LHC Injectors Upgrade

LHC Injectors Upgrade Project: Towards New Territory Beam Parameters

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CERN

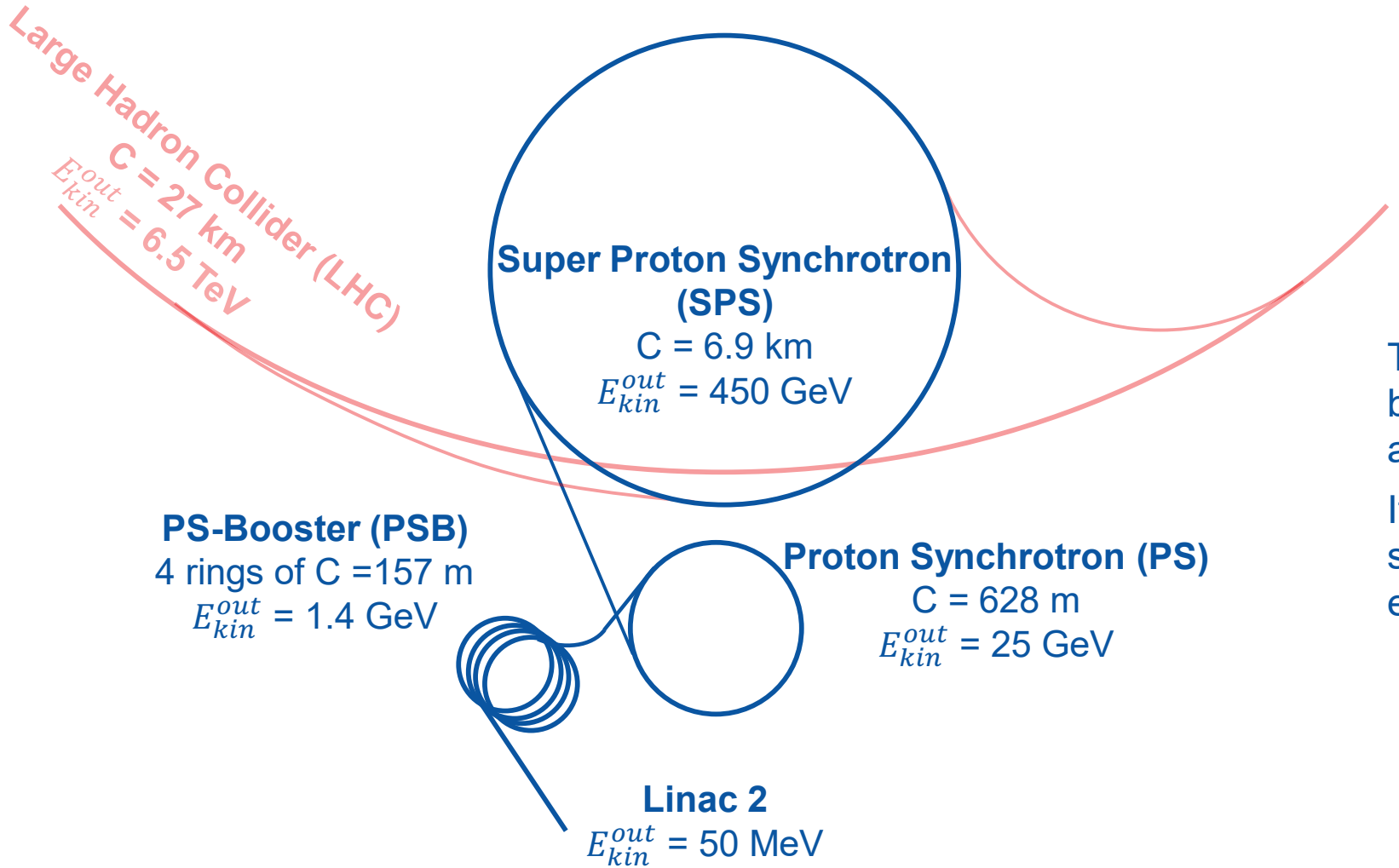
Outline

LHC Injectors Upgrade

- The CERN injectors complex
  - Production scheme for LHC beams – protons and ions
- The LHC Injectors Upgrade (LIU) project
  - Goals and means of LIU
  - Expected beam performance vs. current performance
- The LIU project phases
  - A collection of main achievements
  - Long Shutdown 2 (LS2): Equipment readiness and installation
  - Return to operation and beam performance ramping up after LS2
- Conclusion

The CERN injectors complex: protons

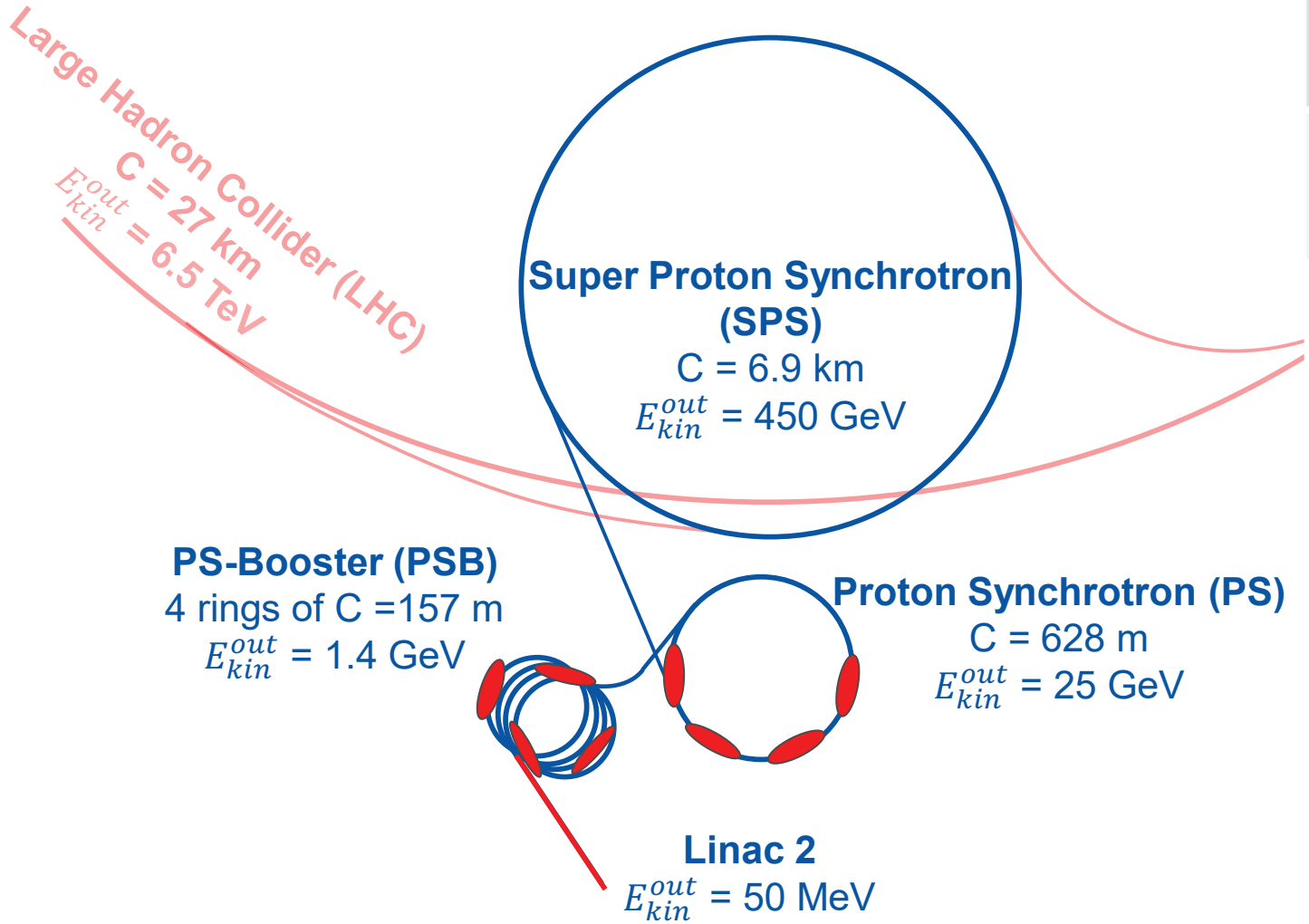
LHC Injectors Upgrade



The **CERN injectors complex** is by itself one of the largest accelerator facilities in the world

It is used to feed **LHC** as well as to serve a number of fixed target experiments

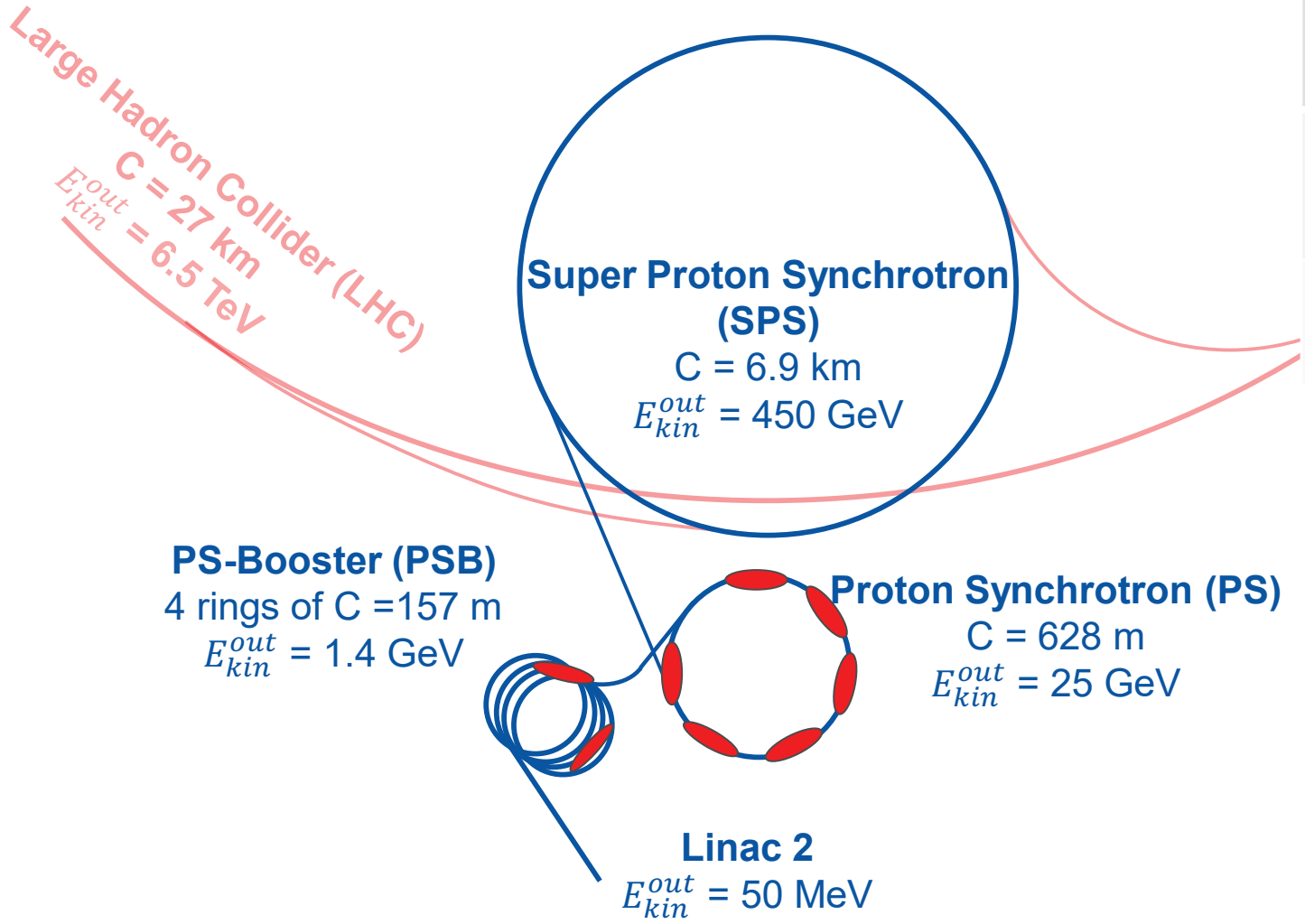
Production scheme of LHC beams



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

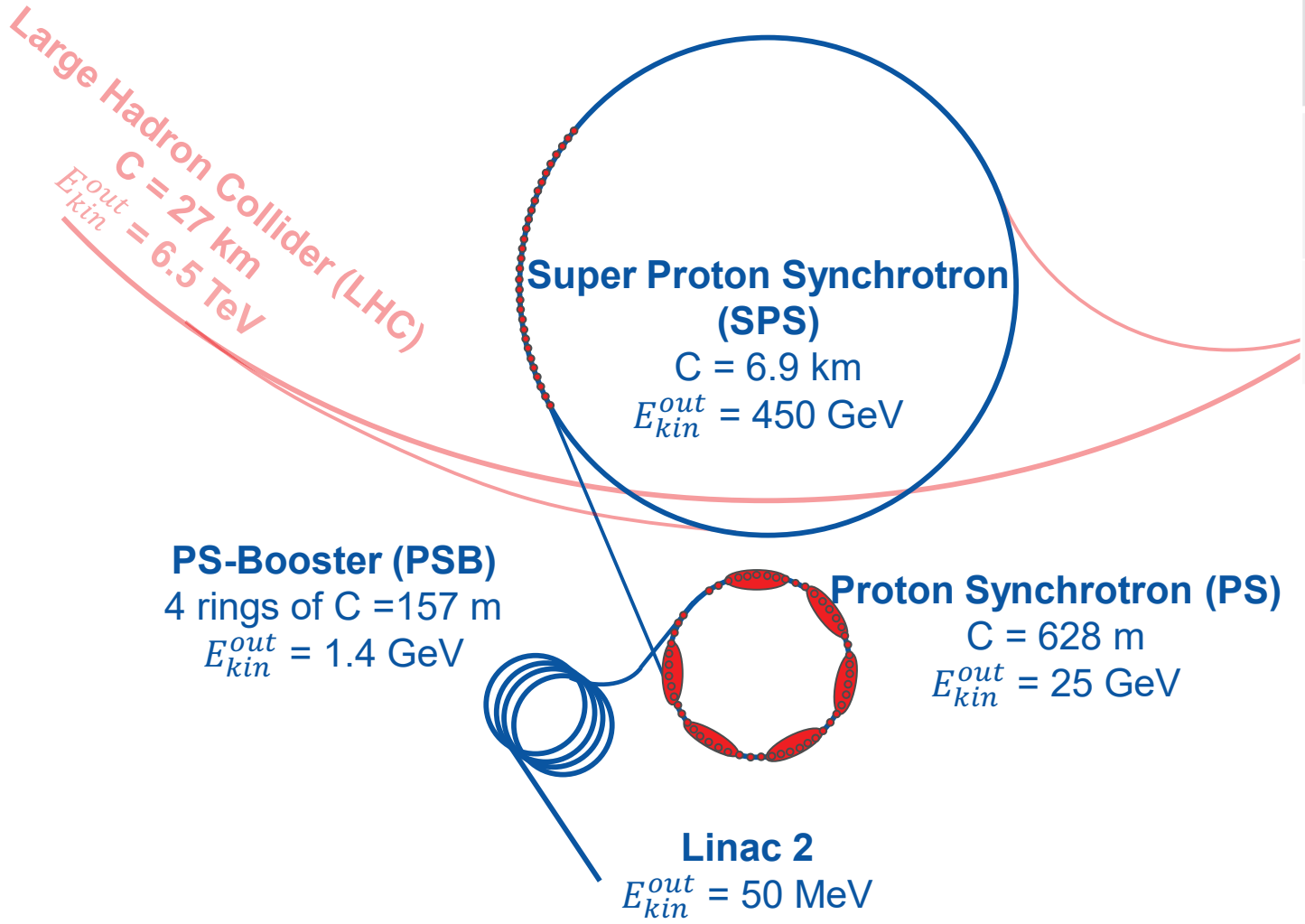
LHC Injectors Upgrade



Beam transfer	Number of bunches	Bunch spacing (ns)
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

LHC Injectors Upgrade



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Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–
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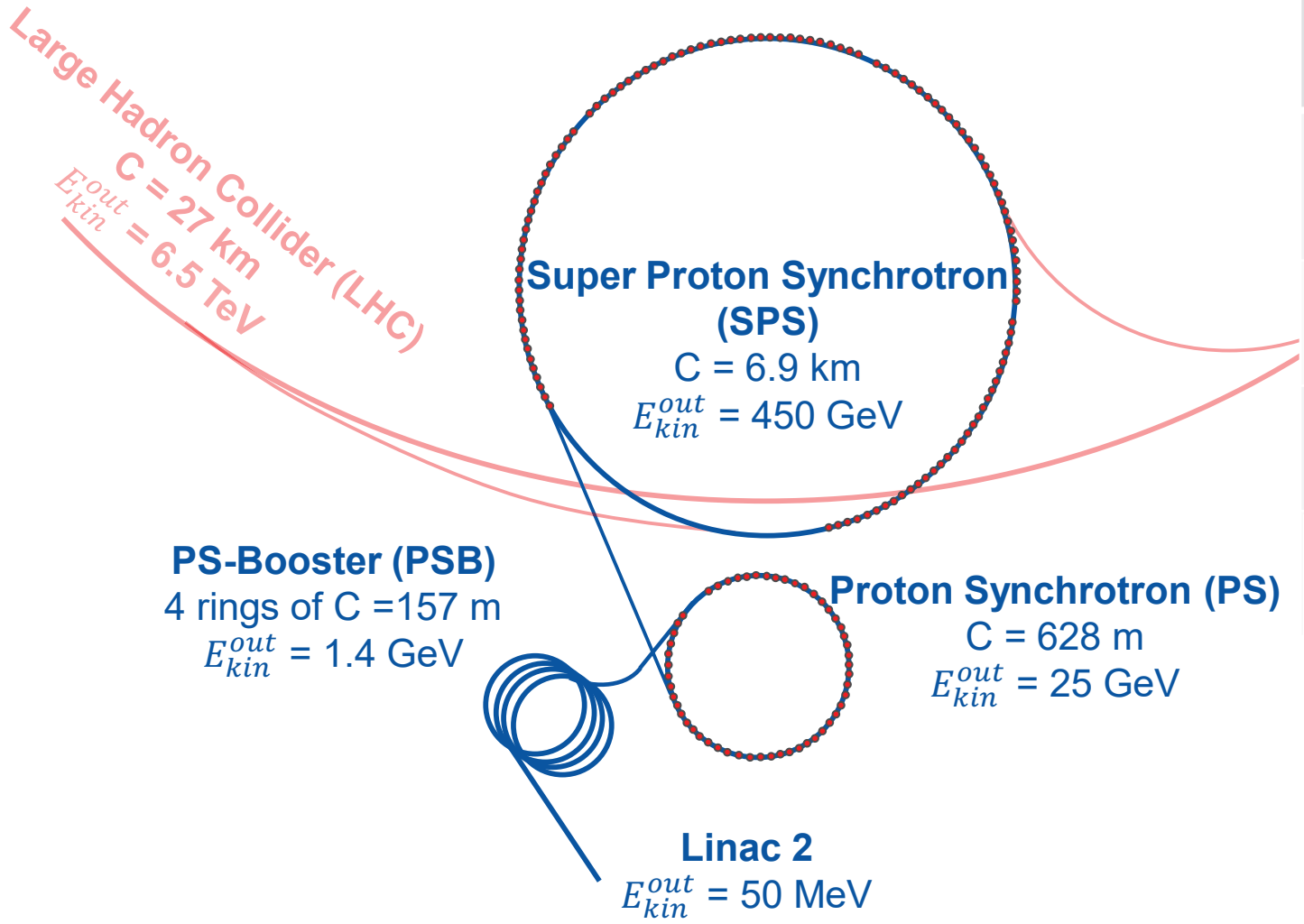
One triple bunch splitting and two double bunch splittings in the PS

Production scheme of LHC beams

LHC Injectors Upgrade

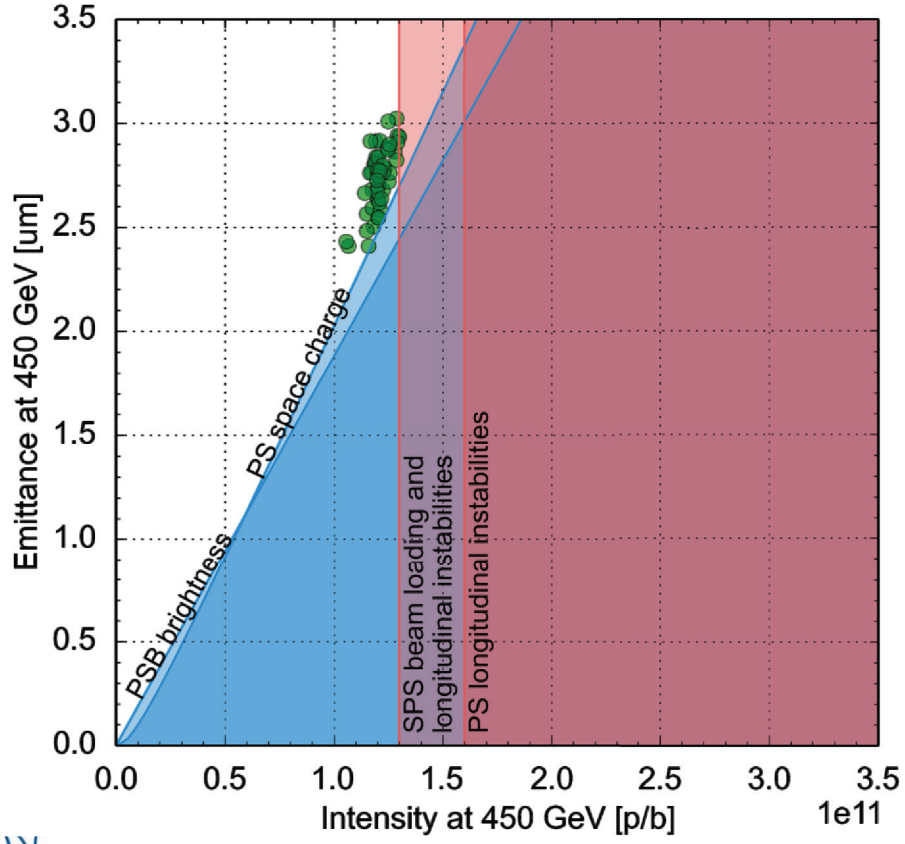


Beam transfer	Number of bunches	Bunch spacing (ns)
Linac2 → PSB E_{kin}^{out} = 50 MeV	Multi-turn injection of coasting beam	–
PSB → PS E_{kin}^{out} = 1.4 GeV	4 + 2	272
PS → SPS E_{kin}^{out} = 25 GeV	72	25

Four injections into the SPS

LHC beam performance before upgrade

- 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

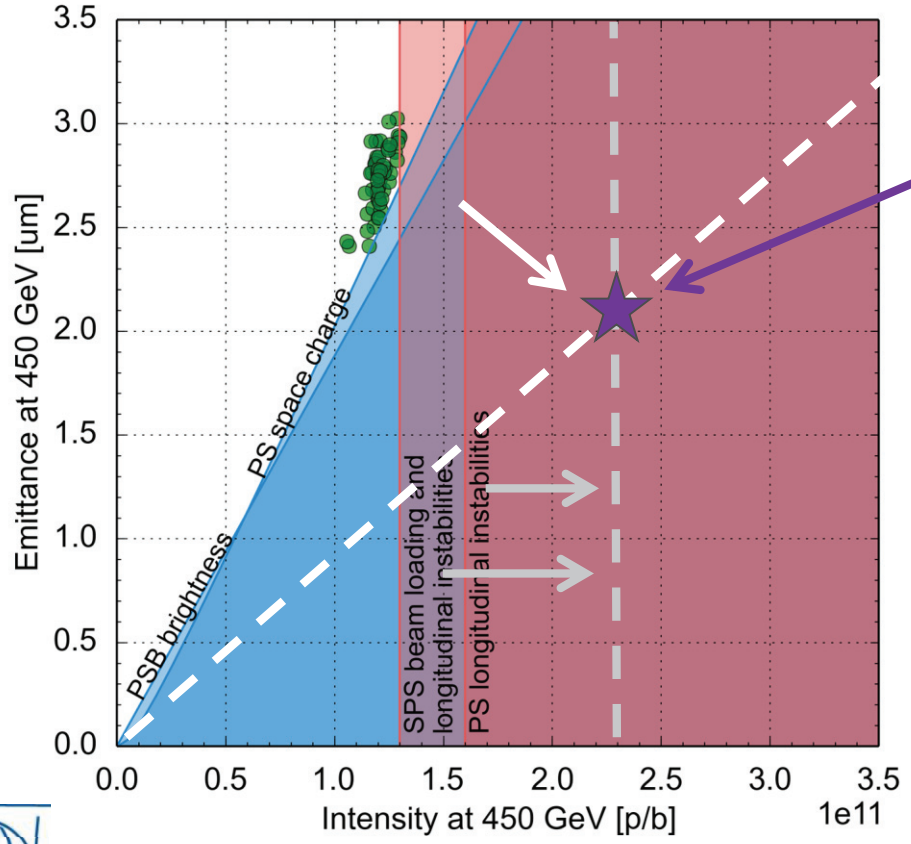


- **Brightness**
  - PSB brightness determined by space charge at injection
  - Limit for PS space charge at injection
- **Intensity**
  - SPS is limited by beam loading and longitudinal instabilities on the ramp and flat top
  - PS is limited by longitudinal coupled bunch instability on the ramp and flat top

Motivation for the LHC Injectors Upgrade (LIU)

LHC Injectors Upgrade

- **Challenge** → Modify injectors such that beam parameters at **SPS extraction** match the **High Luminosity LHC (HL-LHC) target**



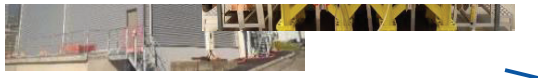
	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)
HL-LHC target	2.3	2.1
Before upgrades	1.3	2.7

- **Main goals of the LHC Injectors Upgrade (LIU) project**
  - Define and deploy means to overcome performance limitations in all injectors and achieve the HL-LHC target parameters
  - Ensure and improve injectors' availability/reliability for operation during the HL-LHC era – complementary to consolidation (CONS) activities

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 - KEK/J-PARC Japanese Contribution

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

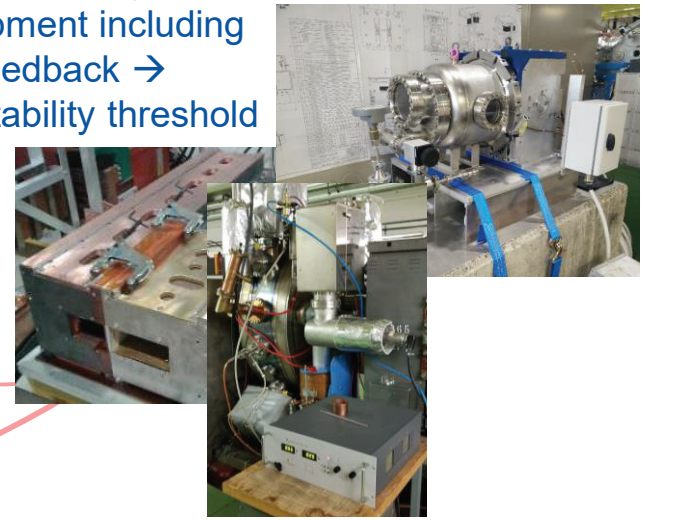
PS-Booster (PSB)
4 rings of C =157 m
E_{kin}^{out} = 2.0 GeV

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

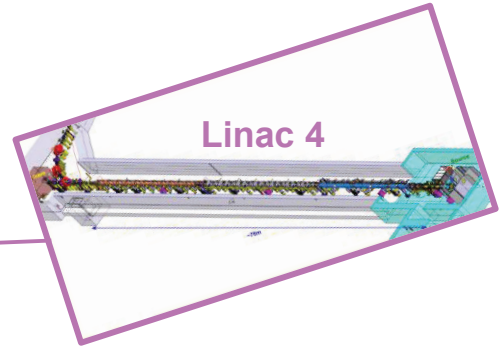
Linac 4
E_{kin}^{out} = **160 MeV**

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

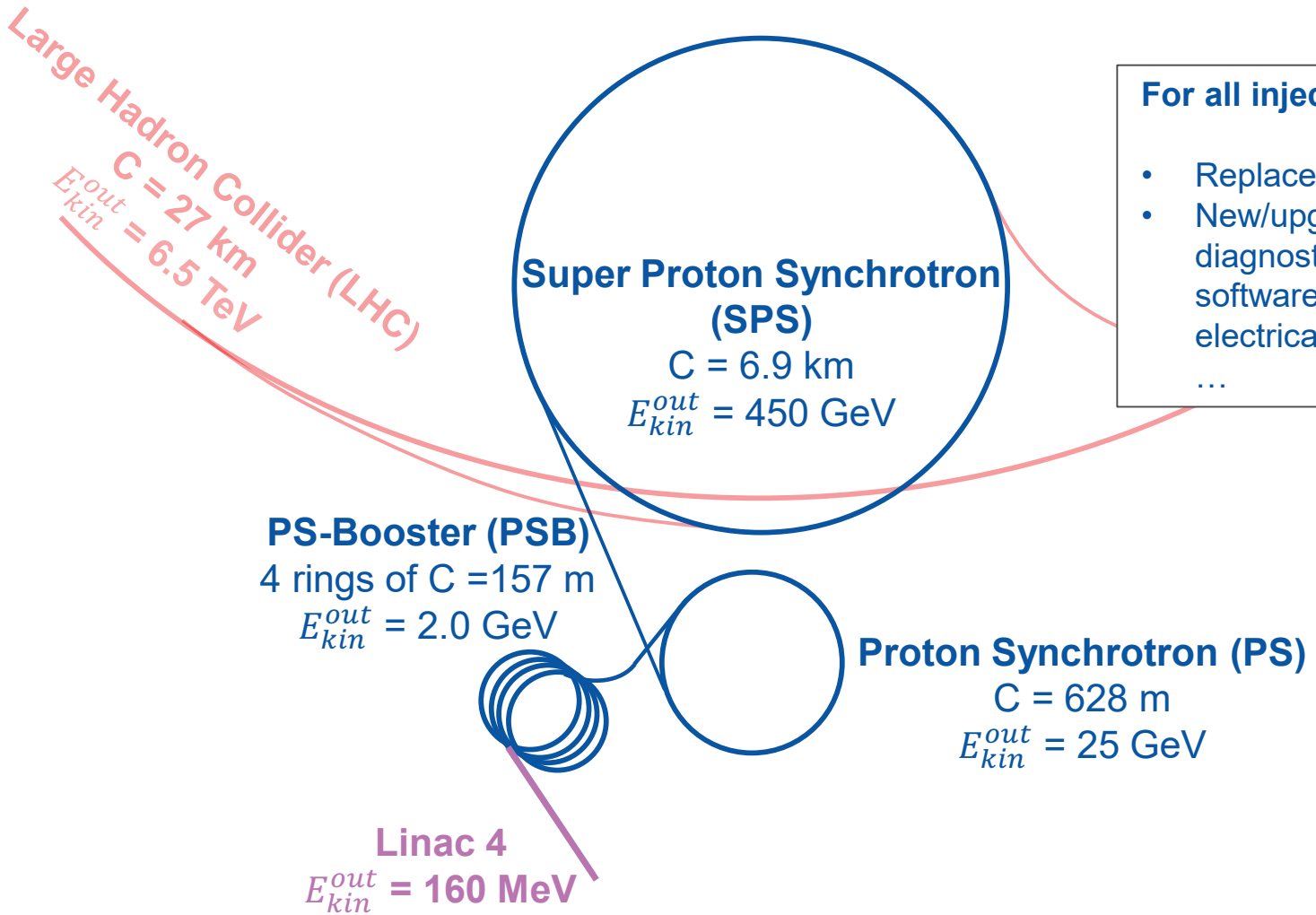


- Acceleration of H^- to **160 MeV**
- Target 25 mA within 0.3 μm



A quick overview on the LIU project

LHC Injectors Upgrade



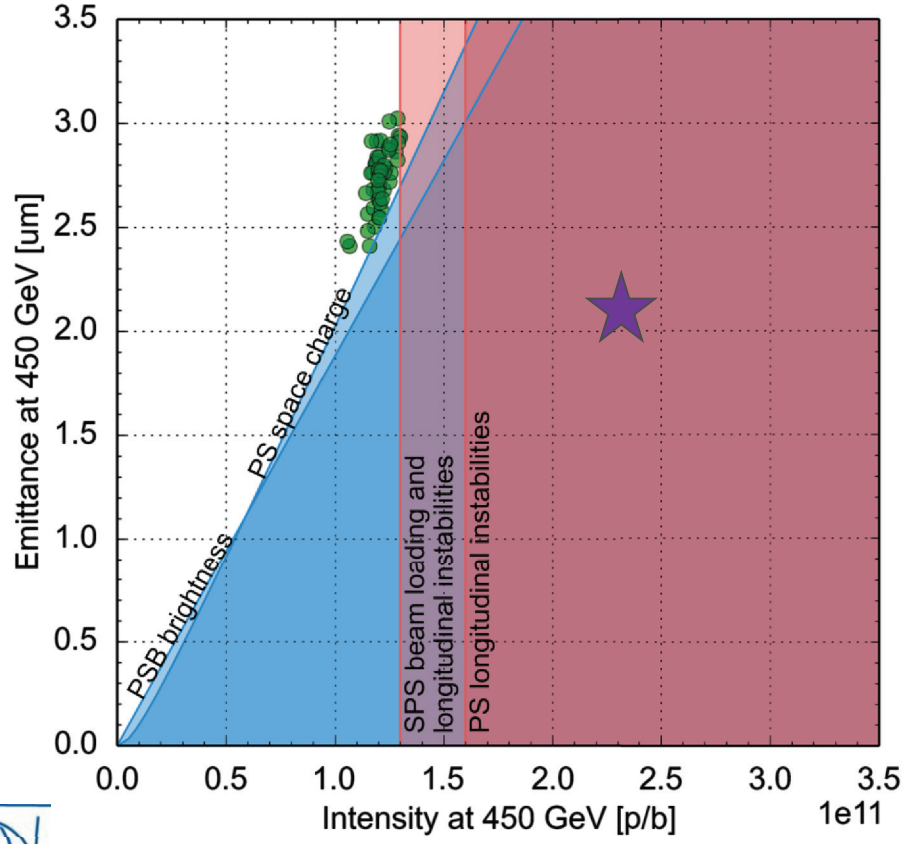
For all injectors :

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

Motivation for the LHC Injectors Upgrade (LIU)

LHC Injectors Upgrade

- **Challenge** → Modify injectors such that beam parameters at **SPS extraction** match the **High Luminosity LHC (HL-LHC) target**



- Scaling laws as well as advanced simulation models of the injectors (e.g. optics, impedance, electron cloud) can be applied to predict performance limitations after LIU upgrades
- **LIU parameter reach matches the HL-LHC target**

Not only protons …

LHC Injectors Upgrade

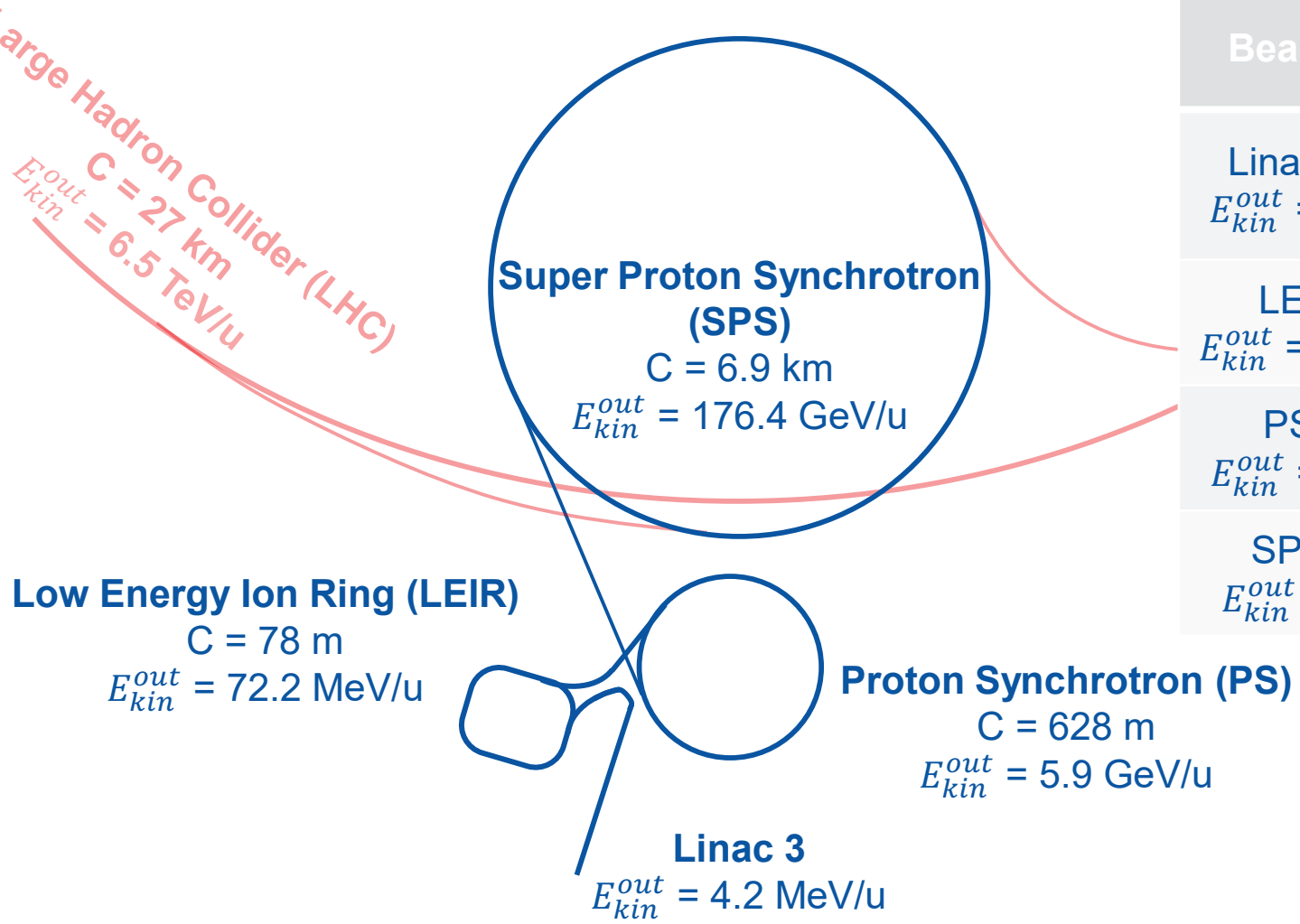
- CERN injectors complex also accelerates **heavy ions (Pb) → See next slide**

→To fulfil the HL-LHC requirement for heavy ions, LIU is requested to produce beams with these parameters at the SPS extraction

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

The CERN injectors complex: Pb ions

LHC Injectors Upgrade



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} = 450 GeV	12 x 4 (12 x 3)	100 / 150 (75 / 150)

Performance reach for Pb ions

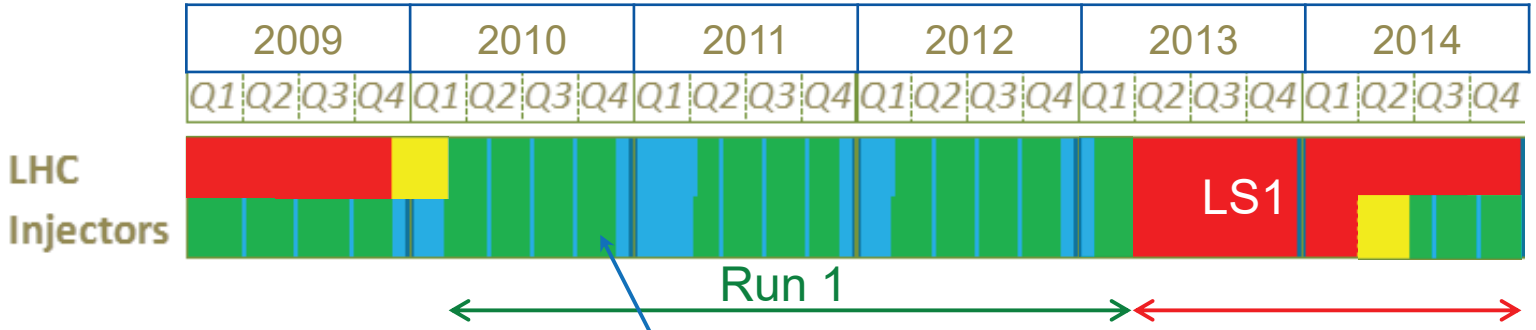
LHC Injectors Upgrade

	N (x 10^8 ions/b)	ε (μm)	# of bunches
Achieved (2018, nominal)	2.0	1.5	648
HL-LHC target	1.9	1.5	1248

- **Single bunch parameters** at SPS extraction already match requested ones with 5% margin
  - As a result of an **LIU dedicated effort** in 2015-2018
- **Number of bunches** only achievable with momentum slip stacking in the SPS, which relies on SPS 200 MHz RF system upgrade
- **Mitigation (already demonstrated)** → 70% of HL-LHC luminosity target is in reach without slip stacking by using 3 bunches with 75 ns spacing from PS

LIU timeline on CERN accelerator schedule

LHC Injectors Upgrade



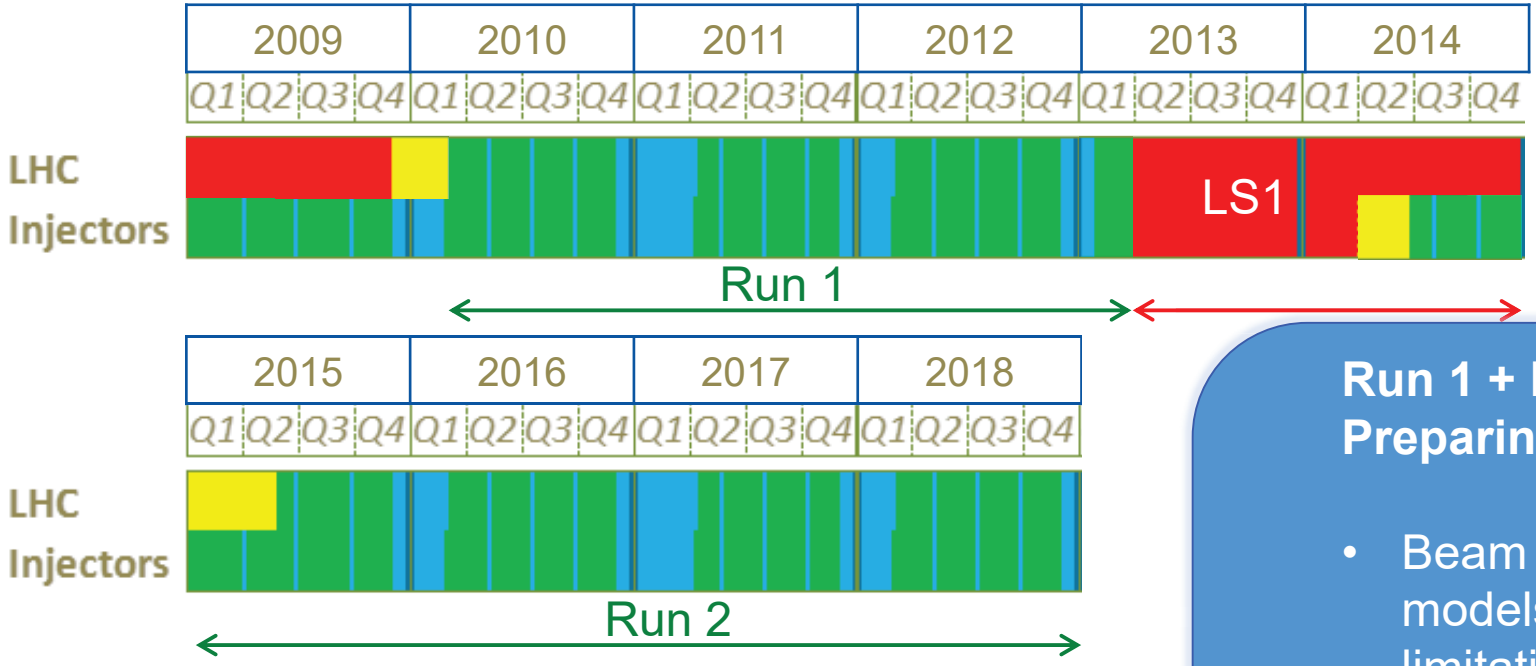
2010: The start

Launch of the LHC Injectors Upgrade project
Definition of goals
Initial planning and costing

Proton Runs **Technical Stops** **Long Shutdowns** **Beam Commissioning**

LIU timeline on CERN accelerator schedule

LHC Injectors Upgrade



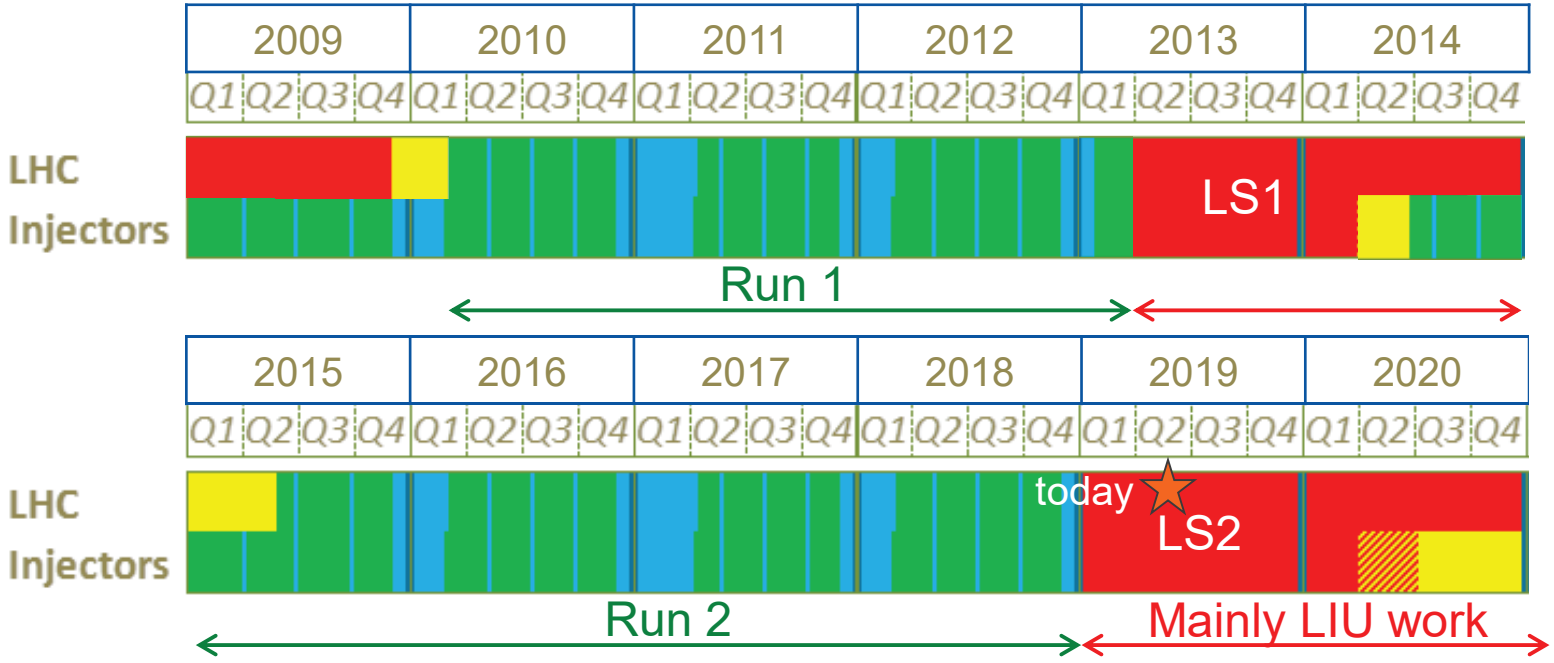
Run 1 + LS1 + Run 2 (2010 – 2018)
Preparing, defining, testing, executing

- Beam studies and development of simulation models to improve understanding of performance limitations and refine the **LIU baseline** items
- **Equipment** specification, design, prototyping, procurement, advanced installation and testing
- Construction of **new buildings** (e.g. new PSB power supply) and improvement of **services**;
- **Linac4** commissioning and quality/reliability runs

Proton Runs **Technical Stops** **Long Shutdowns** **Beam Commissioning**

LIU timeline on CERN accelerator schedule

LHC Injectors Upgrade



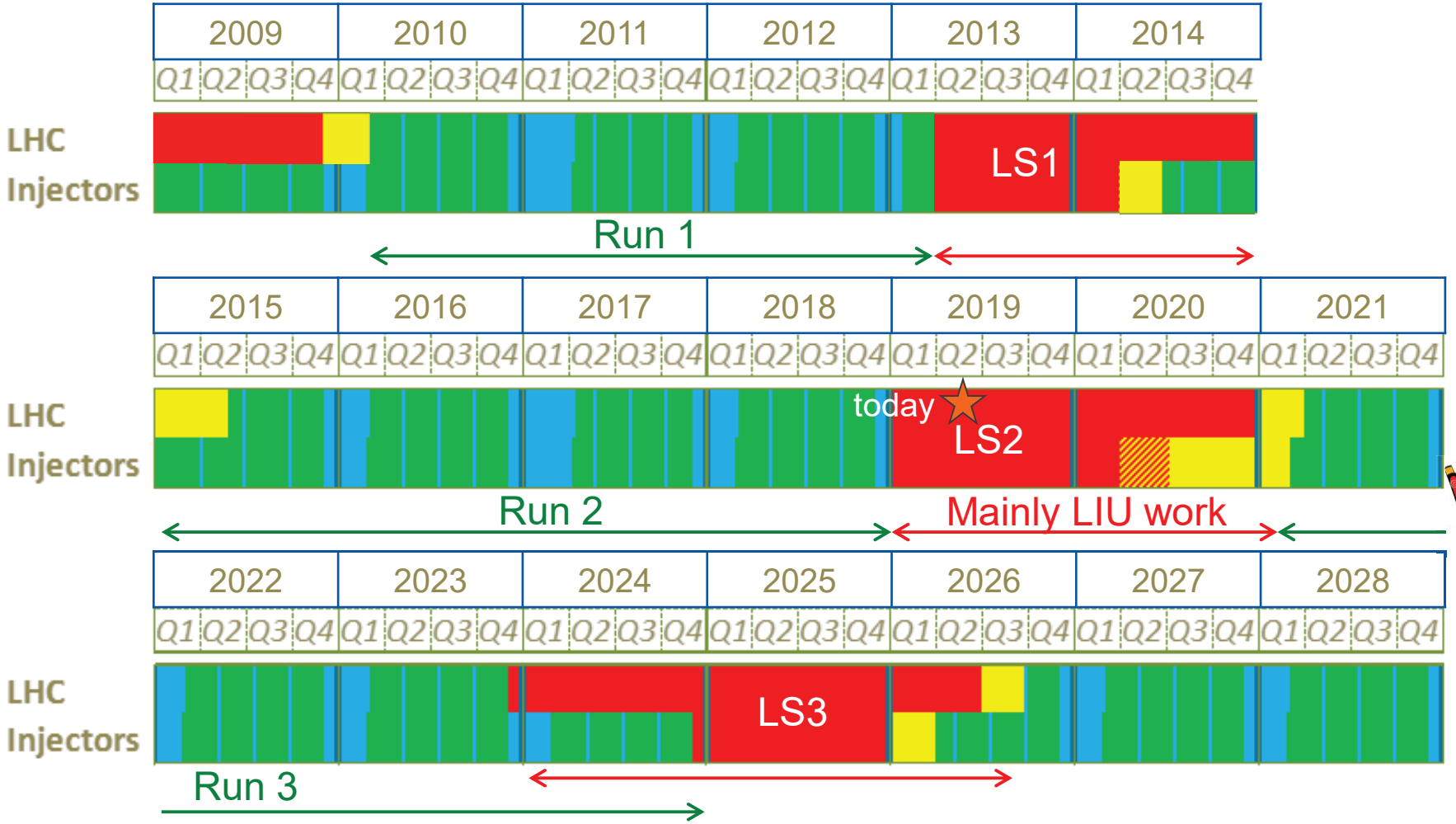
LS2 (2019 – 2020)
Peak of LIU execution phase

- End of LIU equipment production
- **LIU equipment installation** across all injectors
- Preparation of commissioning phases

Proton Runs **Technical Stops** **Long Shutdowns** **Beam Commissioning**

LIU timeline on CERN accelerator schedule

LHC Injectors Upgrade



Run 3 (2020 – 2024)

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

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

Proton Runs **Technical Stops** **Long Shutdowns** **Beam Commissioning**

2010

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

2018

2020

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2024

Run 3 (2020 – 2024)

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- **End of LIU project in 2021**

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

2010

2018

2020

2024

A few selected achievements

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

LS2 (2019 – 2020)
Peak of LIU execution phase

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Run 3 (2020 – 2024)

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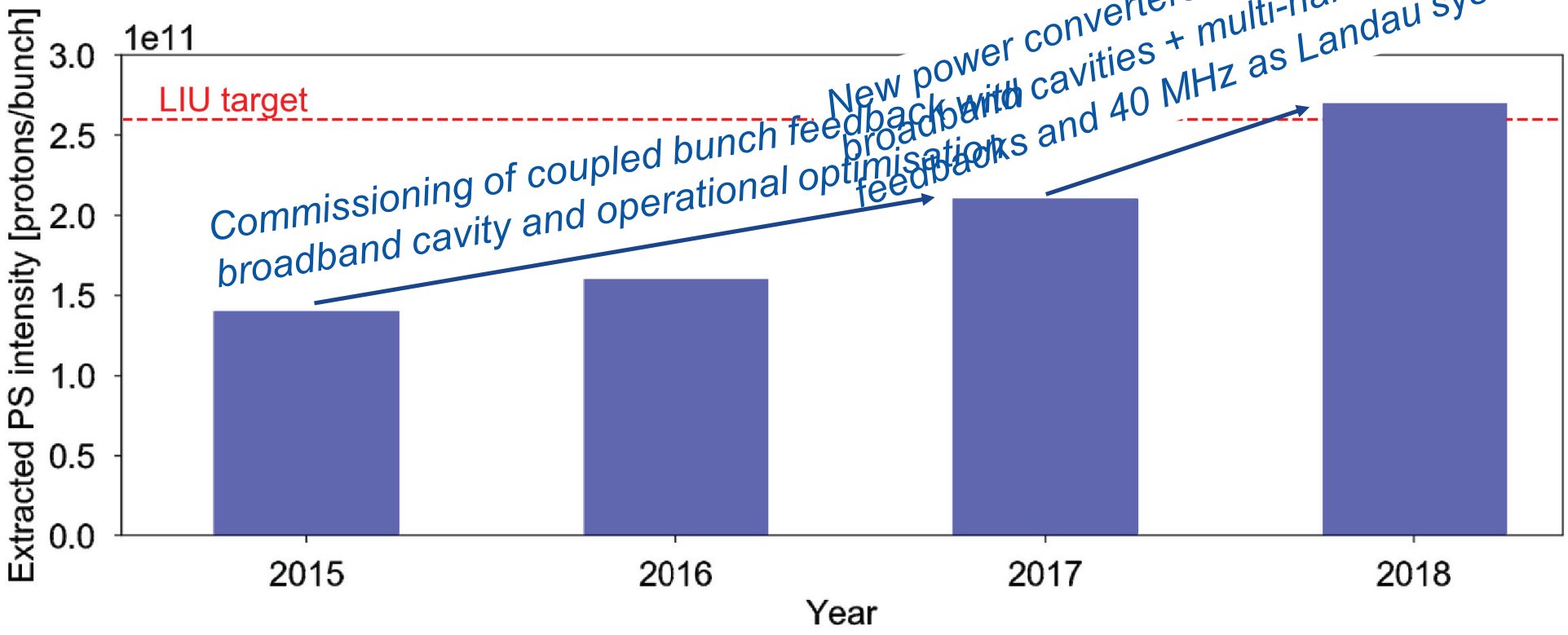
→ Beam commissioning to **LIU specifications** throughout Run 3

Achievements (1): PS intensity reach

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



Achievements (1): PS intensity reach

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 has been already achieved with margin**
  - Disclaimer: LIU brightness only available after LS2 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

Achievements (2): SPS RF system upgrade

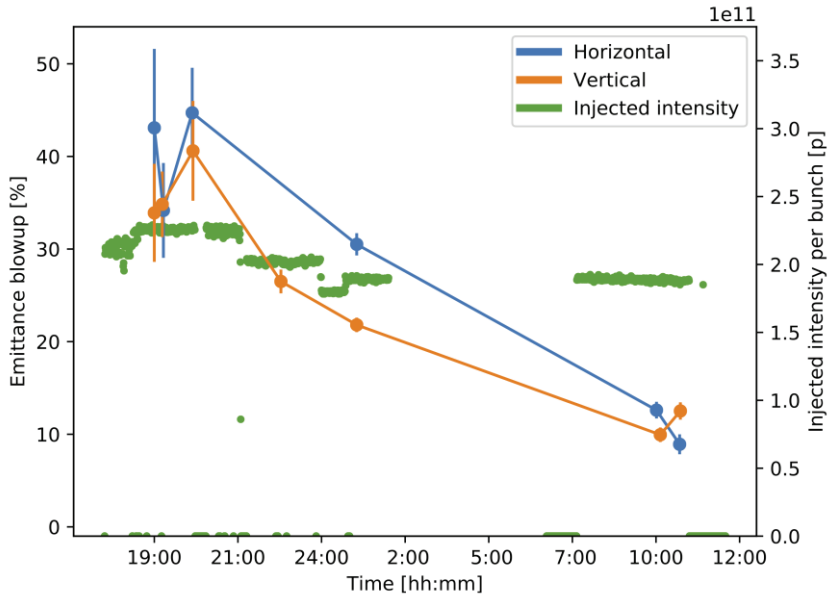
LHC Injectors Upgrade

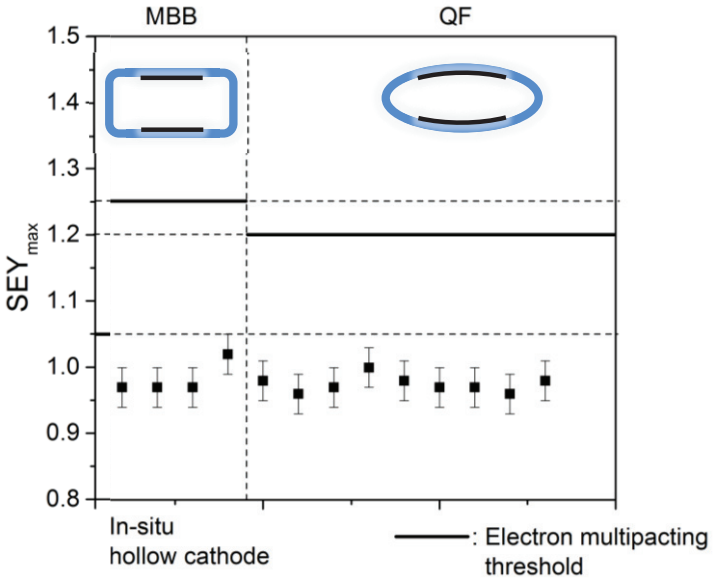
- **Design of Solid State Power Amplifiers (SSPA) for upgrade of SPS 200 MHz RF system** was an important challenge and required development + several iterations with producer
- Upgraded version of the SSPA in 80 module tower successfully passed the required tests in mid 2018
- Module series production currently in progress
  - Now emphasis on quality assurance and control
- Firmly on track for **baseline installation** of the new power plant based on SSPA **during LS2**

Achievements (3): 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**

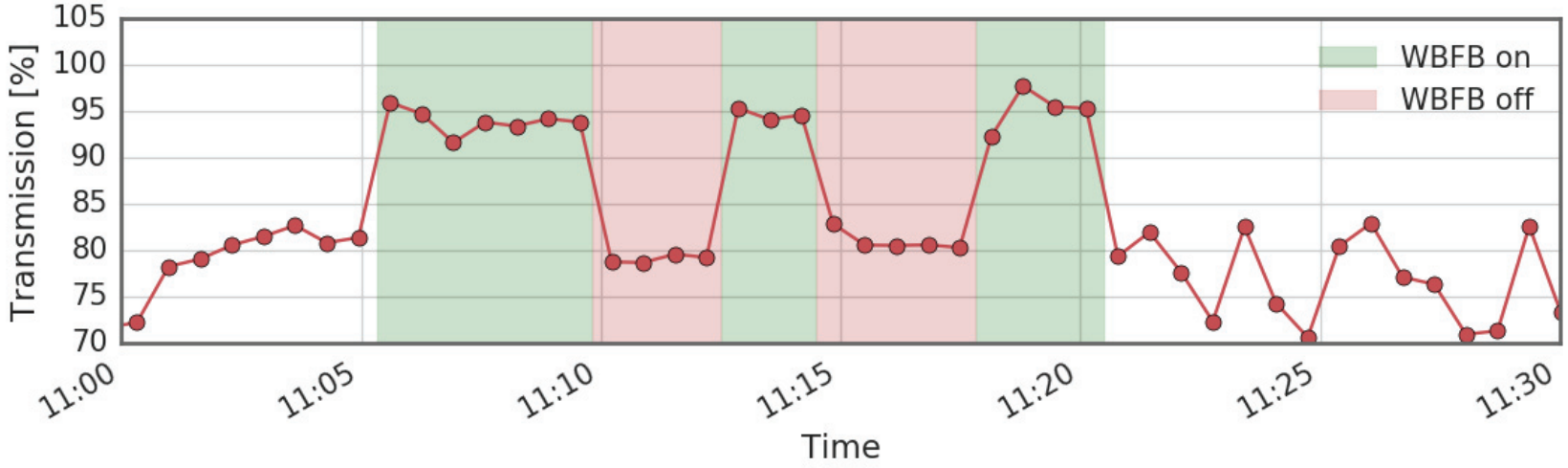




Achievements (4): Wideband Feedback System

LHC Injectors Upgrade

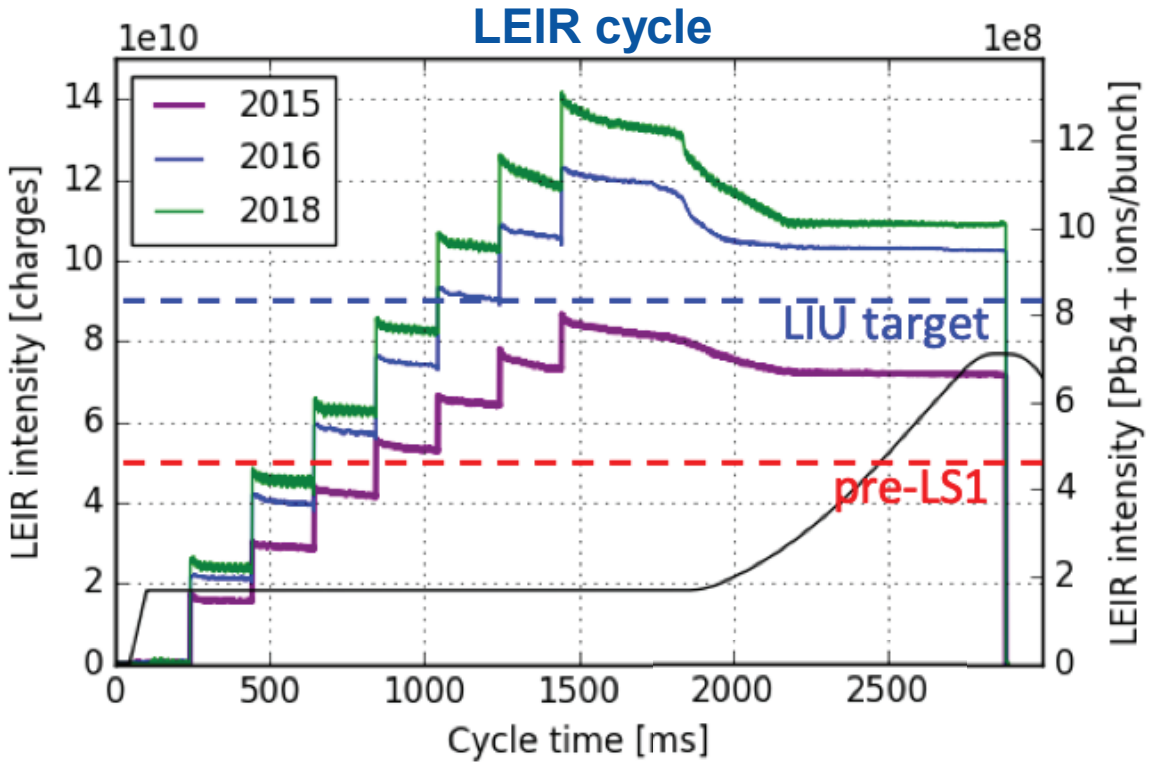
- Prototype of vertical (V) WBFS deployed at SPS – acknowledgement of US LARP collaboration
  - Using stripline pick-ups + two stripline kickers and a slotline kicker, bandwidth up to 1 GHz, power > 1 kW
- Damping of Transverse Mode Coupling Instability (TMCI) with single bunch demonstrated in machine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

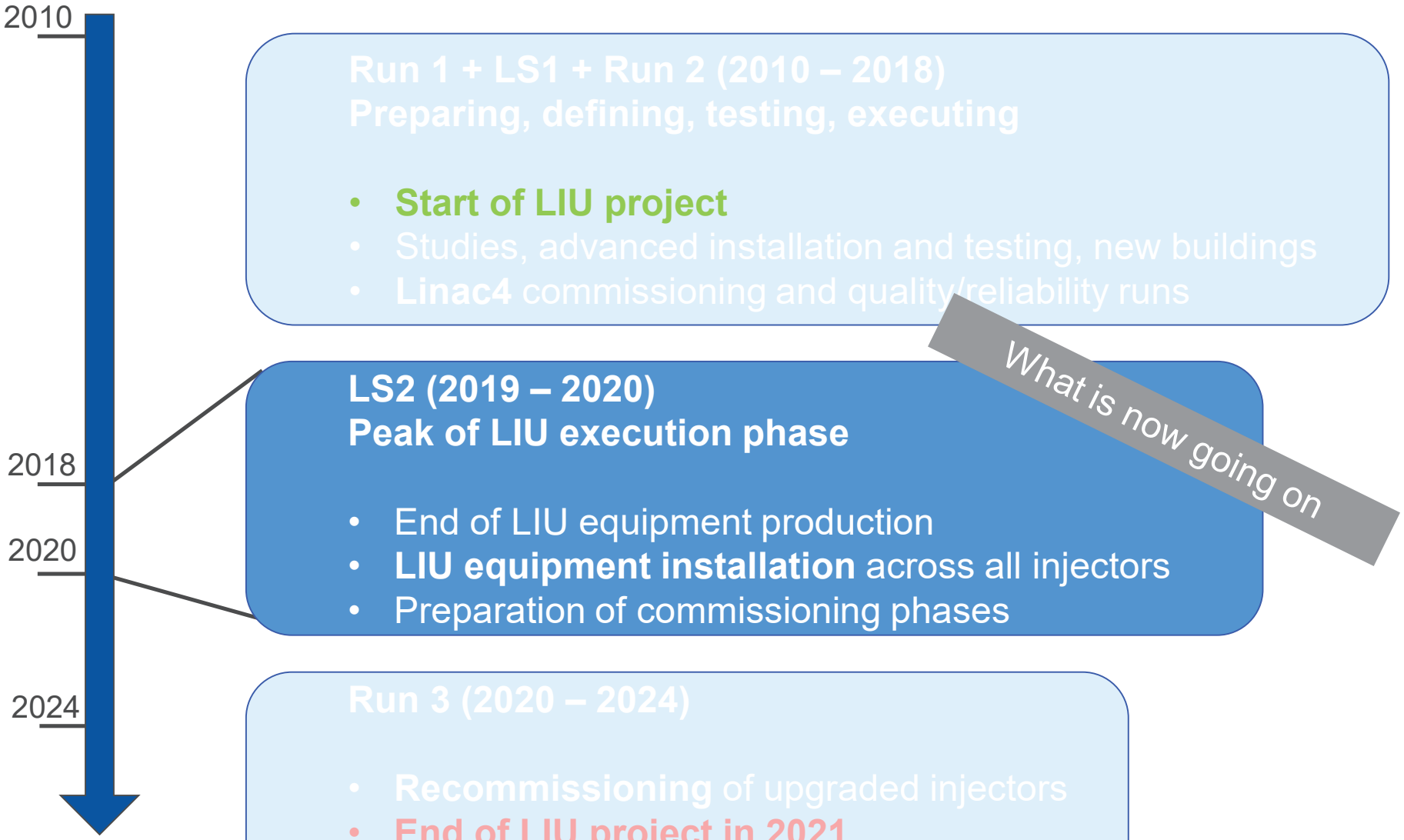


Achievements (5): Linac3 + LEIR Performance

LHC Injectors Upgrade

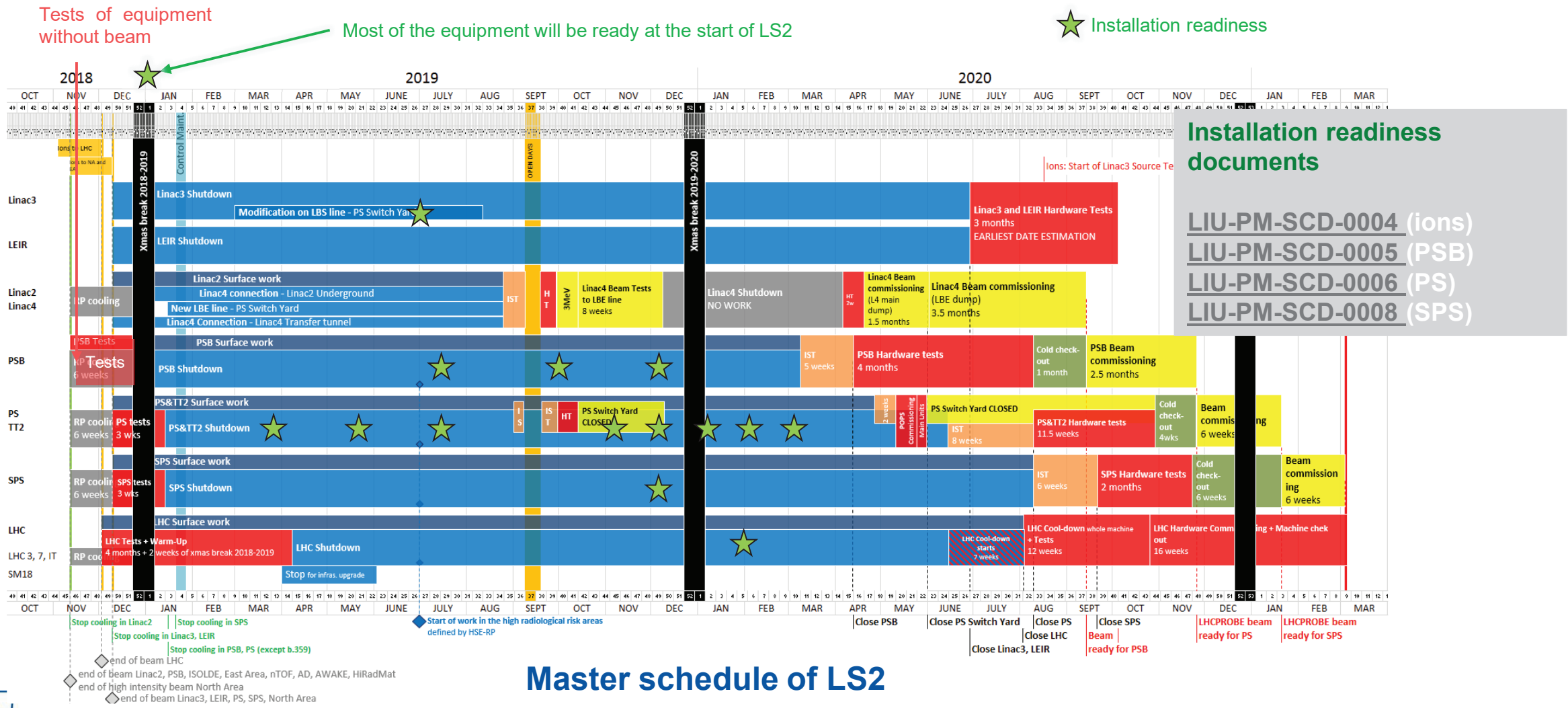
- Intensive study program combined with hardware upgrades during Run 2 led to an impressive **performance boost**
  - Higher current after removal of aperture bottleneck in Linac3 source
  - Optimised injection into LEIR thanks to the new BPMs in injection line
  - Automatised monitoring of injection efficiency into LEIR and correction
  - Mitigation of space charge and IBS at RF capture through working point optimization, bunch flattening and resonance compensation




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
What is now going on
LS2 (2019 – 2020)
Peak of LIU execution phase
• End of LIU equipment production
• LIU equipment installation across all injectors
• Preparation of commissioning phases
Run 3 (2020 – 2024)
• Recommissioning of upgraded injectors
• End of LIU project in 2021
→ Beam commissioning to LIU specifications throughout Run 3

Installation readiness for LIU equipment

LHC Injectors Upgrade



Installation readiness documents

LIU-PM-SCD-0004 (ions)
LIU-PM-SCD-0005 (PSB)
LIU-PM-SCD-0006 (PS)
LIU-PM-SCD-0008 (SPS)

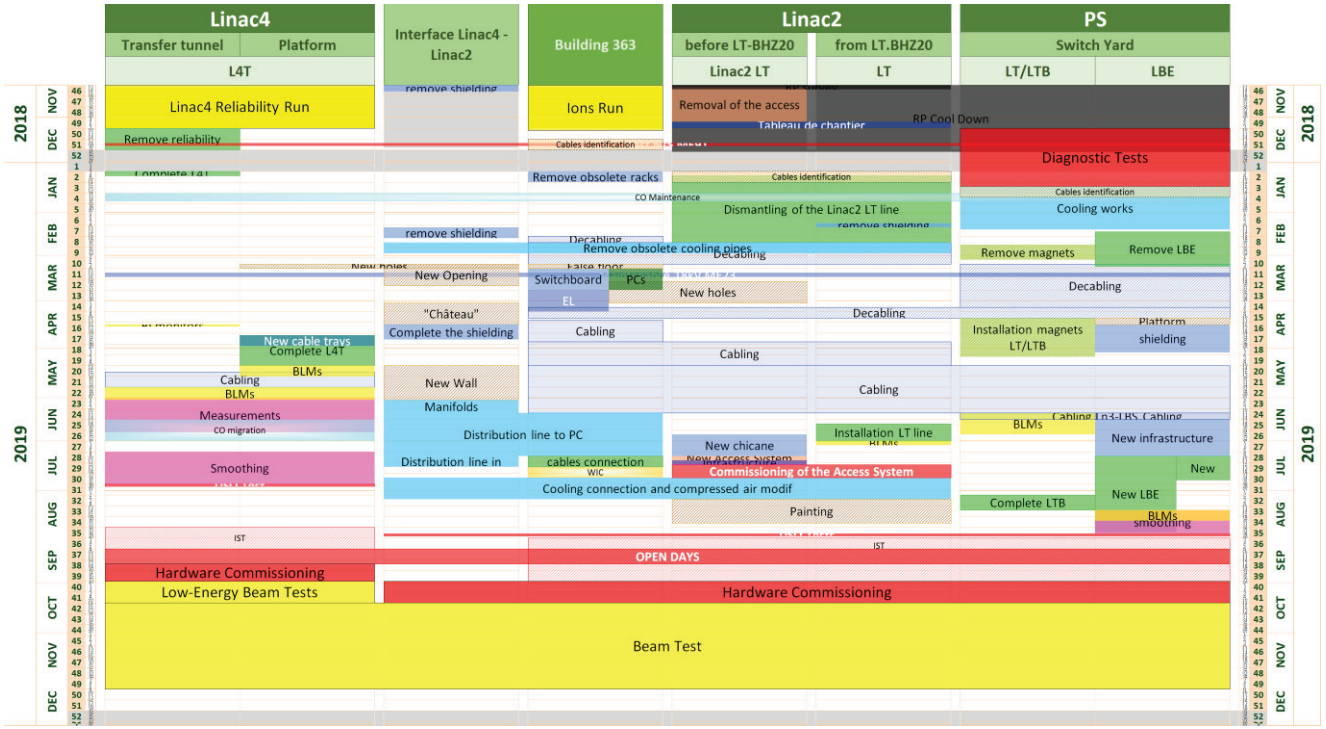
Master schedule of LS2

LIU installation during LS2

LHC Injectors Upgrade

- LS2 schedule
  - LIU project globally on time
  - LS2 linear views for schedules of all machines correctly include resources and highlight coactivity in some areas (within LIU project and with other projects)

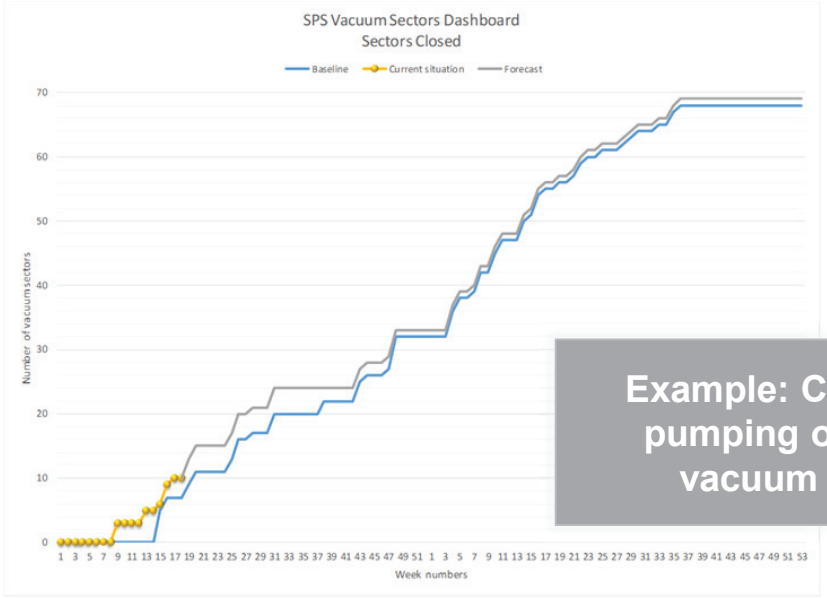
Example: Linear view of the Linac4 to PBS connection



LIU installation during LS2

LHC Injectors Upgrade

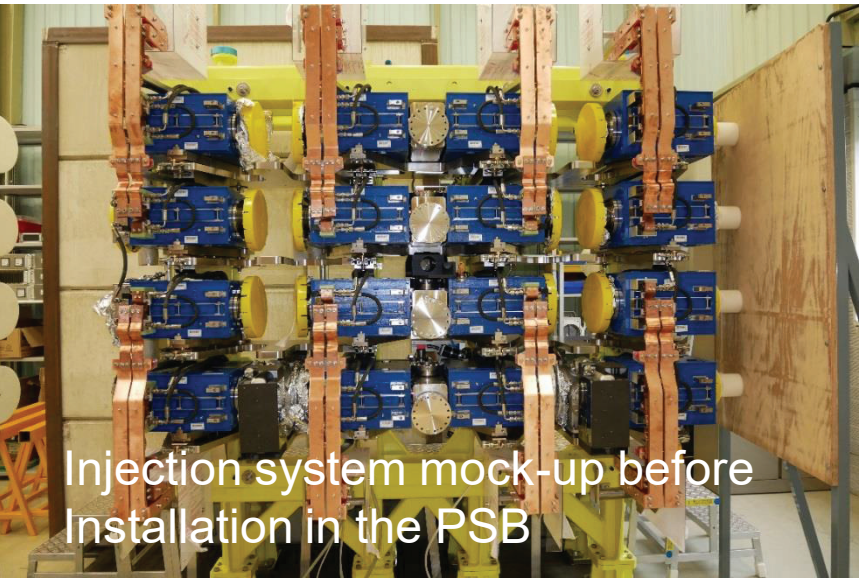
- LS2 schedule
  - LIU project globally on time
  - LS2 linear views for schedules of all machines correctly include resources and highlight coactivity in some areas (within LIU project and with other projects)
  - Daily follow up of the work on-site and weekly meeting to keep the schedules up-to-date
  - Monitoring reports edited with dashboards



https://lhcdashboard.web.cern.ch/lhcdashboard/ls2/

Example: Closure and pumping of the SPS vacuum sectors

Work progress: PSB injection region

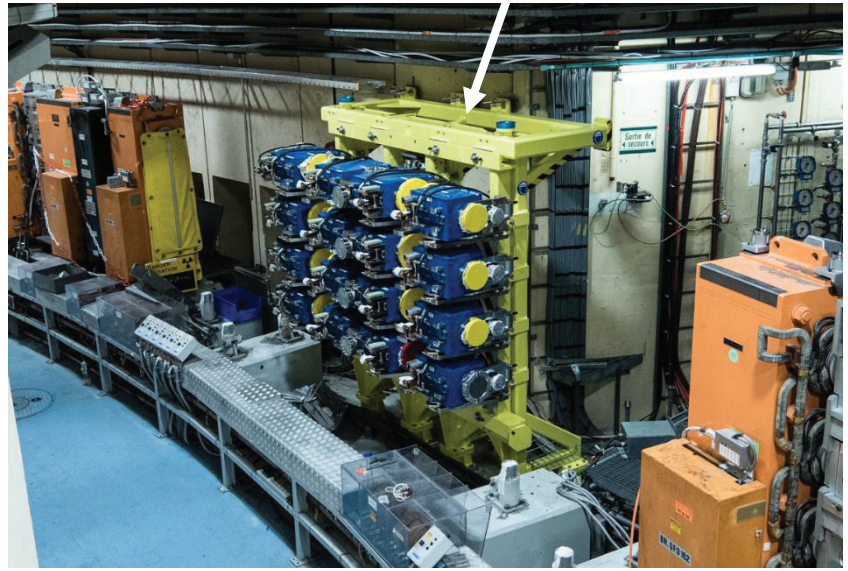


Injection system mock-up before Installation in the PSB

Until 2018: PSB tunnel injection area

Making room in the PSB Tunnel for new injection system

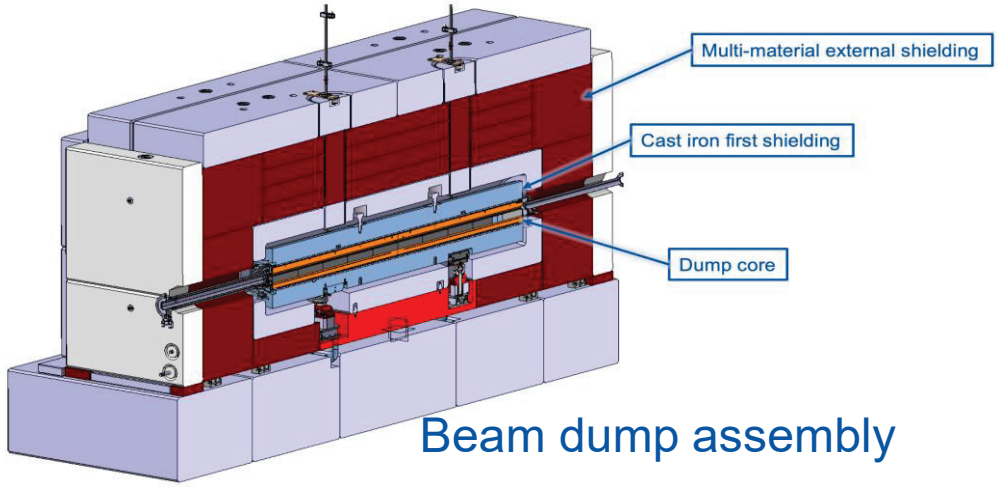
New injection system Installed in the PBS



Time lapse

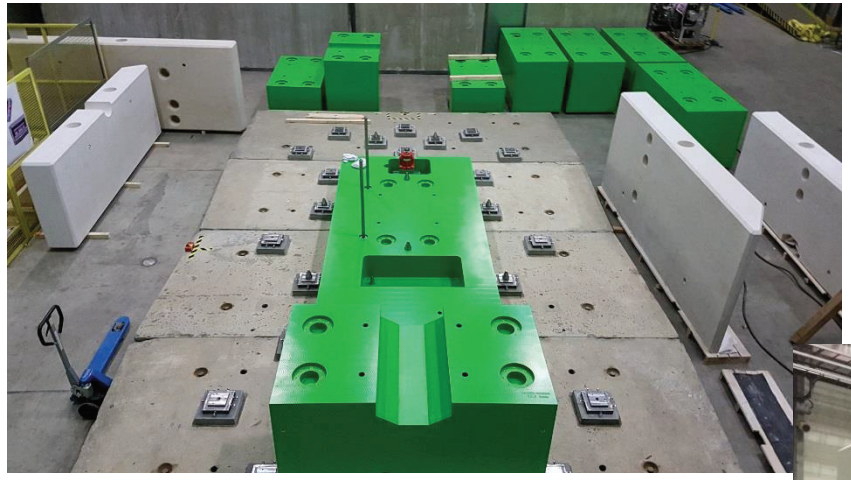
Emptying part of PSB injection area, before installing the new H^- charge exchange injection system

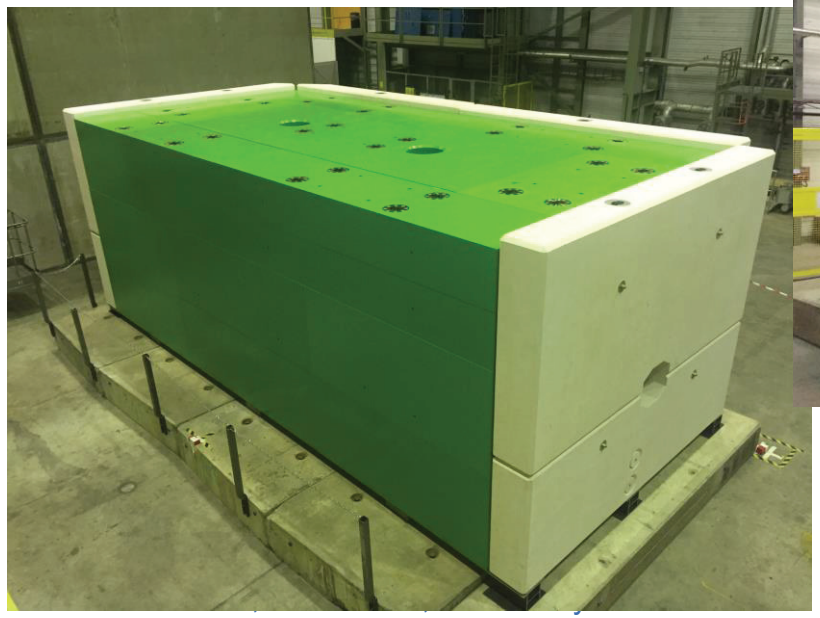
Work progress: SPS new beam dump

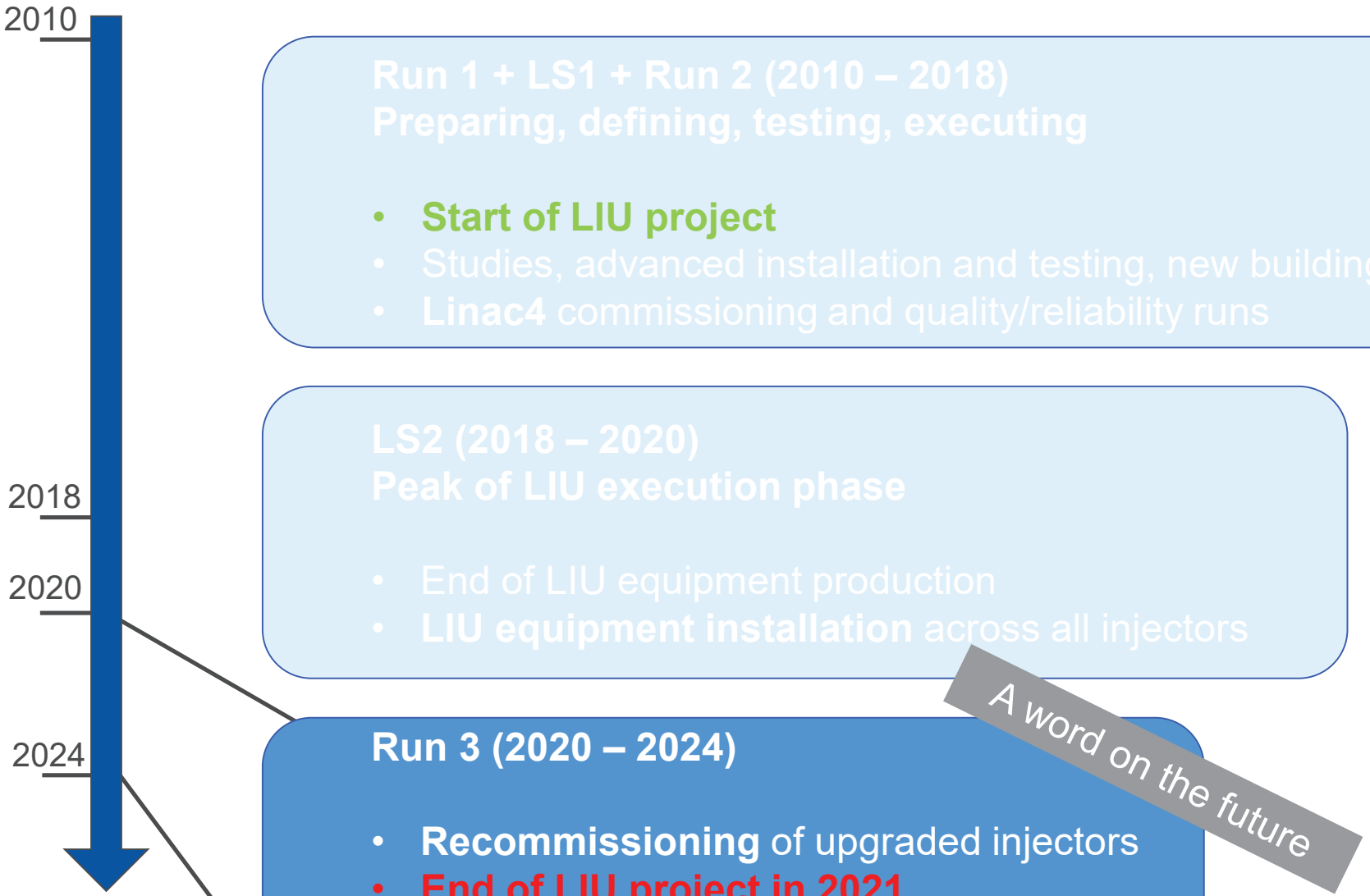


Beam dump assembly

Mock-up of SPS Beam Dump shielding assembly







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

LS2 (2018 – 2020)
Peak of LIU execution phase

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

A word on the future

Run 3 (2020 – 2024)

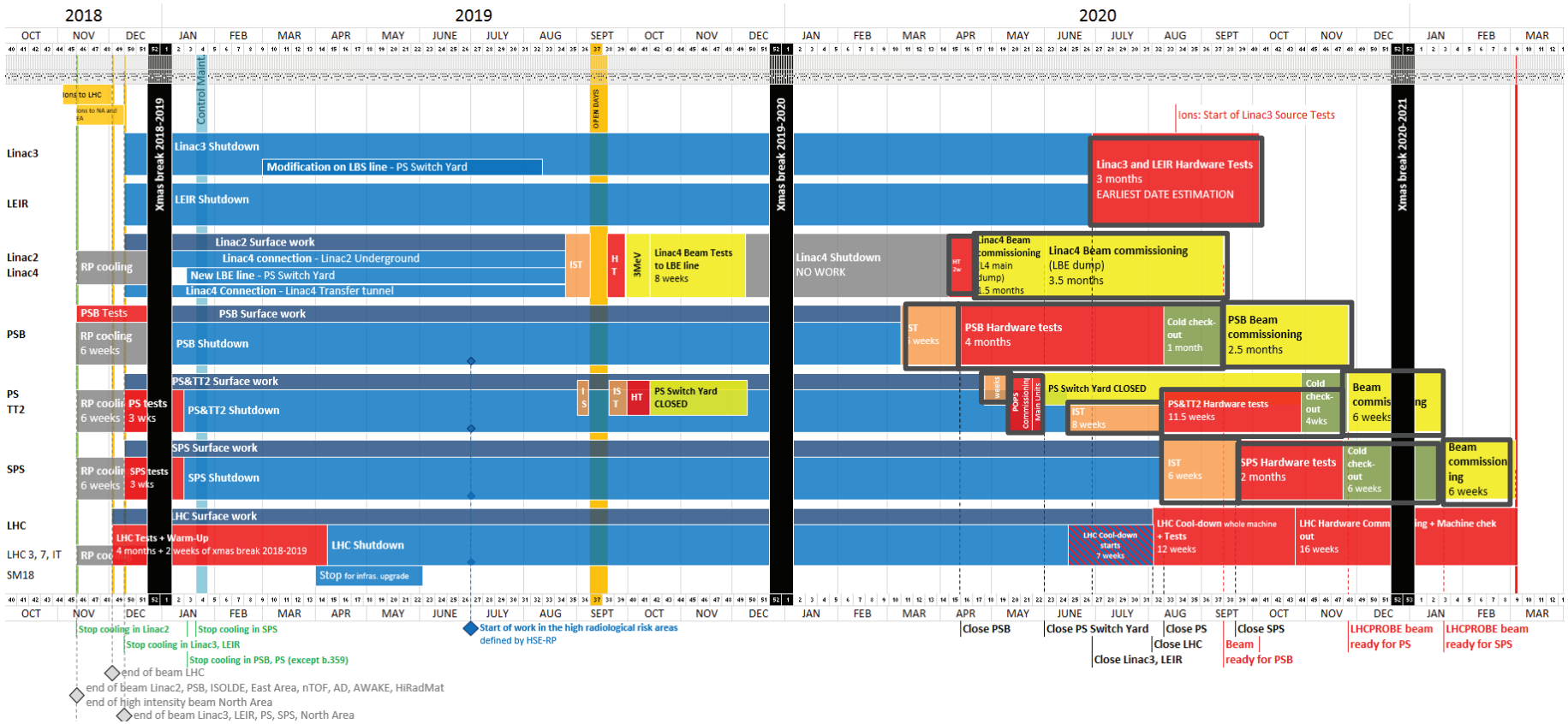
- **Recommissioning** of upgraded injectors
- **End of LIU project in 2021**

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

Recommissioning preparation: hardware and beam

LHC Injectors Upgrade

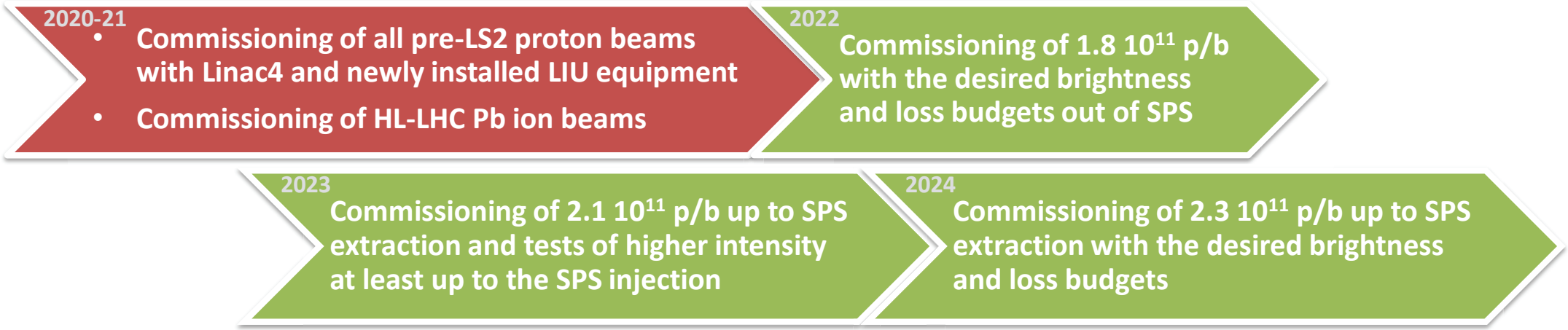
- Individual System Tests during shutdown period
  - Critical transitional phase to be planned in detail
- Hardware commissioning/cold check out
  - Check lists being prepared including new LIU equipment
- Stand-alone beam commissioning
  - **Beam commissioning** steps outlined and added to check lists
  - Cross-machine dependencies included



Beyond LIU: LIU beam ramp up

LHC Injectors Upgrade

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



Conclusion

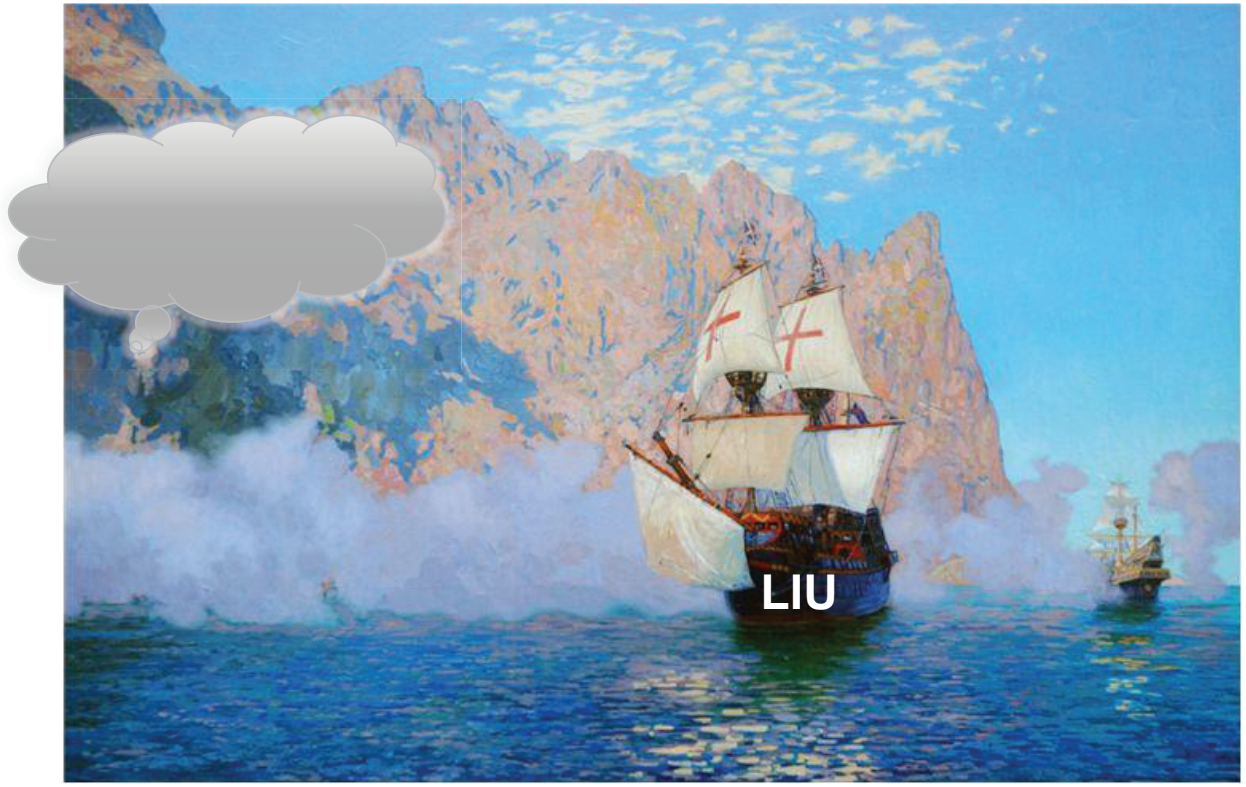
LHC Injectors Upgrade

- **LIU project baseline** fulfils the HL-LHC target parameters
  - Phase of **hardware definition, design and production** drawing to a close – installation, testing and commissioning already done for a few devices
  - Important **milestones** achieved both in beam parameters and technology development

- LIU currently in the middle of its **peak execution phase**
  - CERN accelerator complex **shut down for less than ~2 years** to mainly implement LIU upgrades
  - Work is **on track** to complete installations and restart injectors in cascade as from mid 2020
  - Active preparation of the commissioning phases

- LIU hardware and beam commissioning execution will then start in less than a year

- We will be sailing in uncharted waters for some time
- But hopefully the fog will gradually clear up!
- Looking forward to the challenges of beam commissioning and to turning all our model projections into **real beam**!



Thanks for your attention and stay tuned!