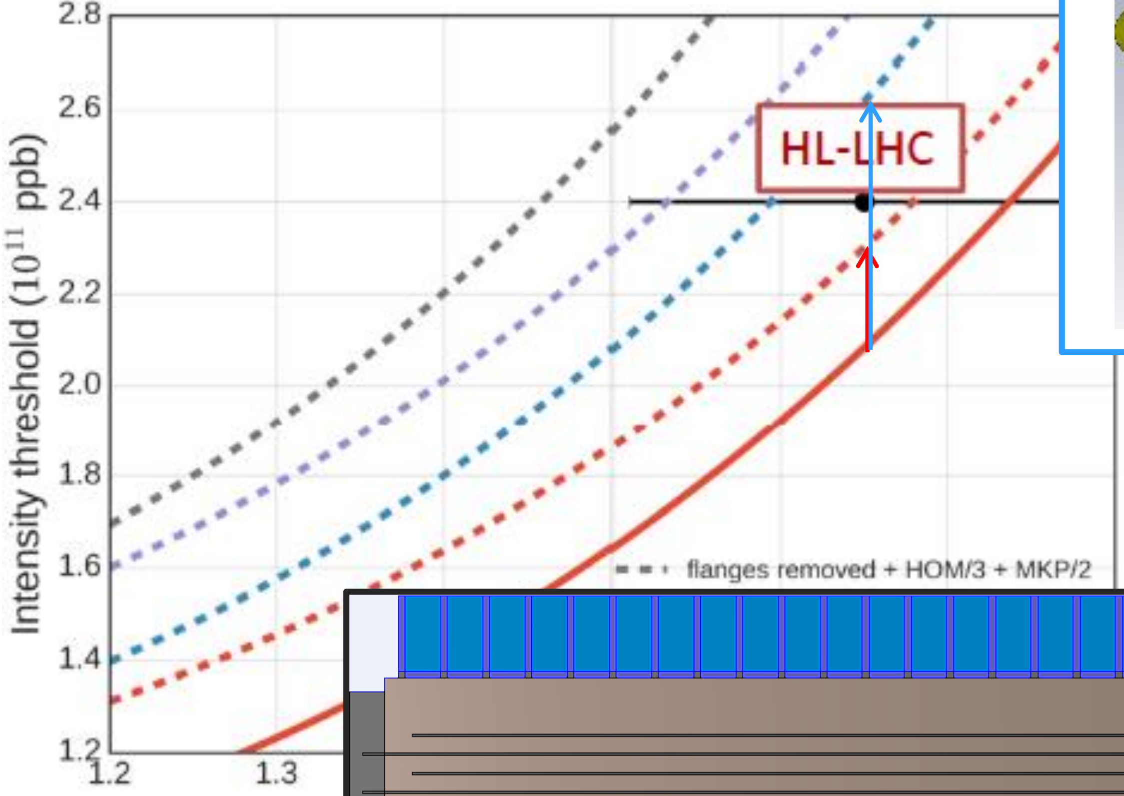
- **SPS intensity limitations**
  - **Beam loading** in the present 200 MHz TW RF system
  - **Longitudinal instabilities** during ramp with very low threshold mitigated by
    - 800 MHz RF system in bunch shortening mode
    - Controlled emittance blow-up (with constraint of 1.7 ns bunch length at extraction)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

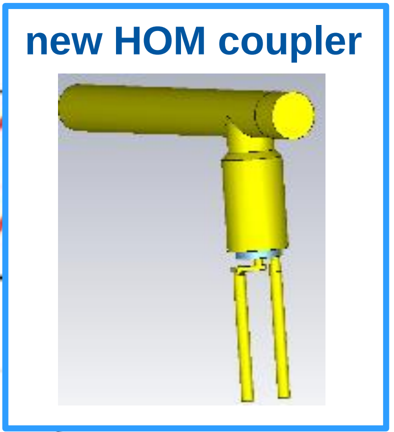


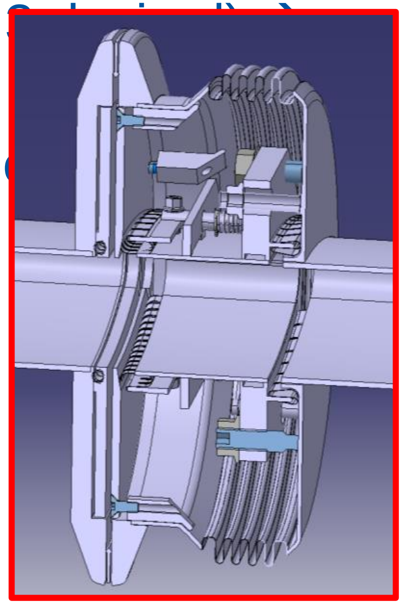
(4) SPS intensity limitation (longitudinal)

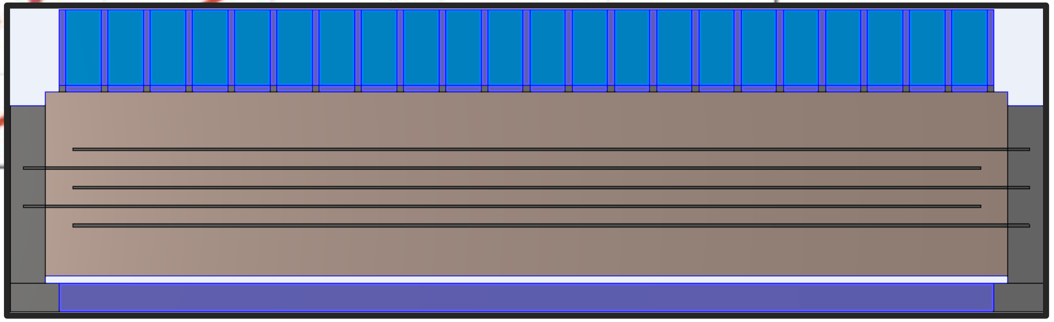
LHC Injectors Upgrade

- **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



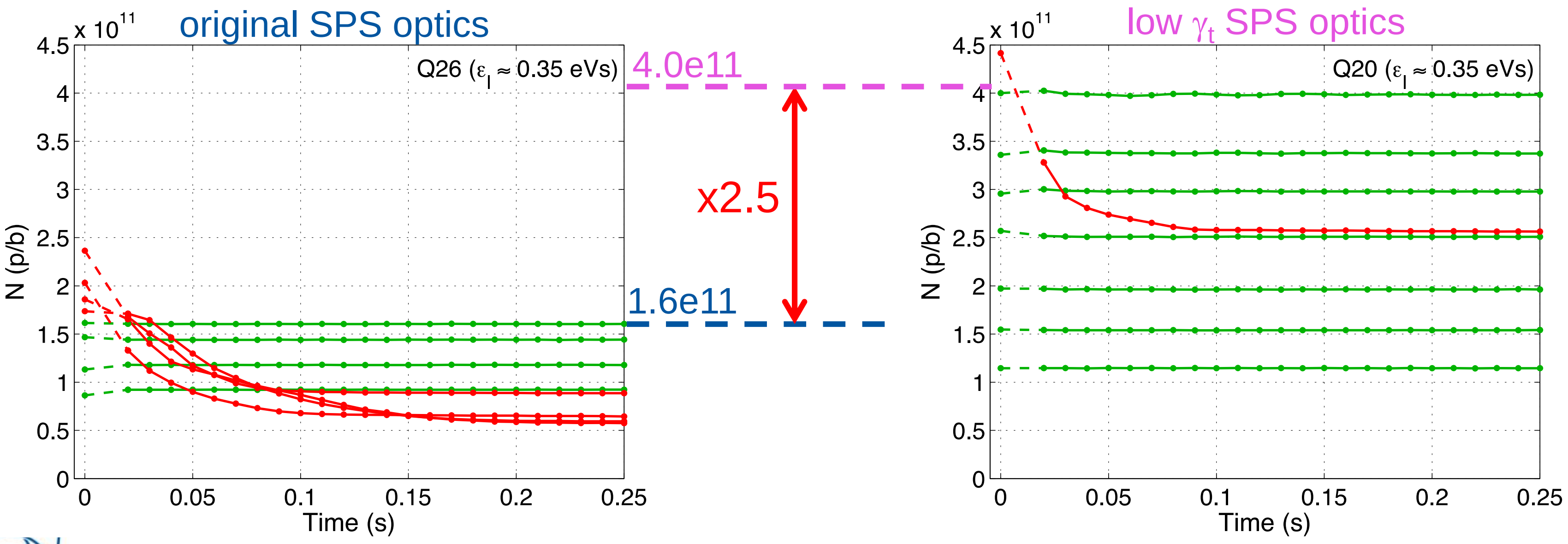






(5) SPS intensity limitation (transverse)

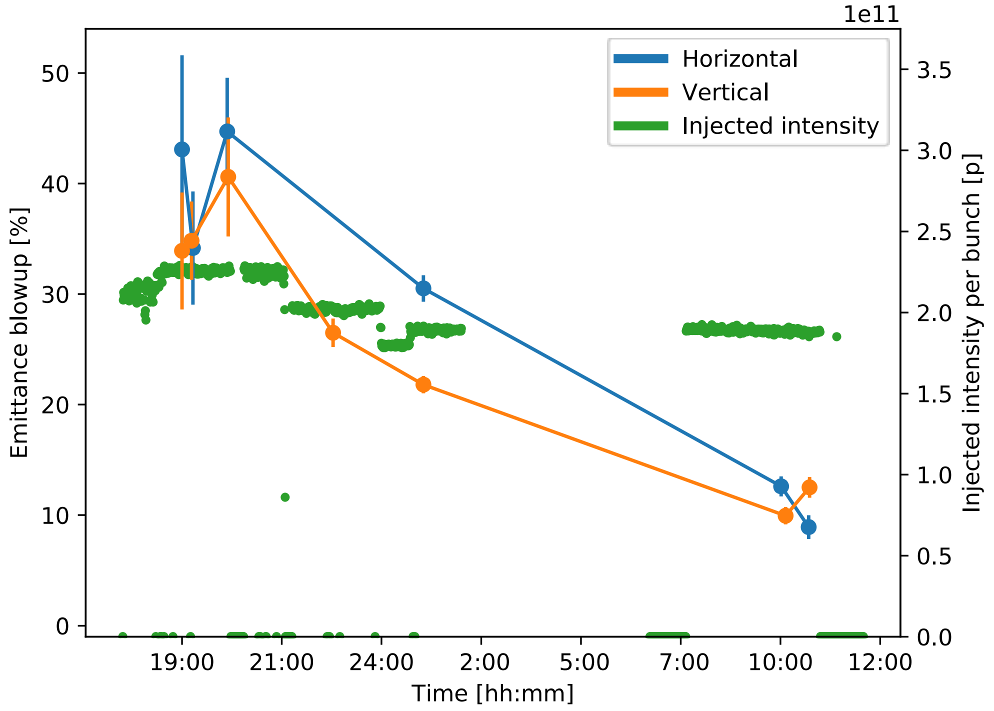
- **Transverse Mode Coupling Instability (TMCI)** threshold was **1.6e11 p/b** with the original Q26 optics (integer part of the tune 26)
- Simulations showed that it could be raised to 4e11 p/b using a low gamma transition (γ_t) optics (Q20)

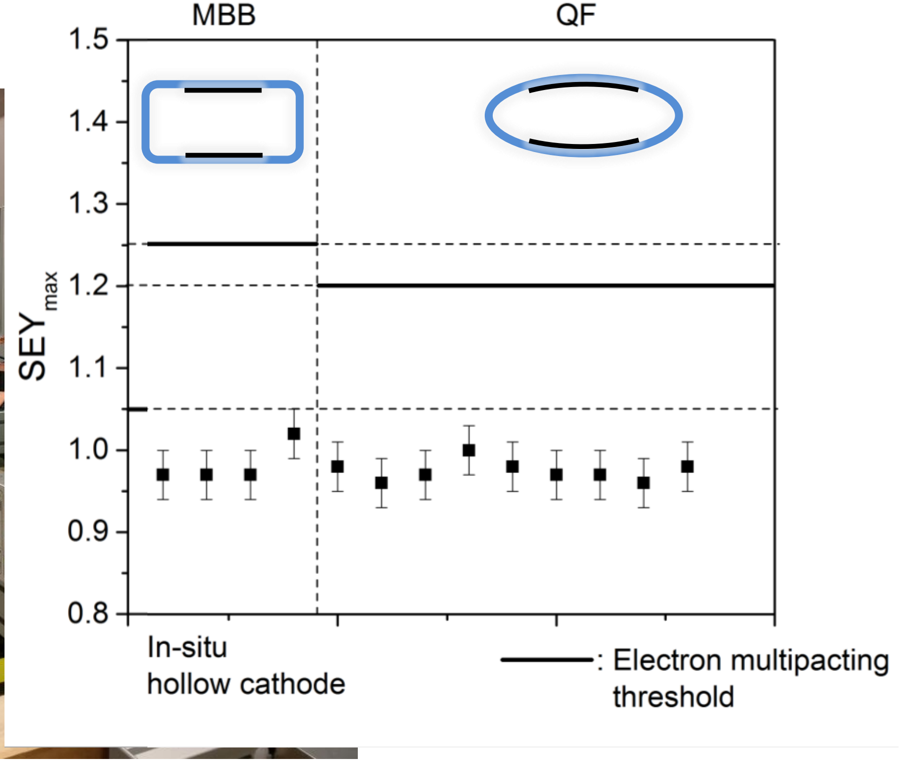


- **Measurements confirmed this 2.5 times higher threshold!**
- **The Q20 optics has been made operational for LHC beams**

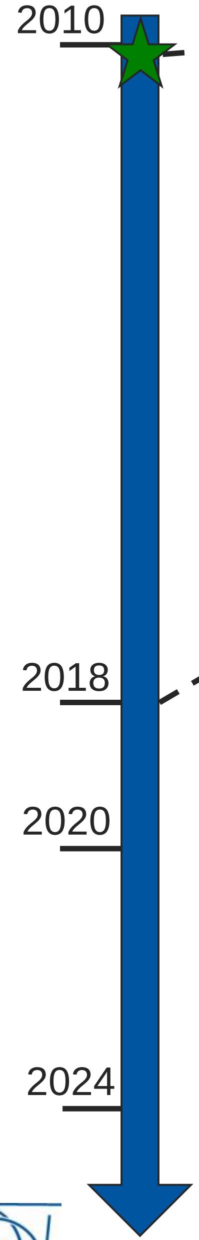
(6) SPS electron cloud

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





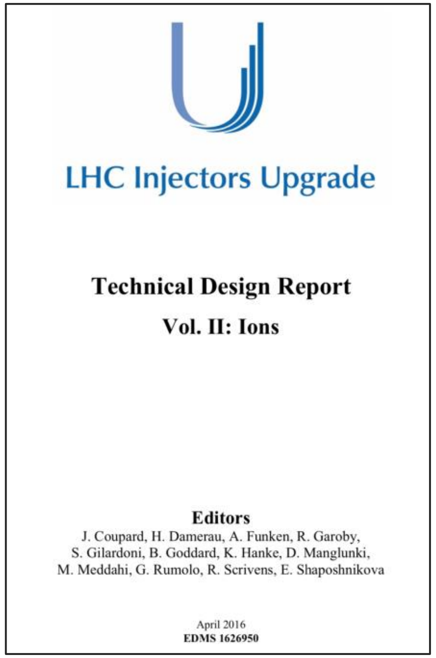
A quick overview on the timeline of the LIU project and results with beam up to 2022



LHC Injectors Upgrade

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


LHC Injectors Upgrade

Technical Design Report

Vol. II: Ions

Editors

J. Coupard, H. Damerau, A. Funken, R. Garoby, S. Gilardoni, B. Goddard, K. Hanke, D. Manglunki, M. Meddahi, G. Rumolo, R. Scrivens, E. Shaposhnikova

April 2016

EDMS 1626950

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

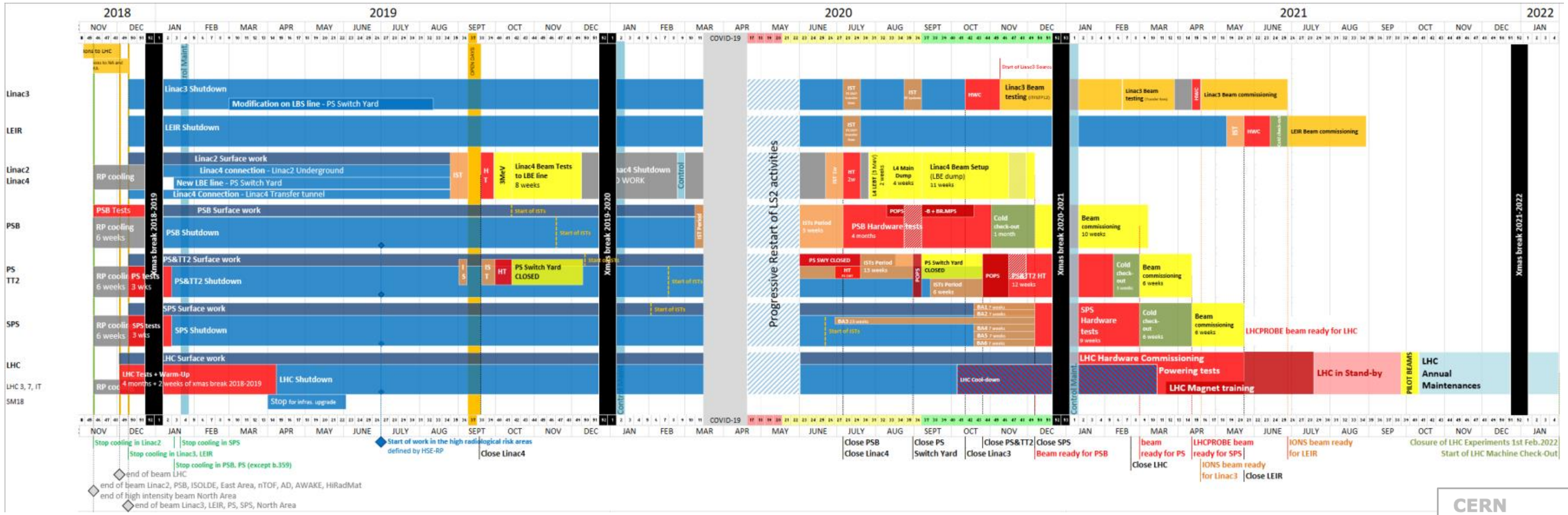
2010

2018

2020

2024

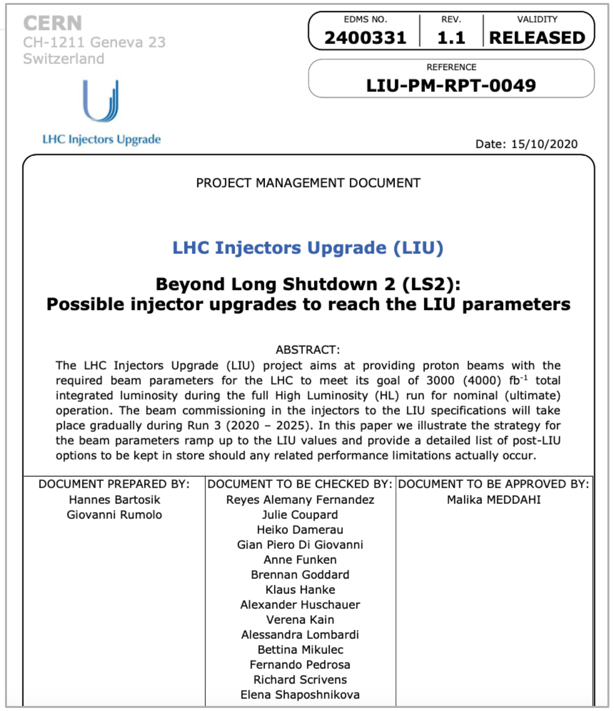
ACC-PM-MS-0002 v.4.0



LHC Injectors Upgrade

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



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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:
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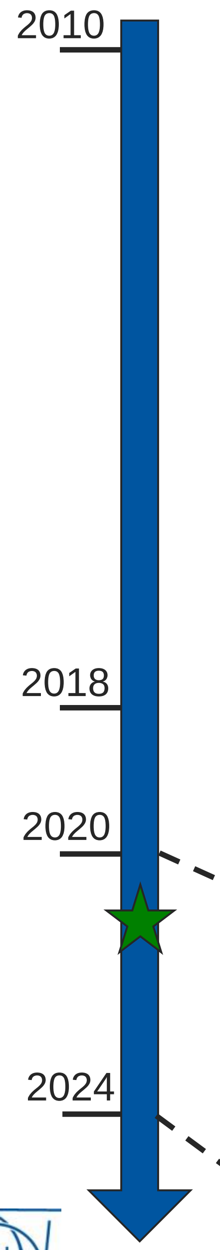
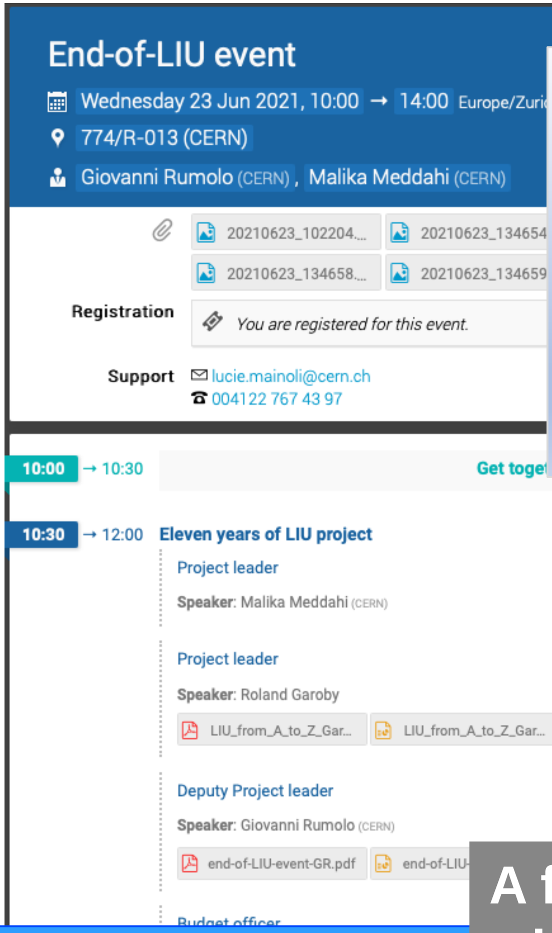
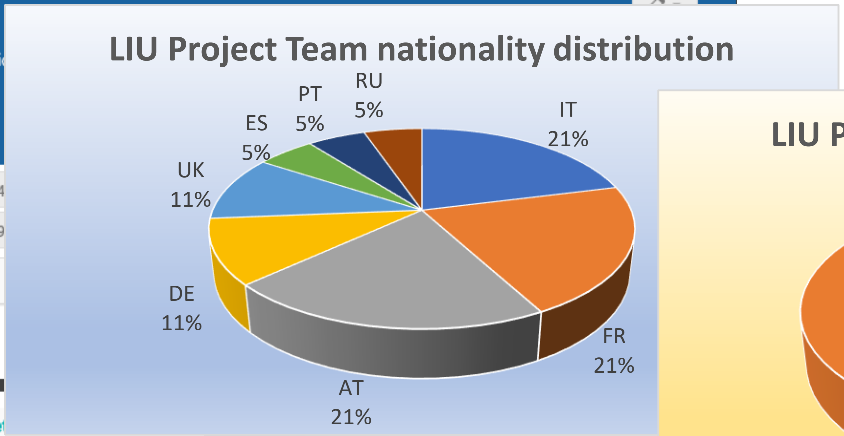
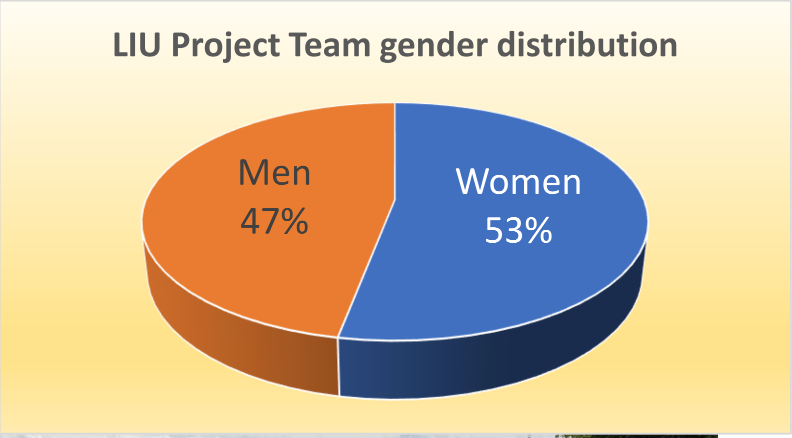


LHC Injectors Upgrade







Run 3 (2020 – 2024)

- **Recommissioning c**
- **End of LIU project c**

A fine example of successful teamwork rich in diversity, which has made it possible to

- **Complete the project in full compliance of safety, schedule and budget**
- **Demonstrate the beam performance goals with a timely and systematic approach**

2010

2018

2020

2024

2020 – 2021 → **2022** → **2023** → **2024**

LHC Injectors Upgrade

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

- Recovery of pre-Long Shutdown proton beams with Linac4 and newly installed LIU equipment

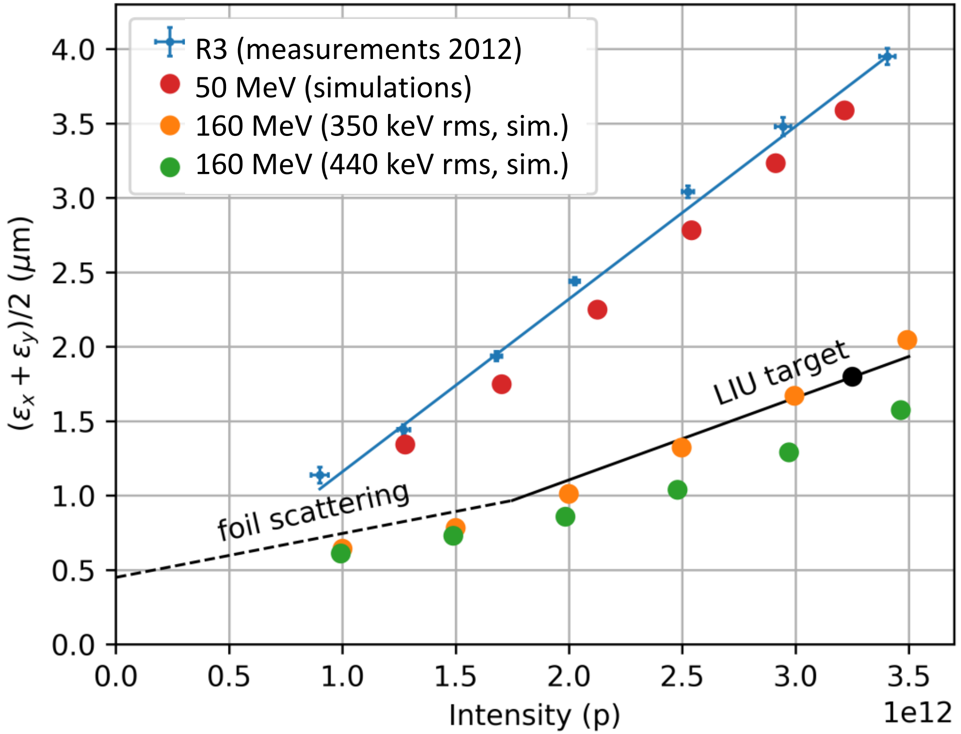
Run 3 (2020 – 2024)

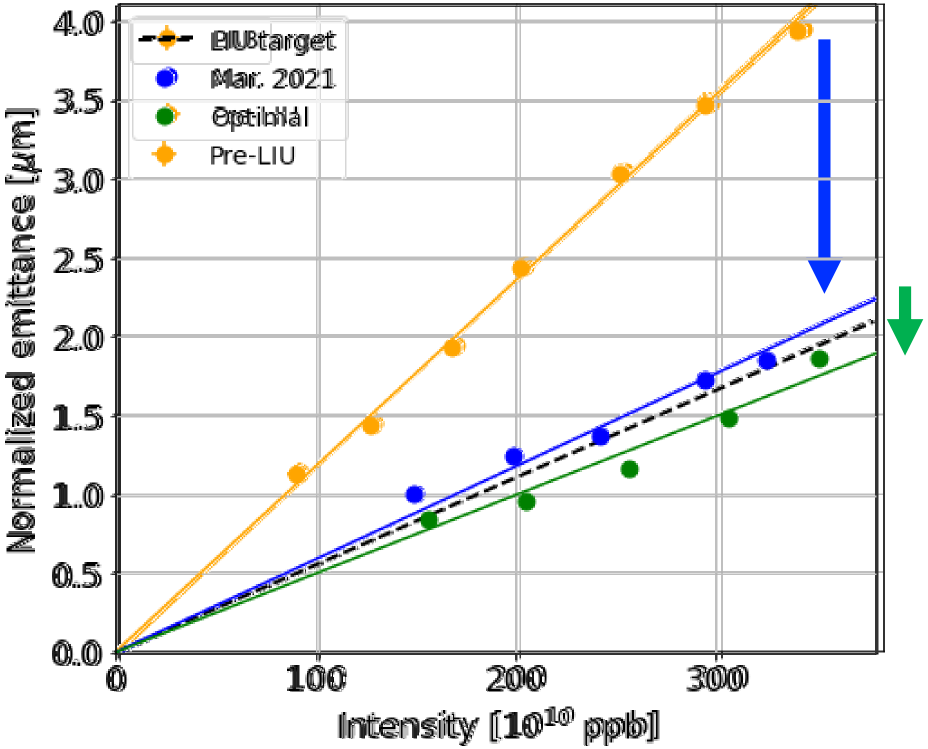
- **Recommissioning** of upgraded injectors
- **End of LIU project on 30 June 2021!**

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

LIU beam commissioning 2021-22 – PSB

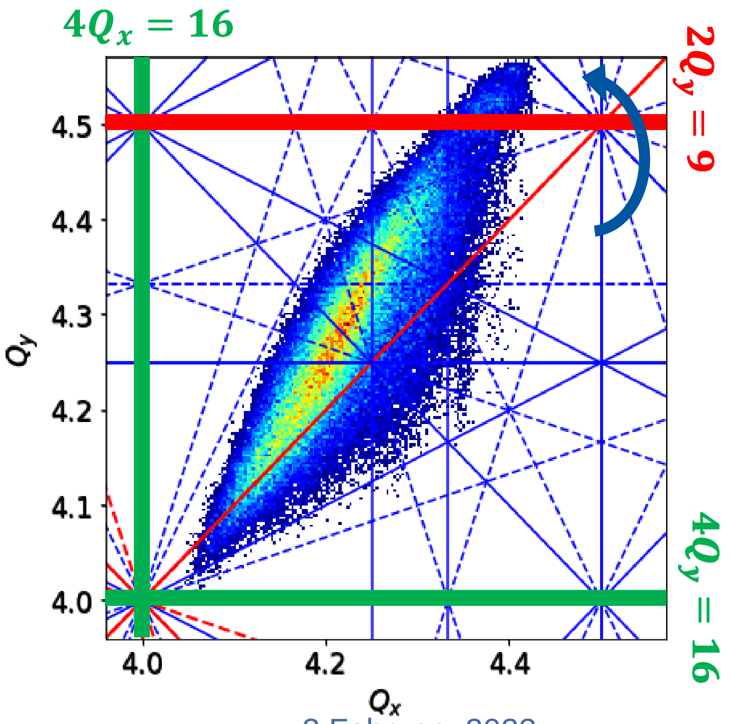
- **PSB brightness line with Linac4**

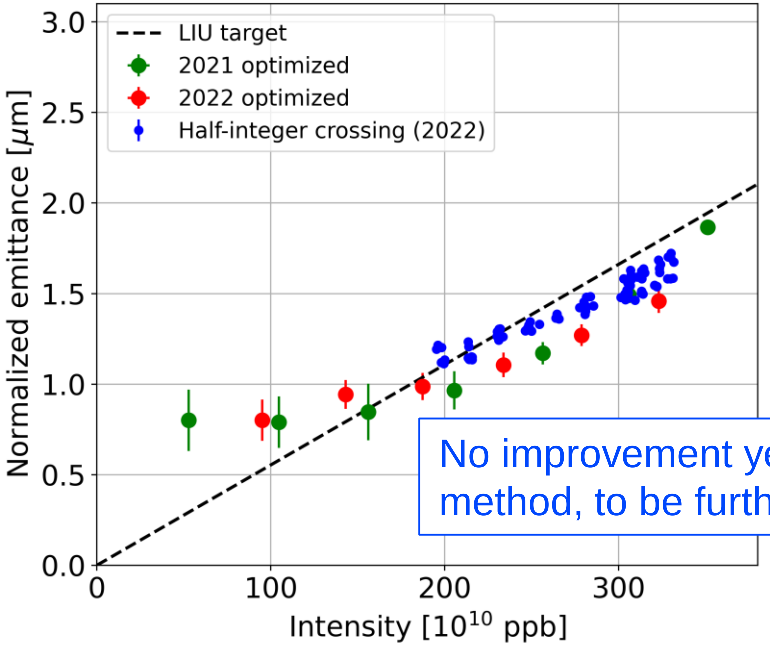




LIU beam commissioning 2021-22 – PSB

- **PSB brightness line with Linac4**
- Target achieved and surpassed, studies still ongoing to further improve the brightness and gain margin for blow-up downstream!
  - Injection above the half-integer to limit integer resonance crossing blow-up



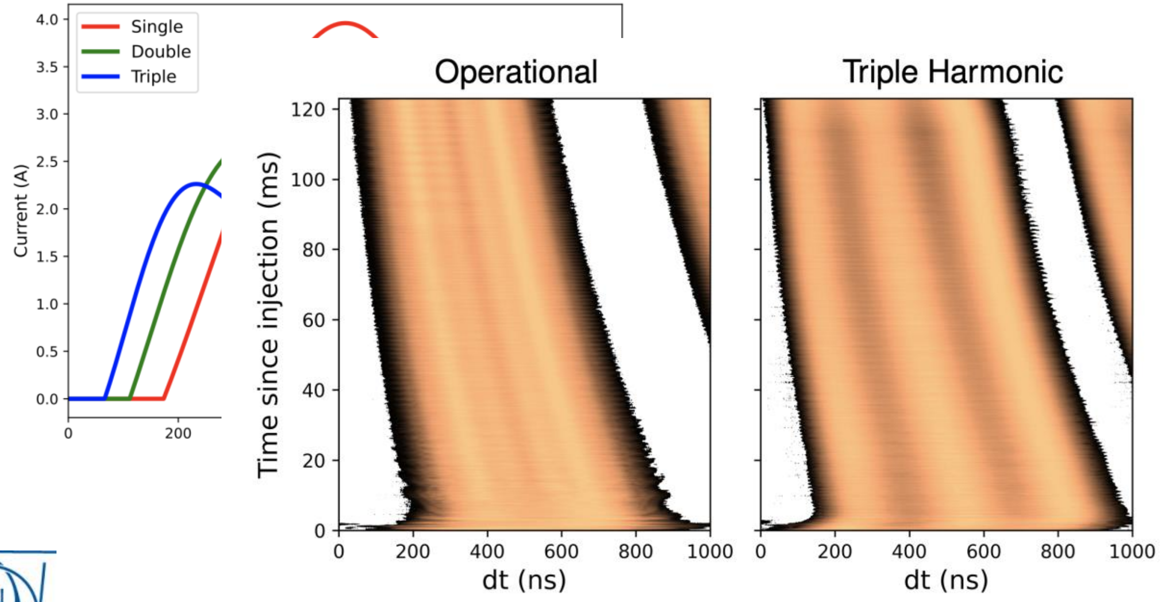


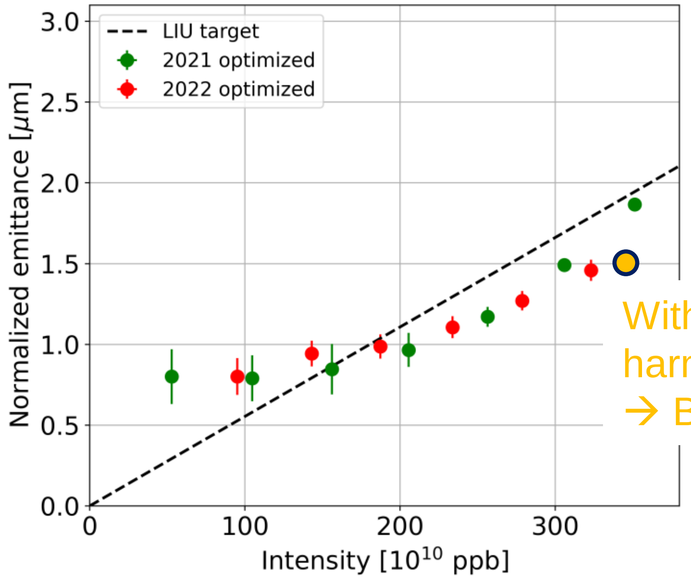
No improvement yet seen with this method, to be further optimized!

LIU beam commissioning 2021-22 – PSB

LHC Injectors Upgrade

- **PSB brightness line with Linac4**
- Target achieved and surpassed, studies still ongoing to further improve the brightness and gain margin for blow-up downstream!
  - Injection above the half-integer to limit integer resonance crossing blow-up
  - Injection into third harmonic bucket to flatten bunch and mitigate space charge

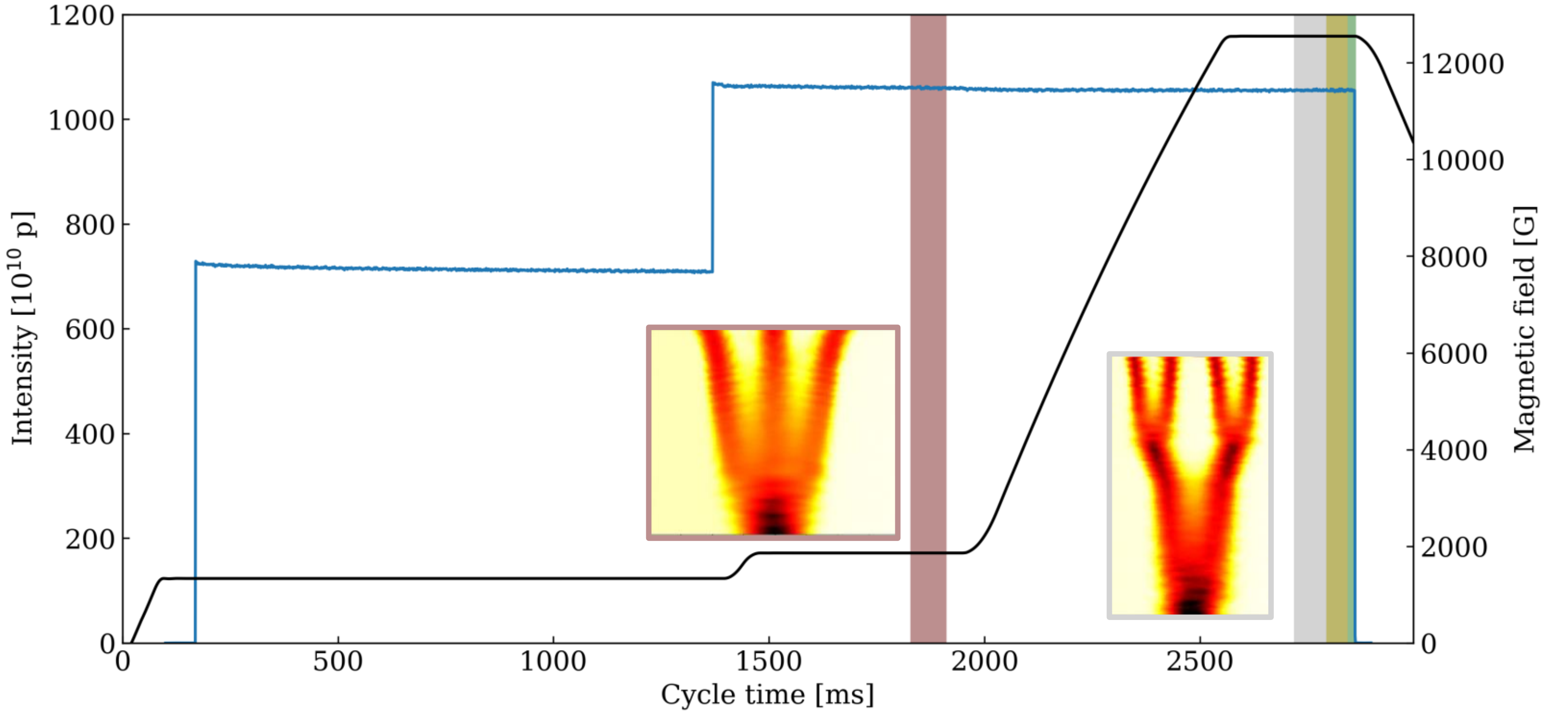




With triple harmonic
→ Brighter!!

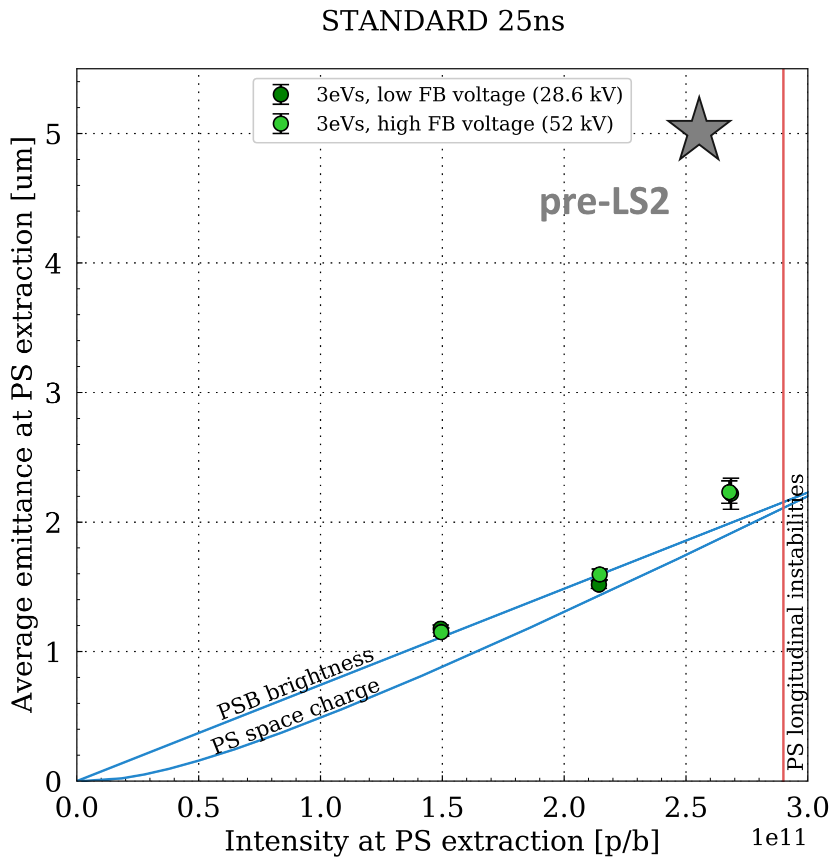
LIU beam commissioning 2021-22 – PS

- The PS in 2021 quickly recovered the pre-LIU performance
  - LHC beam quickly restored up to 1.8e11 p/b extracted
  - Excellent transmission, emittance preservation as expected



LIU beam commissioning 2021-22 – PS

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



LIU beam commissioning 2021-22 – PS

LHC Injectors Upgrade

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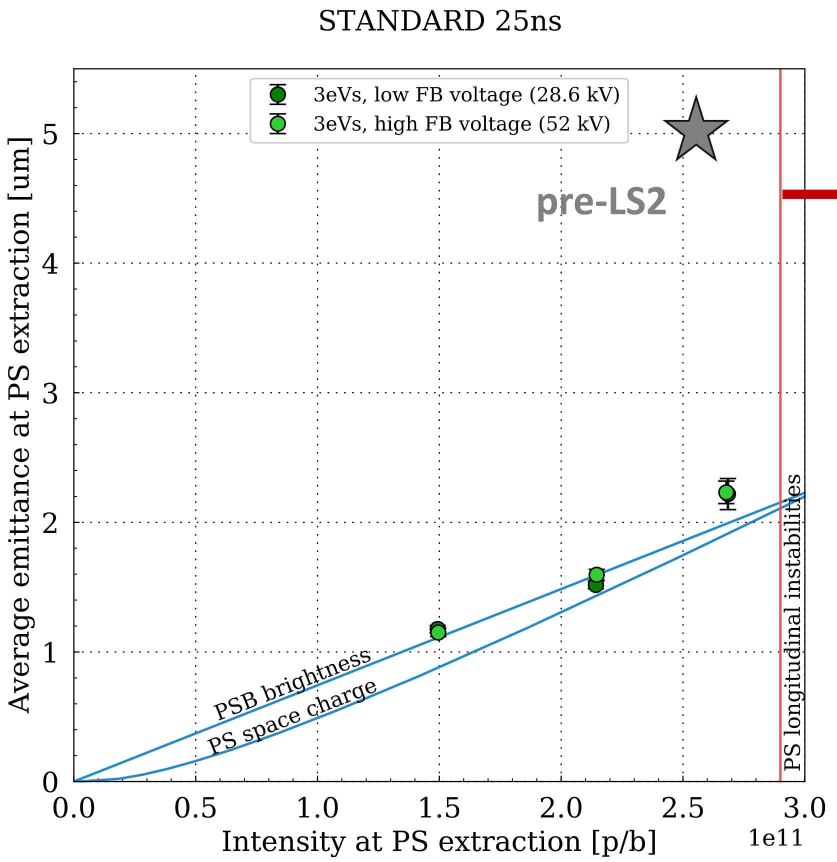
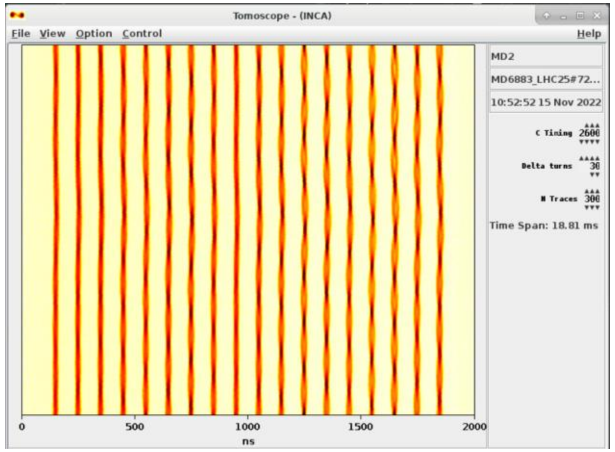
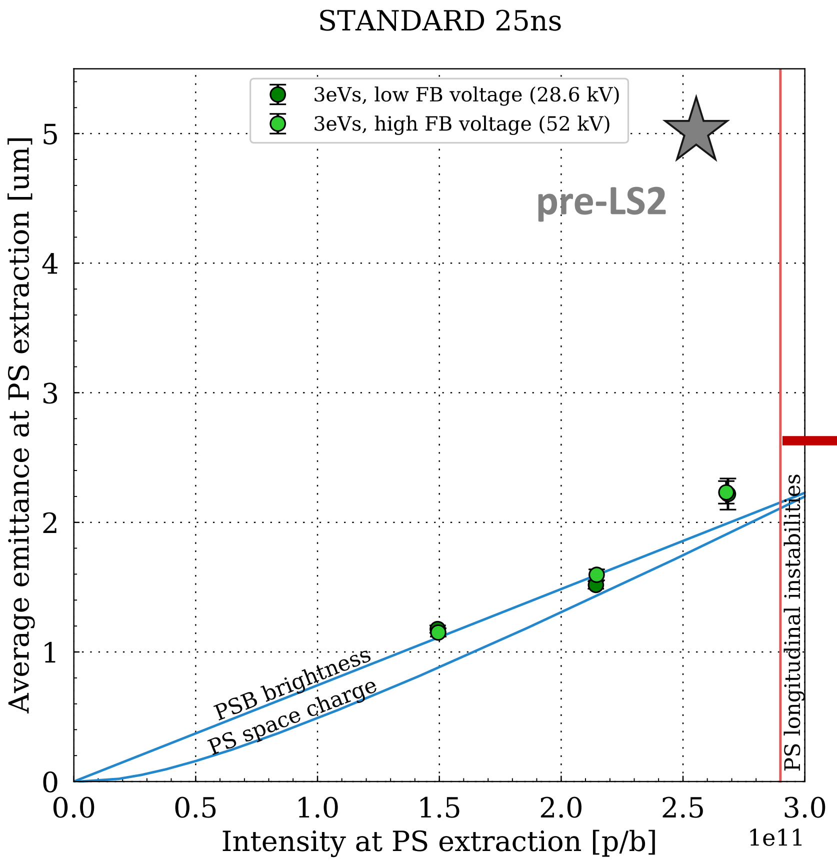




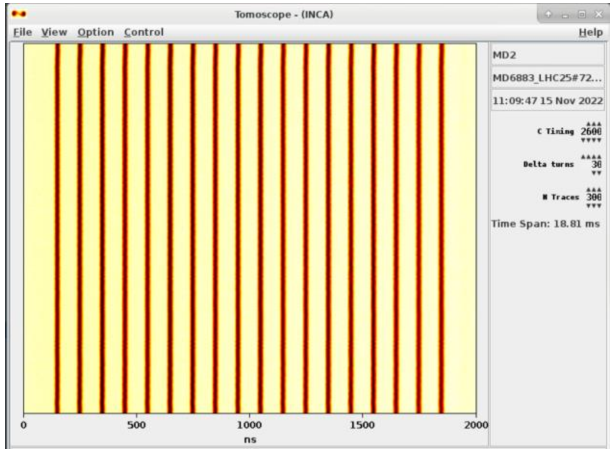
Limited by quadrupolar instabilities for higher intensities

LIU beam commissioning 2021-22 – PS

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



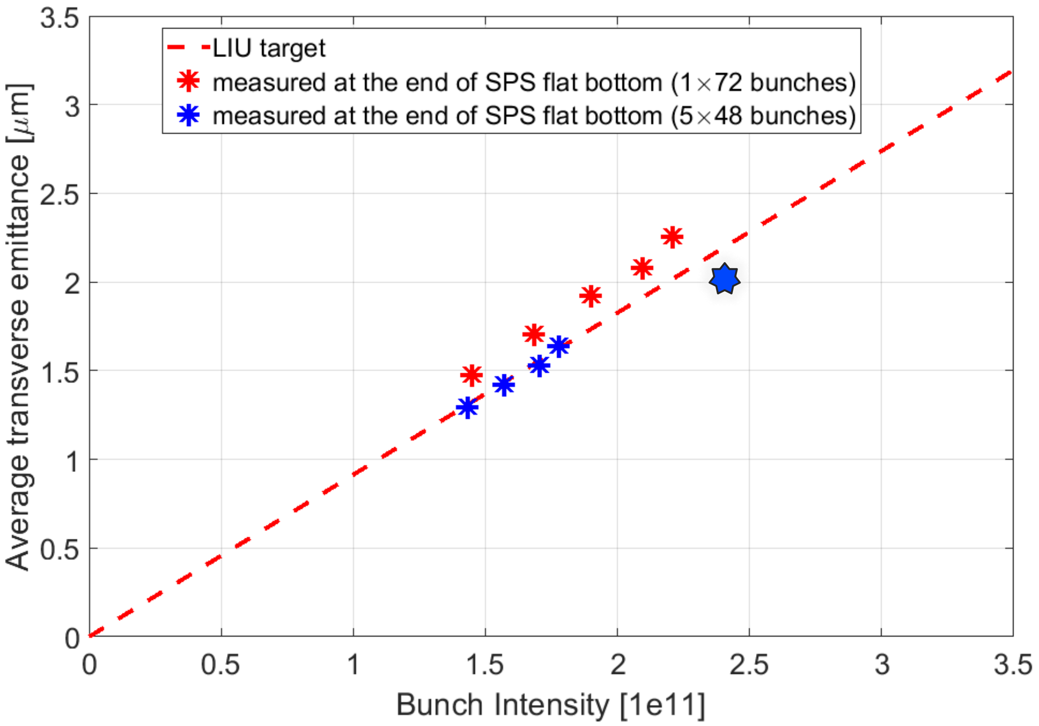
Stabilised by recently developed quadrupolar feedback up to at least 3.15e11 p/b equiv.

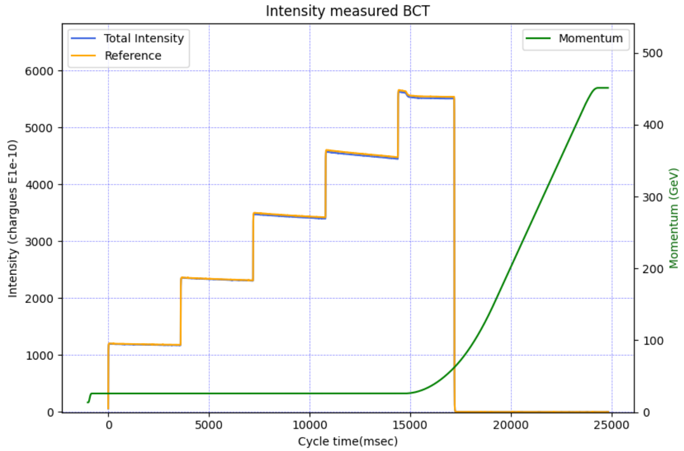


LIU beam commissioning 2021-22 – SPS

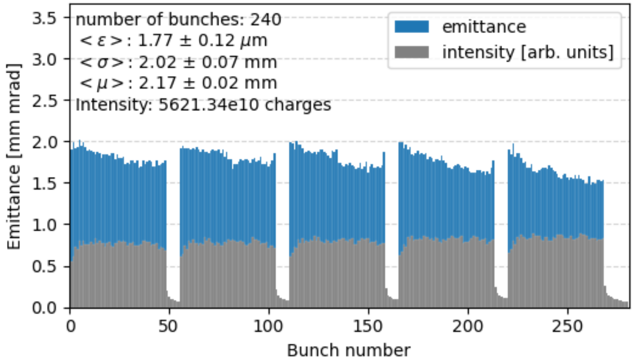
LHC Injectors Upgrade

- The SPS recovered the pre-LIU beams in 2021
- Intensity & brightness ramp-up at injection (26 GeV/c) successful in 2022





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



LIU beam commissioning 2021-22 – SPS

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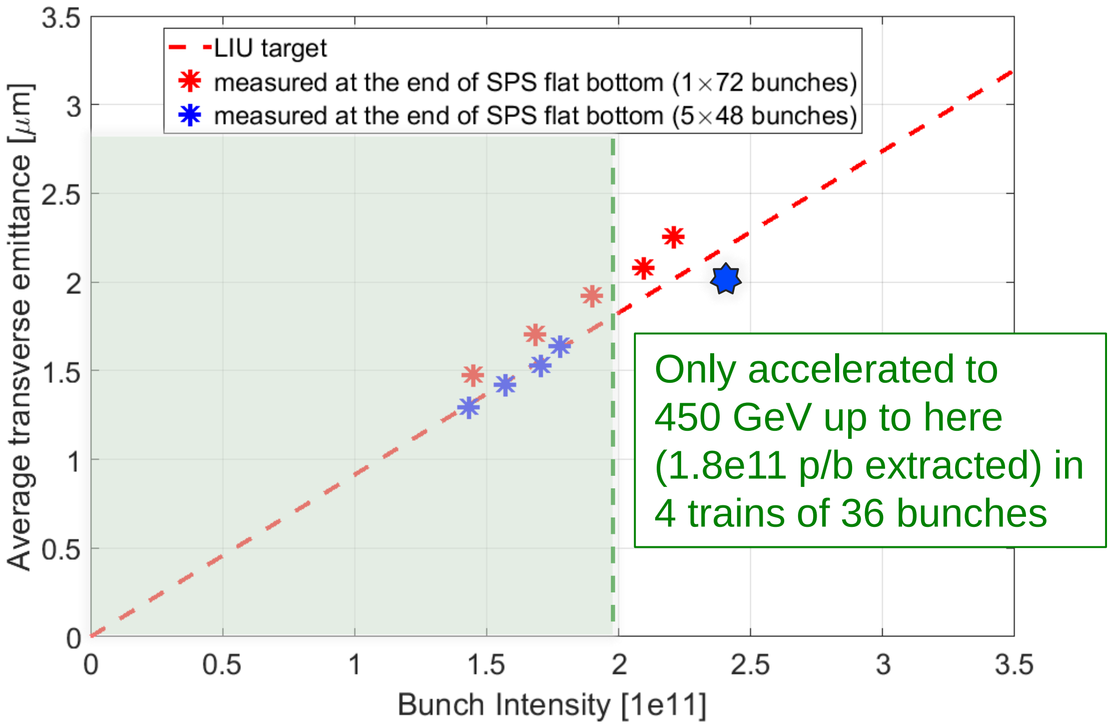
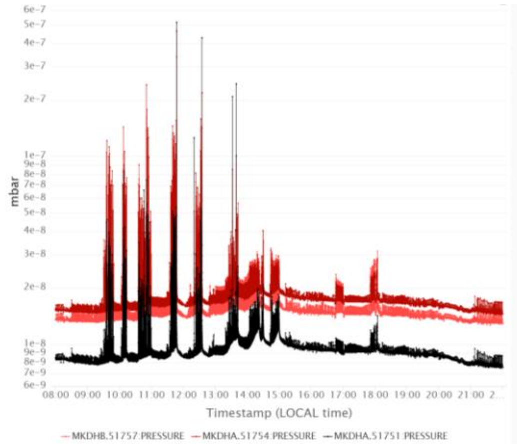


- Currently limited by severe pressure spikes in one of the dump kickers at 450 GeV



LIU beam commissioning 2021-22 – SPS

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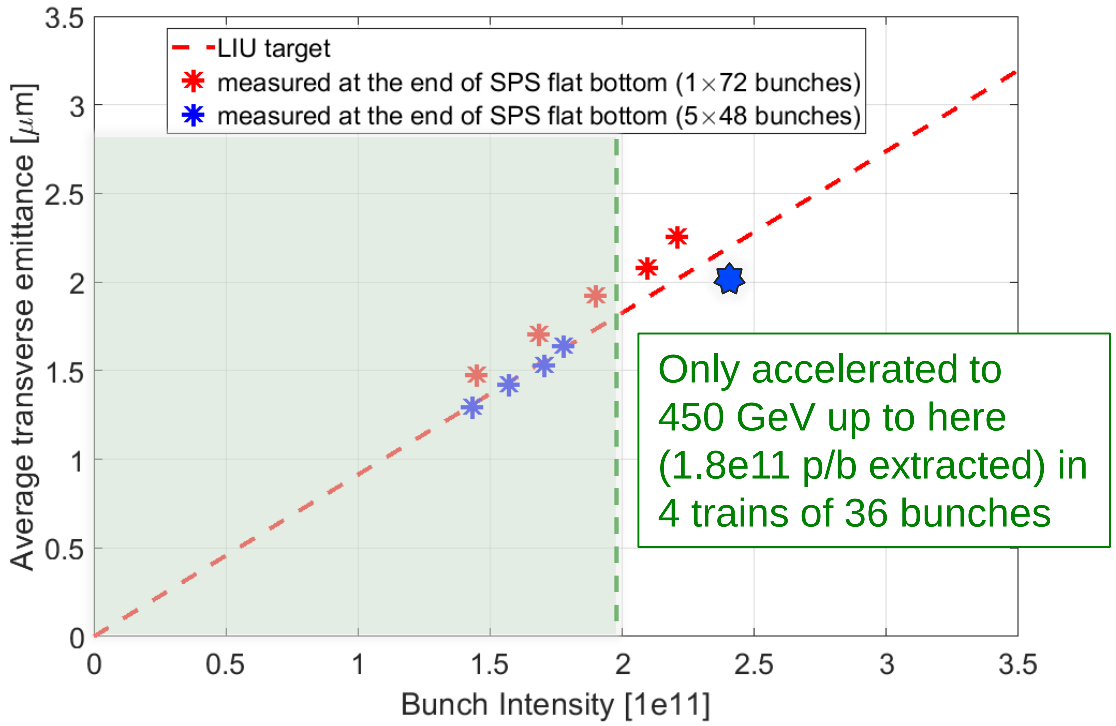

- Currently limited by severe pressure spikes in one of the dump kickers at 450 GeV
- Unfortunately not included in the beyond-LIU risk register … studies ongoing to understand how to get over this limitation!

Summary

- **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 this 10-year long process
  - Main phase of **installation** lasted almost **two years of long shutdown (LS2)**
  - Injectors back to operation in cascade since July 2020

- LIU project officially came closed on **30 June 2021**

- **Beam commissioning on schedule up to 2022**, with PSB and PS having already fulfilled and exceeded LIU targets and SPS closely following with some new limitations to be addressed to fully fulfil the LIU potential

→ **Stay tuned for the next steps!**

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THANK YOU FOR YOUR ATTENTION