CERN

LHC Injectors Upgrade

Status of the
LHC Injectors Upgrade (LIU) project

in 4th ICFA Mini-Workshop on Space Charge 2019, 4-6 November, CERN, Geneva

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https://indico.cern.ch/event/828559/

Outline

LHC Injectors Upgrade

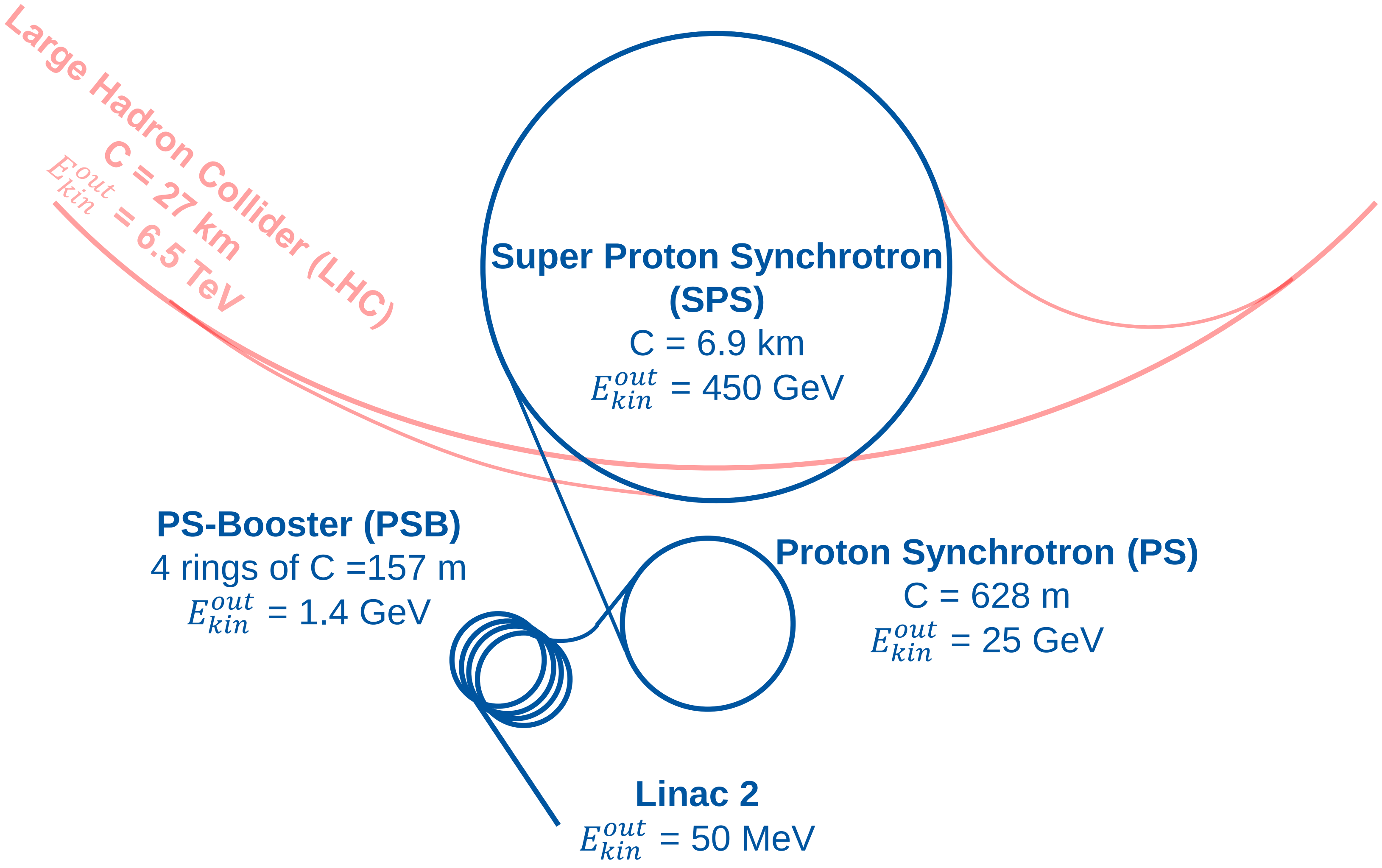
- LHC beam performance of the injectors complex and upgrade
- LIU project timelines
- Relevance of space charge within LIU
- Conclusions

Outline

LHC Injectors Upgrade

- LHC beam performance of the injectors complex and upgrade
  - Pre-LIU performance
  - Definition of the LIU goals and baseline upgrades
- LIU project timelines
- Relevance of space charge within LIU
- Conclusions

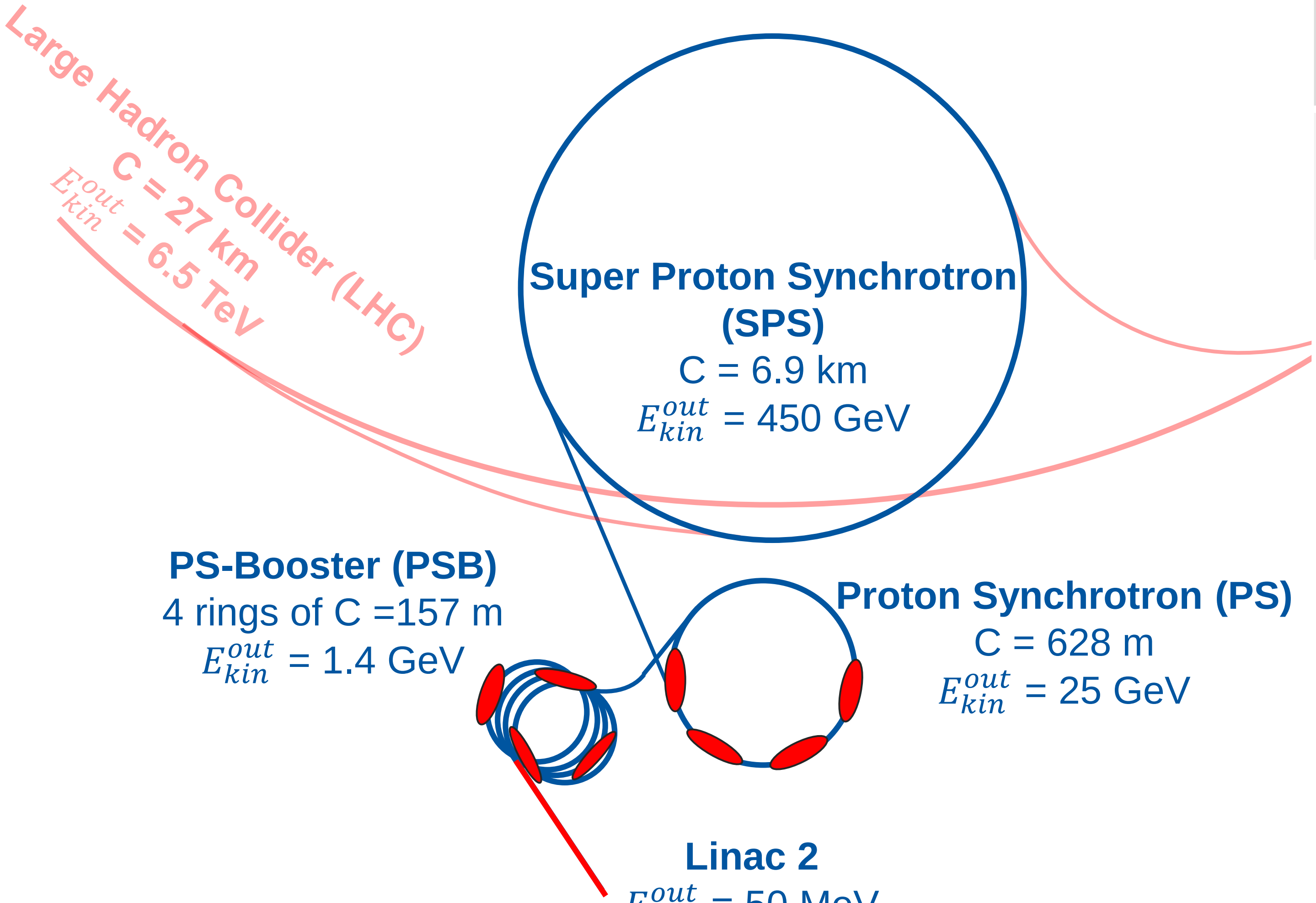
The CERN injector complex: protons



The **CERN injector complex** is used to feed **LHC** as well as to serve a number of fixed target experiments

Production scheme of LHC beams

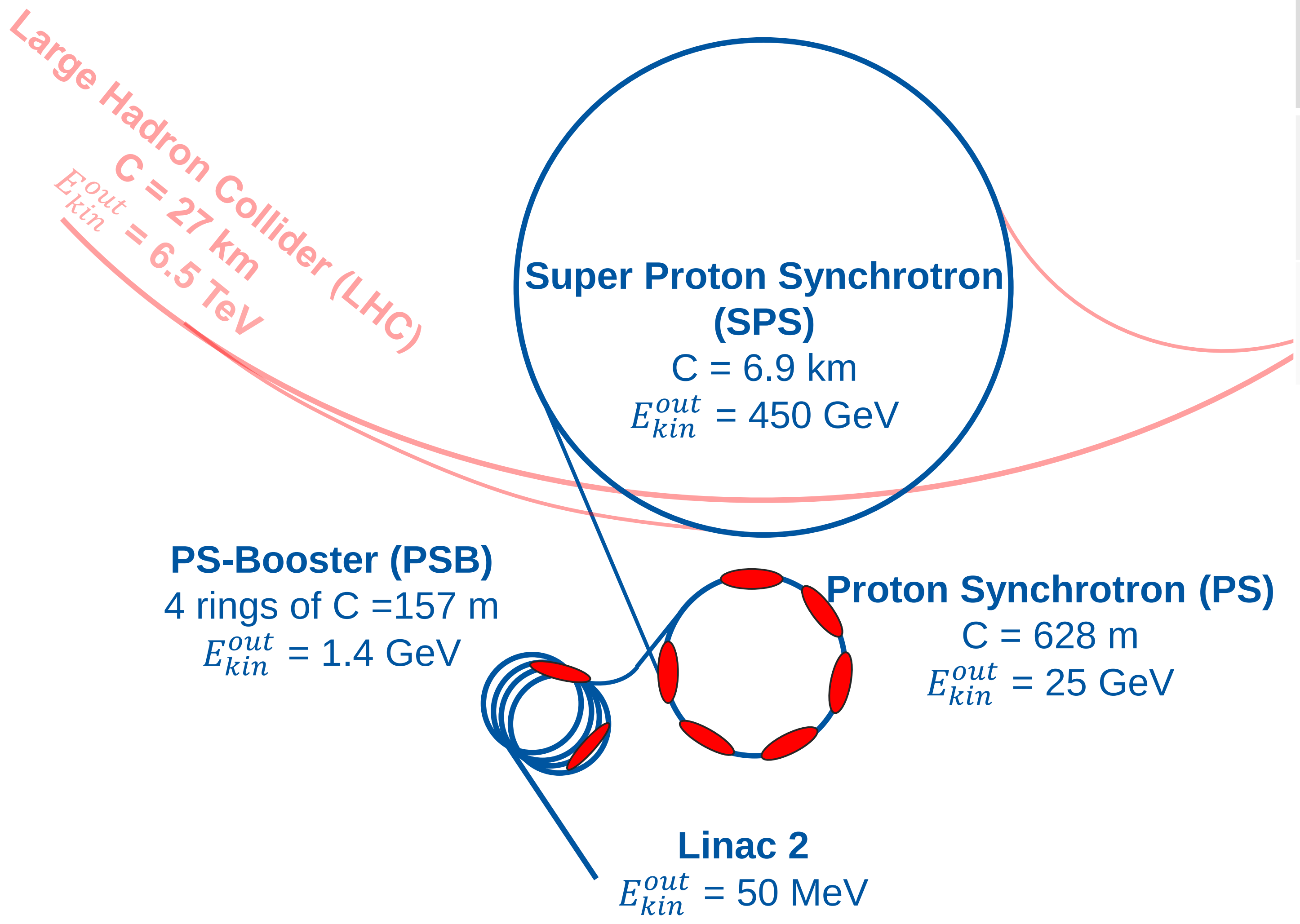
LHC Injectors Upgrade



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

LHC Injectors Upgrade



Beam transfer	Number of bunches	Bunch spacing (ns)
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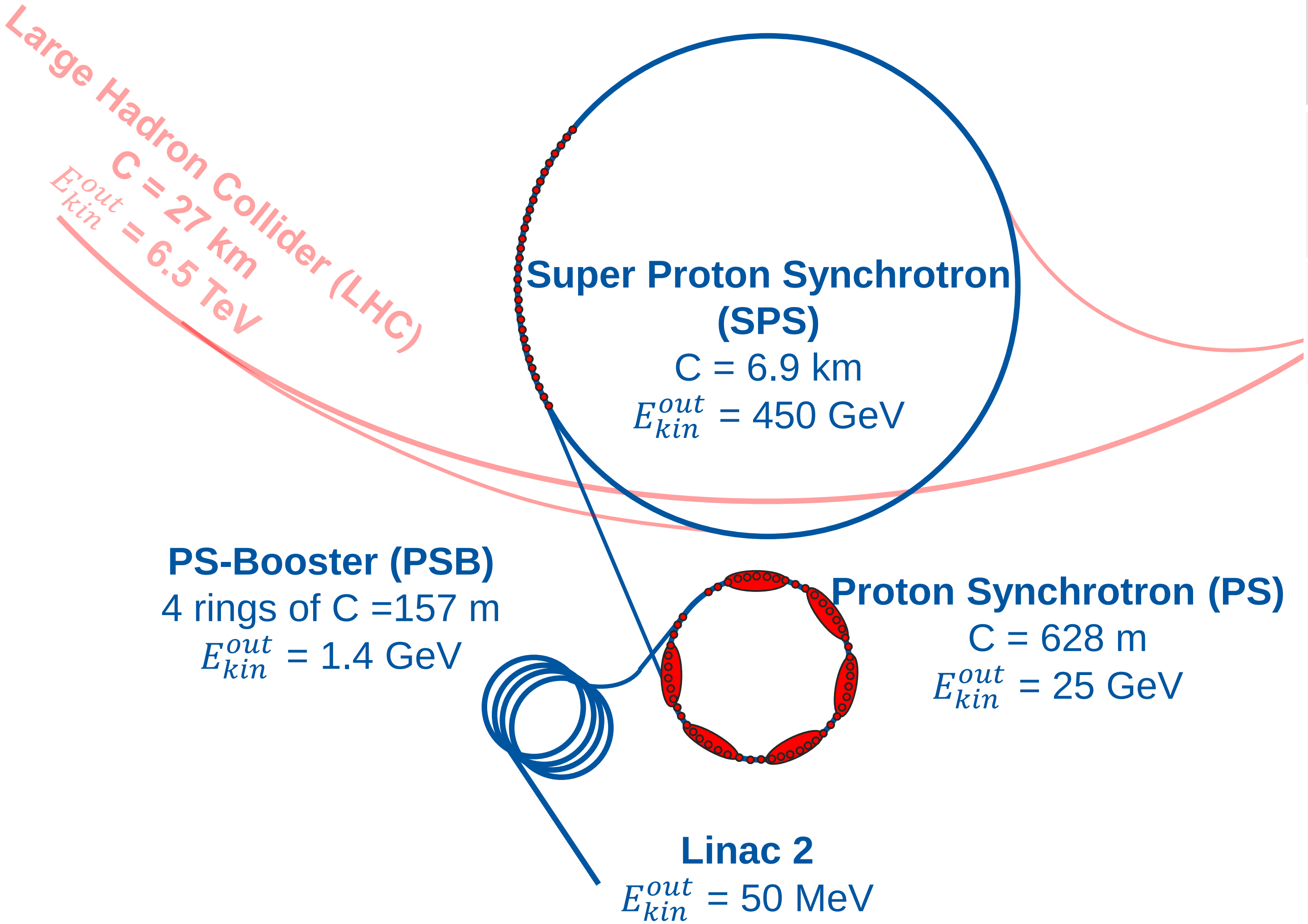
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272

Production scheme of LHC beams

LHC Injectors Upgrade



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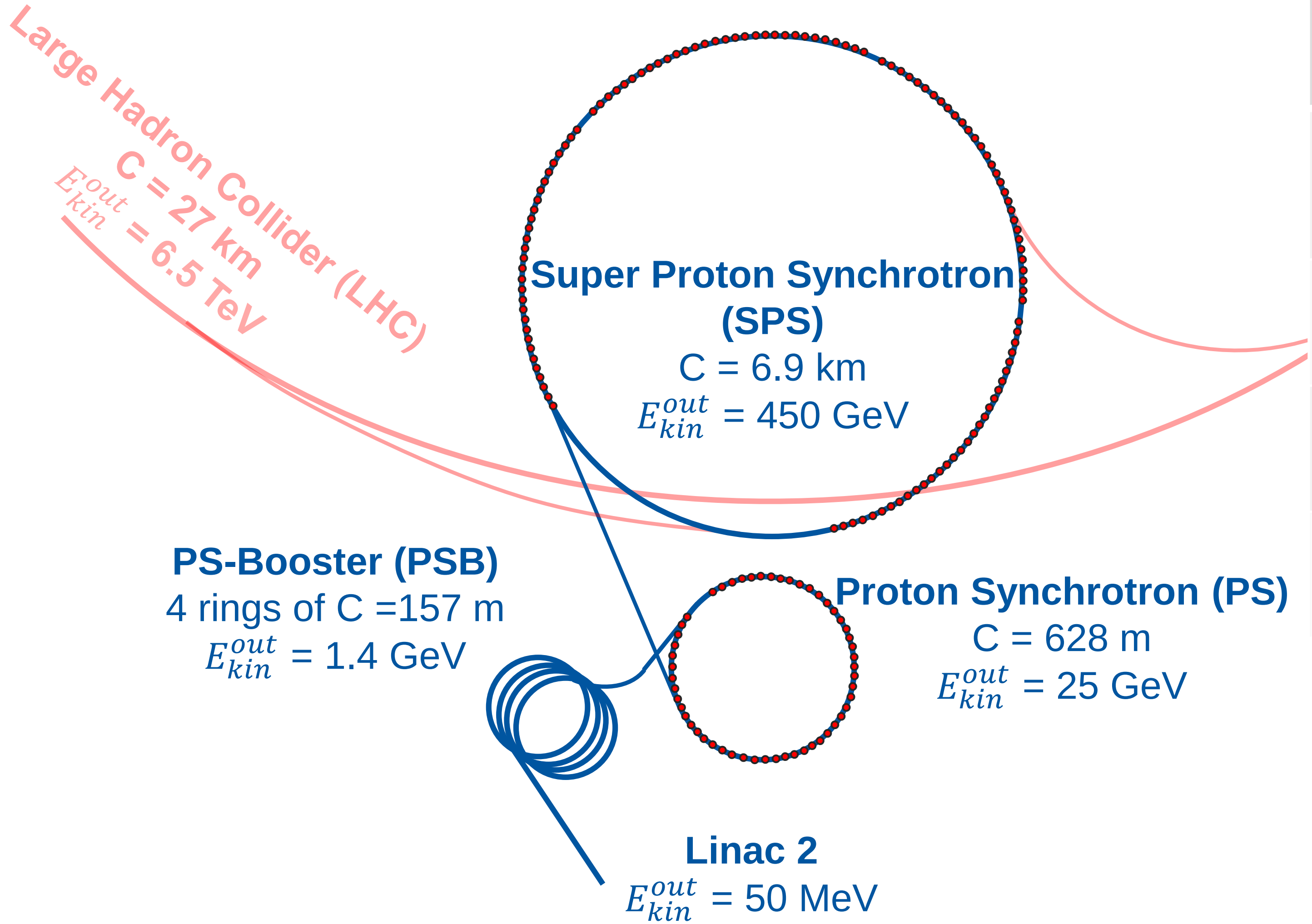
One triple bunch splitting and two double bunch splittings in the PS

Production scheme of LHC beams

LHC Injectors Upgrade



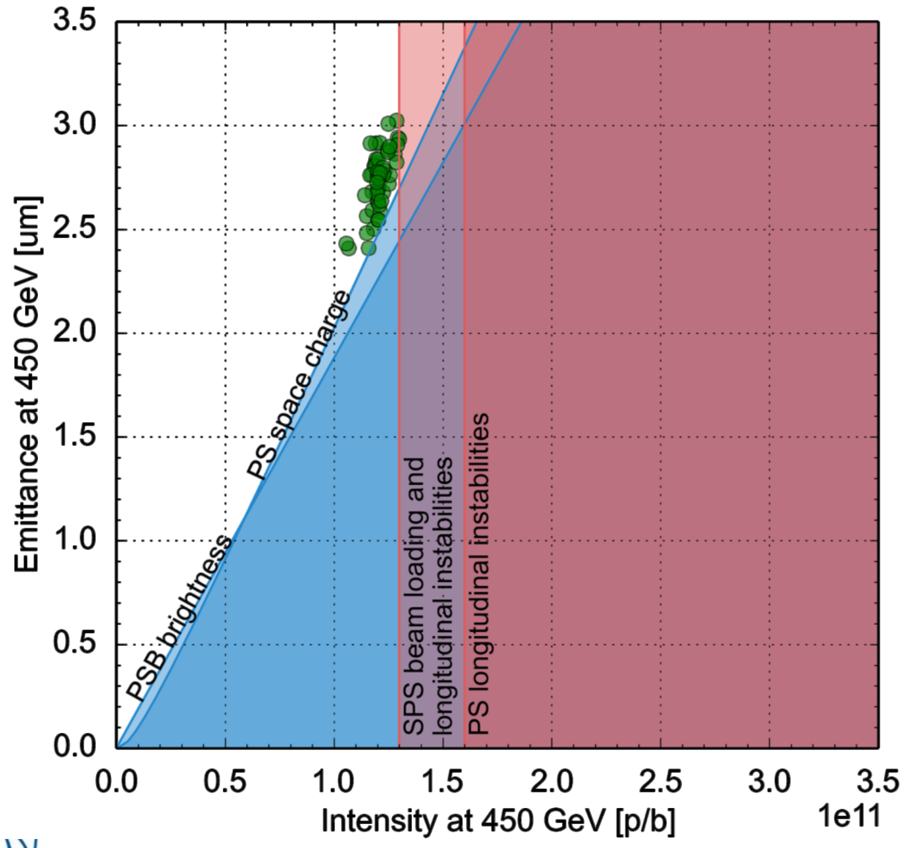
Beam transfer	Number of bunches	Bunch spacing (ns)
Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272
PS → SPS E_{kin}^{out} = 25 GeV	72	25

Four injections into the SPS

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

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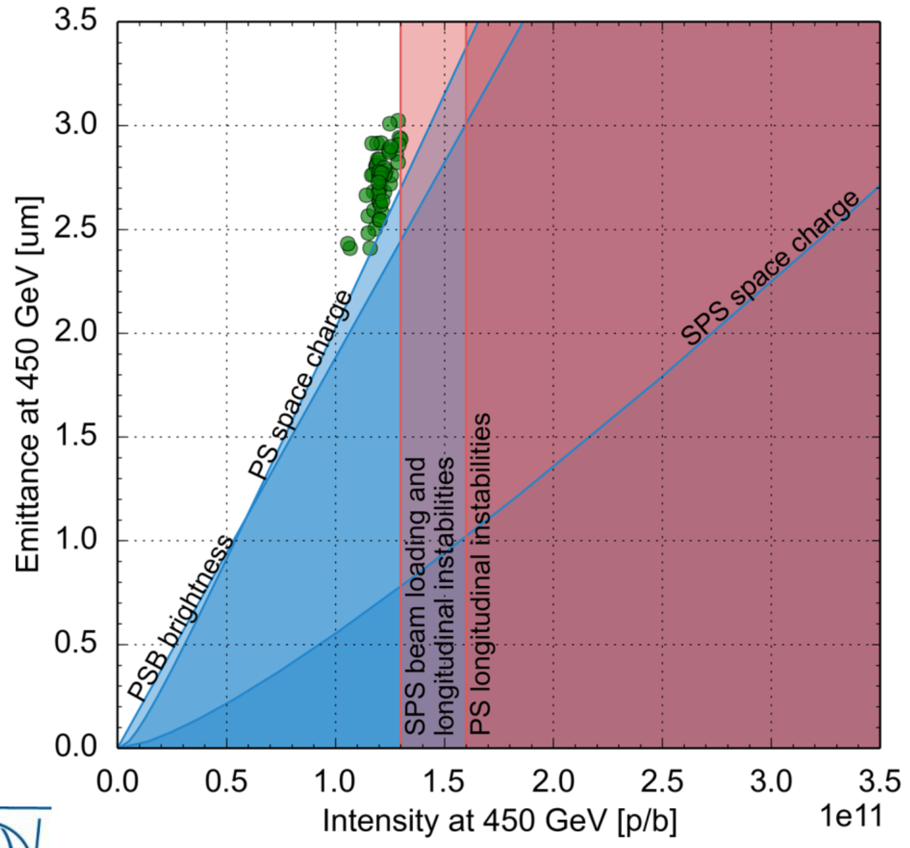
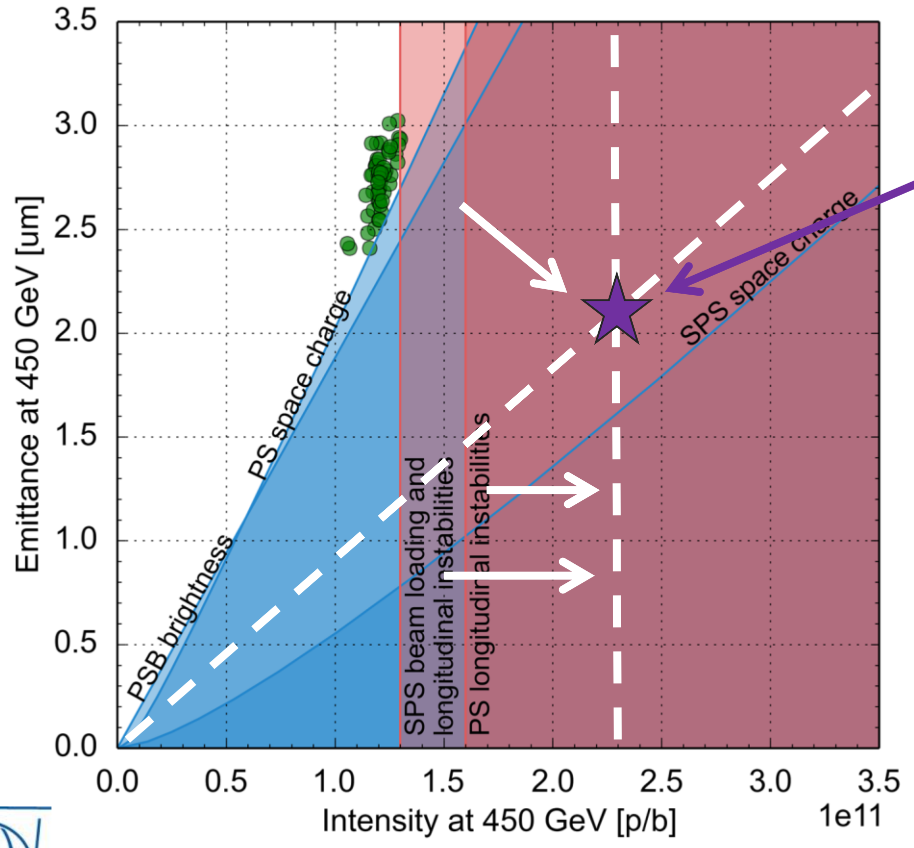


- **Brightness**
  - PSB brightness determined by space charge at injection
  - Limit for PS space charge at injection $\Delta Q_y < 0.31$
  - ✓ *Space charge in SPS not a limit for LHC beams*
- **Intensity**
  - SPS is limited by beam loading and longitudinal instabilities on the ramp and flat top
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

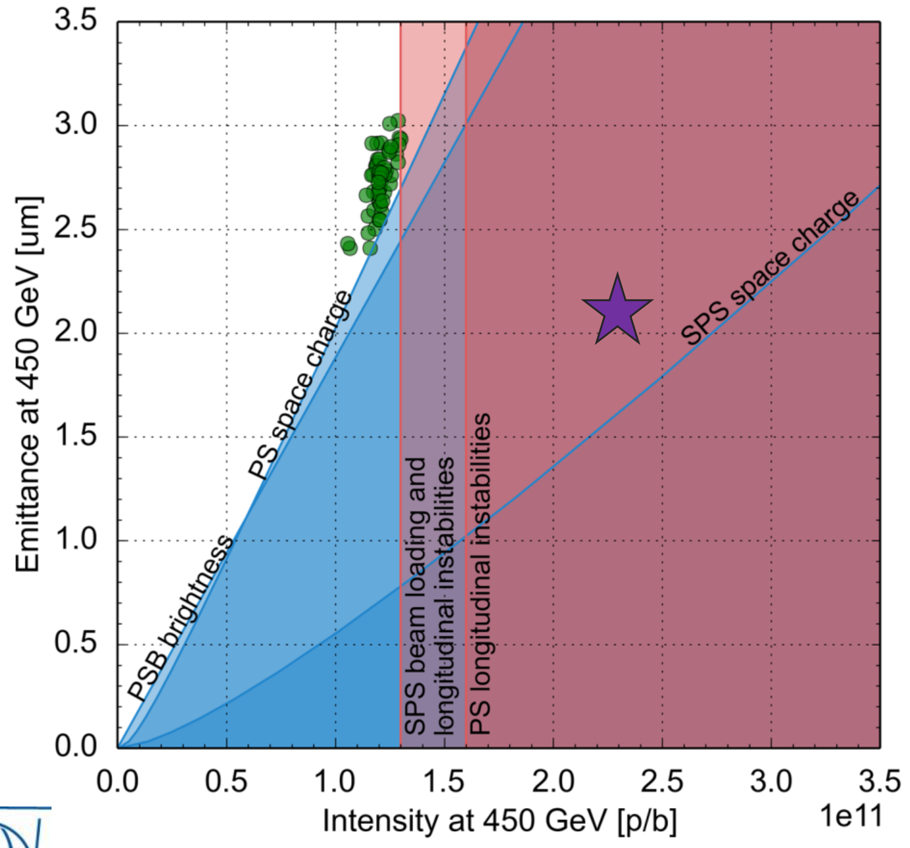


	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	2.3	2.1
Before upgrades	1.3	2.7

- **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

The LHC Injectors Upgrade (LIU) project

- Effect on **beam parameter reach at SPS extraction** of the upgrade items in the LIU project baseline



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LHC Injectors Upgrade

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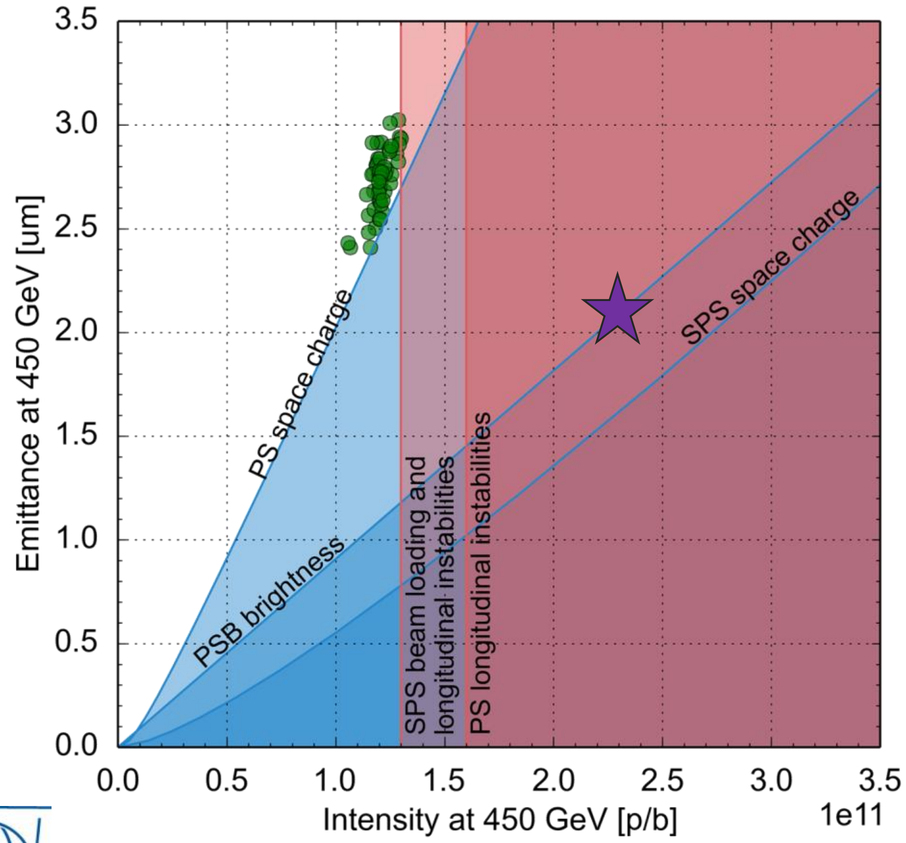
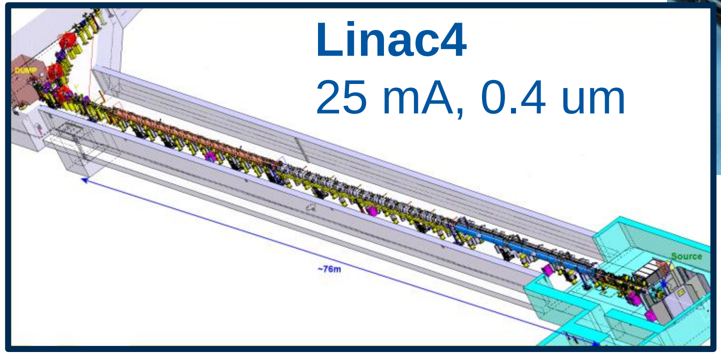


- **Connection of PSB to Linac4**
  - Charge exchange H^- injection at 160 MeV into PSB



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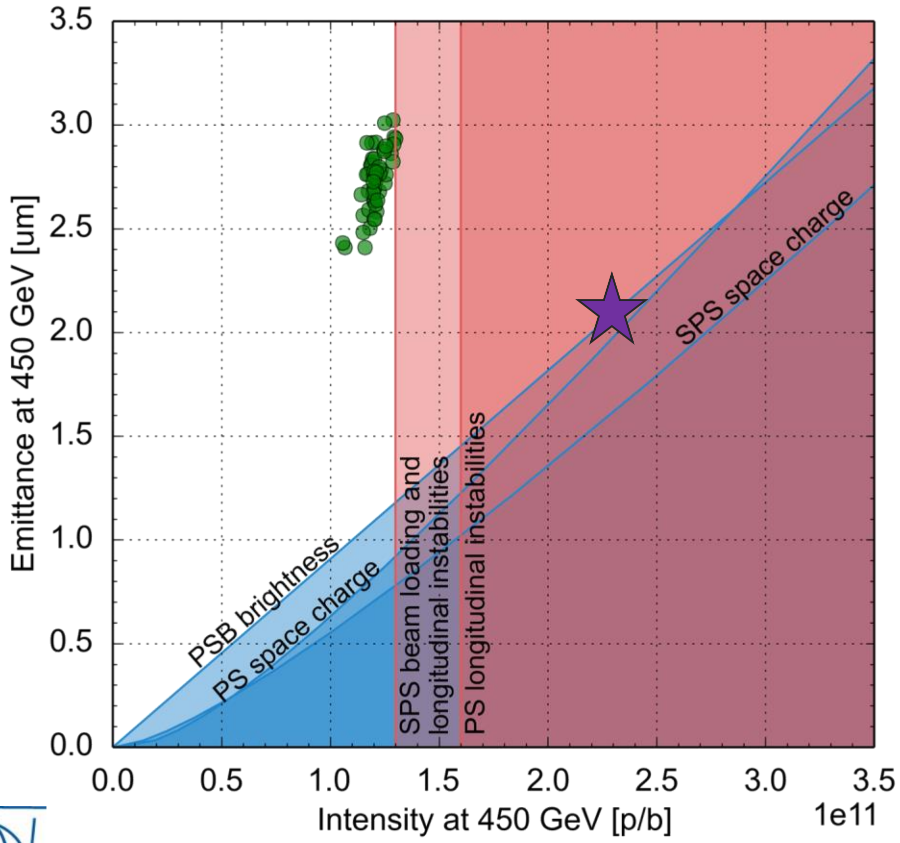


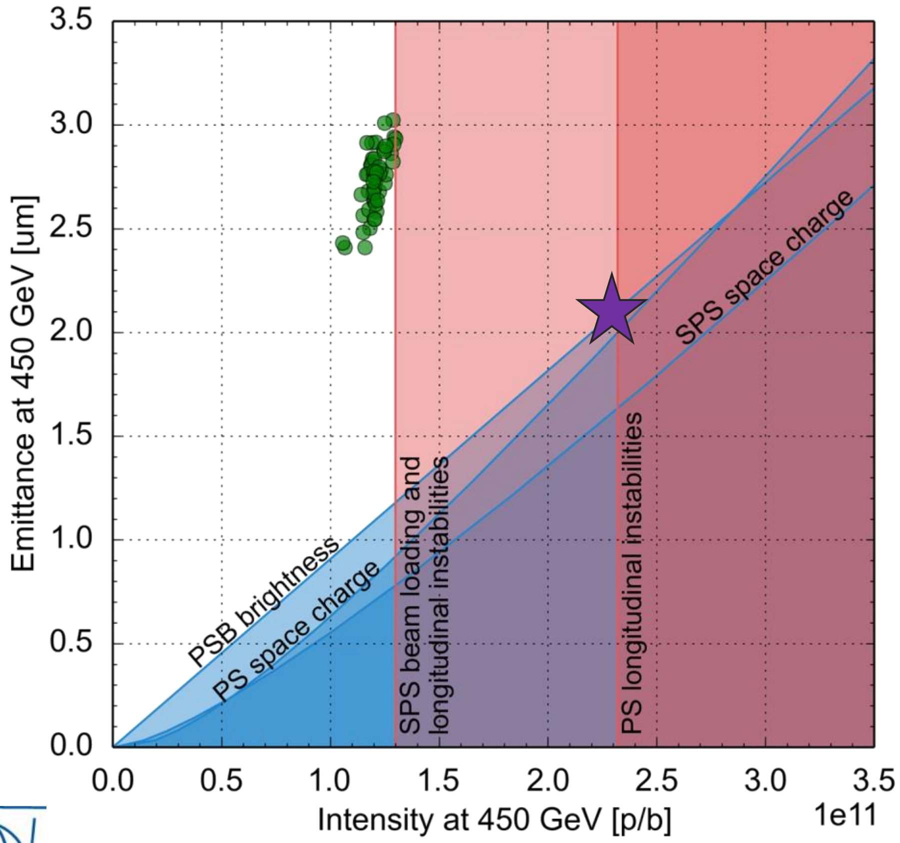
✓ Connection of PSB to Linac4

- **PSB acceleration to 2 GeV**
  - Reduced $\beta\gamma^2$ at PS injection by 40%
  - Updated longitudinal parameters at PSB-PS transfer to further reduce PS space charge tune spread

The LHC Injectors Upgrade (LIU) project

LHC Injectors Upgrade

- Effect on **beam parameter reach at SPS extraction** of the upgrade items in the LIU project baseline



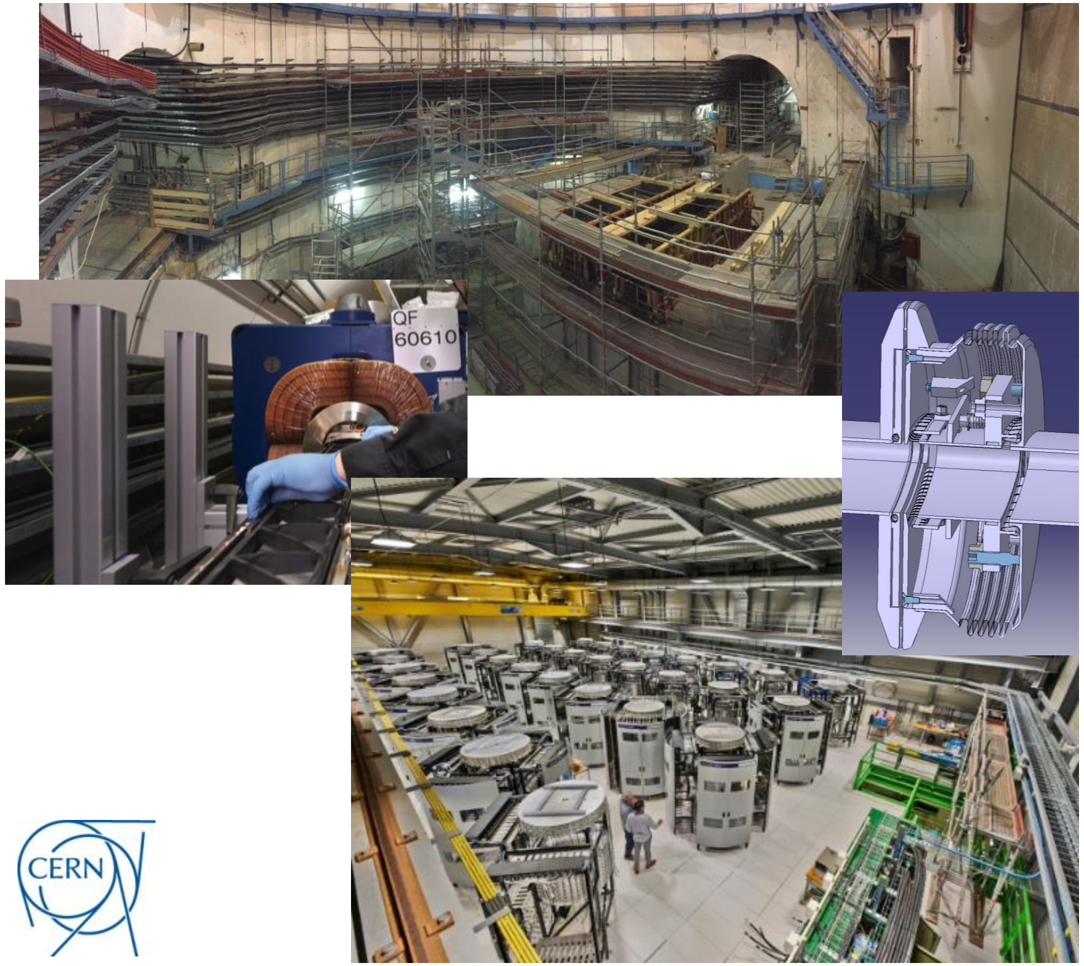
✓ Connection of PSB to Linac4

✓ PSB acceleration to 2 GeV

- **PS RF upgrades, e.g.**
  - New Finemet cavity for longitudinal feedback system
  - Impedance reduction of RF systems

The LHC Injectors Upgrade (LIU) project

- Effect on **beam parameter reach at SPS extraction** of the upgrade items in the LIU project baseline



✓ 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

The LHC Injectors Upgrade (LIU) project

LHC Injectors Upgrade

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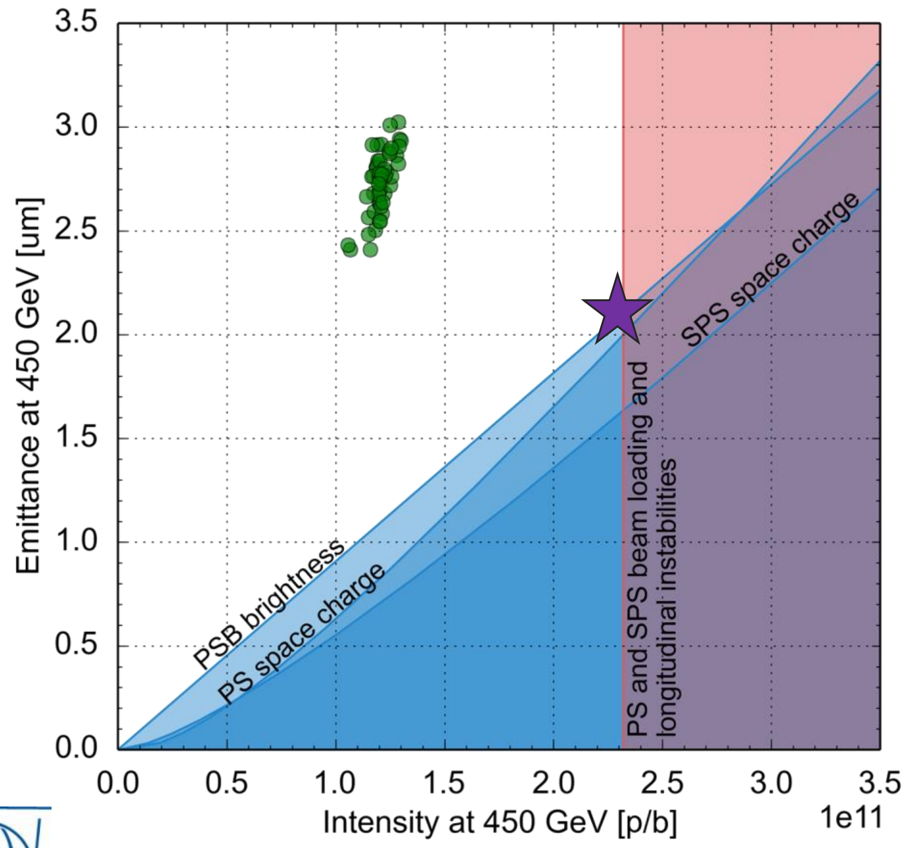

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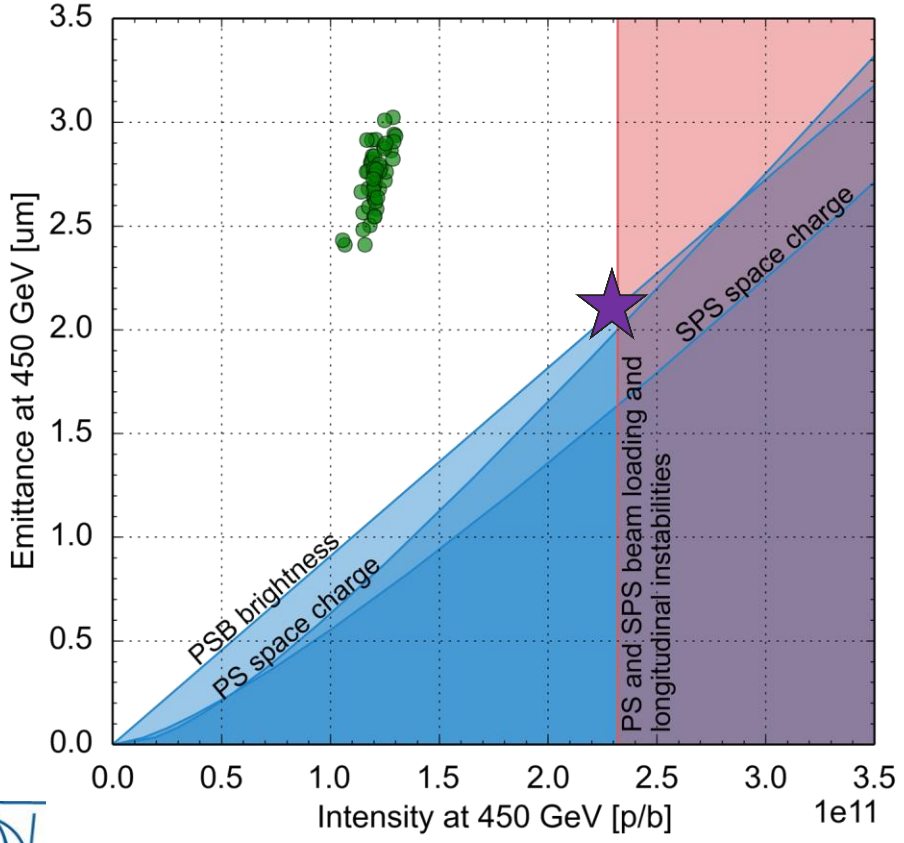


✓ Connection of PSB to Linac4

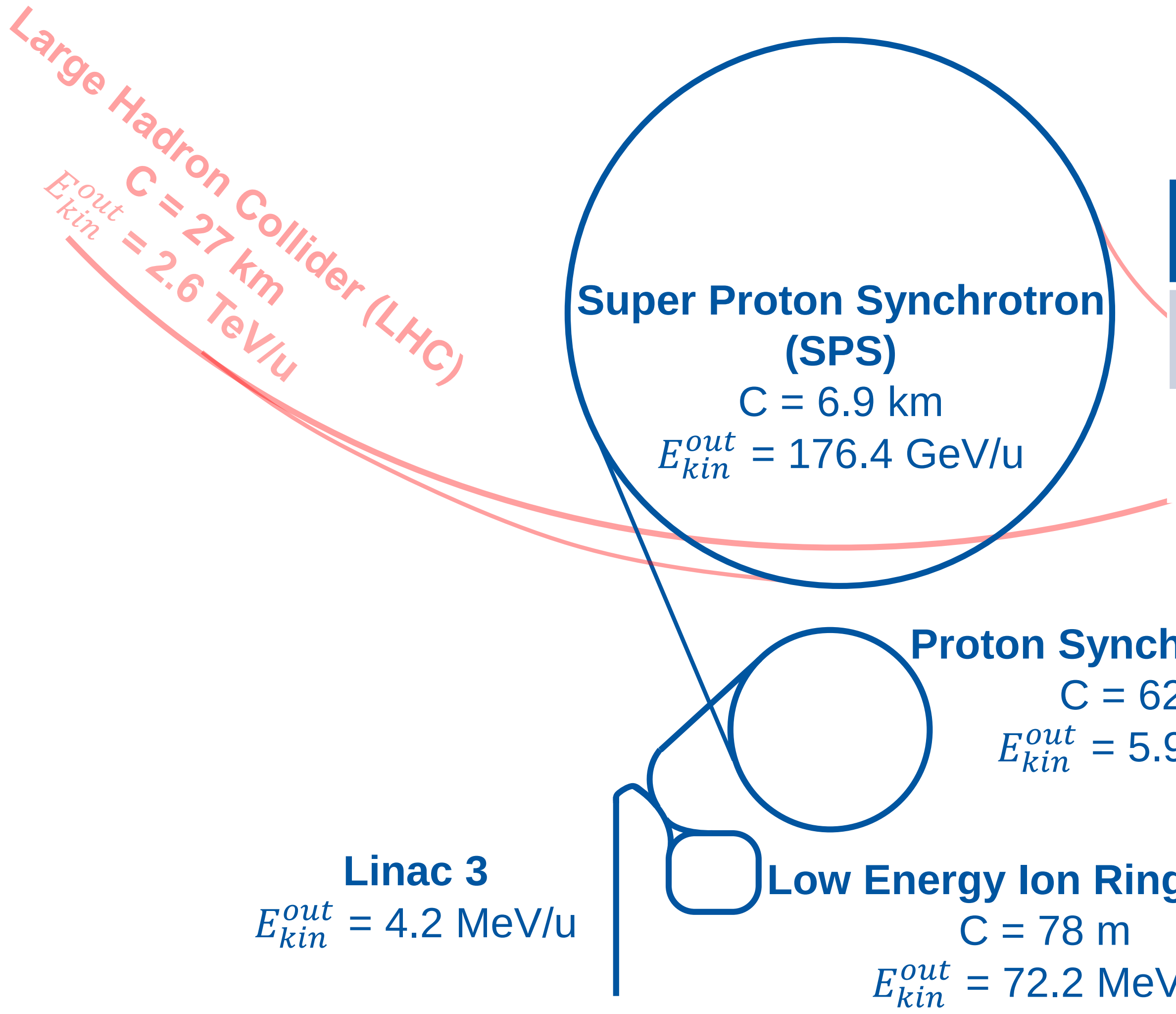
✓ PSB acceleration to 2 GeV

✓ PS RF upgrades

✓ SPS upgrade

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

Not only protons …



- CERN injector complex also accelerates **heavy ions (Pb)**

	N (x 10^8 ions/b)	**ε (μm)**	**# of bunches**
HL-LHC target (7x 8 bunches, 50 ns)	1.9	1.5	1248

Single bunch parameters already achieved

Relies on SPS slip stacking

Outline

LHC Injectors Upgrade

- LHC beam performance of the injectors complex
- LIU project timelines
  - Project evolution
  - Current status and future steps
- Relevance of space charge within LIU
- Conclusions

LHC Injectors Upgrade

2010

2018

2020

2024

Run 1 + LS1 + Run 2 (2010 – 2018)
Preparing, defining, testing, executing

- **Start of LIU project**
- Studies, advanced installation and testing, new buildings
- **Linac4** commissioning and quality/reliability runs

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

- End of LIU equipment production
- **LIU equipment installation** across all injectors

Run 3 (2020 – 2024)

- **Recommissioning** of upgraded injectors
- **End of LIU project in 2021!**

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

LHC Injectors Upgrade

2010

2018

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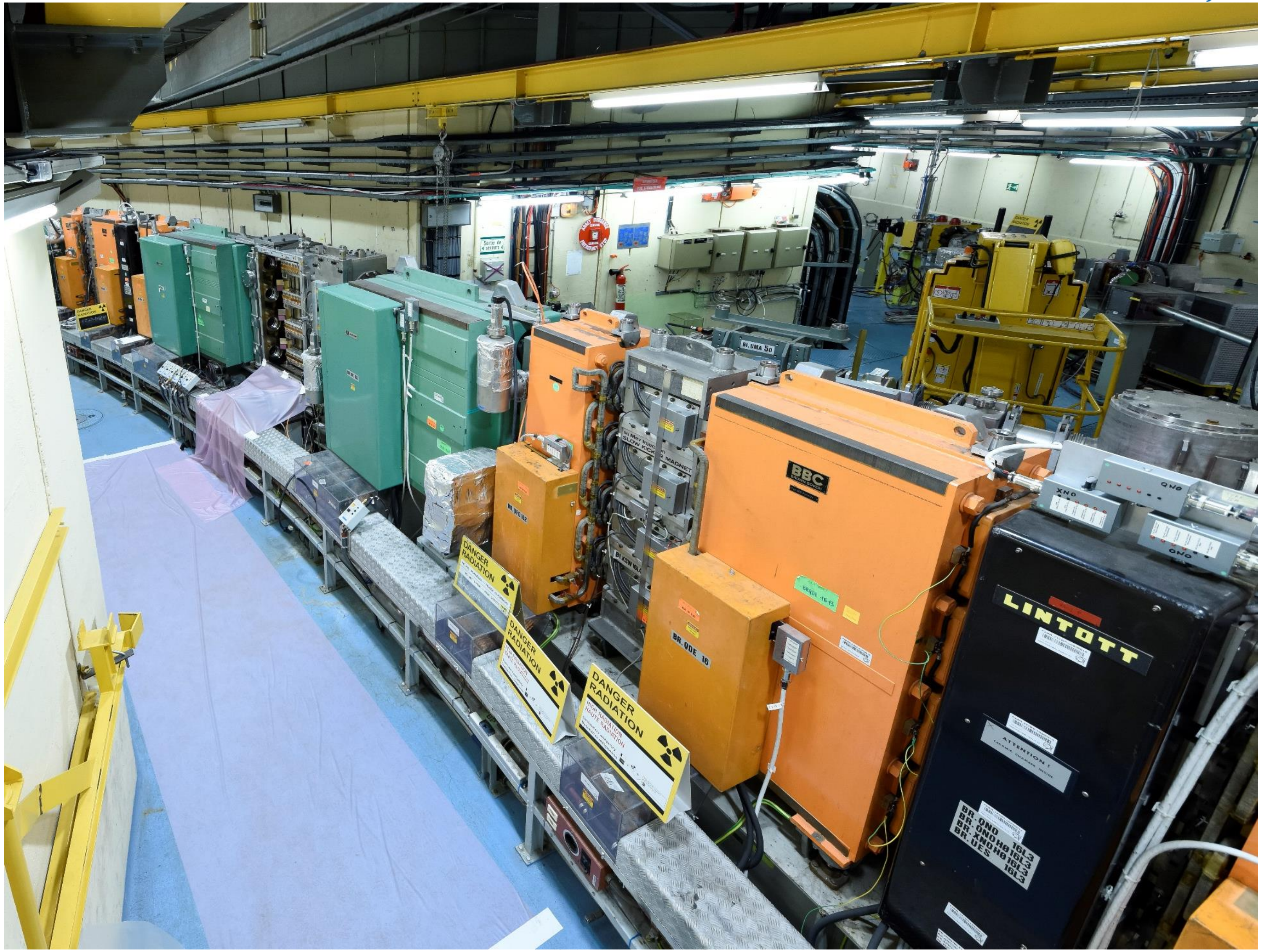
Time lapse

LHC Injectors Upgrade

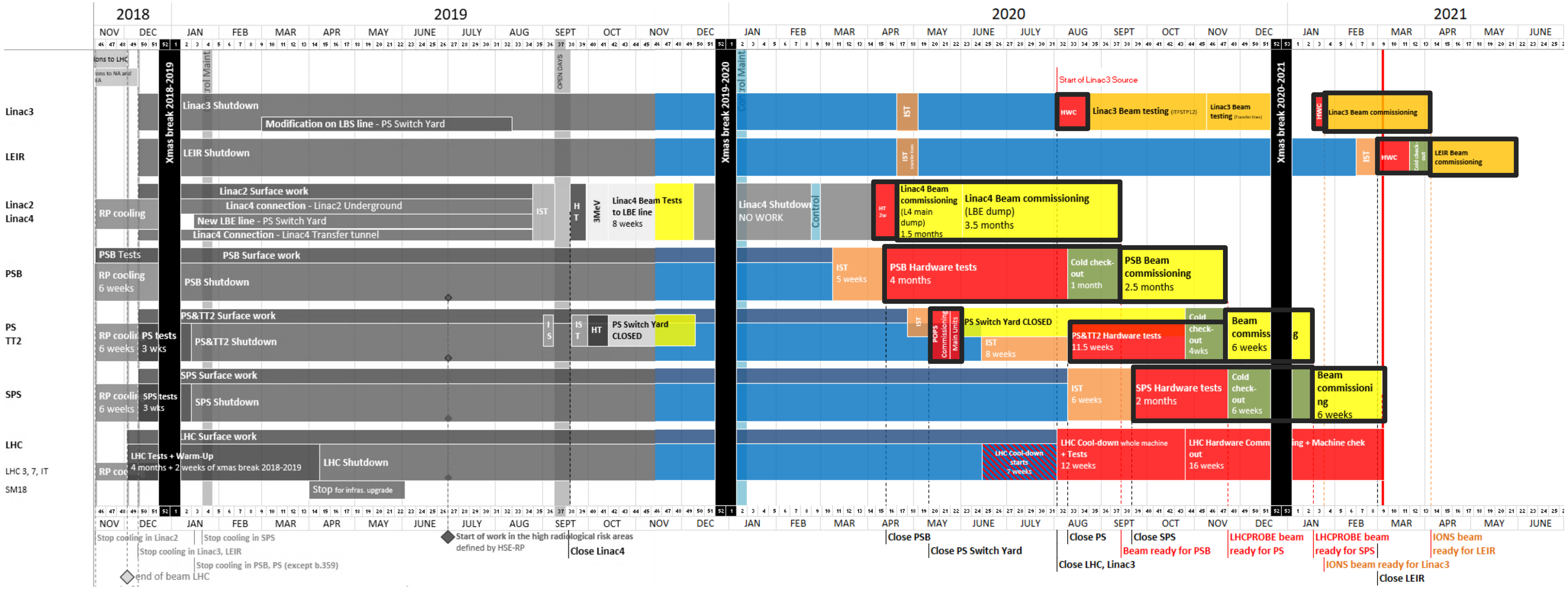
Emptying part of PSB injection area, before installing the new H^- charge exchange injection system



Hardware and beam commissioning in 2020

LHC Injectors Upgrade

J. Coupard *et al.*, LS2 Master Schedule v.2.3 (Released) – EDMS 1687788



- Hardware commissioning/cold check out
- Beam commissioning

LIU beam ramp up

LHC Injectors Upgrade

LIU beam commissioning plan: a gradual intensity ramp up all through Run 3

2021 → 2022 → 2023 → 2024

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

2022: Intensity and brightness ramp up to 1.8e11 p/b within desired loss budgets

2021:
- Recovery of pre-LS2 proton beams with Linac4 and newly installed LIU equipment
- Commissioning of LIU ion beams

Outline

LHC Injectors Upgrade

- LHC beam performance of the injectors complex and upgrade
- LIU project timelines
- Relevance of space charge within LIU
  - Tune spreads across the injectors chain for proton
  - Ions in LEIR and SPS
- Conclusions

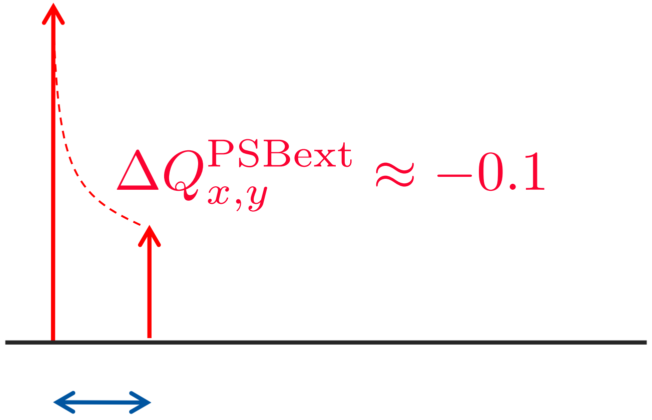
Tune spread across proton injectors (pre-LIU)

LHC Injectors Upgrade

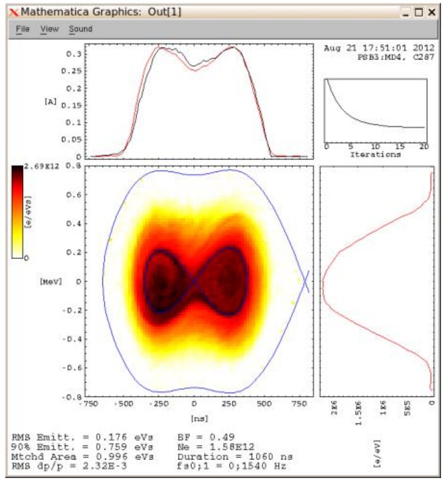
- Space charge plays a crucial role for brightness across the injector chain
  - Large tune spread at PSB injection already mitigated with
    - Injection on the ramp with capture in h=2 BSM
    - Dynamic working point and resonance compensation

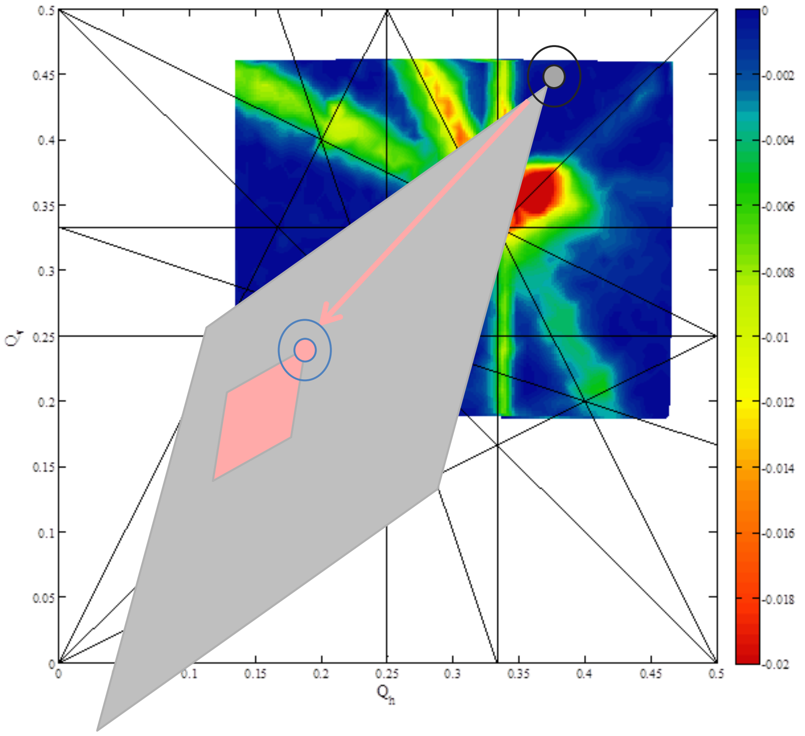
$$\Delta Q_{x,y}^{\mathrm{PSBinj}} \approx -0.5$$

$$\Delta Q_{x,y}^{\mathrm{PSBext}} \approx -0.1$$



PSB cycle (0.5 s)

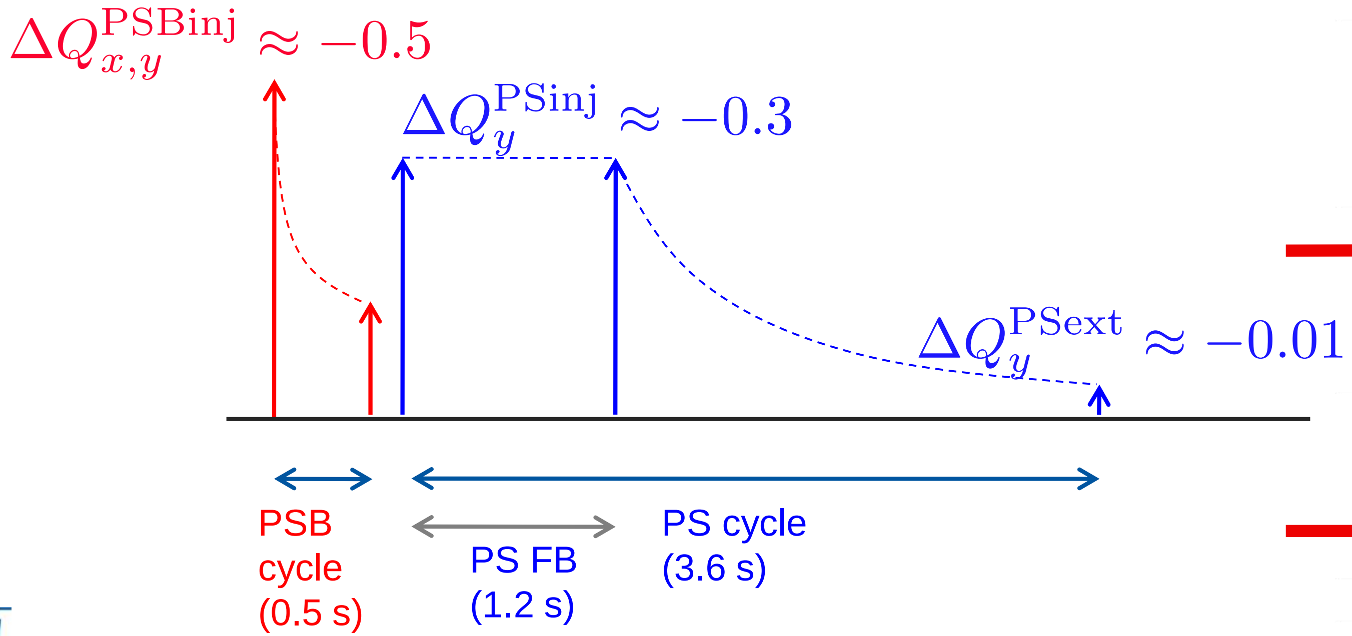


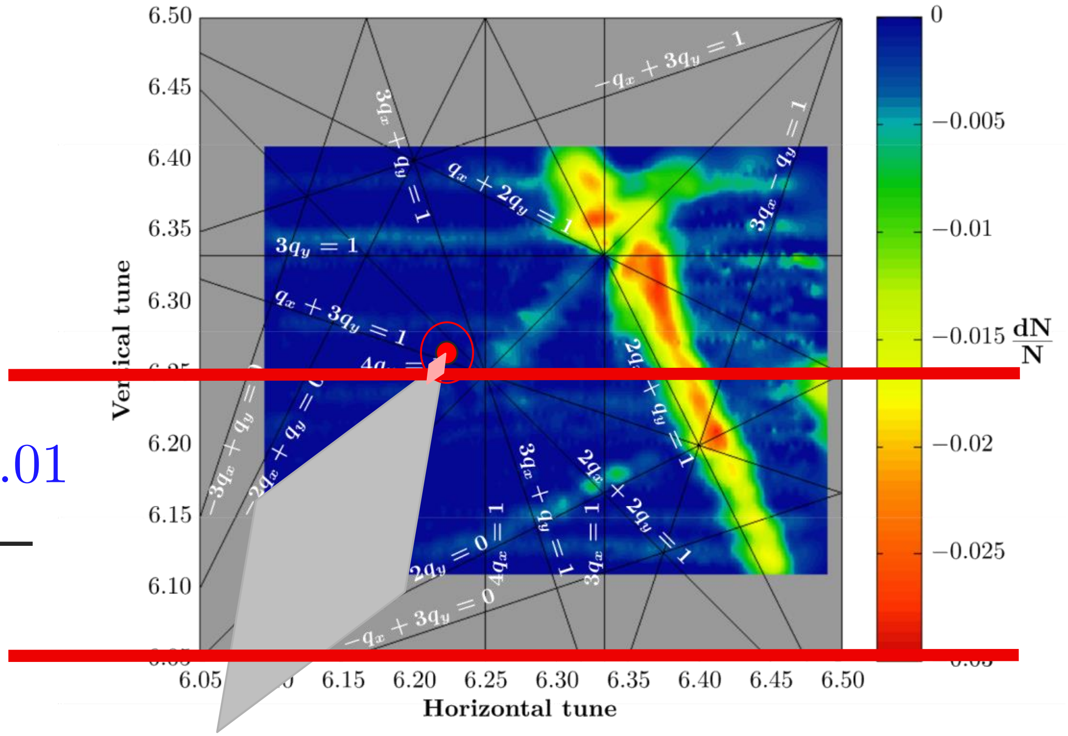


Tune spread across proton injectors (pre-LIU)

LHC Injectors Upgrade

- Space charge plays a crucial role for brightness across the LHC injector chain
  - Large tune spread at PS injection
  - Crammed between integer resonance and space charge driven structural resonance $8Q_y$=50 during **1.2 sec flat bottom**

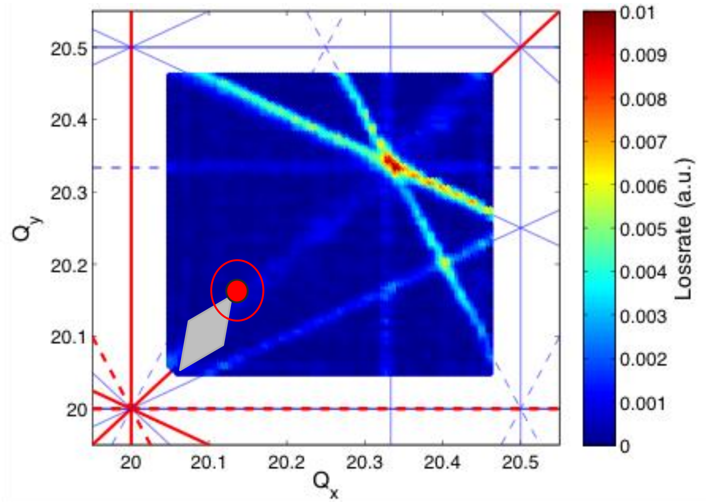


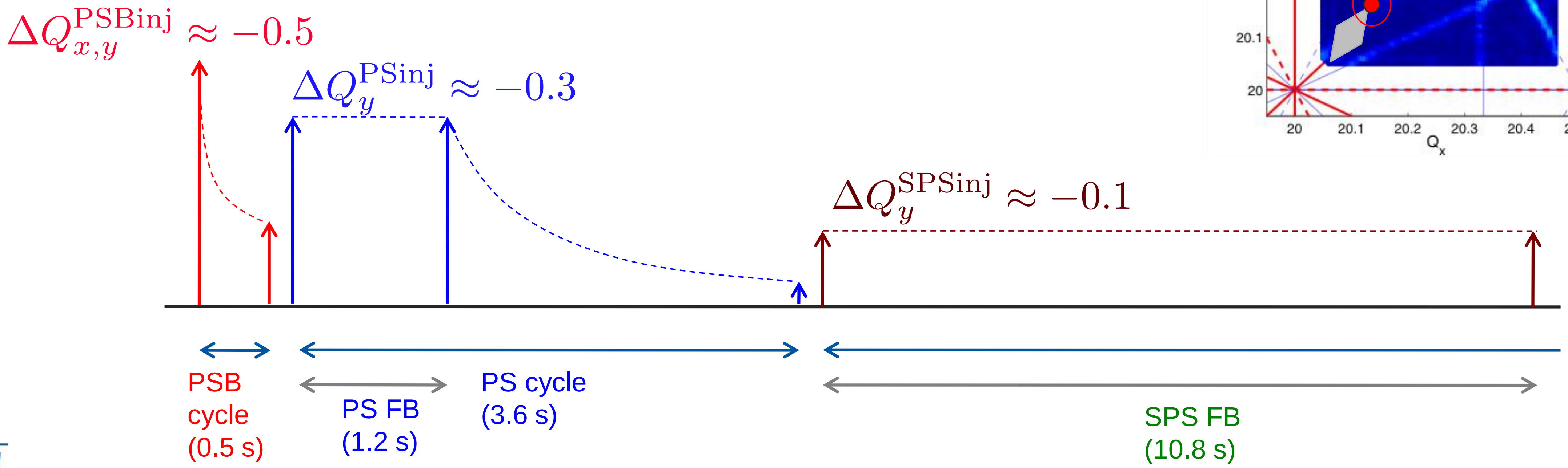


Tune spread across proton injectors (pre-LIU)

LHC Injectors Upgrade

- Space charge plays a crucial role for brightness across the LHC injector chain
  - Tune spread in SPS still has margin
  - However, long flat bottom – other effects? E.g. effect of space charge on instability thresholds, interplay with e-cloud, …

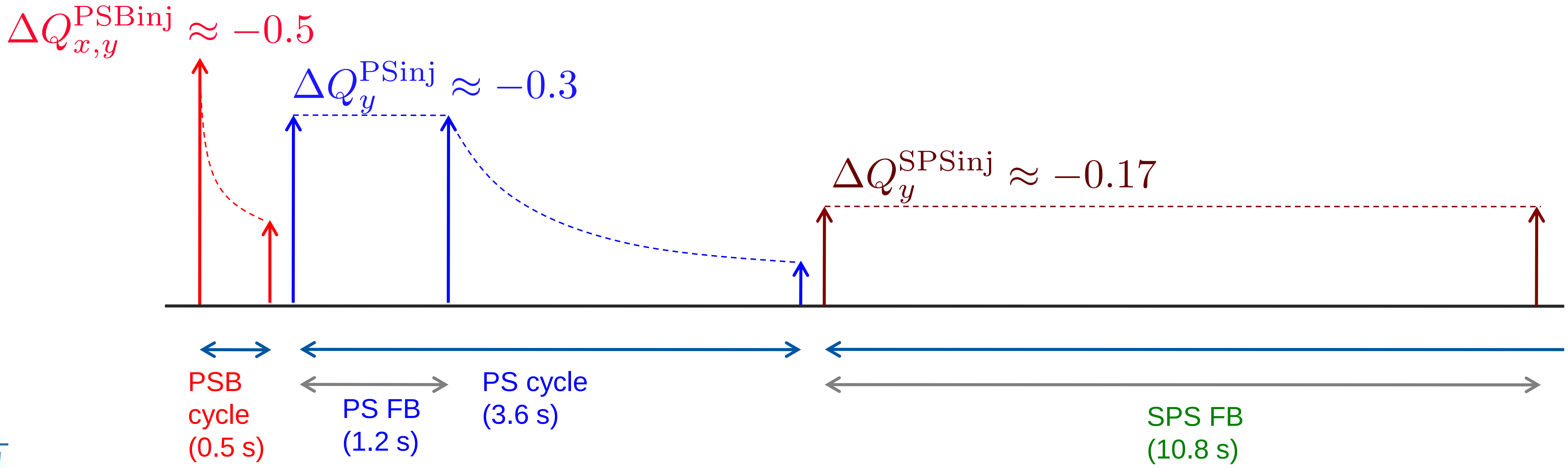




Tune spread across proton injectors (post-LIU)

LHC Injectors Upgrade

- Space charge plays a crucial role for brightness across the LHC injector chain
  - After LIU, the tune spreads will stay approximately the same up to PS injection
    - Increase of PSB and PS injection energy + larger longitudinal emittance at PSB-PS transfer allow for double intensity within the same transverse emittance and same tune spread
    - SPS tune spread gets closer to its limit of 0.21



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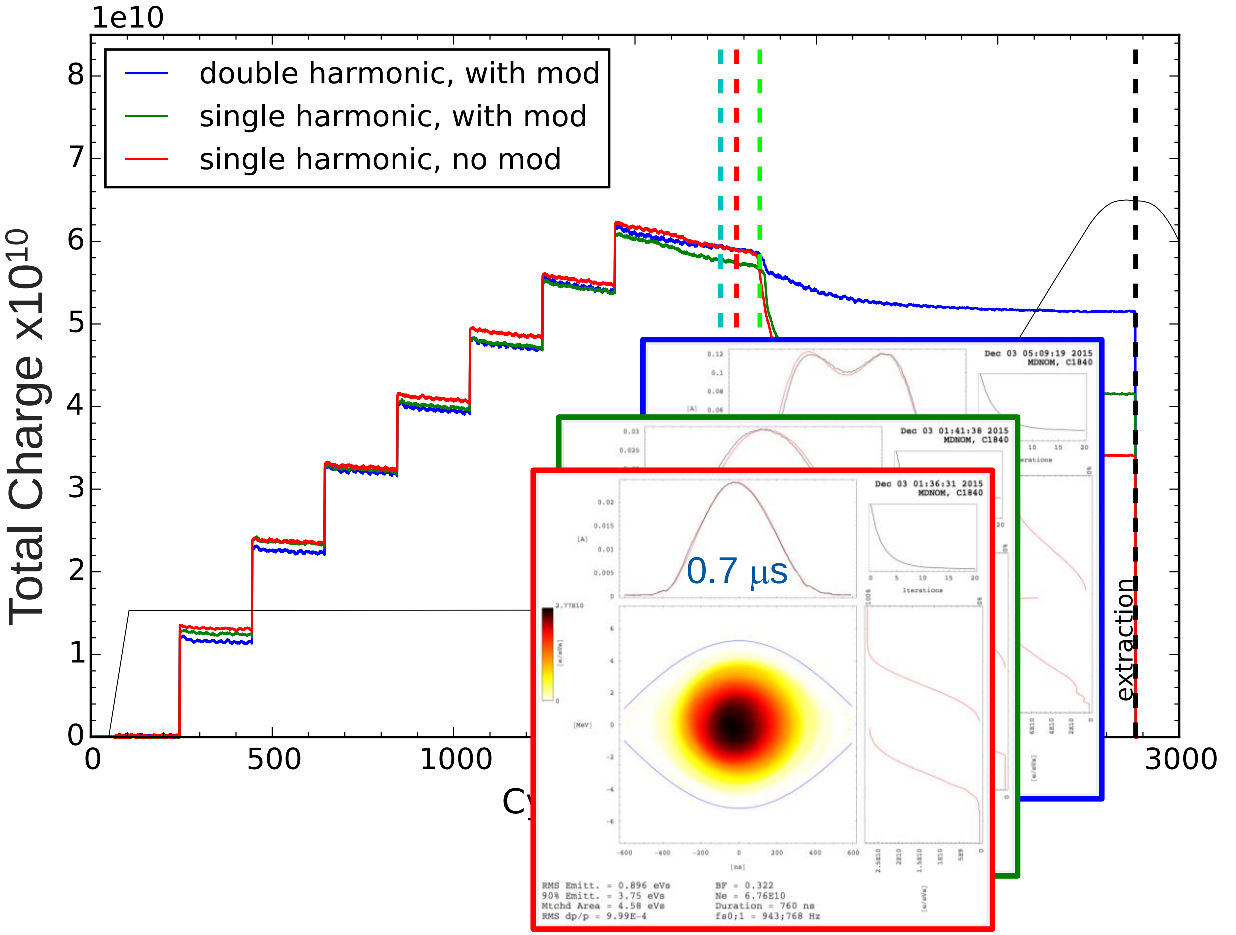
⇒ **Still to demonstrate** with continuing simulations and then with beam

- New PSB brightness line with new injection scheme and new magnetic errors from BSW
- Validity of PS tune spread limit at 2 GeV and with new injection elements
- Benefits from larger longitudinal emittance at PS injection
- No detrimental effects from larger SPS tune spread (and compatibility with the possible request of lower longitudinal emittance from PS)
- Capability of staying within the tight emittance growth budgets in all machines
- …

A dense and challenging program in front of us
→ Necessary for efficient beam commissioning in Run 3

Space charge for the ions: LEIR

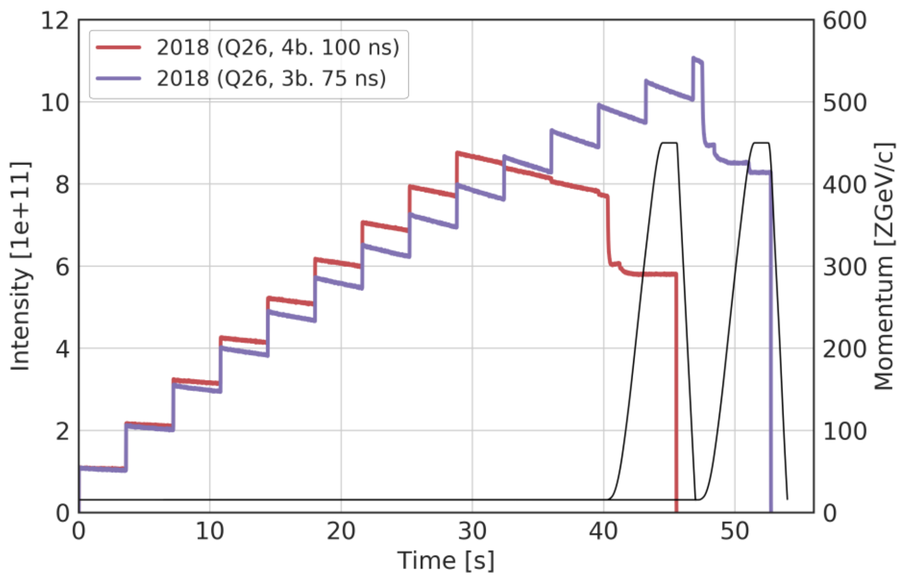
- Intensive study program + hardware upgrades during Run 2 led to impressive **performance boost**
  - **Mitigation of space charge** and IBS at RF capture was a breakthrough in 2015, mainly through working point optimization and bunch flattening
  - Process optimised over the years contributing to further improved LEIR performance in 2016-2018
  - More work ongoing on active resonance compensation and electron cooling optimization **to further reduce brightness effects at RF capture**



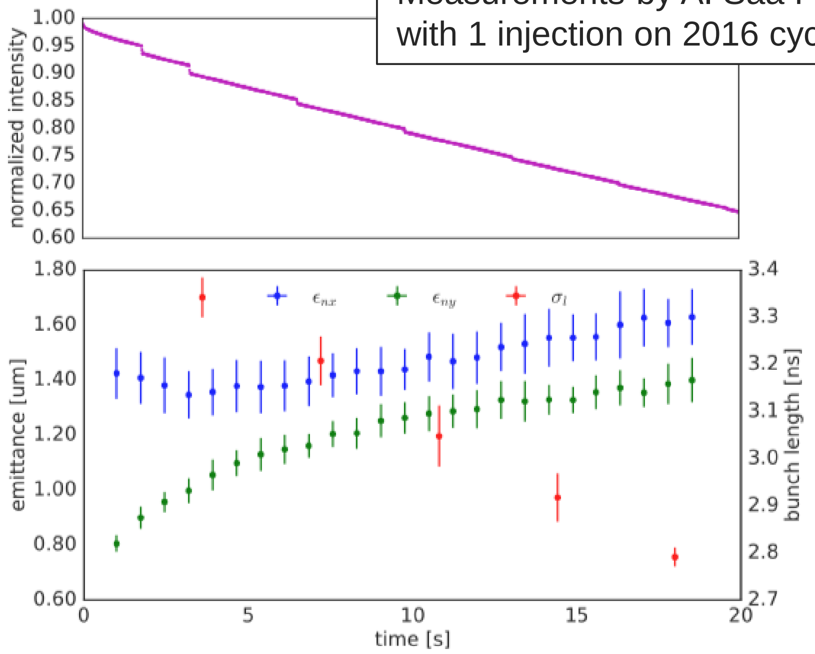
Space charge for the ions: SPS

LHC Injectors Upgrade

- Space charge effects on Pb ion beams in the SPS are not negligible
  - Large space charge tune spreads ($|\Delta Q_y|>0.21$) along long flat bottom (14 injections)
  - Intensity dependent transmission
  - Losses, emittance growth, bunch shortening
  - Simulations ongoing to pin down mechanism



Measurements by A. Saa Fernandez *et al*.
with 1 injection on 2016 cycle for 7 injections



Conclusions

LHC Injectors Upgrade

- **LIU project baseline** fulfils the HL-LHC target parameters
  - LS2 works now ongoing in all the injectors to put in place the upgrades
- **LIU hardware and beam commissioning** will start in 2020
  - HL-LHC ion beams to be commissioned by the end of 2021
  - Performance ramp up defined for LIU proton beams throughout Run 3
- **Space charge** a fundamental ingredient to define LIU baseline
  - Steered the choices for injection energy into PSB and PS
  - Important limitation crucial to improve ion beams in LEIR and SPS
  - Simulations still ongoing for all machines to improve predictions, define and guide operational scenarios for post-LIU performance

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LHC injectors will be operating in uncharted territory after LS2

The production of brighter beams and the brightness preservation along the injector chain will be a big challenge and instrumental for the success of LIU!

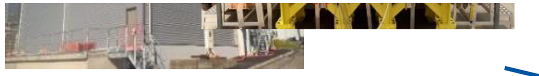
www.cern.ch

THANK YOU FOR YOUR ATTENTION

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

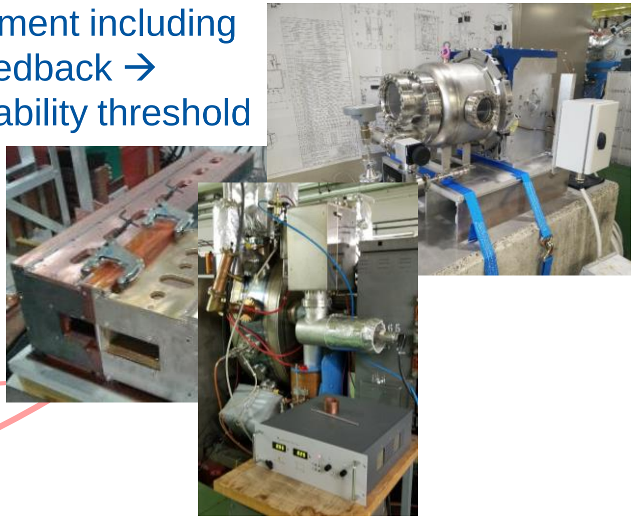
PS-Booster (PSB)
4 rings of C =157 m
E_{kin}^{out} = 1.4 / 2.0 GeV

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

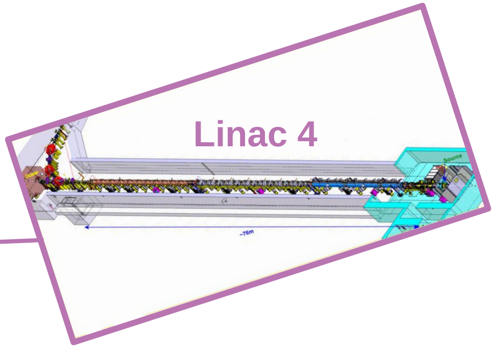
Linac 4
E_{kin}^{out} = **160 MeV**

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**
- Target 25 mA within 0.3 μm



LHC Injectors Upgrade

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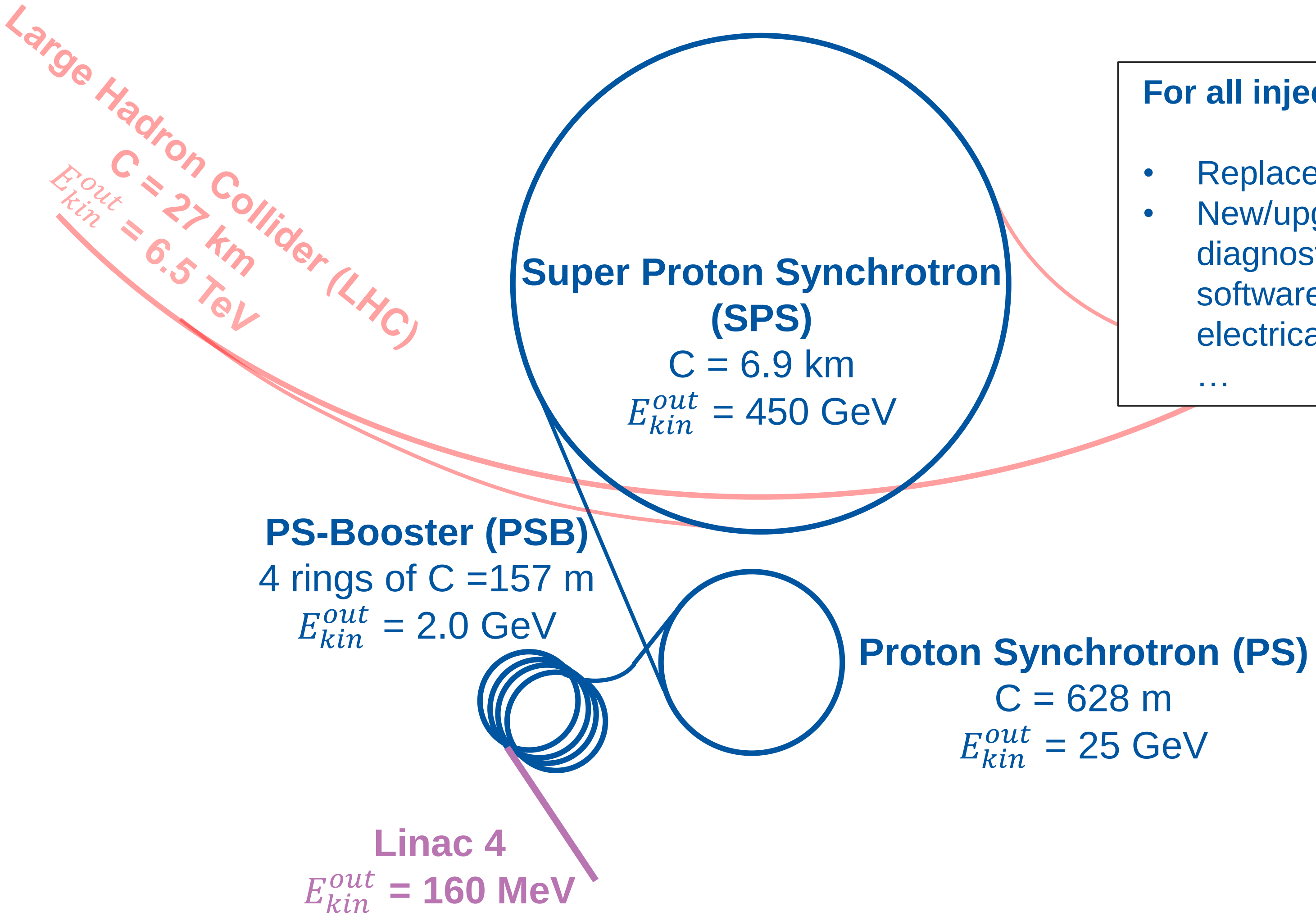
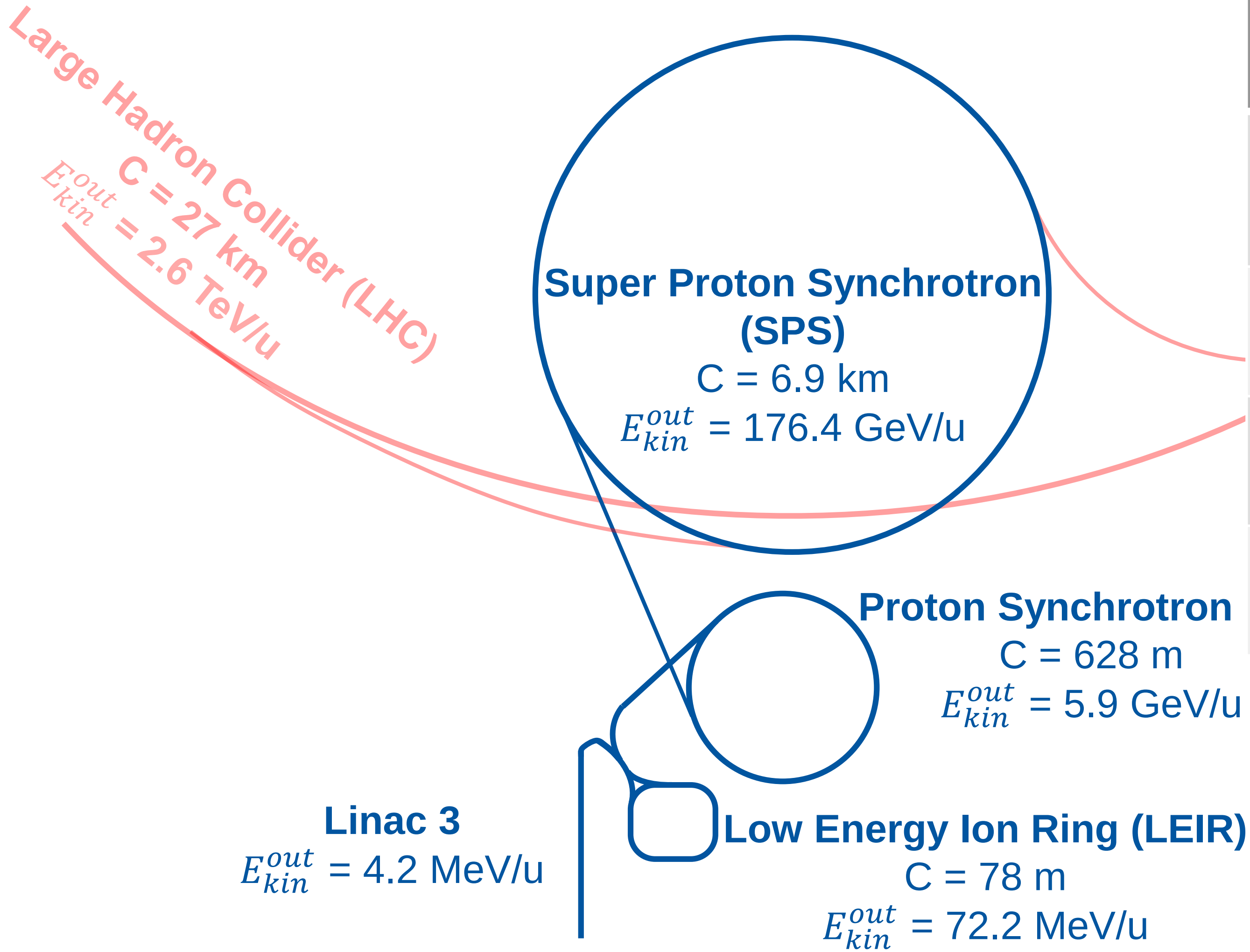


For all injectors :

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

The CERN injector complex: Pb ions

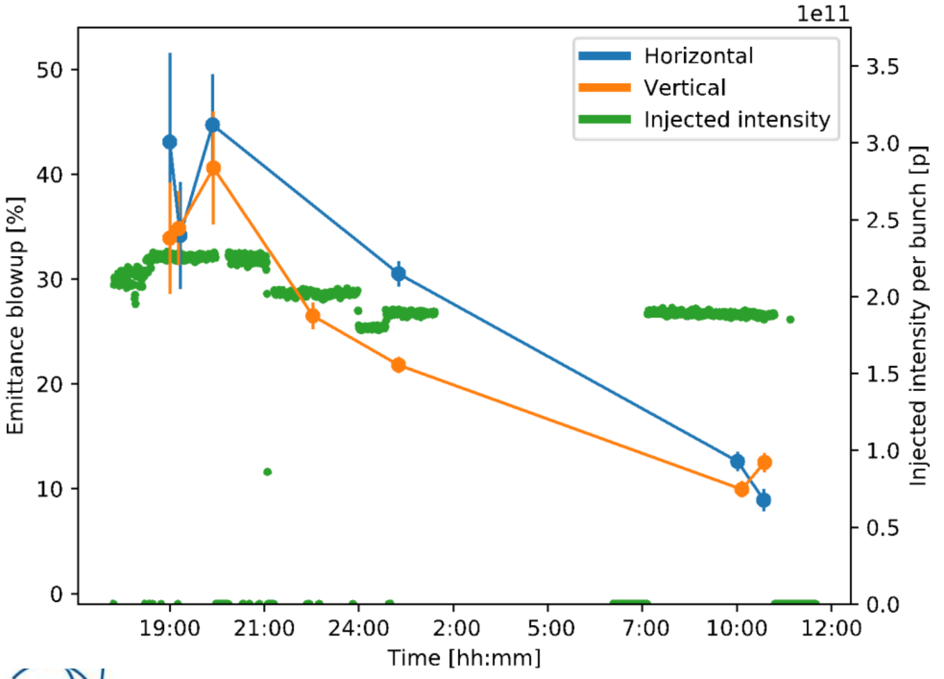


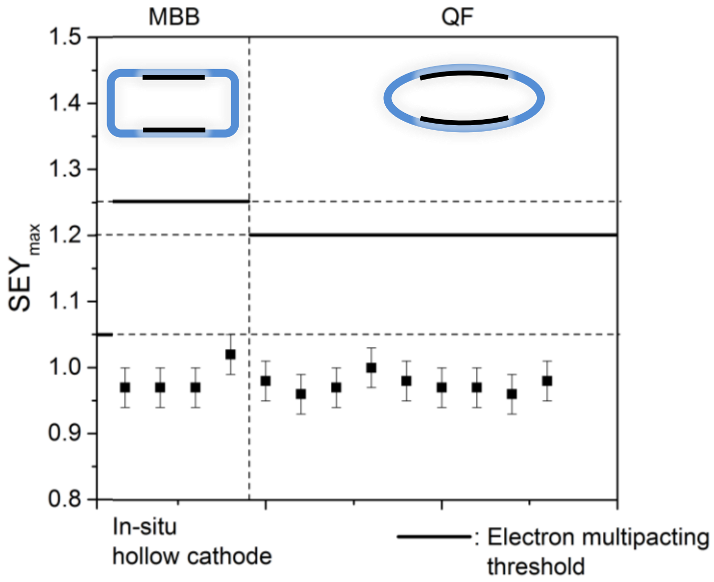
Beam transfer	Number of bunches	Bunch spacing (ns)
Linac3 → LEIR E_{kin}^{out} = 4.2 MeV/u	Multi-turn injection of coasting beam	–
LEIR → PS E_{kin}^{out} = 72.2 MeV/u	2 (3)	354 (472)
PS → SPS E_{kin}^{out} = 5.9 GeV/u	4 (3)	100 (75)
SPS → LHC E_{kin}^{out} = 176.4 GeV	14 x 4 (14 x 3)	100 / 150 (75 / 150)

Hihglights (2): Electron cloud in SPS

LHC Injectors Upgrade

- **Electron cloud mitigation in SPS** will mainly rely on
  - Beam induced scrubbing
- Industrialisation of **in-situ a-C coating** of magnet chambers developed and demonstrated for potential **application after LS2**

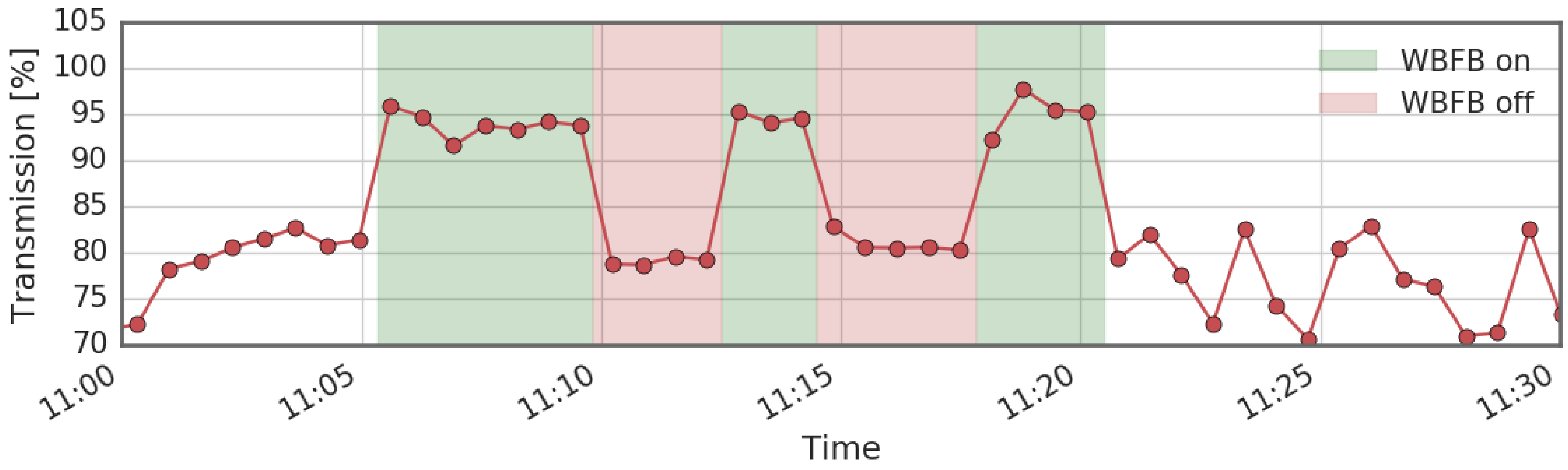




Achievements (4): Wideband Feedback System

LHC Injectors Upgrade

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



Achievements (4): Wideband Feedback System

LHC Injectors Upgrade

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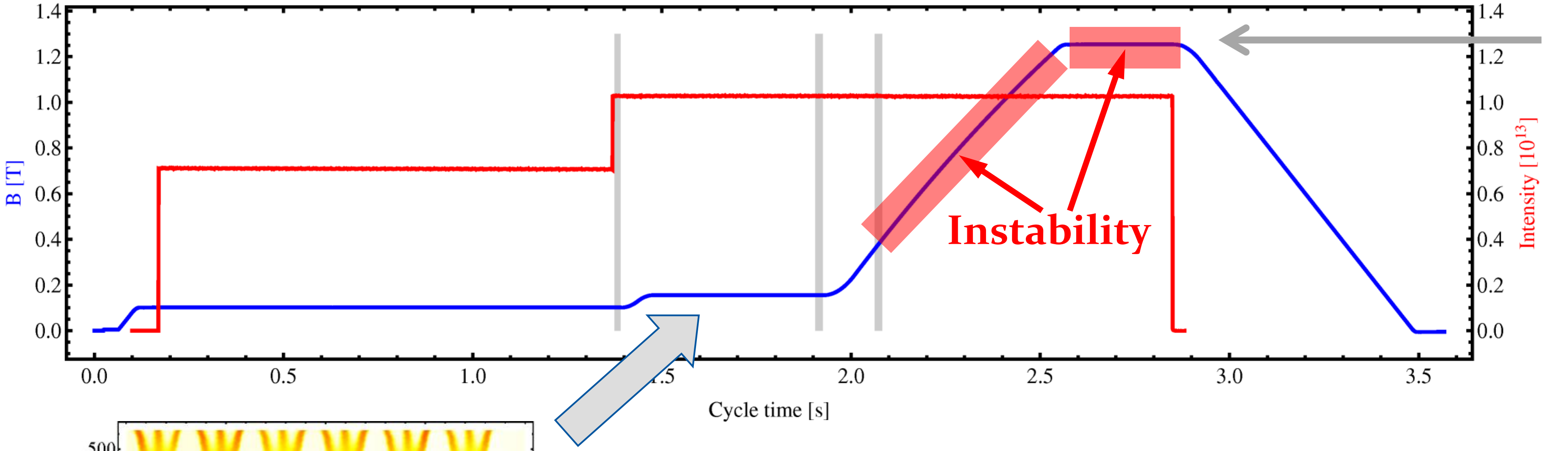
  - Using stripline pick-ups + two stripline kickers and a slotline kicker, bandwidth up to 1 GHz, power > 1 kW
- Damping of Transverse Mode Coupling Instability (TMCI) with single bunch demonstrated in machine experiments in 2017-18
- Operational deployment not pursued within LIU, however kept as **post-LS2 option** in case of unexpected transverse instabilities to reach LIU parameters

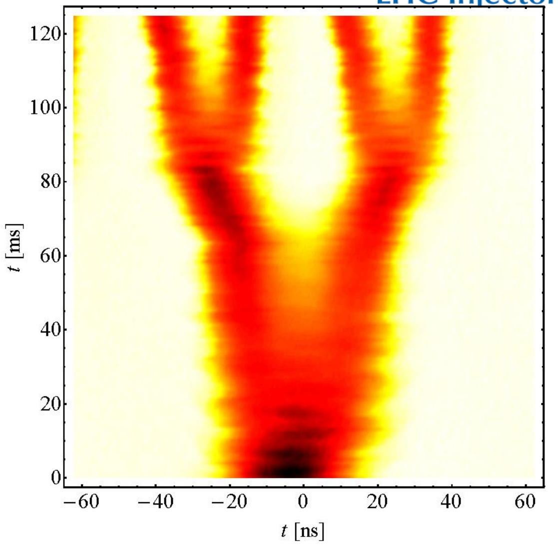
LIU beam ramp-up – possible additional needs

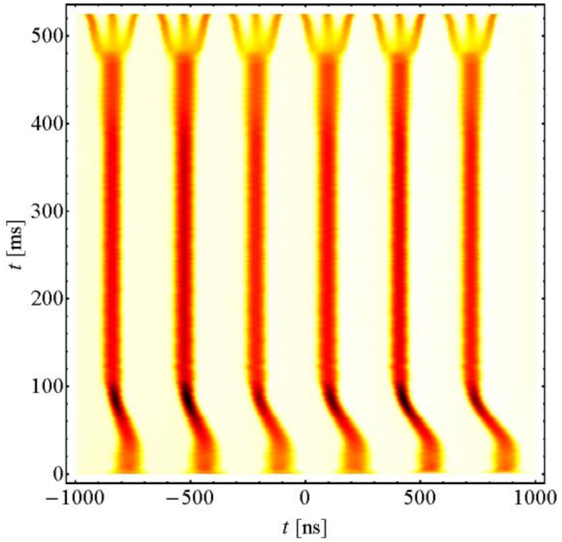
To follow-up and document post-LS2 upgrades list at the defined checkpoints

Item	Decision point	Cost estimate (MCHF)
Booster extraction kicker impedance reduction	2021	0.1
Landau cavity	2023	4
a-C coating of all MBBs, quads + 159 drifts	2023 – 2024	4
Further impedance reduction (SPS injection kicker, flanges & valves shielding)	2022 – 2023	0.2 + 3.5
Remaining QD aperture improvement	2021	0.6
New wideband feedback system	2022 – 2023	>2
Final BSRT	2022	0.2
New collimation system	2022 – 2023	1

Lifting the PS intensity limitation







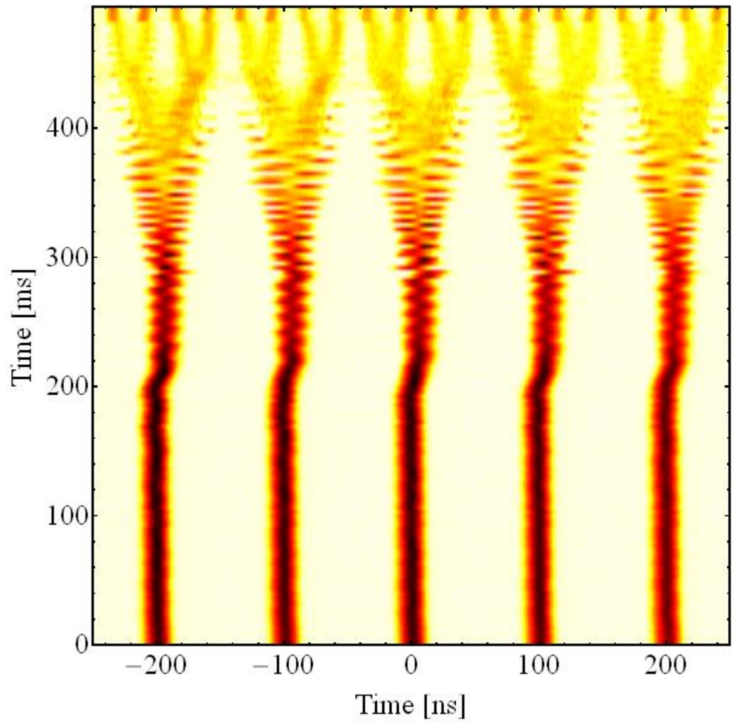
- Bunch current limited to **1.6e11 p/b at extraction**
- Above 1.6e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
  - Dipolar oscillation, caused by **10 MHz RF system impedance** (as found also in simulations)

Lifting the PS intensity limitation

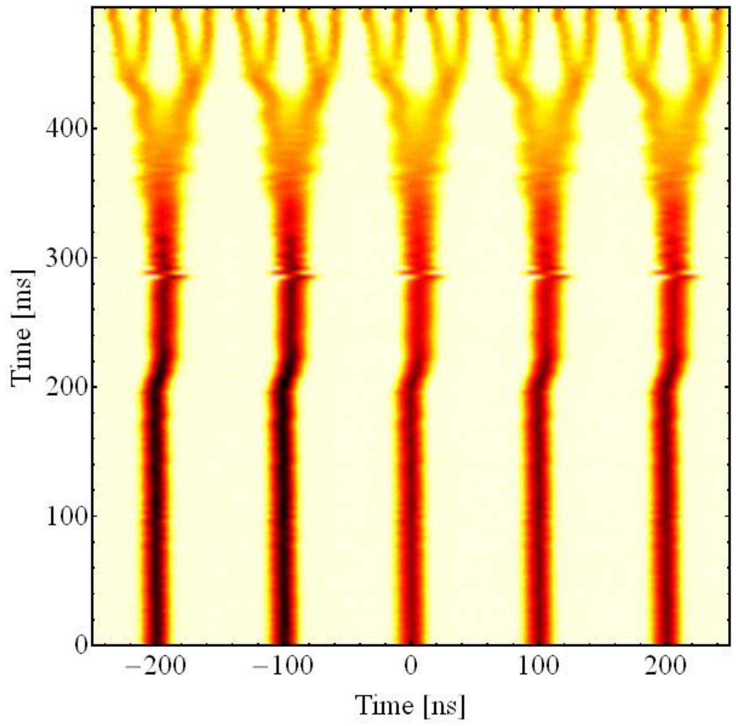
LHC Injectors Upgrade

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years → stabilizes above 2e11 p/b

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



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



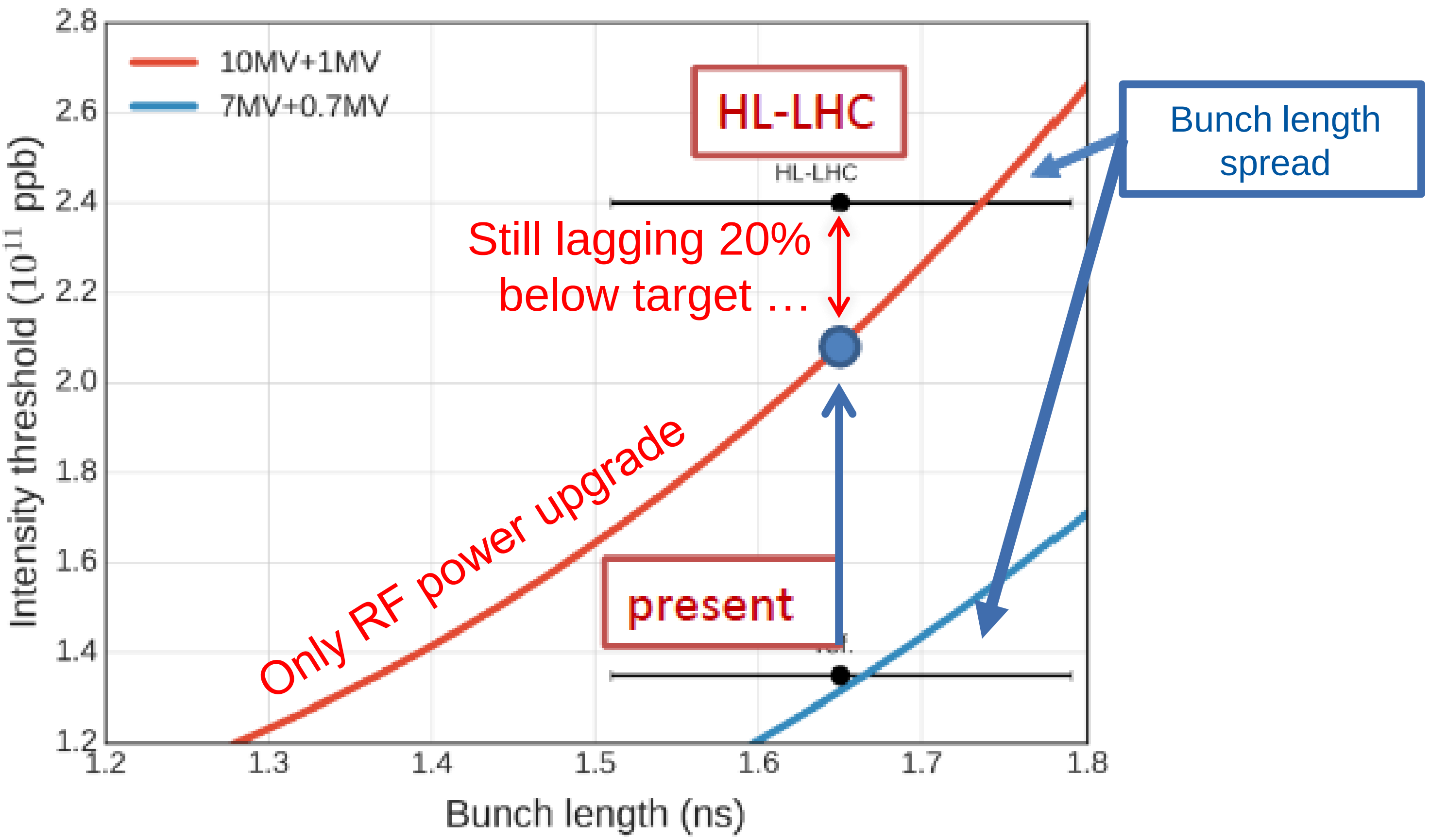
Lifting the PS intensity limitation

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years → stabilizes above 2e11 p/b
- **Impedance reduction** of the 10 MHz cavities with upgrade of power amplifier → currently tested on one cavity, to be deployed on all cavities in LS2
- Ongoing study on the option of a **higher harmonic (‘Landau’) cavity** to have another weapon against longitudinal instabilities and reach the target LIU/HL-LHC intensity

Lifting the SPS intensity limitation

LHC Injectors Upgrade

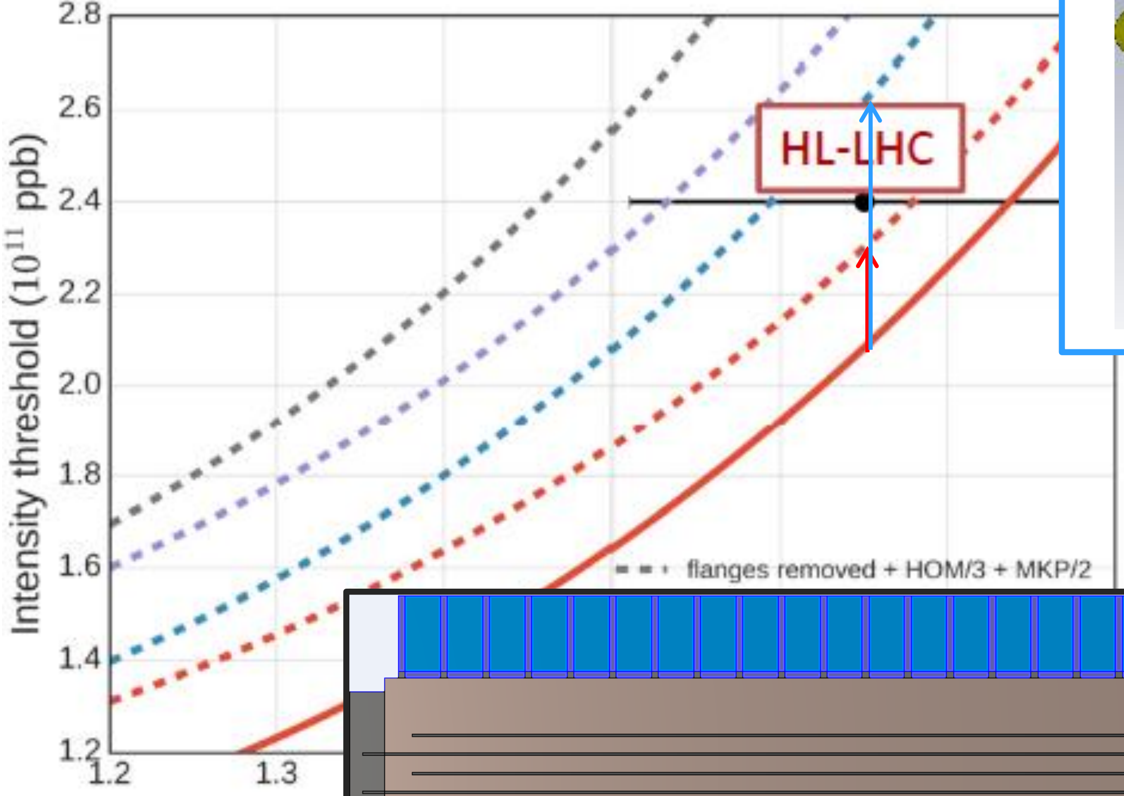
- **Beam loading** in the present 200 MHz TW RF system – intensity limited to about 1.3e11 p/b
- **Longitudinal instabilities** during ramp with very low threshold currently cured by
  - 800 MHz RF system in bunch shortening mode
  - Controlled emittance blow-up (with constraint of 1.7 ns bunch length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

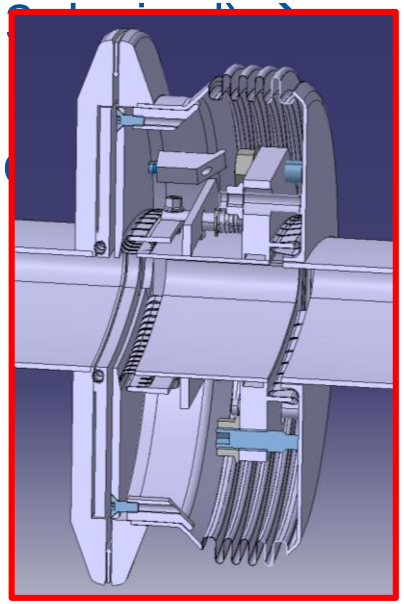


Lifting the SPS intensity limitation

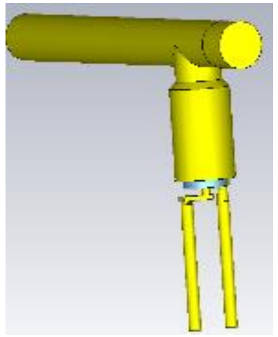
LHC Injectors Upgrade

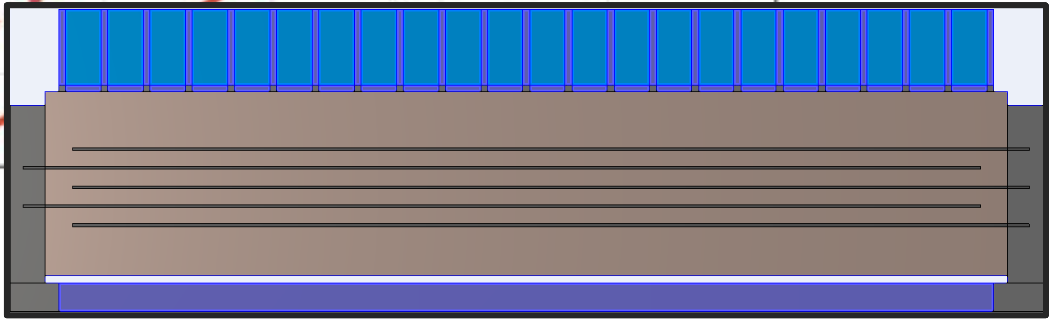
- **Impedance reduction** needed in addition
  - Shielding of a subset of vacuum flanges
  - Enhanced damping of HOMs of 200 MHz (factor
    baseline for LIU
  - Serigraphy on th
    kickers MKP





new HOM coupler





Other SPS intensity limitations?

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