CERN

LHC Injectors Upgrade Project: Towards New Territory Beam Parameters

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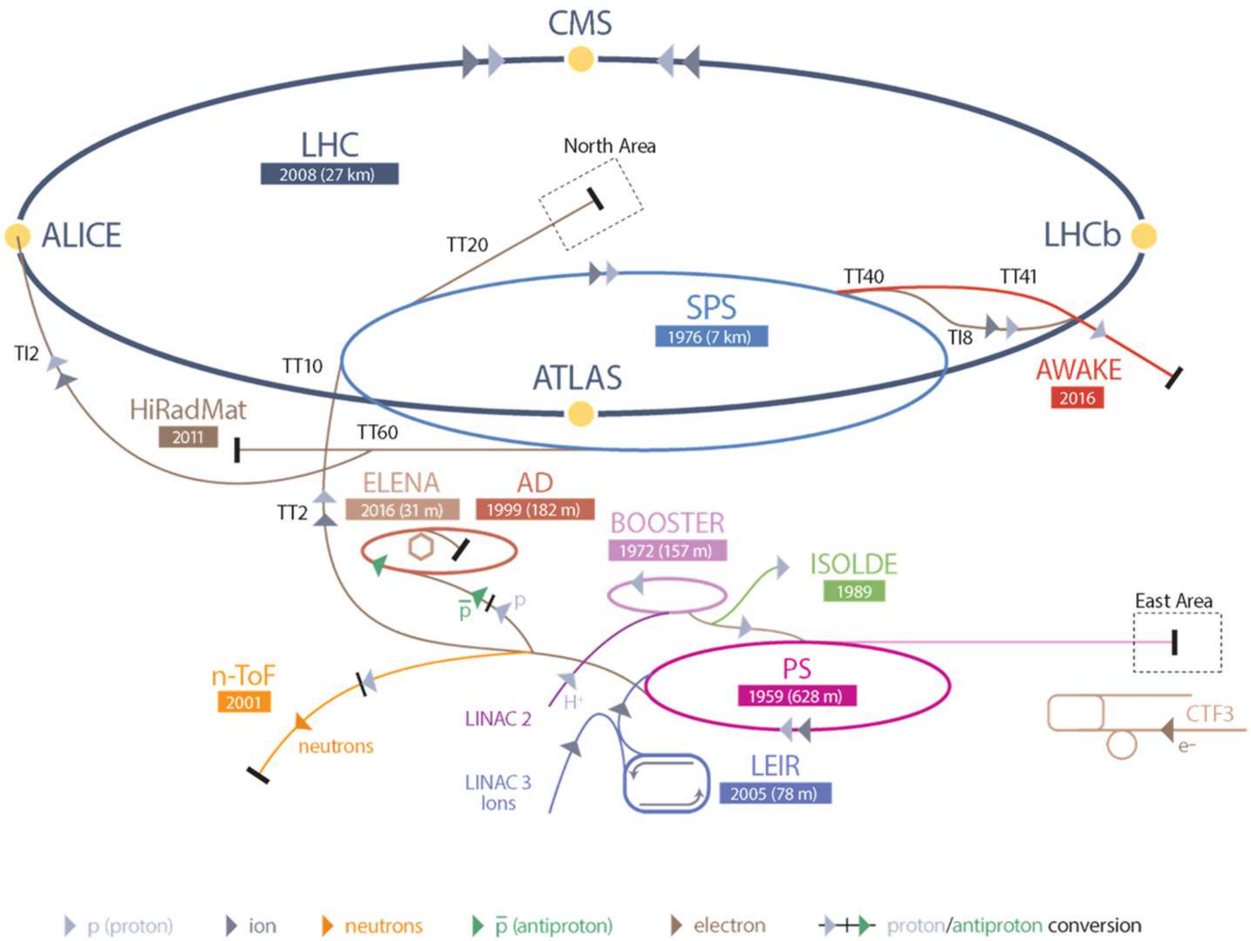
Outline

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 (protons)
  - LIU for ion beams
- The LIU project phases
  - Long Shutdown 2 (LS2): Equipment readiness and installation
  - Return to operation and beam performance ramping up after LS2
- Conclusions

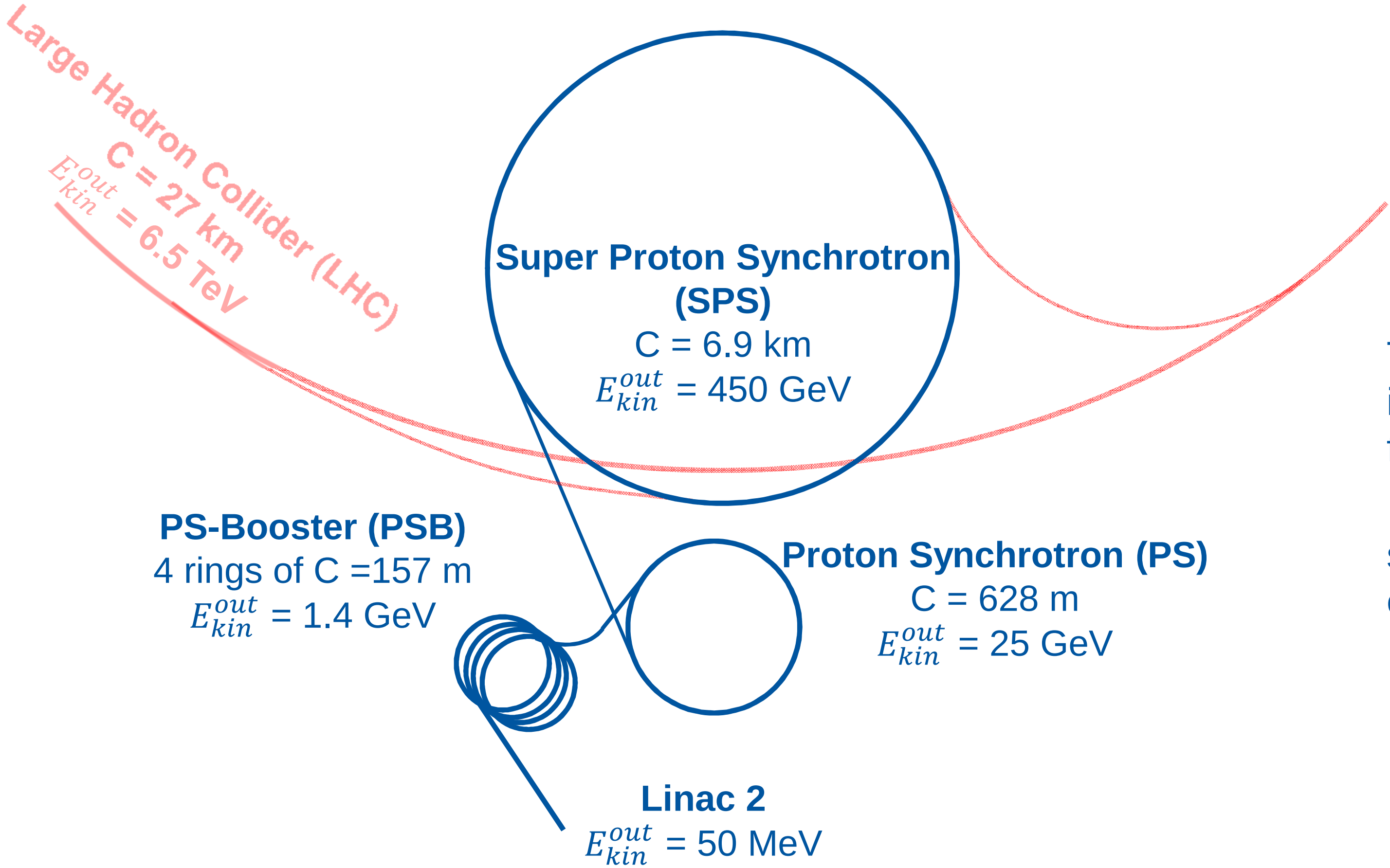
The CERN accelerator complex

LHC Injectors Upgrade



The CERN injectors complex: protons

LHC Injectors Upgrade

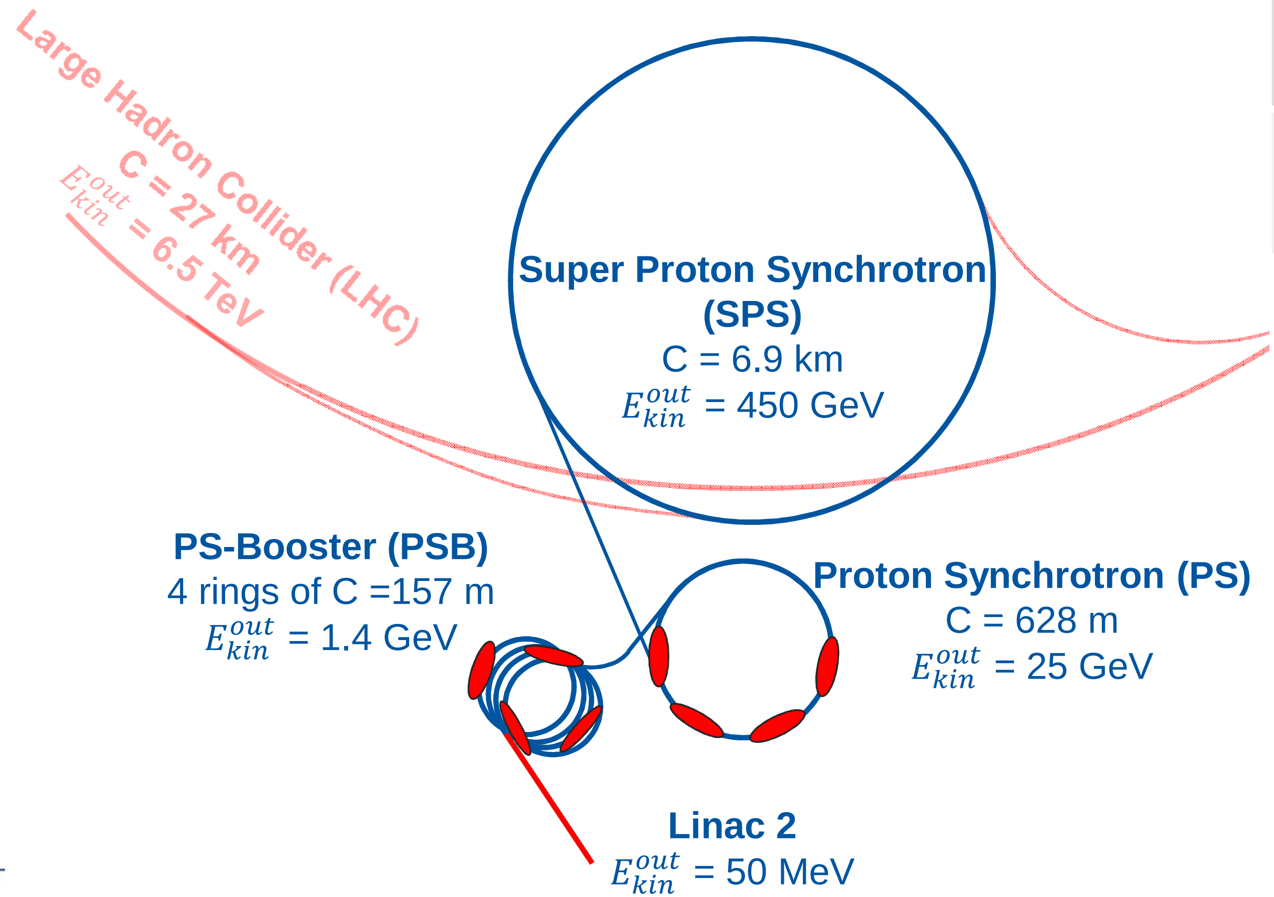


The **CERN injector complex** is by itself one of the largest accelerator facilities in the world

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

Production scheme of LHC beams

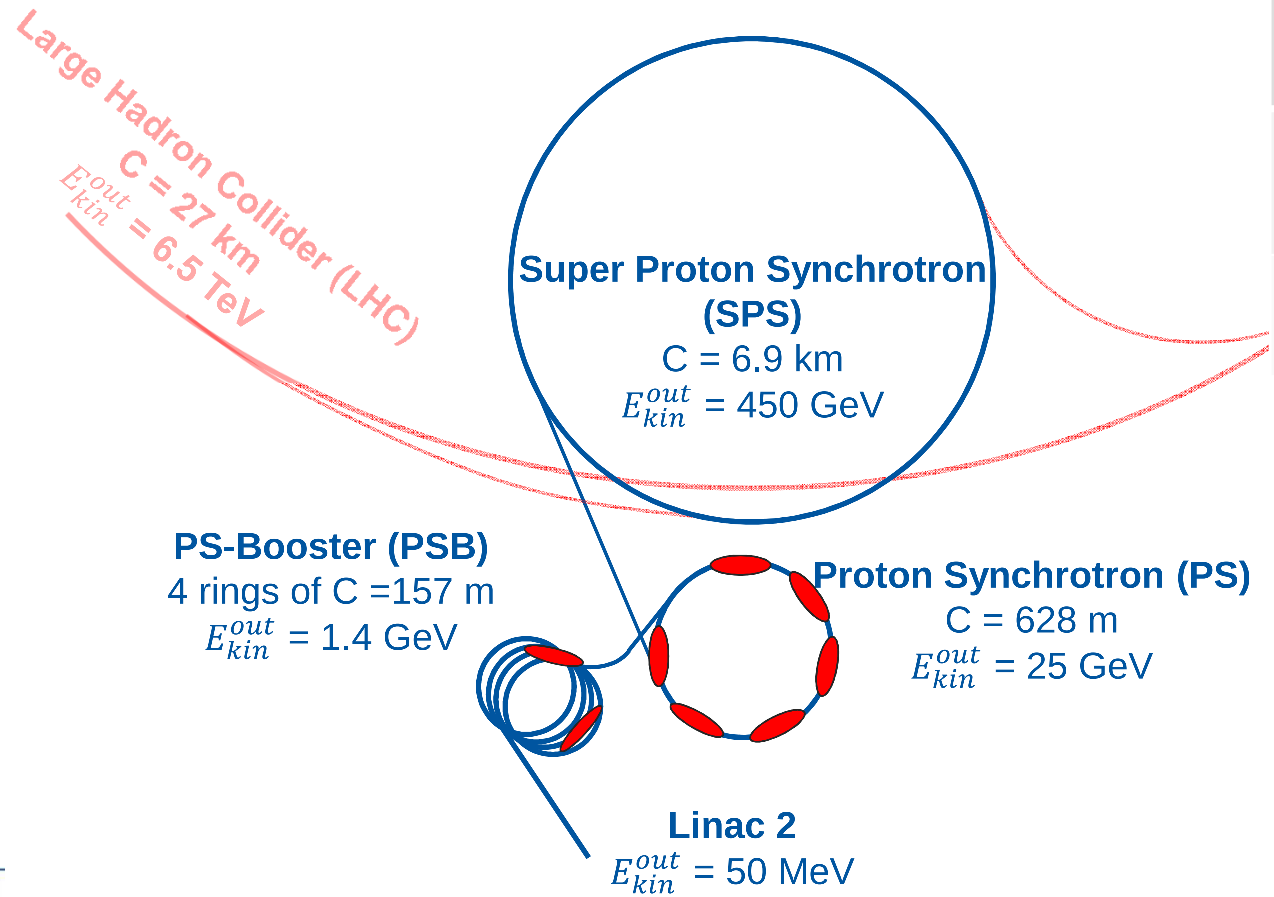
LHC Injectors Upgrade



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

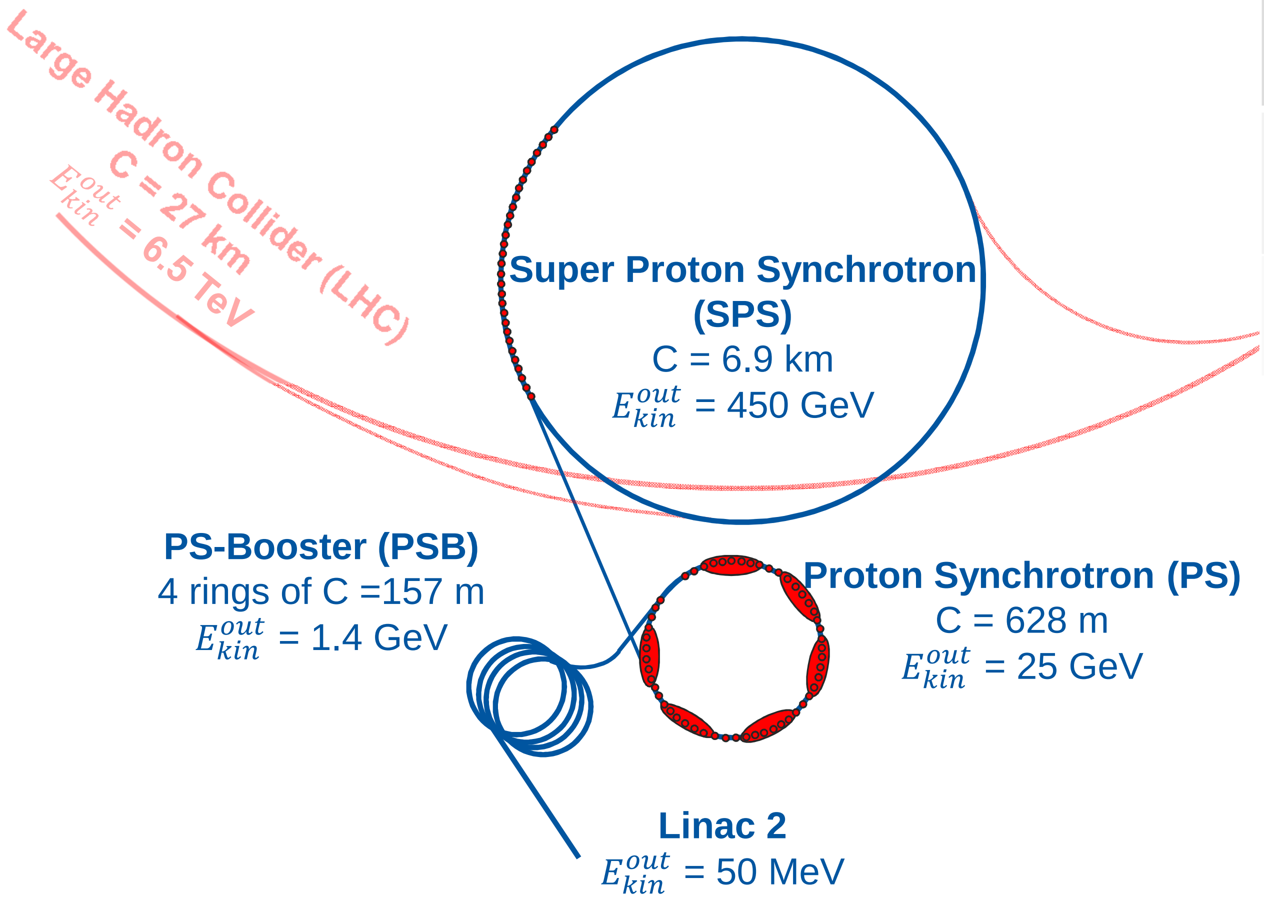
LHC Injectors Upgrade



Beam transfer	Number of bunches	Bunch spacing (ns)
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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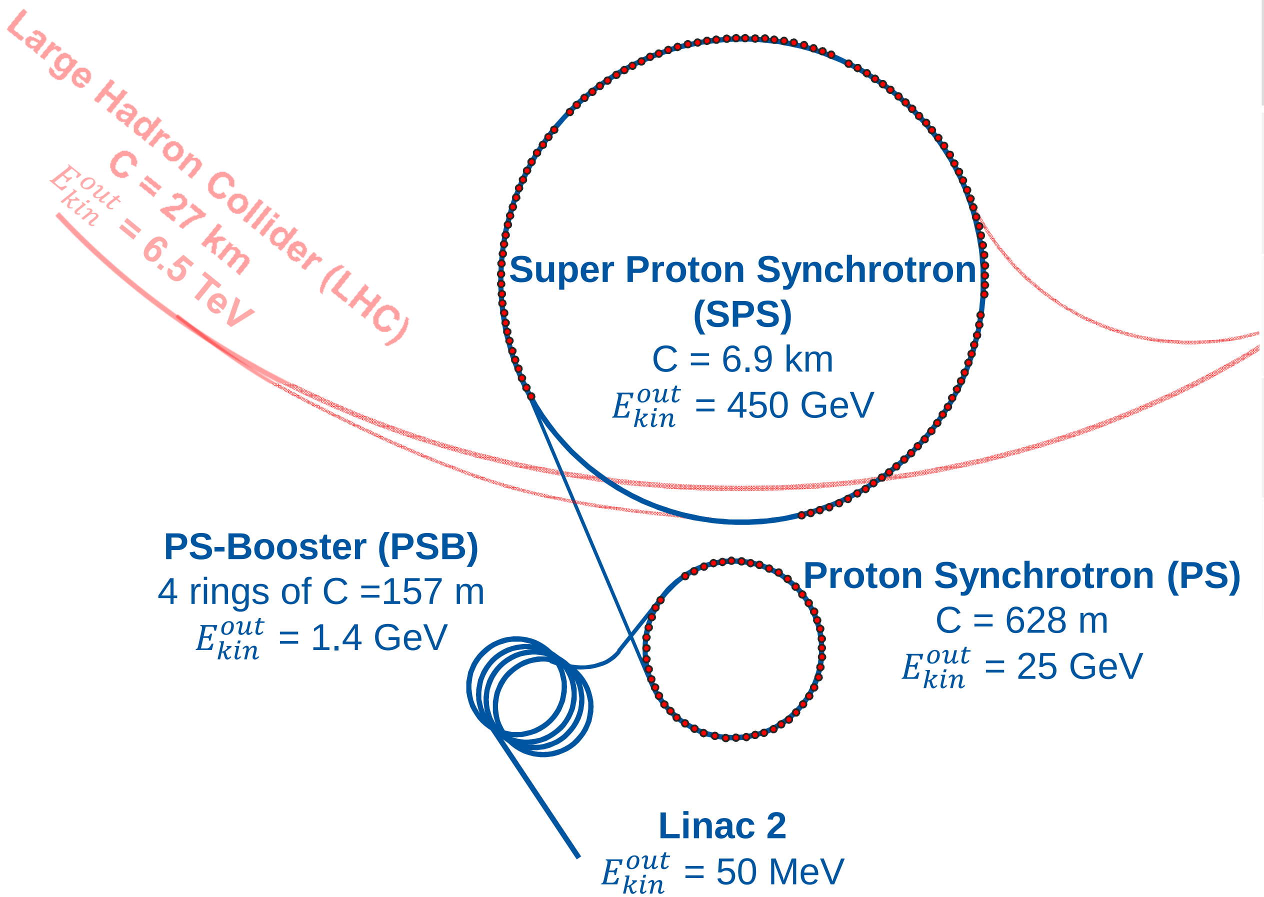
One triple bunch splitting and two double bunch splittings in the PS

Production scheme of LHC beams

LHC Injectors Upgrade



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PS → SPS E_{kin}^{out} = 25 GeV	72	25

Four injections into the SPS

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

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

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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

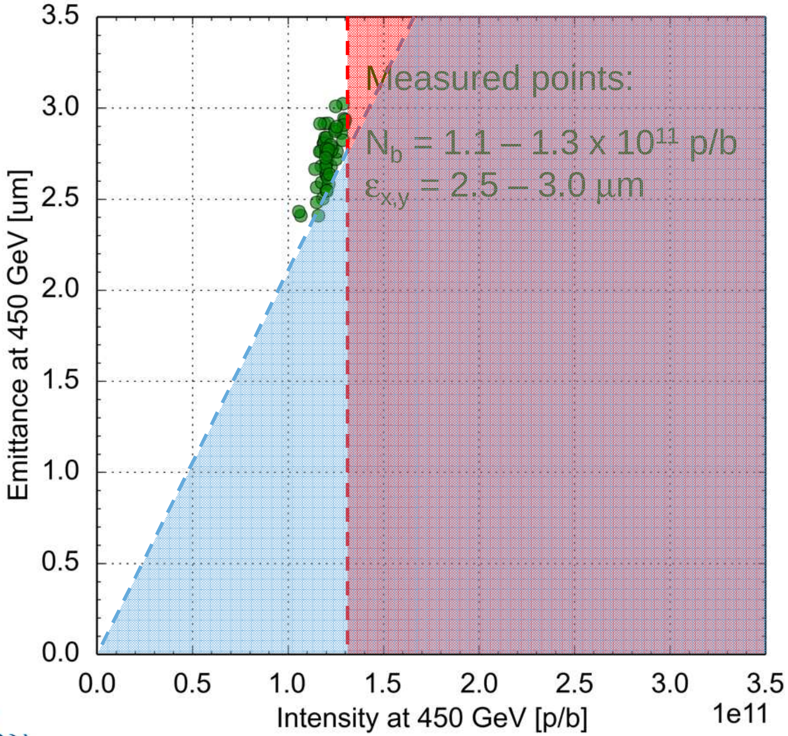
The **LHC Injectors Upgrade (LIU)**

- 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 performance before upgrade

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



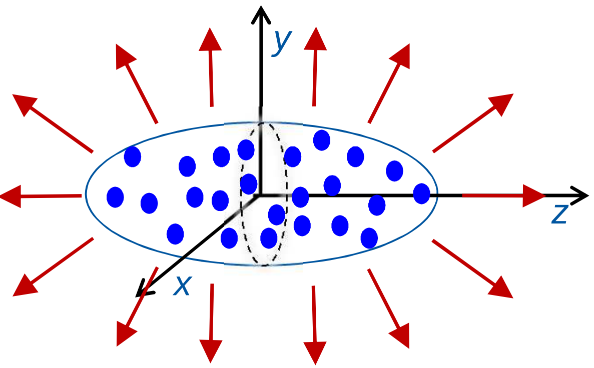
- But what are the **physical processes** limiting the **intensity**

$$N_b < N_{\max}$$

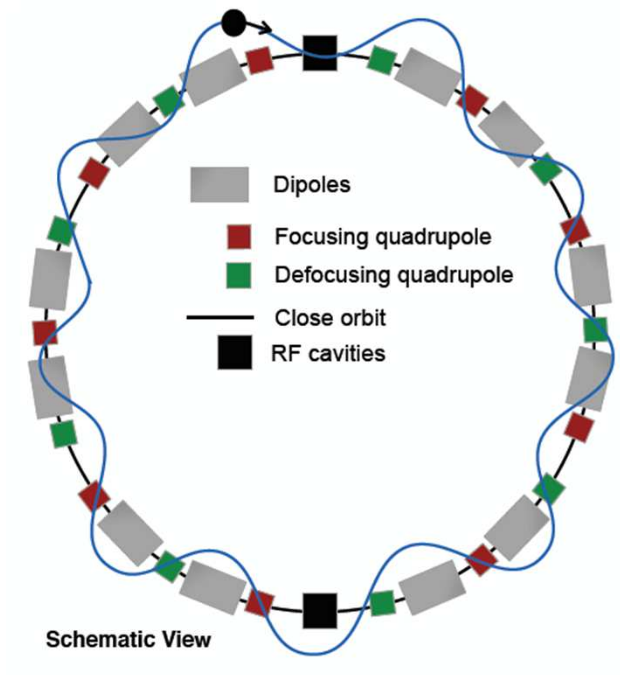
Brightness limitations: **space charge**

LHC Injectors Upgrade

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



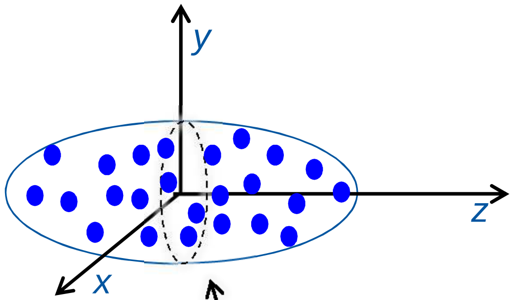
- This is an additional defocusing force on single particles, whose oscillation frequencies around the accelerator (**tunes**) consequently decrease
- Furthermore, particles feel different space charge defocusing forces according to their positions → Spread of tunes within the bunch



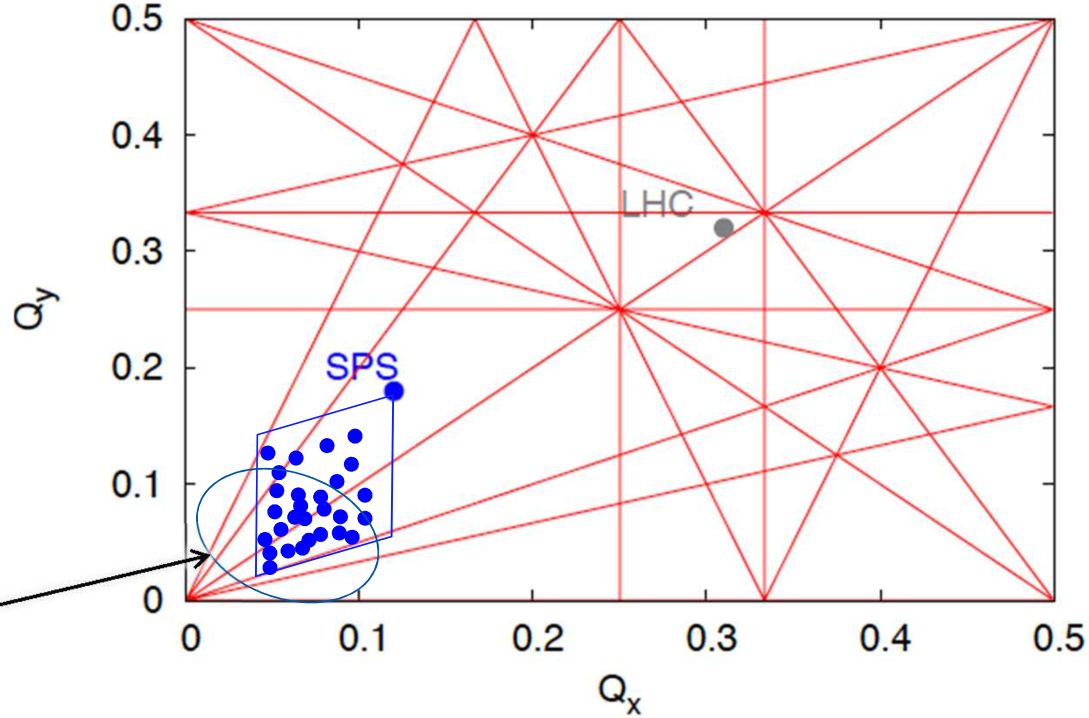
Brightness limitations: **space charge**

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 orbit instability)
- Space charge shifts the tunes of the single particles shift, which may hit the resonance lines!



Particles oscillating close to the bunch peak density



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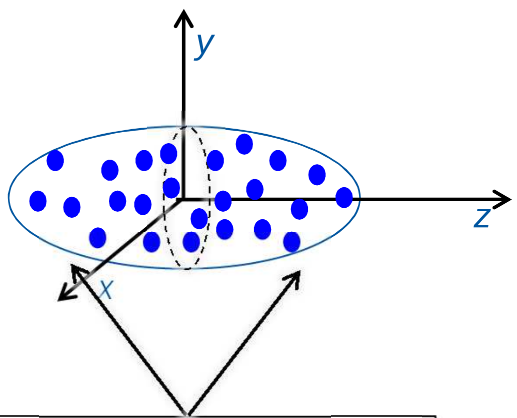
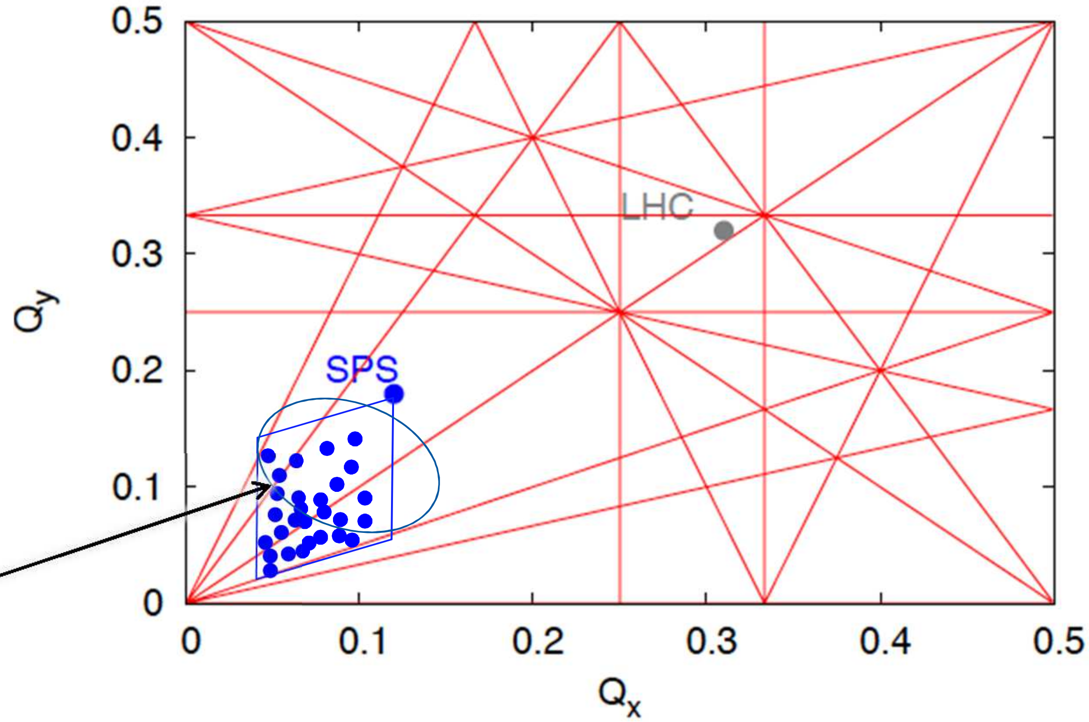


Particles at the tails of the longitudinal distribution



Brightness limitations: **space charge**

LHC Injectors Upgrade

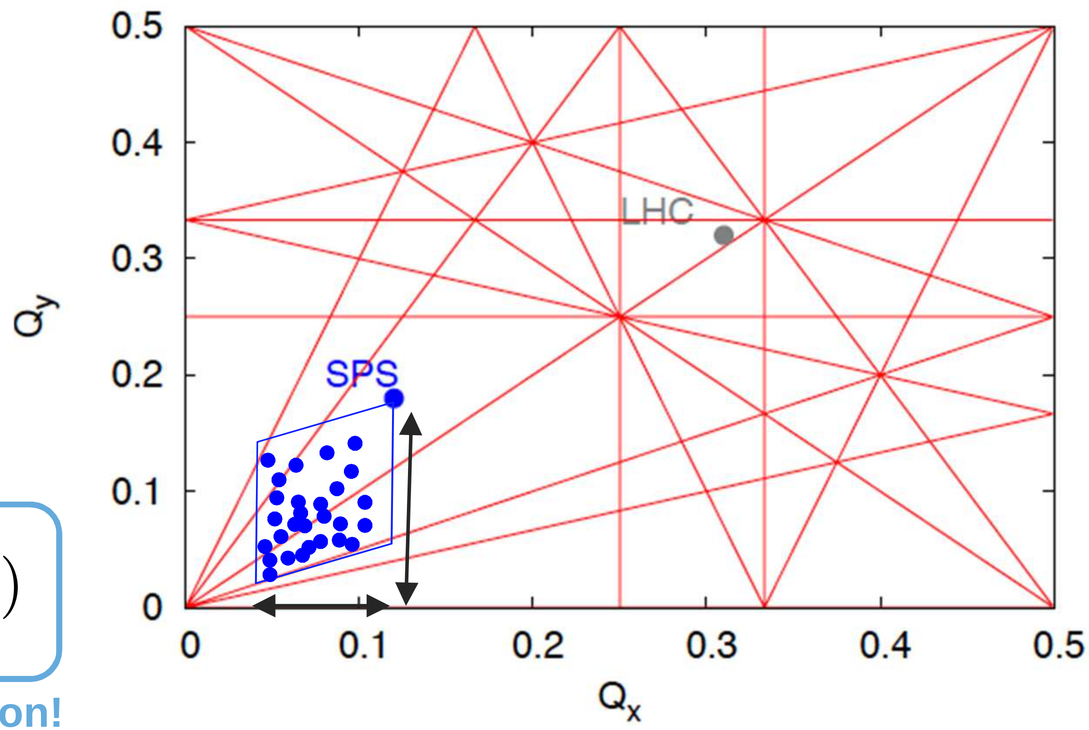
- Due to their shifted tunes, some of the trajectories of the single particles can
  - Grow to large amplitudes and get stabilised → **emittance growth**
  - Become unstable and hit the machine aperture → **beam loss**

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

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

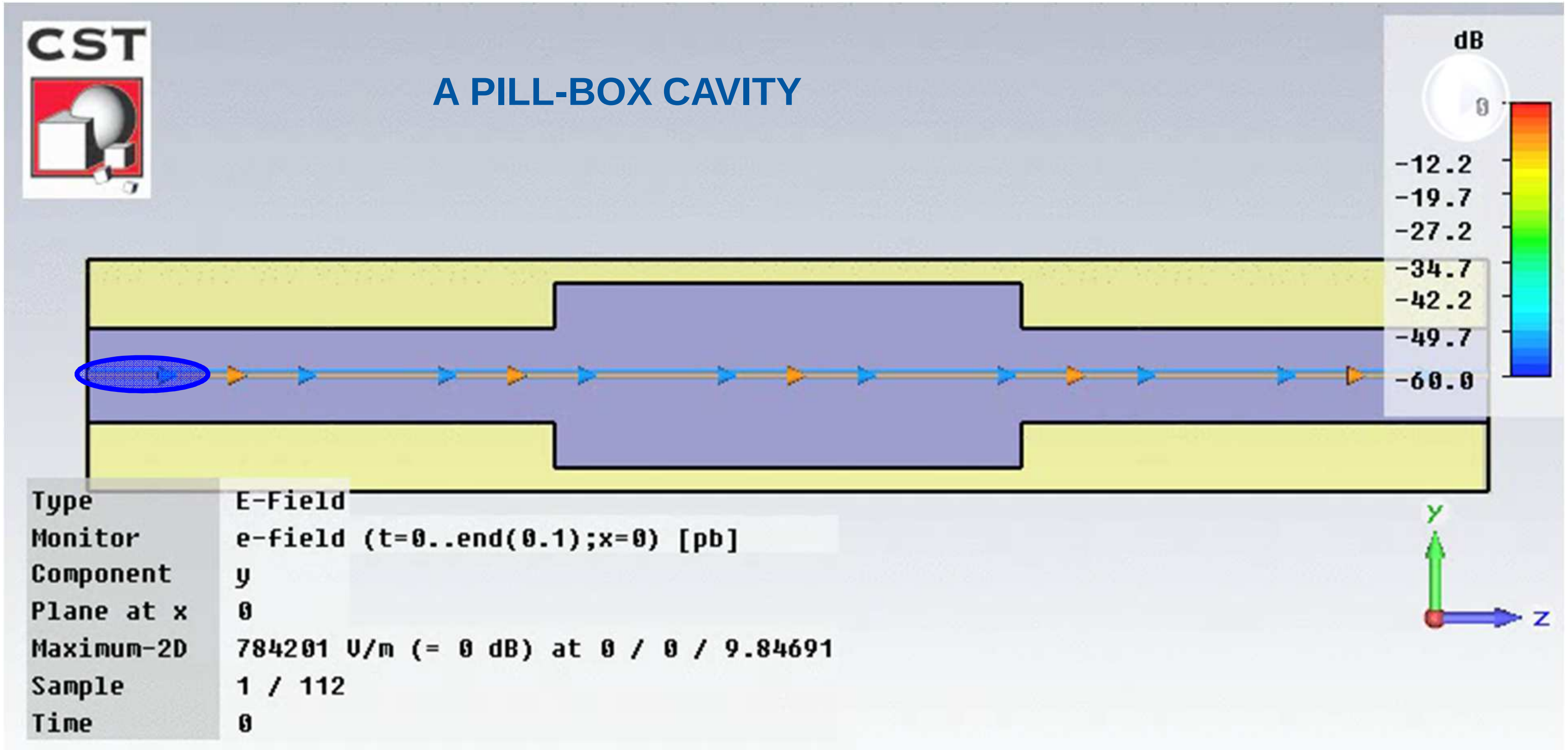
$$\frac{\epsilon_{x,y}}{N_b} > b_{\max}(\sigma_z, C, \gamma, \ldots)$$

Brightness limitation!



Intensity limitations: **Impedance**

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



Intensity limitations: **Impedance**

- 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

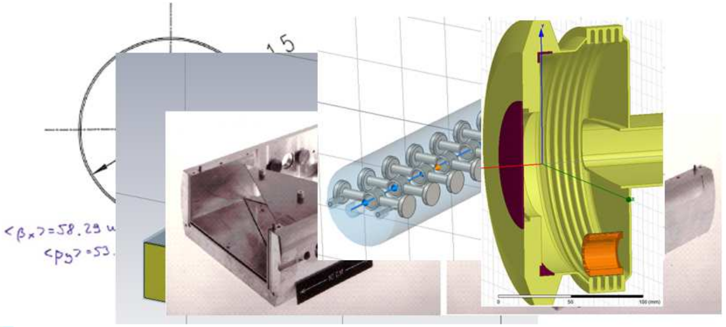
$$W(z) = -\frac{1}{e^2}\int_0^L F(s,z)ds$$

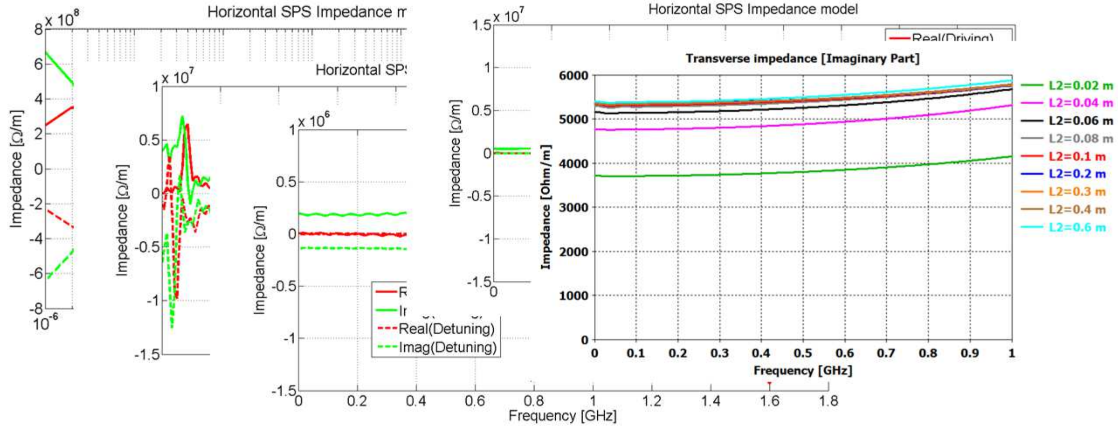
  - **Beam coupling impedance** in frequency domain → The Fourier transform of the wake function

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

Intensity limitations: **Impedance**

- 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

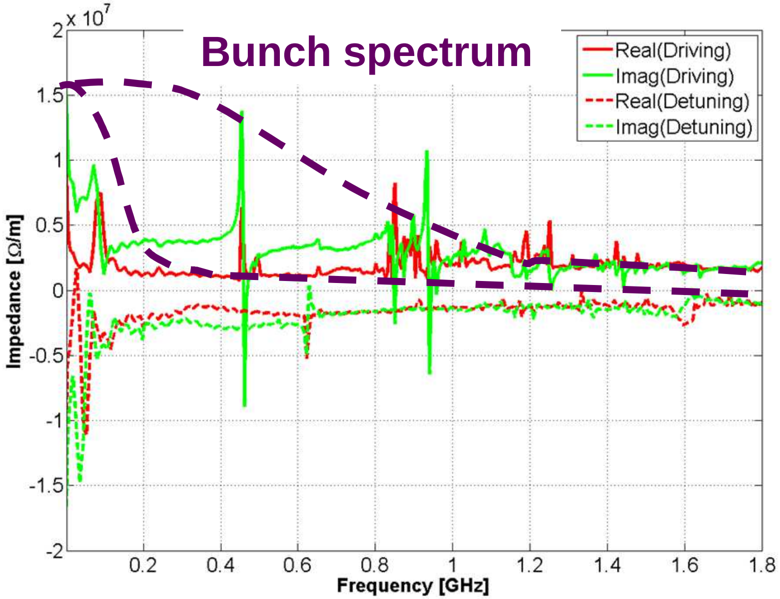




Intensity limitations: **Impedance**

- 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

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



Intensity limitations: **Impedance**

LHC Injectors Upgrade

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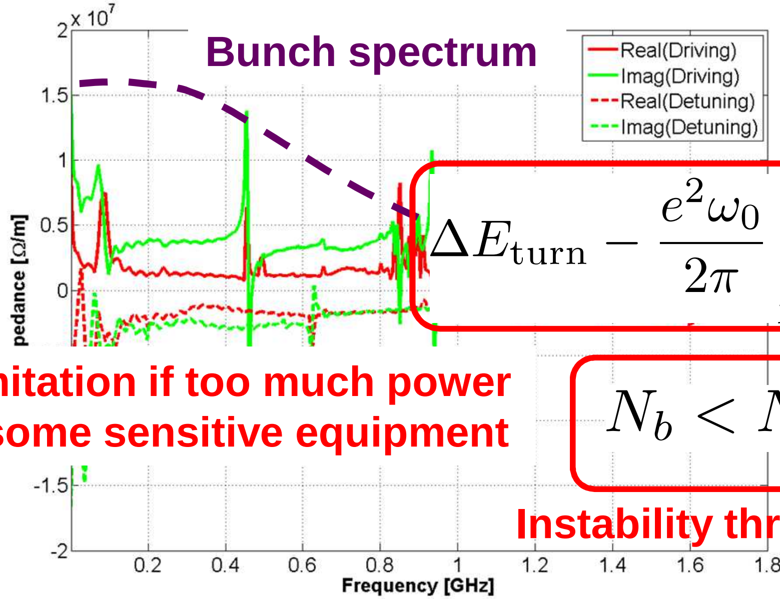


$$\Delta E_{\mathrm{turn}} - \frac{e^2\omega_0}{2\pi}\sum_{p=-\infty}^{\infty}|\tilde{\lambda}(p\omega_0)|^2\cdot \mathrm{Re}[Z_{||}(p\omega_0)]$$

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

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

Instability threshold → Intensity limitation!

Intensity limitations: **Impedance and more**

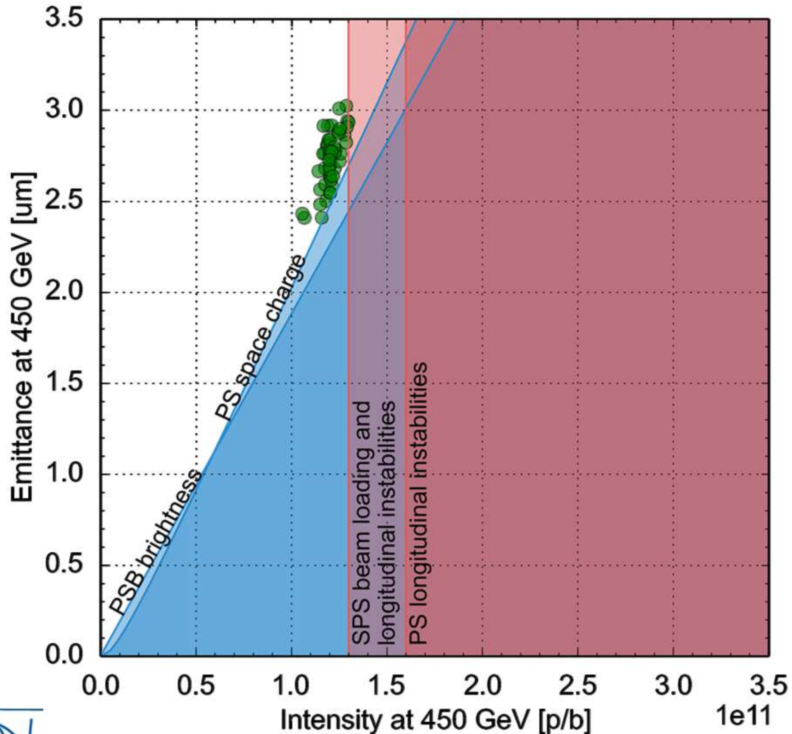
LHC Injectors Upgrade

- 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
- Other interactions can also lead to energy loss, beam loss and instabilities, e.g.
  - Electron cloud
  - UFO-type events
- Intensity limitations may also come from the tolerance of existing beam intercepting devices (protection elements, beam dump)

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

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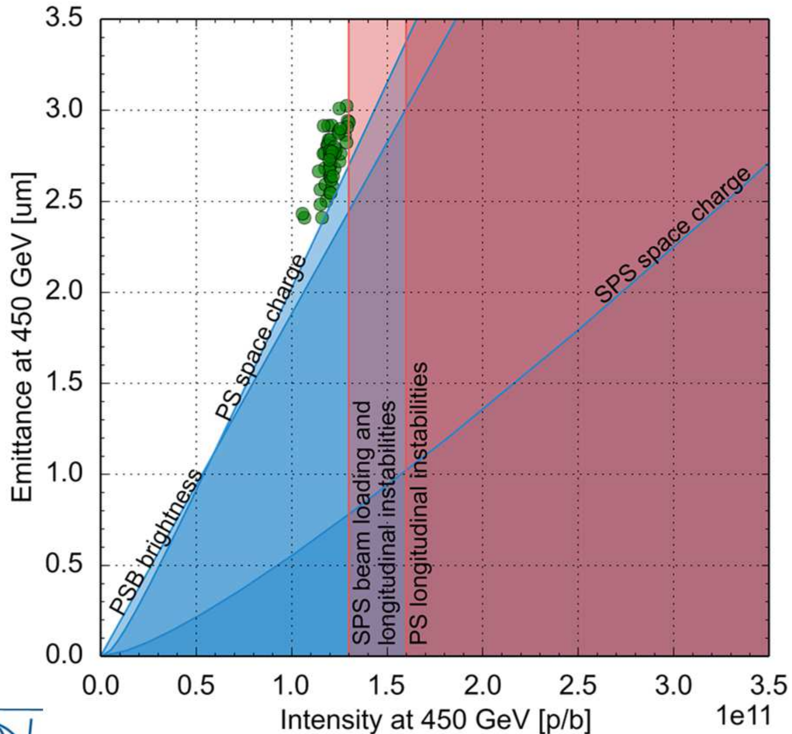
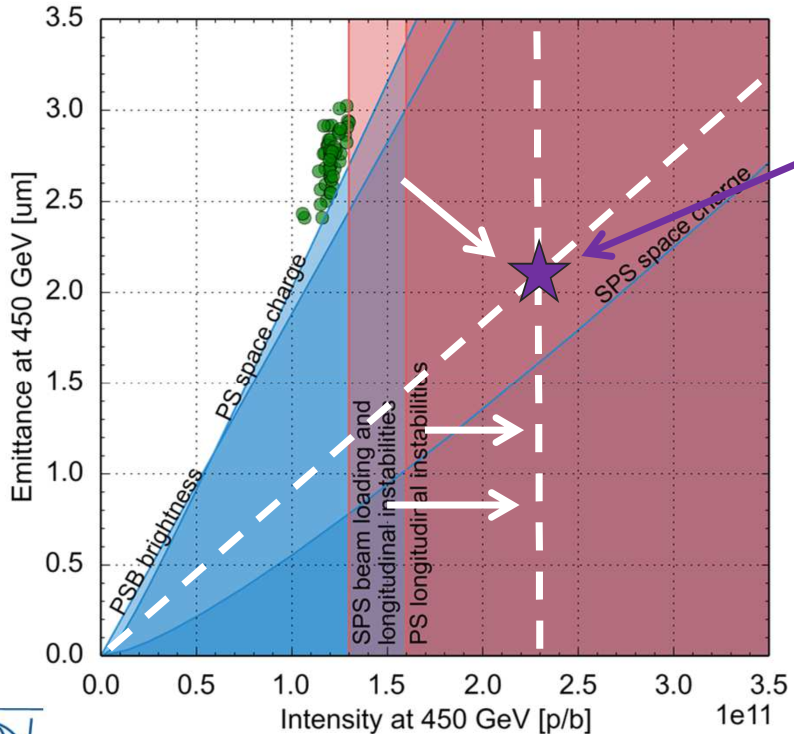


- **Brightness**
  - PSB brightness determined by space charge at injection
  - Limit for PS space charge at injection $\Delta Q_y < 0.31$
  - ✓ *Space charge in SPS not a limit for LHC beams*
- **Intensity**
  - SPS is limited by beam loading and longitudinal instabilities on the ramp and flat top
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

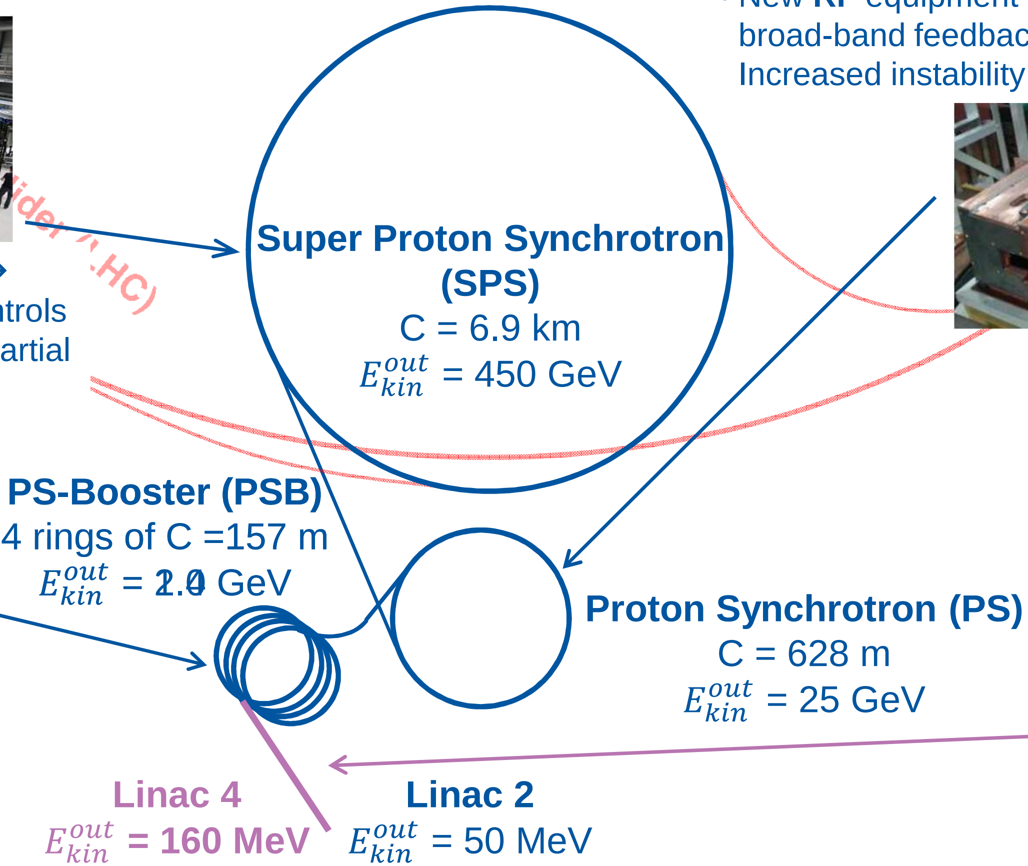
- **LIU strategy**
  - →Identify the sources of the performance limitations in each of the injectors impeding the achievement of the HL-LHC target parameters
  - →Define and deploy the necessary upgrade items to overcome these limitations

A quick overview on the LIU project

LHC Injectors Upgrade

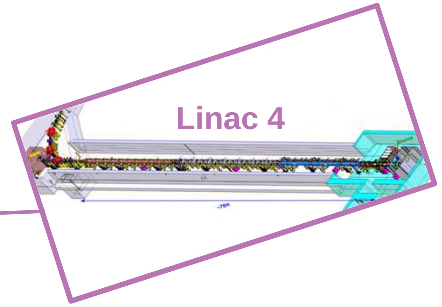
- Main **RF** system (200 MHz) upgrade → Increased RF power and improved controls
- Longitudinal **impedance** reduction & partial a-C coating → Increased instability thresholds
- New **beam dump** and protection devices

- **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



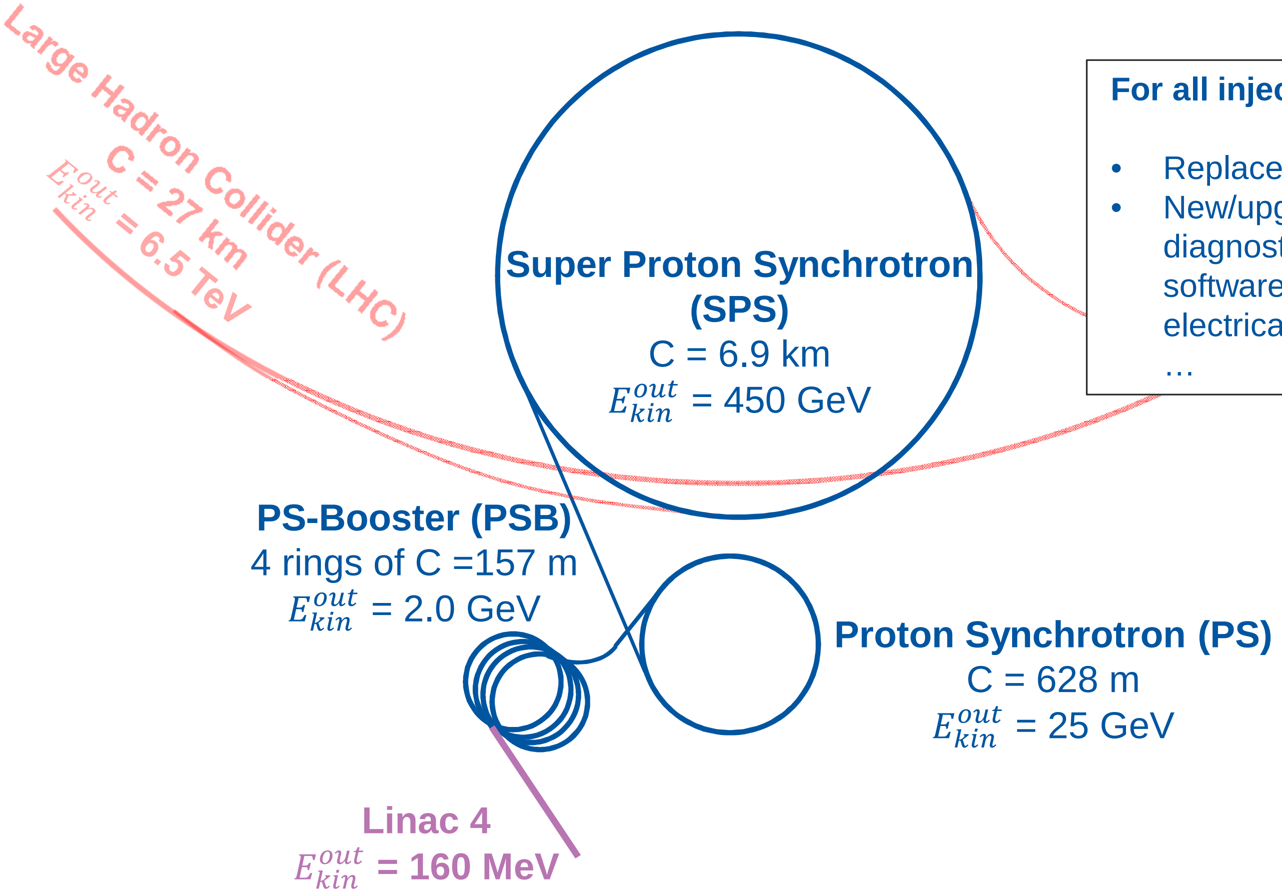
- **2 GeV** injection → Reduced space charge at PS injection
- New **RF** equipment including broad-band feedback → Increased instability threshold

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



A quick overview on the LIU project

LHC Injectors Upgrade

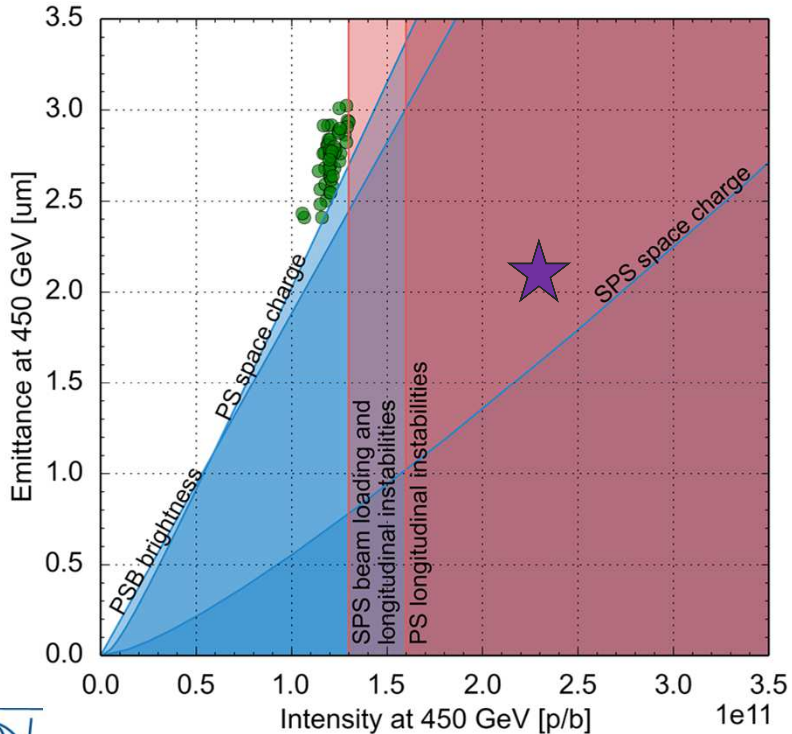


For all injectors :

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

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



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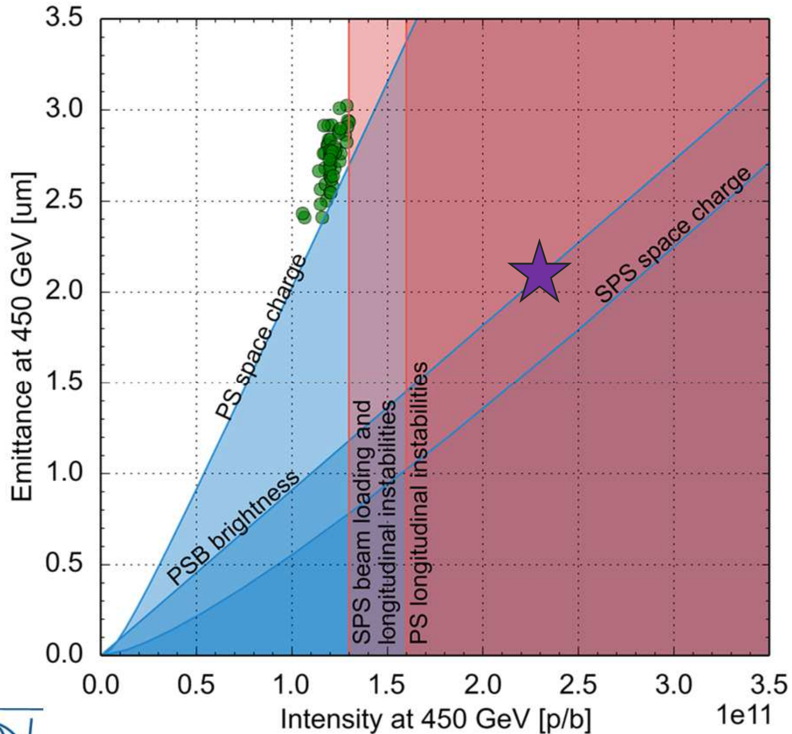
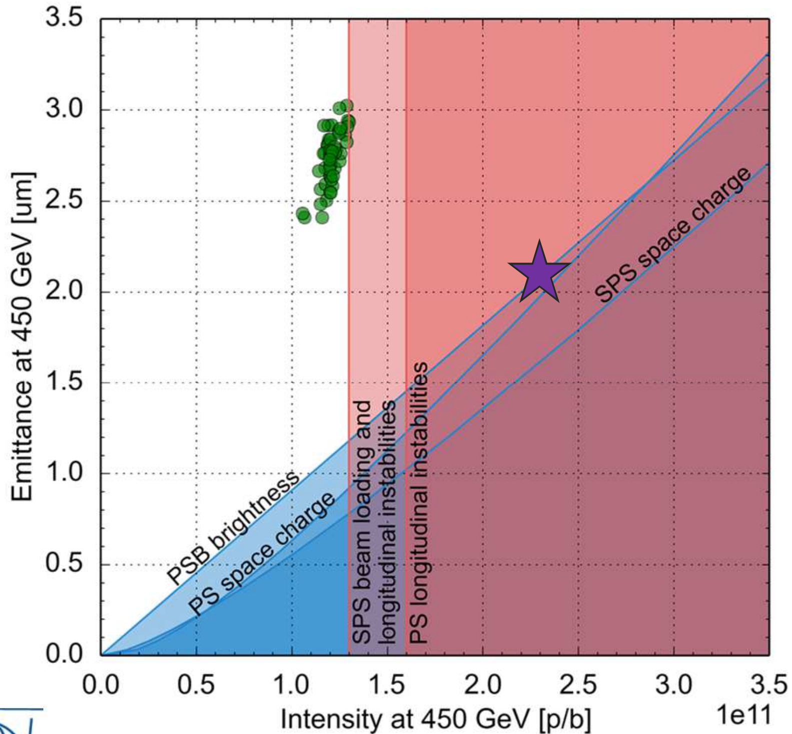


- **Connection of PSB to Linac4**
  - o Linac4 providing 25 mA within 0.4 um
  - o Charge exchange H^- injection at 160 MeV into PSB

Beam performance with LIU upgrades

LHC Injectors Upgrade

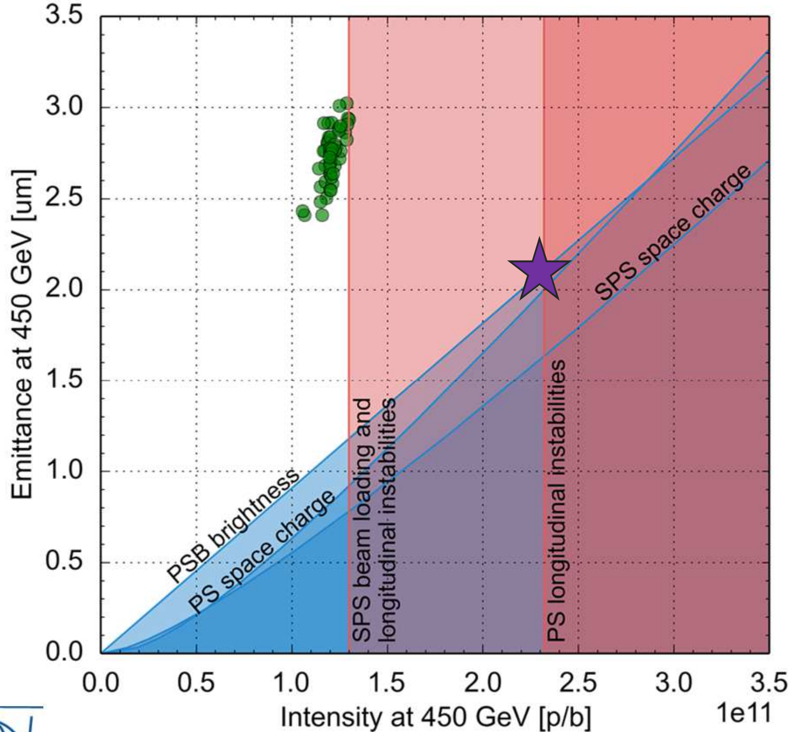
- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



- Connection of PSB to Linac4
- **PSB acceleration to 2 GeV**
  - o Reduced tune spread by 40% at PS injection due to energy scaling
  - o Longer bunches at PSB-PS transfer further reduce PS space charge tune spread

Beam performance with LIU upgrades

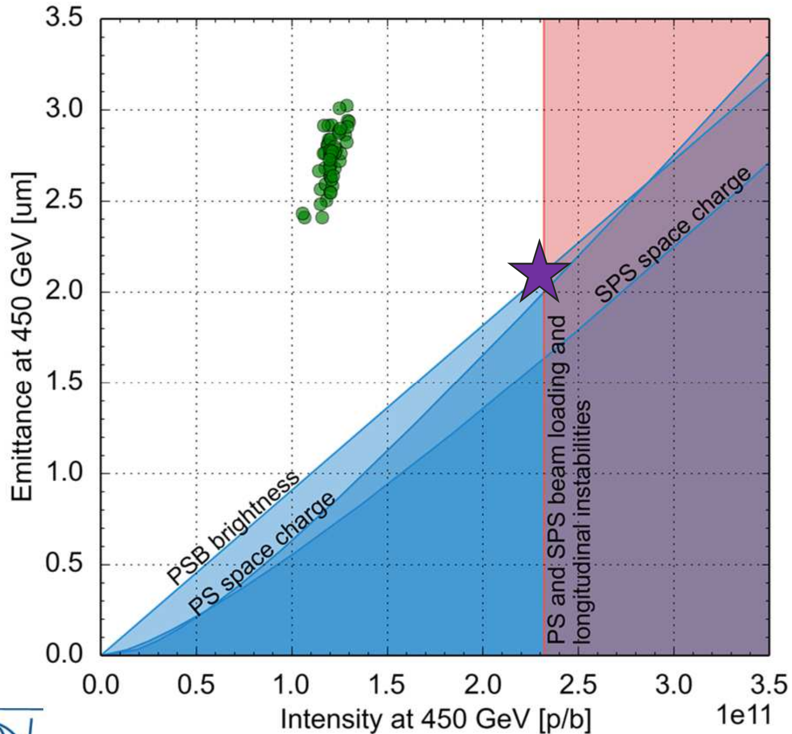
- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



- 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

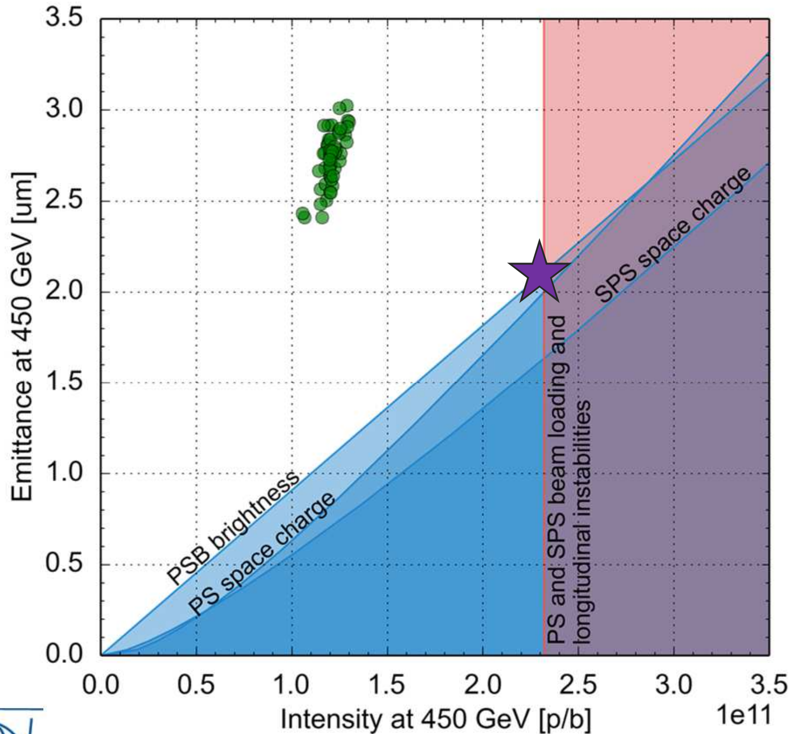
- Effect of the LIU baseline upgrade items on **beam parameter reach**, based on existing machine models and anticipated equipment performance



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

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

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

Not only protons …

LHC Injectors Upgrade

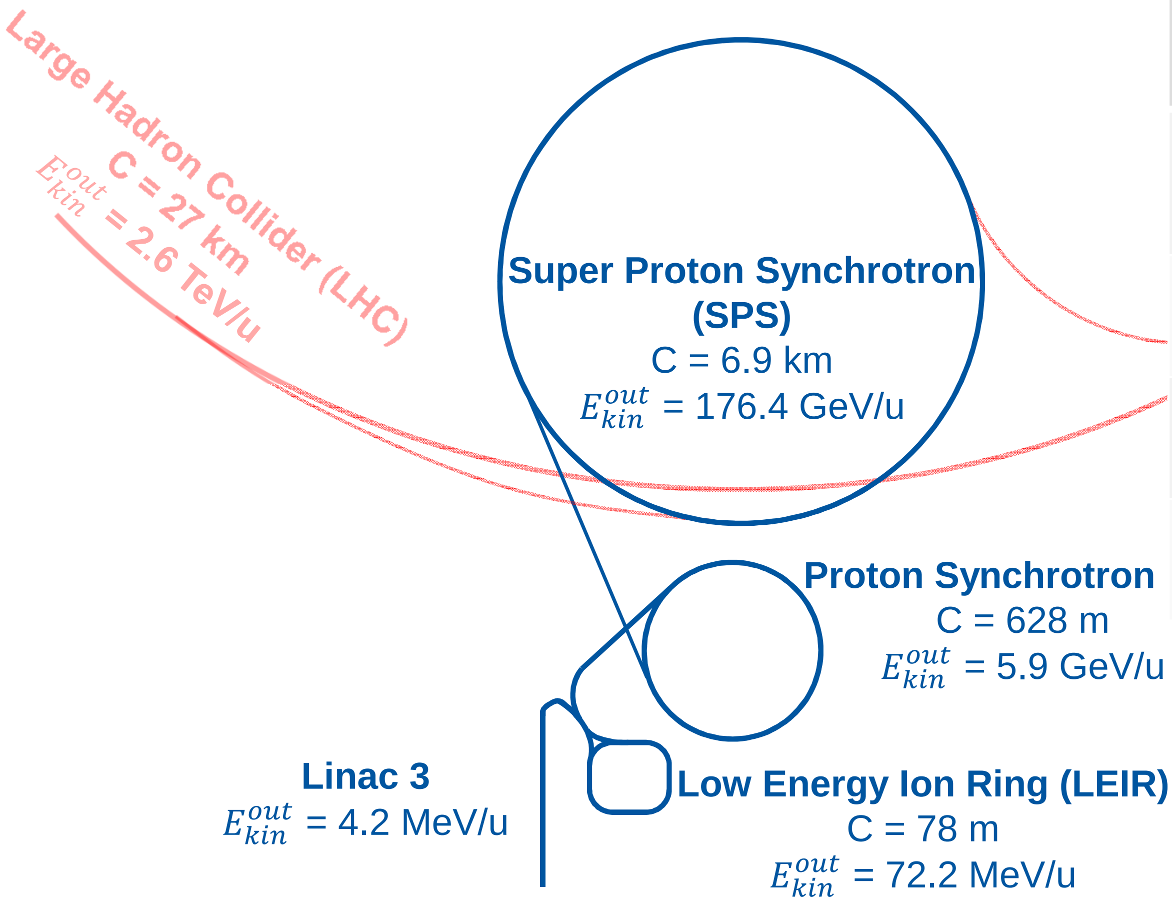
- CERN injector complex also accelerates **heavy ions (Pb) → See next slide**

→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 injector 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

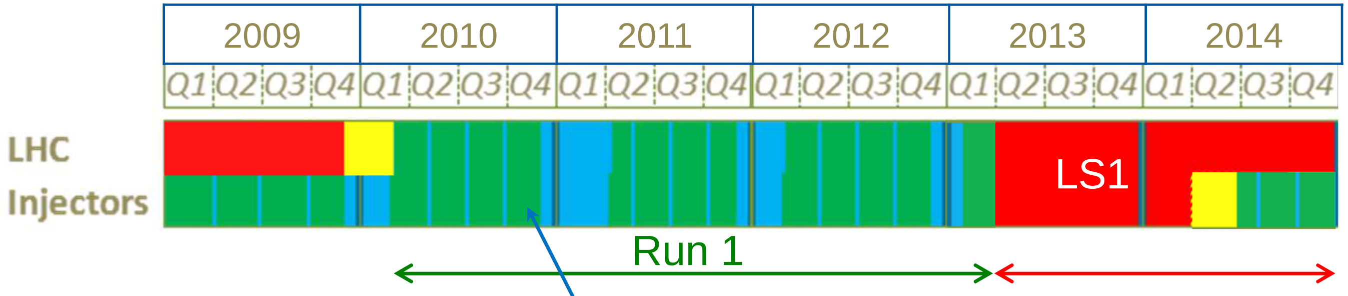
LHC Injectors Upgrade

	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



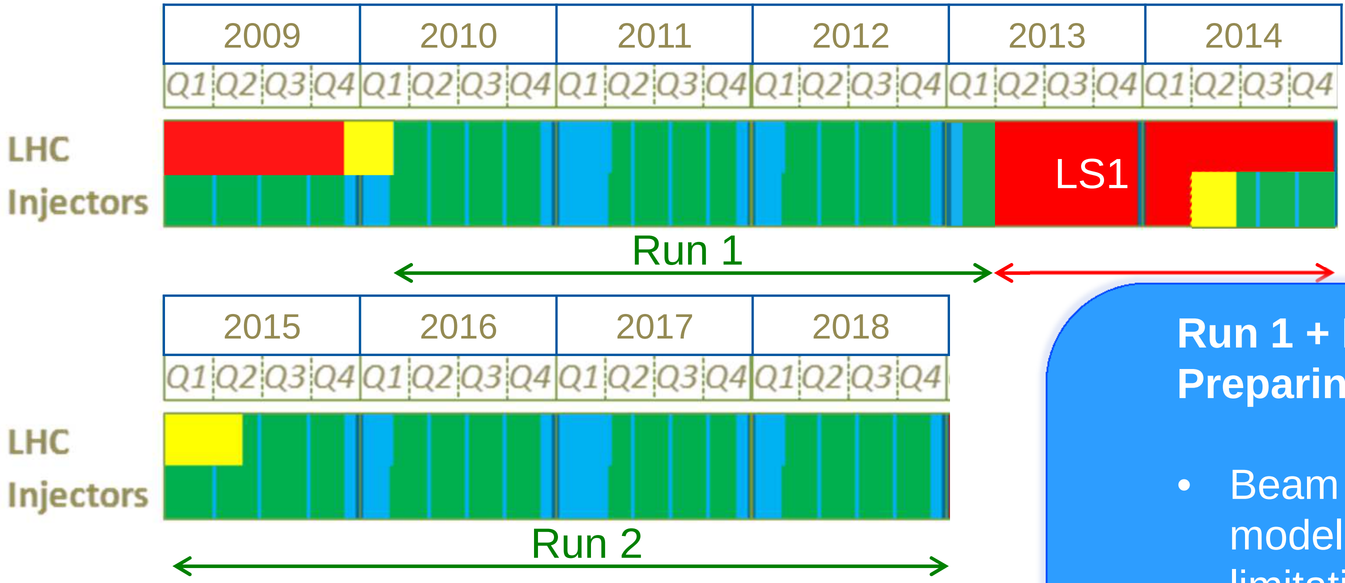
2010: The start

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



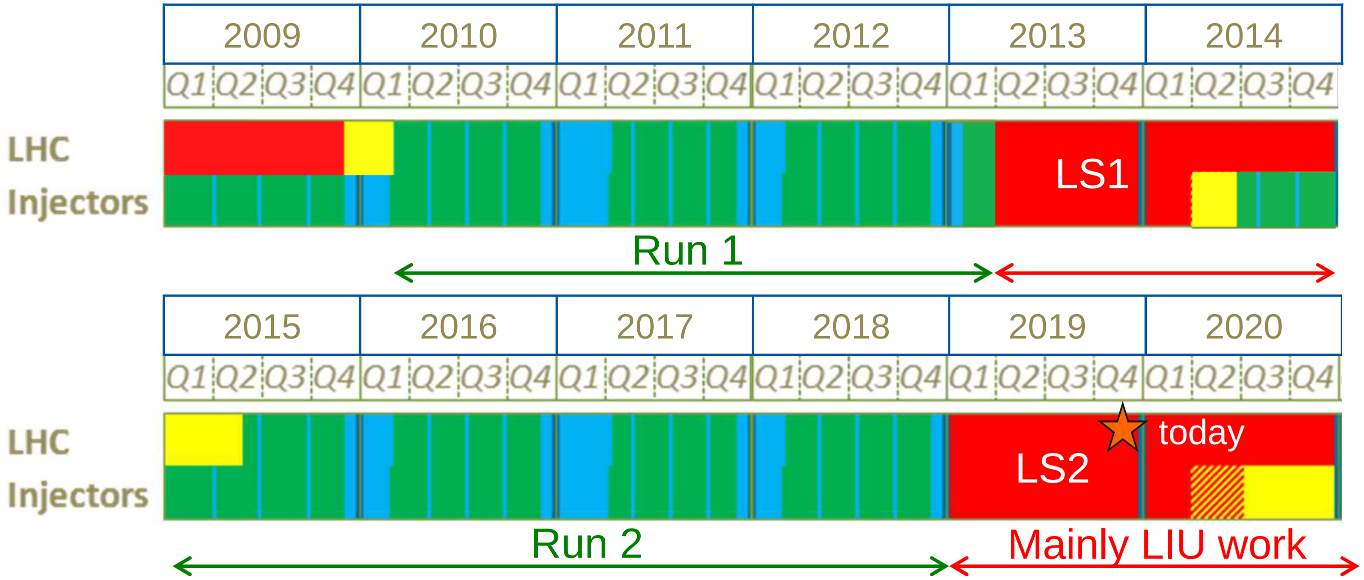
Run 1 + LS1 + Run 2 (2010 – 2018)
Preparing, defining, testing, executing

- 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



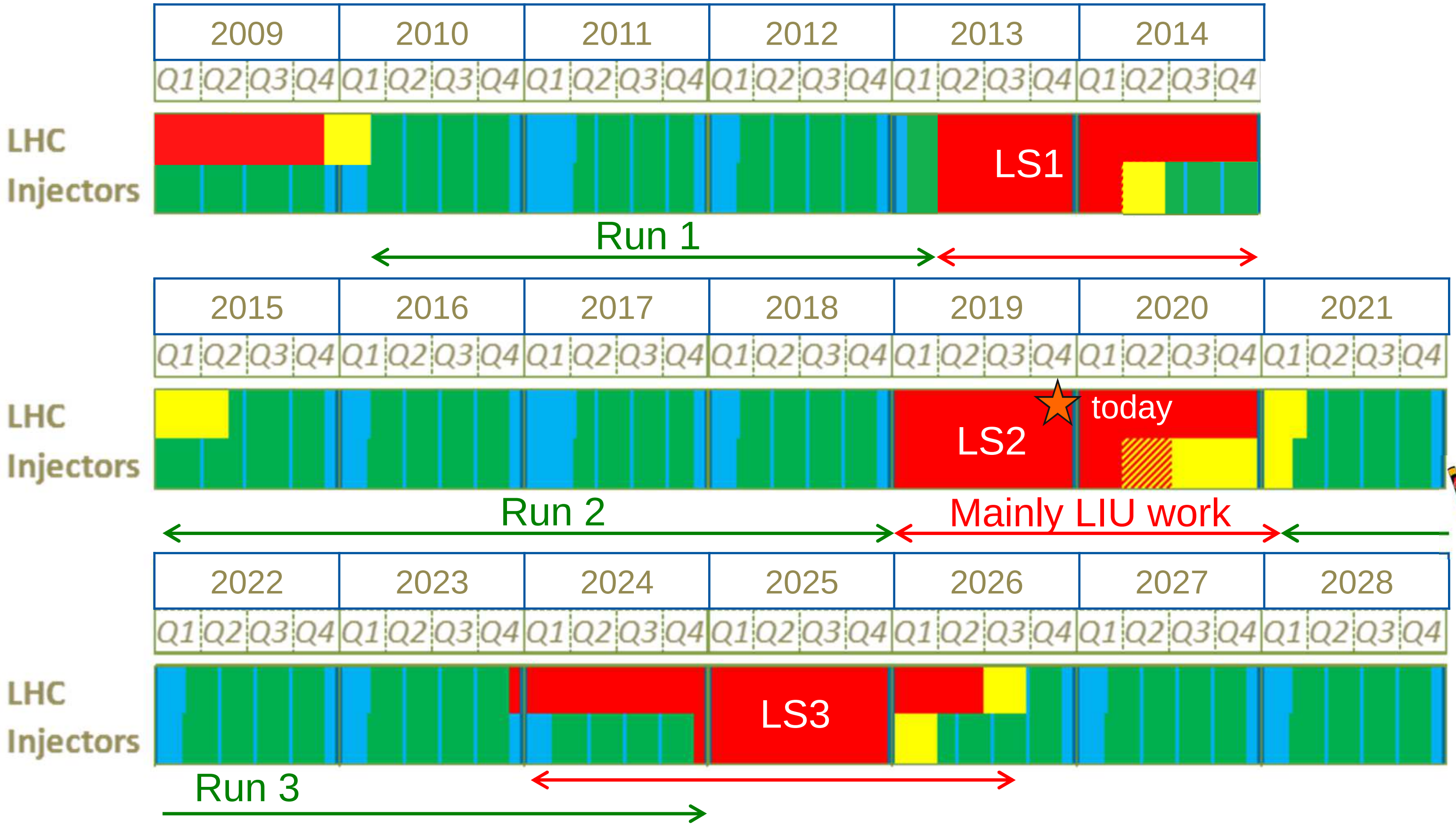
LS2 (2018 – 2020)
Peak of LIU execution phase

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

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**

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

LS2 (2018 – 2020)
Peak of LIU execution phase

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

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What is going on now, planning and installations

Run 3 (2020 – 2024)

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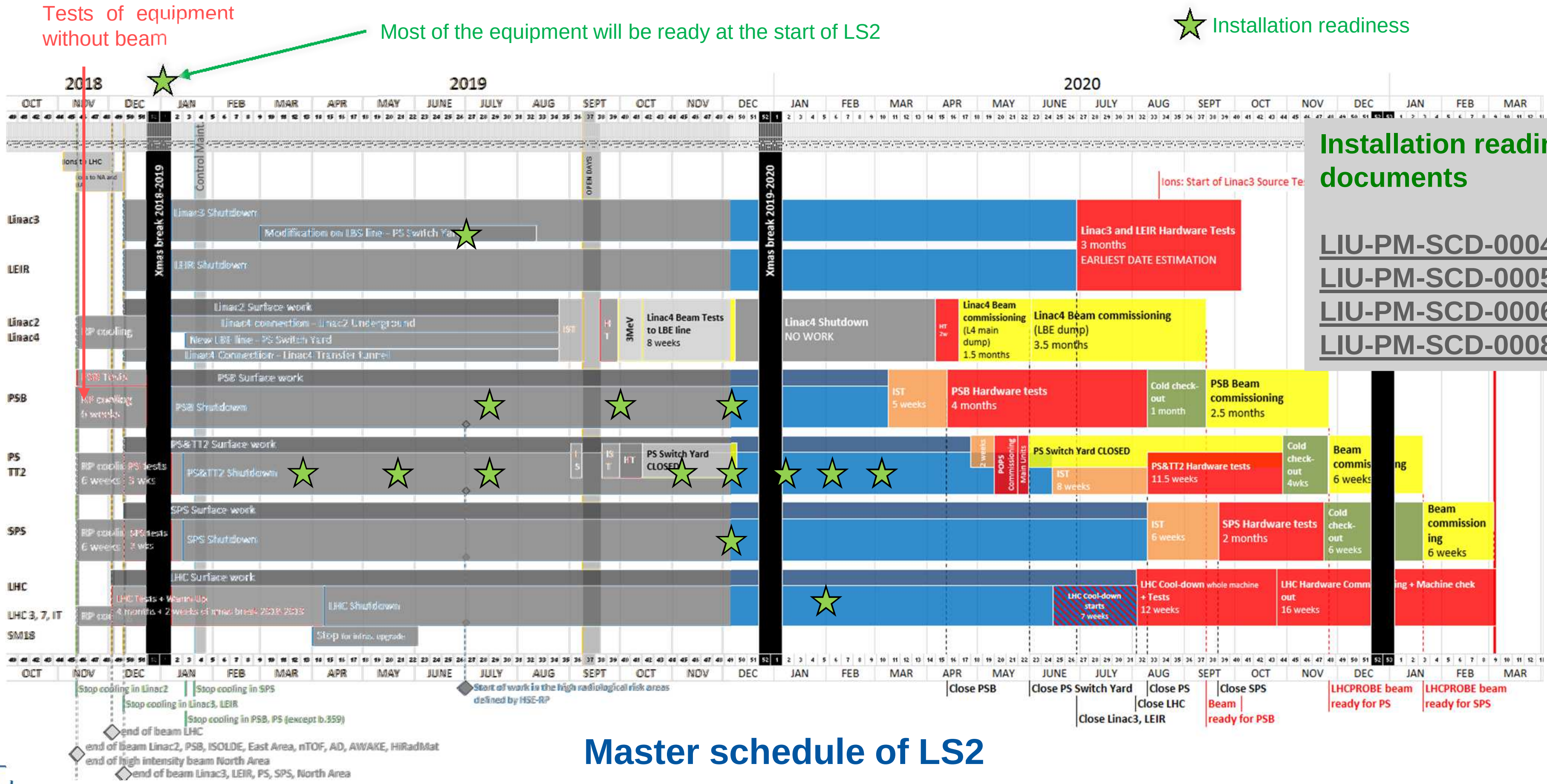
Installation readiness for LIU equipment

LHC Injectors Upgrade



Master schedule of LS2

Installation readiness documents

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

LIU installation during LS2

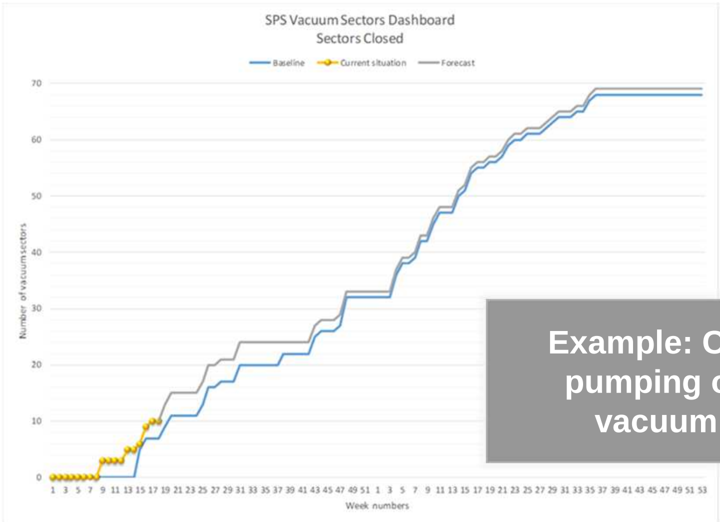
- LS2 schedule
  - LIU project globally on time
  - LS2 linear views for schedules of all machines correctly include resources and highlight coactivity in some areas (within LIU project and with other projects)

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 every two weeks 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

Making room in the PSB
Tunnel for new injection
system

New injection system
Installed in the PBS

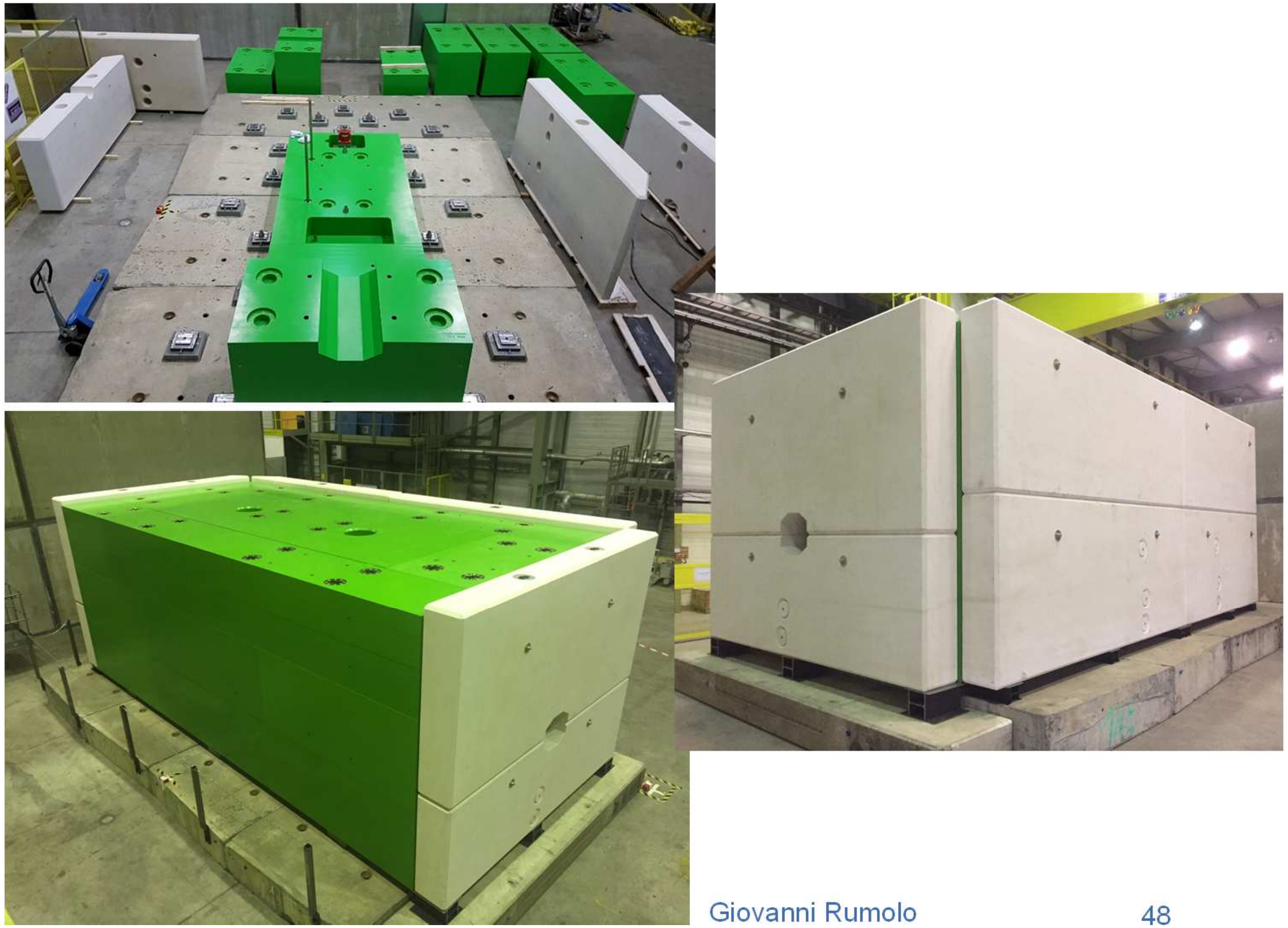
Until 2018: PSB tunnel injection area

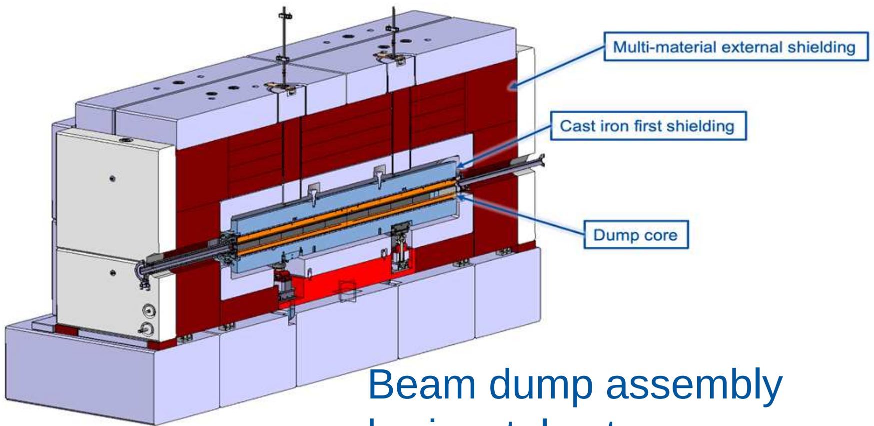
Time lapse

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

Work progress: SPS new beam dump

Mock-up of SPS Beam Dump shielding assembly





Beam dump assembly horizontal cut

2010

2018

2020

2024

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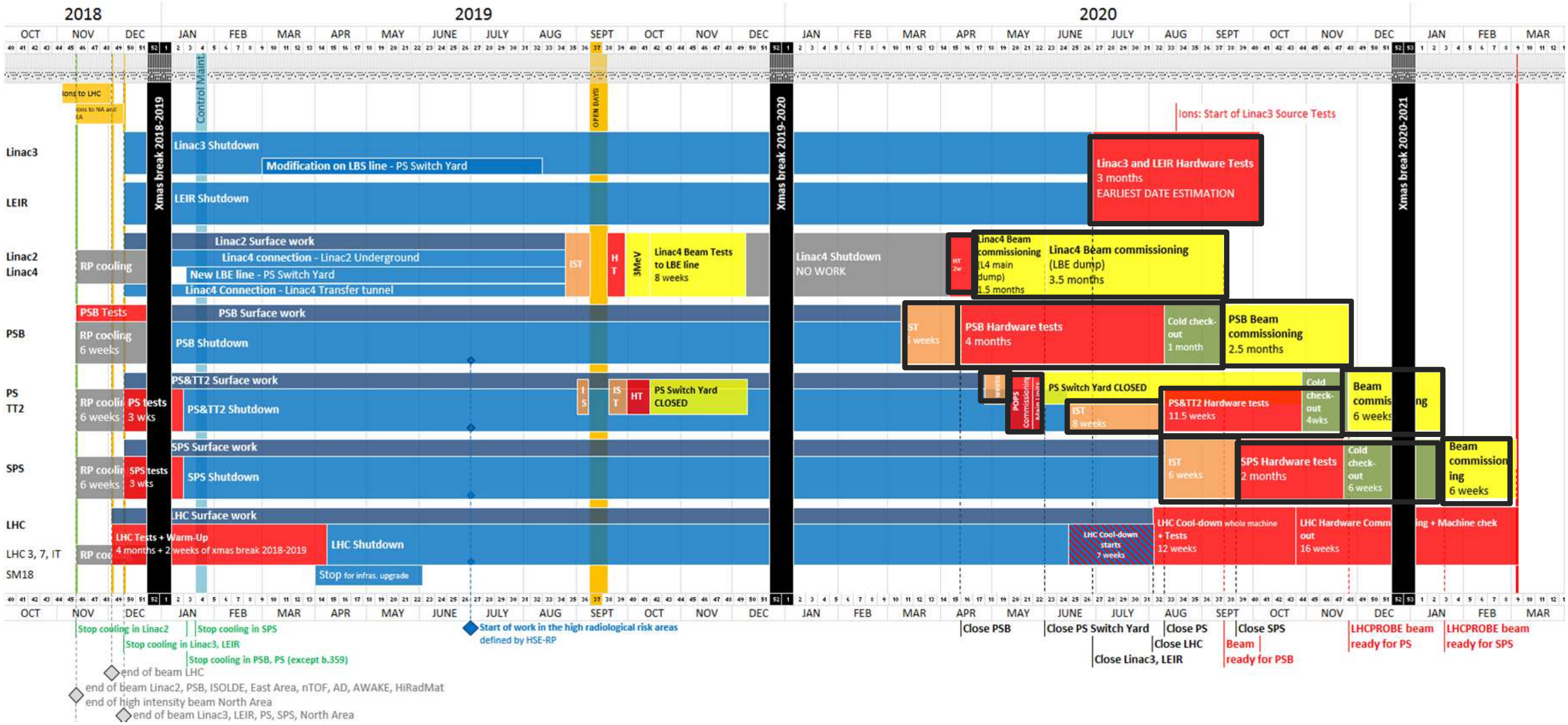
A word on the future

LHC Injectors Upgrade

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



LIU beam ramp up

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

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 within desired loss budgets

- Out of LS2: Individual system tests, hardware commissioning, cold check out, commissioning with beam
- Recovery of pre-LS2 proton beams with Linac4 and newly installed LIU (and non-LIU) equipment
- Commissioning of LIU ion beams for HL-LHC operation in 2021

LIU beam ramp up

LHC Injectors Upgrade

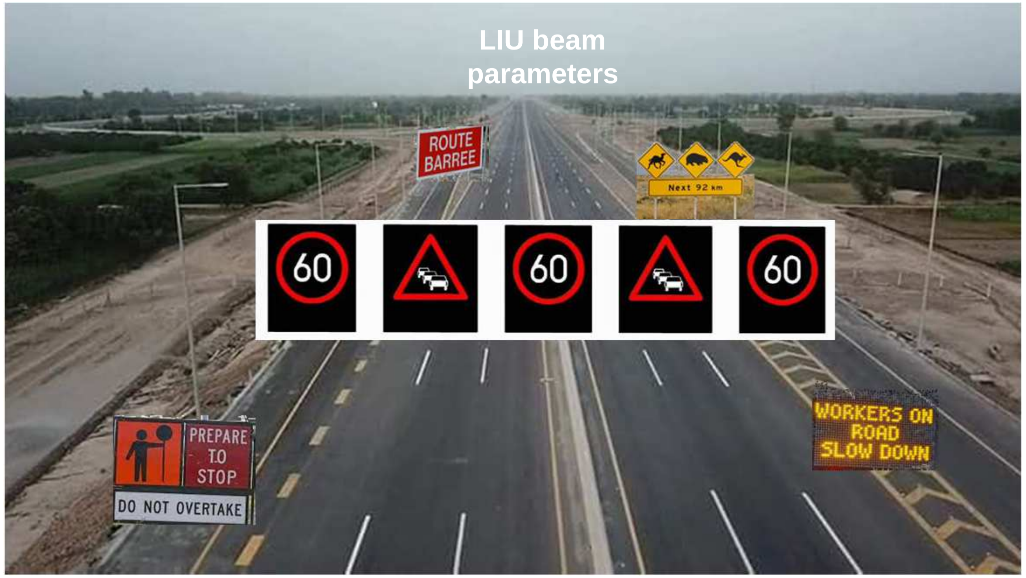
LIU beam commissioning plan: a gradual intensity ramp up all through Run 3

An easy ride to the achievement of the LIU beam parameters??

LIU beam ramp up

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

Quite likely that **real life scenarios** will materialize in the process



LIU beam ramp up

LHC Injectors Upgrade

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

Quite likely that **real life scenarios** will materialize in the process, e.g.

- Lower brightness than anticipated, due to production in Linac4/PSB or emittance preservation in PSB/PS/SPS
- High losses on SPS injection plateau
- Inefficient SPS scrubbing
- Longitudinal instabilities from unmitigated sources in the SPS
- Horizontal instability in the SPS not stabilized with operational knobs
- …

Post-LIU performance recovery catalogue

LHC Injectors Upgrade

Item	Decision point	Cost estimate (MCHF)
PSB extraction kicker impedance reduction	2021	0.1
PS Landau cavity	2023	4
SPS		
a-C coating of all MBBs, quads + 159 drifts	2023 – 2024	4
Further impedance reduction (MKP, flanges & valves shielding)	2022 – 2023	0.2 + 3.5
Remaining QD aperture improvement	2021	0.6
New wideband feedback system	2022 – 2023	2 – 3
Momentum collimation system	2021 – 2022	1

More details to be found in:
G. Rumolo, “Beyond LS2: spares, NCs and upgrades after LS2” in LIU Workshop, 13 – 15 Feb, 2019 , Montreux (CH), slides
M. Meddahi *et al.*, “LIU project: Towards new territory beam parameters” THXPLM1 in IPAC2019, paper

Conclusions

LHC Injectors Upgrade

- **LIU project baseline** built to fulfil 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
  - **Mitigations** envisaged for post-LS2 to recover performance for some scenarios

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

- LIU hardware and beam commissioning will start in only few months by now…

LHC Injectors Upgrade

- 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 of use for the experiments**!

Thanks for your attention and stay tuned!

www.cern.ch

THANK YOU
FOR YOUR
ATTENTION

LHC Injectors Upgrade

A few selected achievements

2010

2018

2020

2024

Run 1 + LS1 + Run 2 (2010 – 2018)
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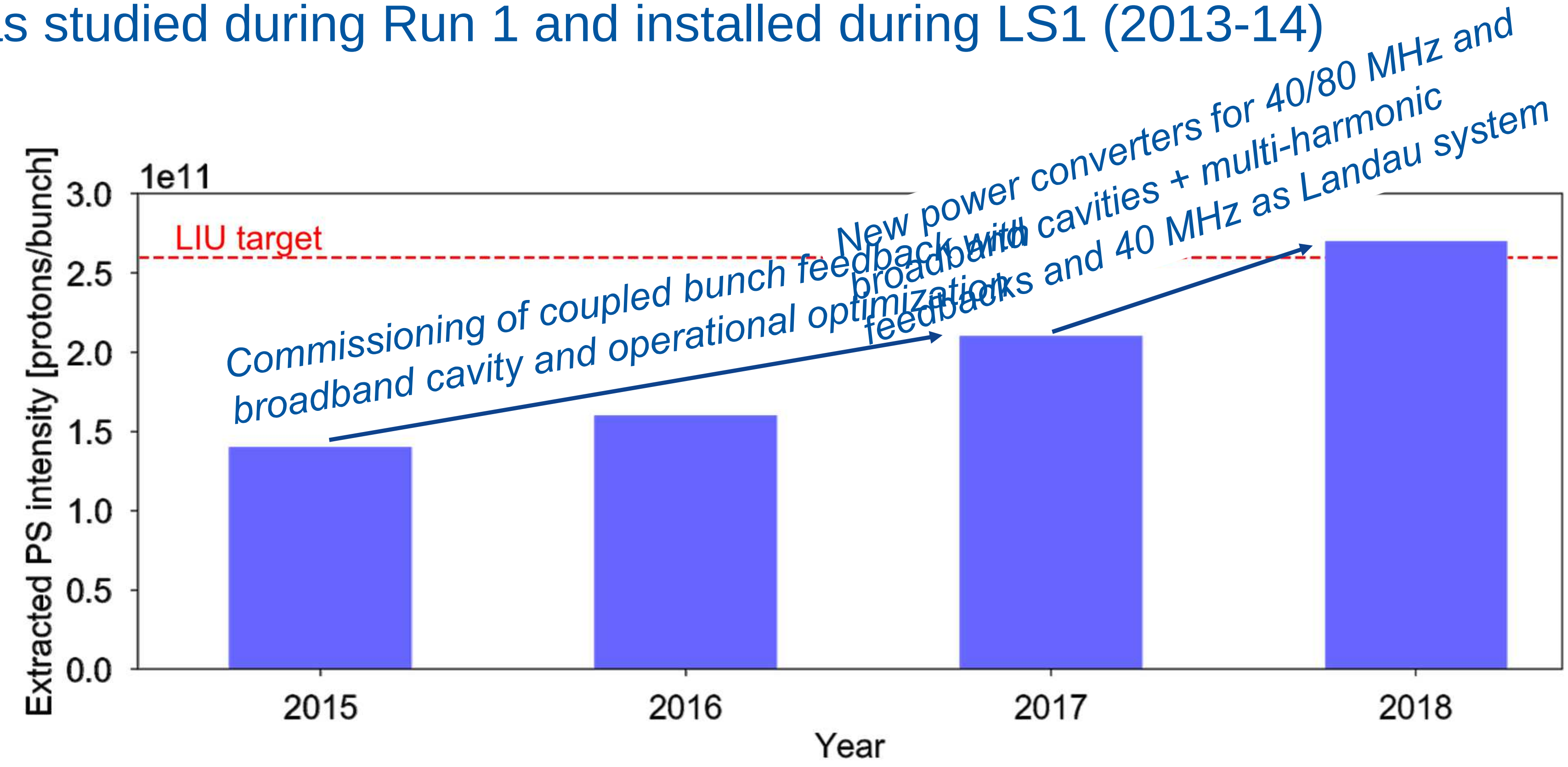
Achievements (1): PS intensity reach

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)



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

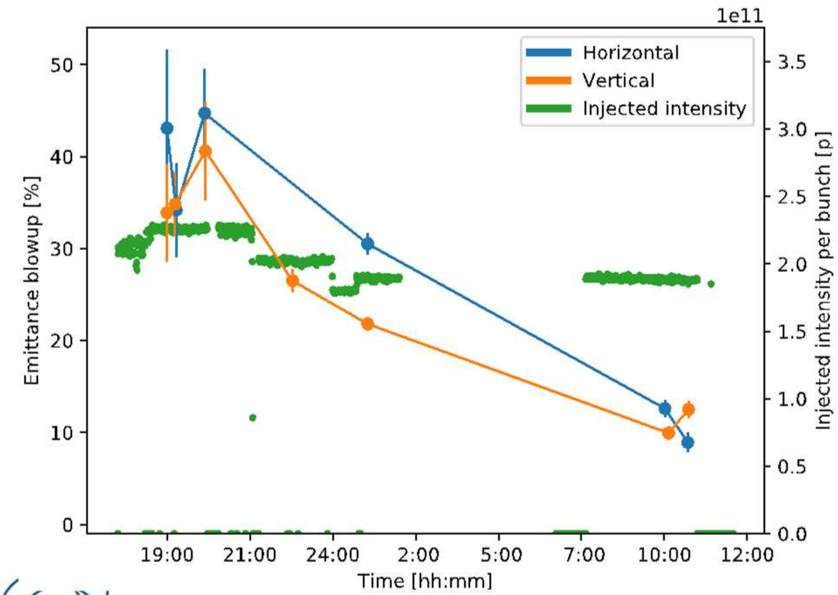
LHC Injectors Upgrade

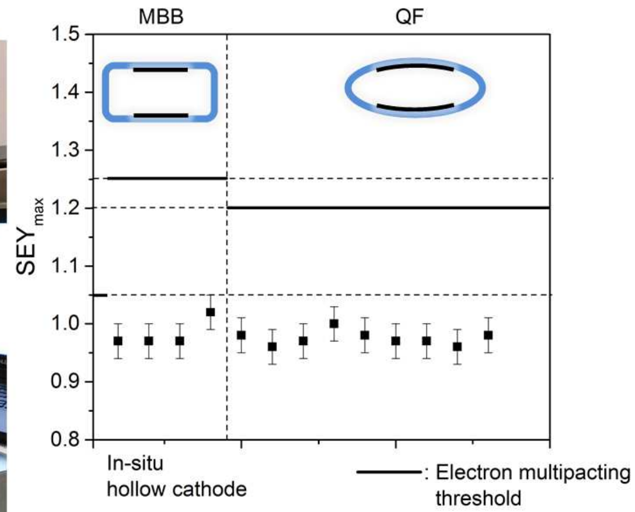
- **Design of Solid State Power Amplifiers (SSPA) for upgrade of SPS 200 MHz RF system** was an important challenge and required development + several iterations with producer
- Upgraded version of the SSPA in 80 module tower successfully passed the required tests in mid 2018
- Module series production 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**

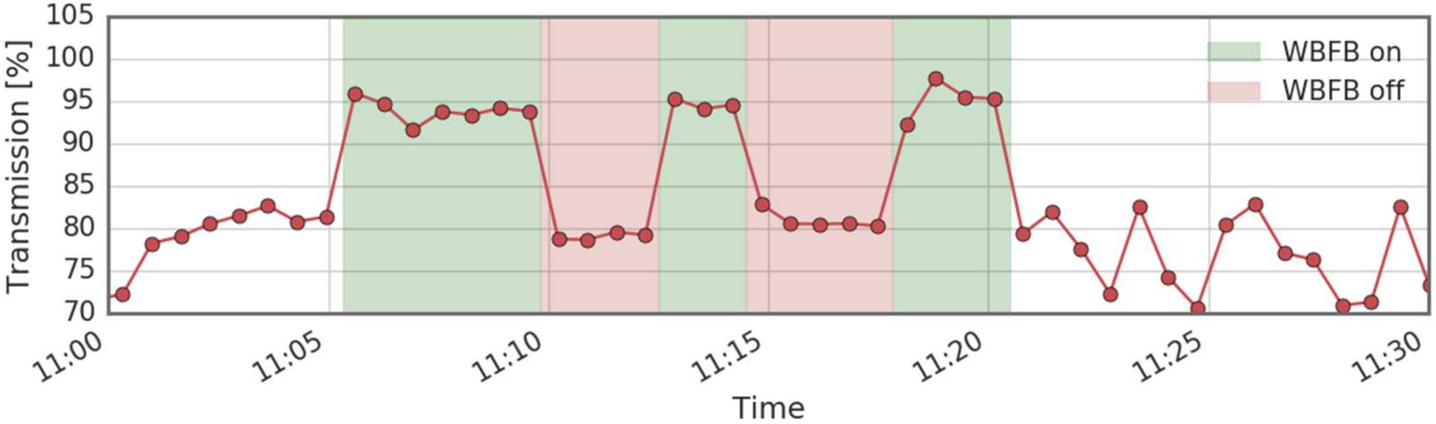




Achievements (4): Wideband Feedback System

LHC Injectors Upgrade

- Prototype of vertical (V) WBFS deployed at SPS
  - 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



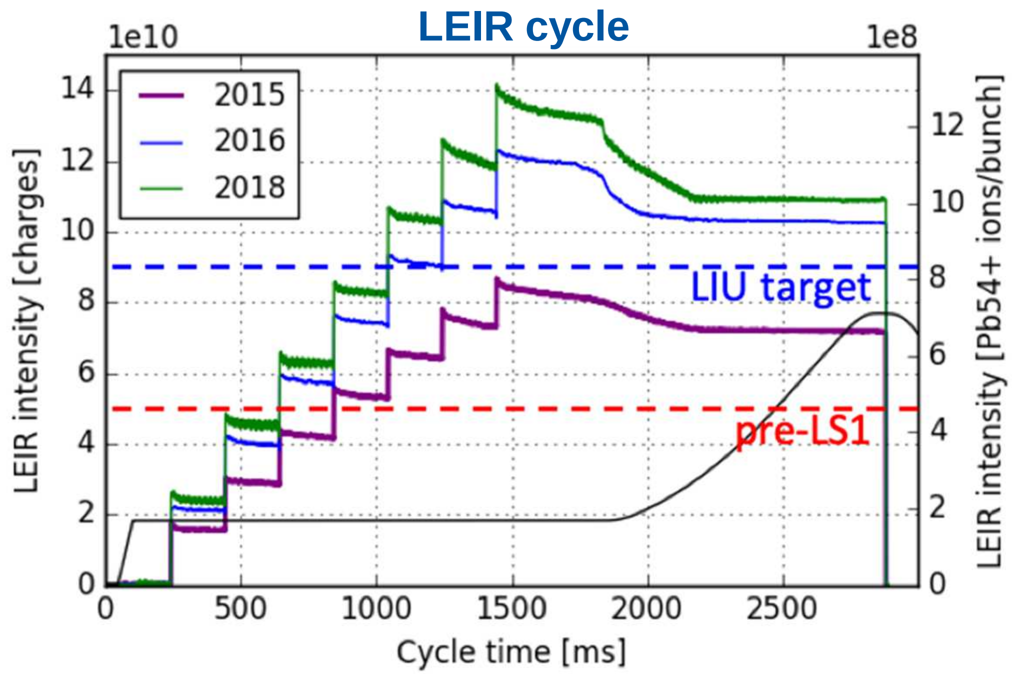
Achievements (4): Wideband Feedback System

- 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
- Operational deployment not pursued within LIU, however kept as **post-LS2 option** in case of unexpected transverse instabilities to reach LIU parameters

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



Recommissioning preparation: hardware and beam

LHC Injectors Upgrade

Hardware commissioning preparation is already actively on-going

- **Check-list tool** deployed for all machines and extensively used (and debriefed) during the 2018 restart
- **LIU equipment** being integrated in the operational environment with requirements (e.g. availability of signals, applications to be developed)

Beam commissioning planning

- **Stand alone beam commissioning steps** included in check lists
- Analysis and development plan of the necessary **commissioning tools**
- Cross-machine dependency included
- **Beam documentation** and **pre-LS2 reference measurements** made available through e-logbook tool

Recommissioning preparation: general

LHC Injectors Upgrade

- Injectors progressively restart in 2020, while installation and tests are being completed in the downstream ones
- LIU commissioning coordination committee sets the strategic view of the injectors re-commissioning and ensure work progress and decision consistency throughout machines
- LIU machine commission working group follow up the preparation phase of the related machine commissioning
- Overlap period between final installation in the tunnels/surface buildings and start of Individual System Tests (IST) is critical
  - Detailed planning of IST is done and will be included in LS2 general plan

Conclusions

LHC Injectors Upgrade

- LIU moving into the **final project phases**
  - **Beam performance targets** unchanged for both protons and ions
  - Remarkable **progress in 2018** machine studies – combining already installed LIU equipment and commissioning in operation
    - **Nominal LIU intensity** achieved at PS extraction
    - **High intensity used in SPS** to further study limitations (instability, losses) and with potential to be used in LHC to collect important information before LS2
    - Performant and reliable **Pb ion beam production** across the chain (including mitigation scenario)
- **LIU installation** during LS2 and post-LS2 restart
  - Equipment tests in PSB already at the end of 2018, Linac4 beam tests in 2019 (planning being finalised)
  - SPS 200 MHz RF system upgrade confirmed in LS2 for commissioning and use in Run 3
  - LIU equipment readiness included in LS2 schedule and compatible with overall planning
    - Detailed LS2 schedule with resources and coactivity being completed
  - Planning for injector restart and beam commissioning in post-LS2 era progressing

LIU beam ramp-up – possible additional needs

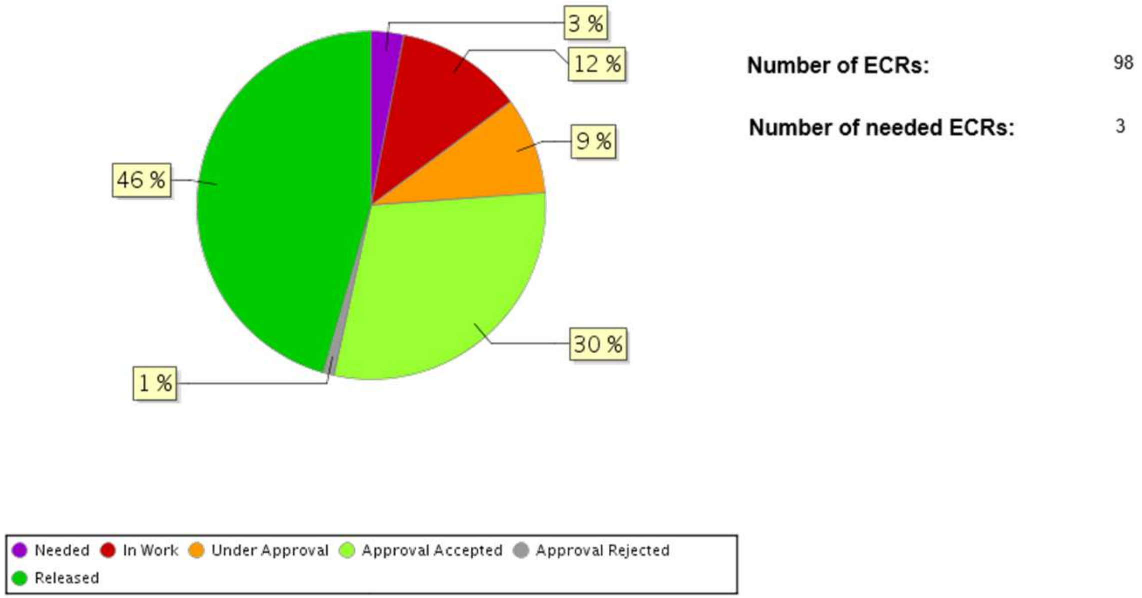
To follow-up and document post-LS2 upgrades list at the defined checkpoints

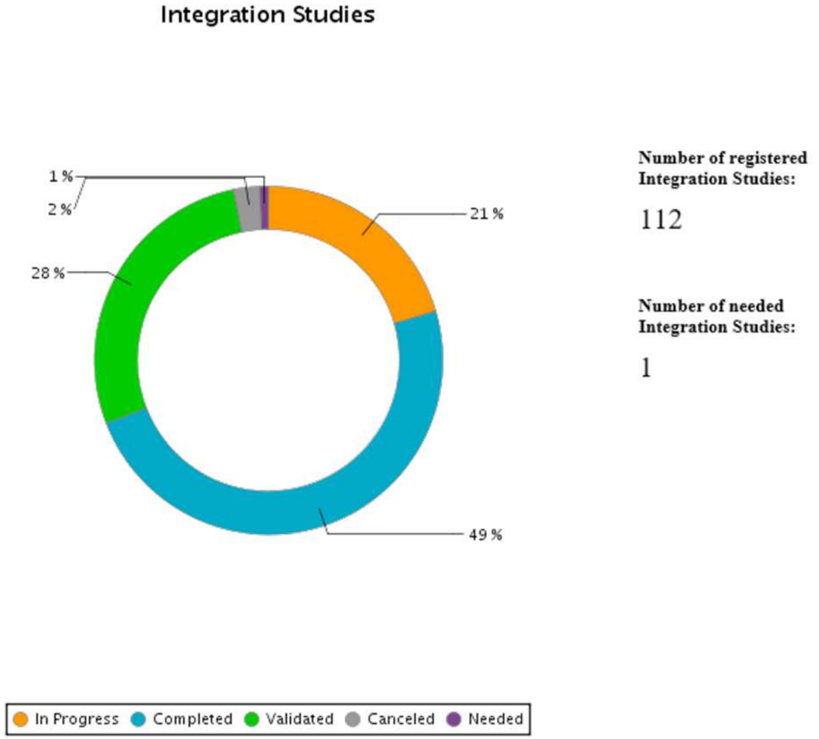
Item	Decision point	Cost estimate (MCHF)
Booster extraction kicker impedance reduction	2021	0.1
Landau cavity	2023	4
a-C coating of all MBBs, quads + 159 drifts	2023 – 2024	4
Further impedance reduction (SPS injection kicker, flanges & valves shielding)	2022 – 2023	0.2 + 3.5
Remaining QD aperture improvement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

Integration 3D Studies and Engineering Change Requests

LHC Injectors Upgrade

LIU modifications in the LHC injectors chain and their impacts on other systems are documented and approved (Engineering Change Requests - ECRs). The ECRs are based on integration 3D studies.



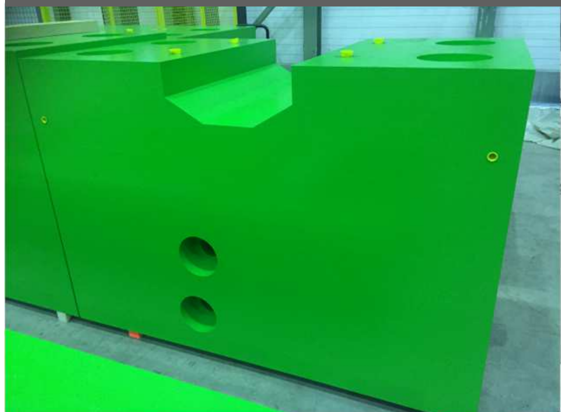


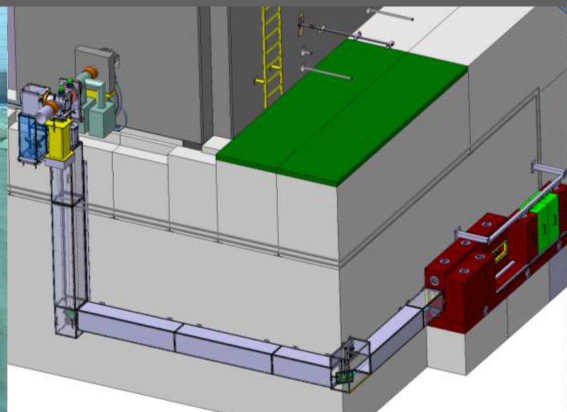
SPS Dump Upgrade


Dump external shielding marble layer


HIPed CuCr1Zr cooling plate test bench

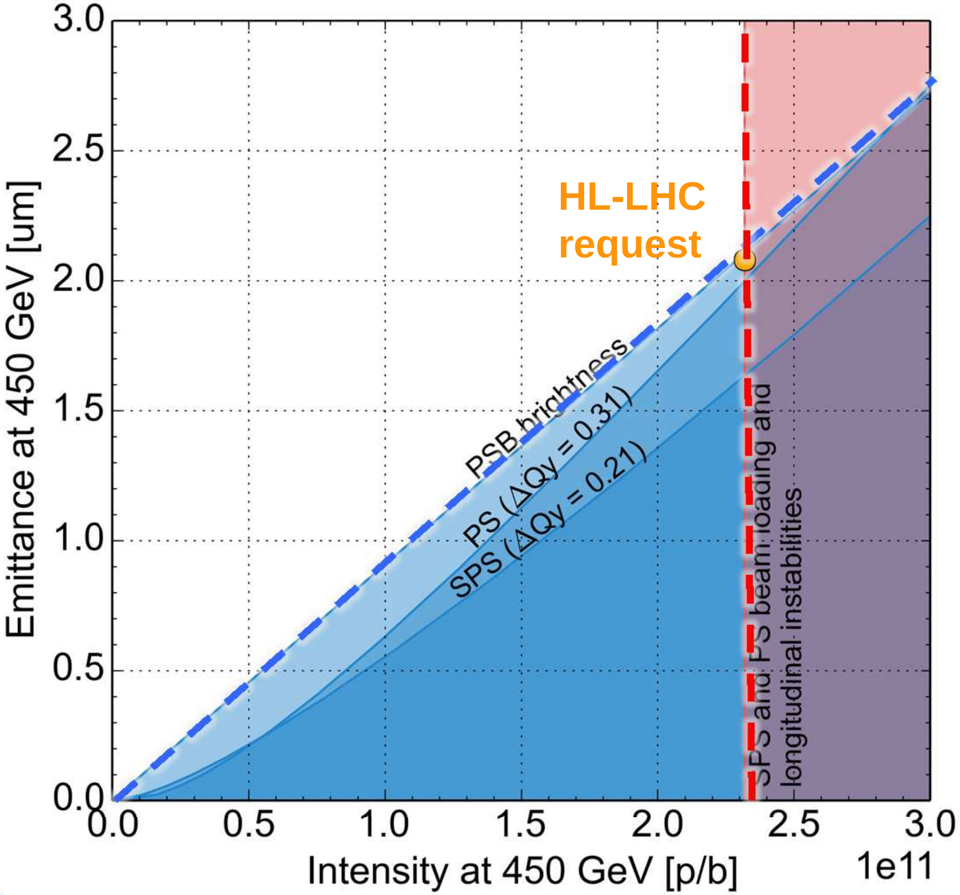

Vertical kicker magnet


Cast iron dump external shielding


17m long Beam Profile Monitor optical line


Vertical kicker pulsed generator

LIU performance reach for protons



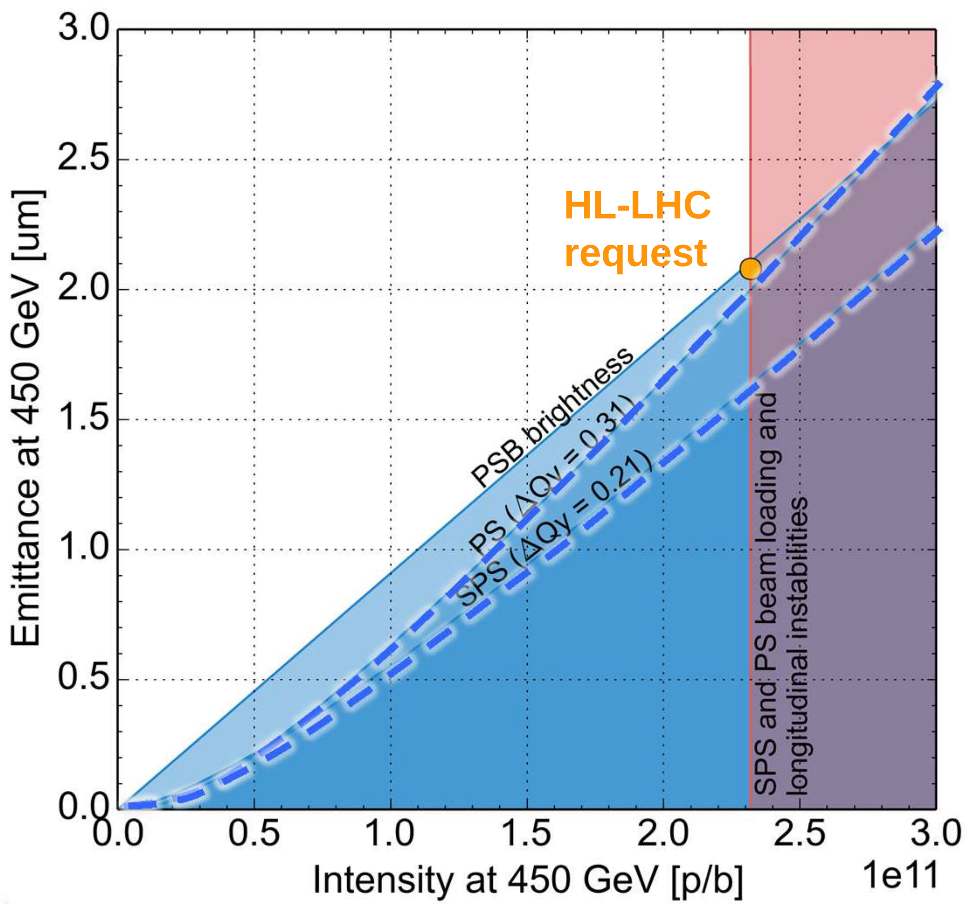
- Beam loss and emittance blow up budgets

budget	PSB & PS	SPS
losses	5%	10%
blow-up	5%	10%

- PSB brightness + intensity limitations in PS and SPS inferred from simulations, assuming
  - Linac4 providing reliably 20-40 mA
  - PS RF upgrades including Finemet cavity as longitudinal broadband FB
  - SPS main RF power upgrade, e-cloud mitigation and impedance reduction

LIU performance reach for protons

LHC Injectors Upgrade



- Beam loss and emittance blow up budgets

budget	PSB & PS	SPS
losses	5%	10%
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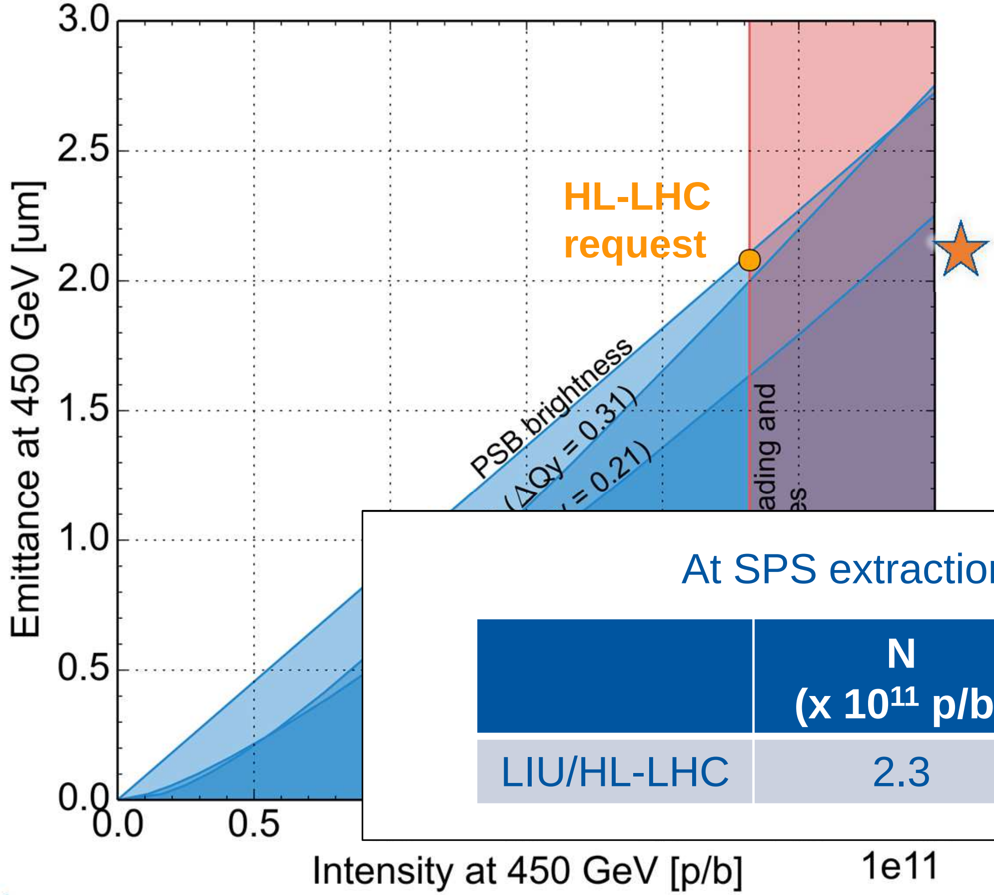
- PSB brightness + intensity limitations in PS and SPS inferred from simulations
- Space charge limitation curves in PS and SPS based on assumed tune spreads and optimised beam parameters at transfers

	PS	SPS
$\Delta Q_{V,\,max}$	0.31	0.21

LIU performance reach for protons



At SPS extraction:

	N (x 10^{11} p/b)	e (mm)
LIU/HL-LHC	2.3	2.1

- Beam loss and emittance blow up budgets

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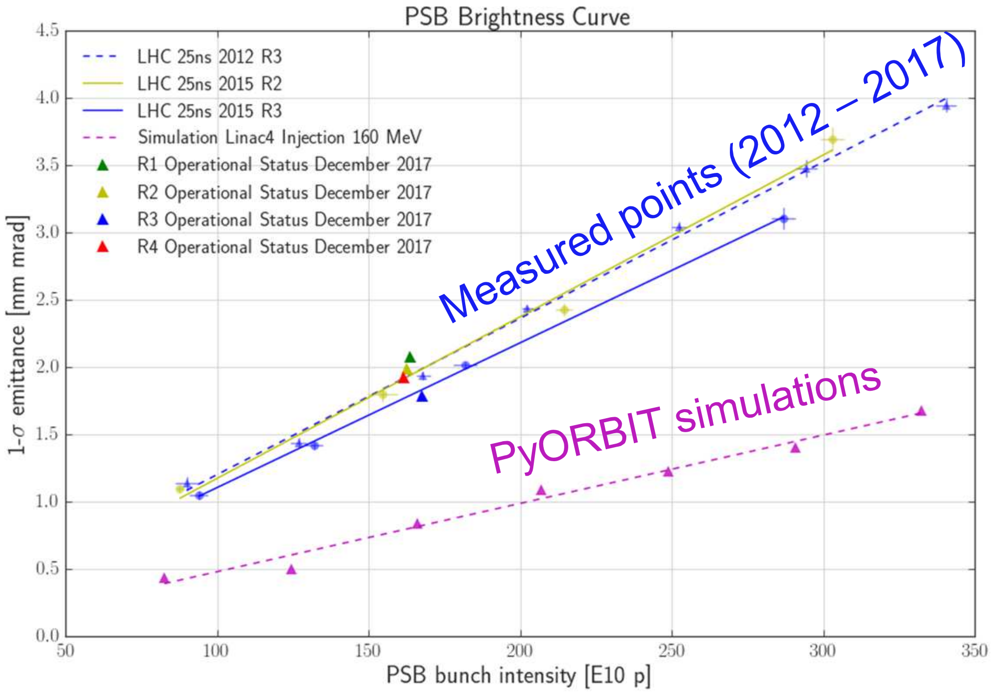
	PS	SPS
$\Delta Q_{V,\,max}$	0.31	0.21

Lifting the brightness limitations

LHC Injectors Upgrade

- Halve the slope of the **PSB brightness line**
  - 160 MeV H^- charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2



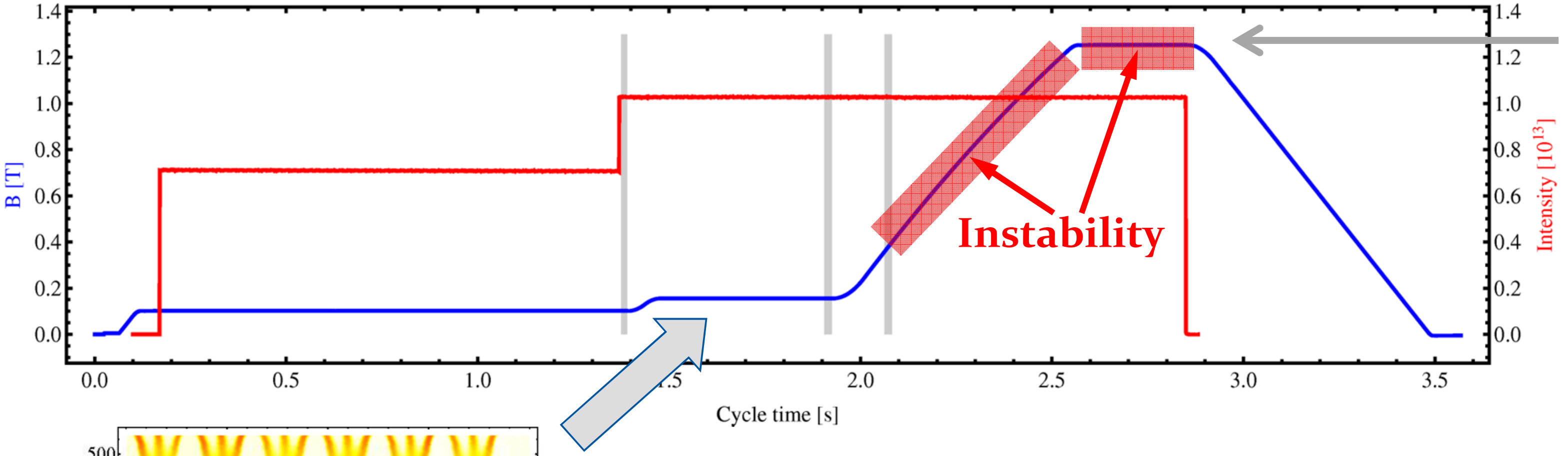
$$\left[\frac{(\beta\gamma^2)_{160\,\mathrm{MeV}}}{(\beta\gamma^2)_{50\,\mathrm{MeV}}}\right] = 2$$

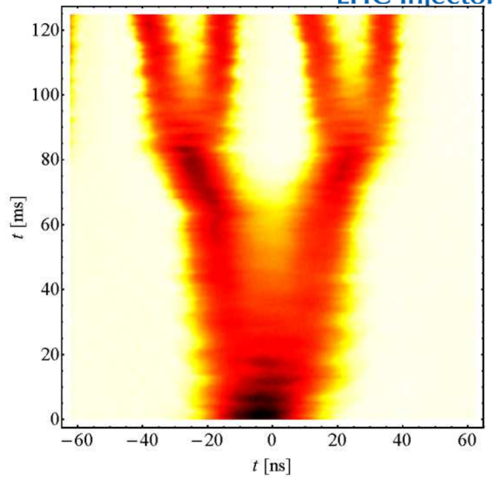
Lifting the brightness limitations

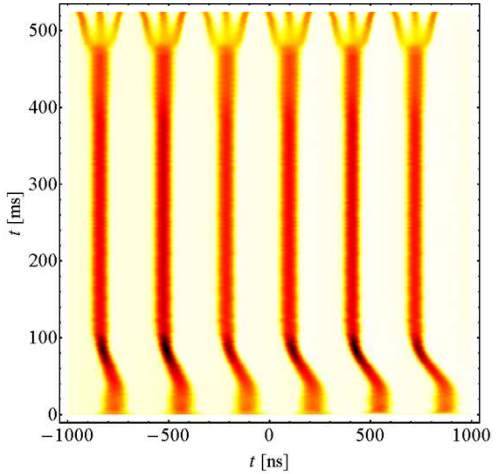
- Halve the slope of the **PSB brightness line**
  - 160 MeV H^- charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2
- Reduce **space charge at PS injection** to accommodate same tune spread as current LHC beam (*ΔQ_y=-0.31*)
  - Increase of PS injection energy from 1.4 GeV to 2 GeV
  - Increase of longitudinal emittance (compatibly with other constraints) at transfer in order to gain from decreasing λ_{max} and increasing $\delta=(\delta p/p_0)$

$$\Delta Q_{x,y} = \frac{\lambda_{\max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)ds}{\sqrt{\epsilon_{x,y}\beta_{x,y}(s)+D_{x,y}^2(s)\delta^2}\left(\sqrt{\epsilon_x\beta_x(s)+D_x^2(s)\delta^2}+\sqrt{\epsilon_y\beta_y(s)+D_y^2(s)\delta^2}\right)}$$

Lifting the PS intensity limitation







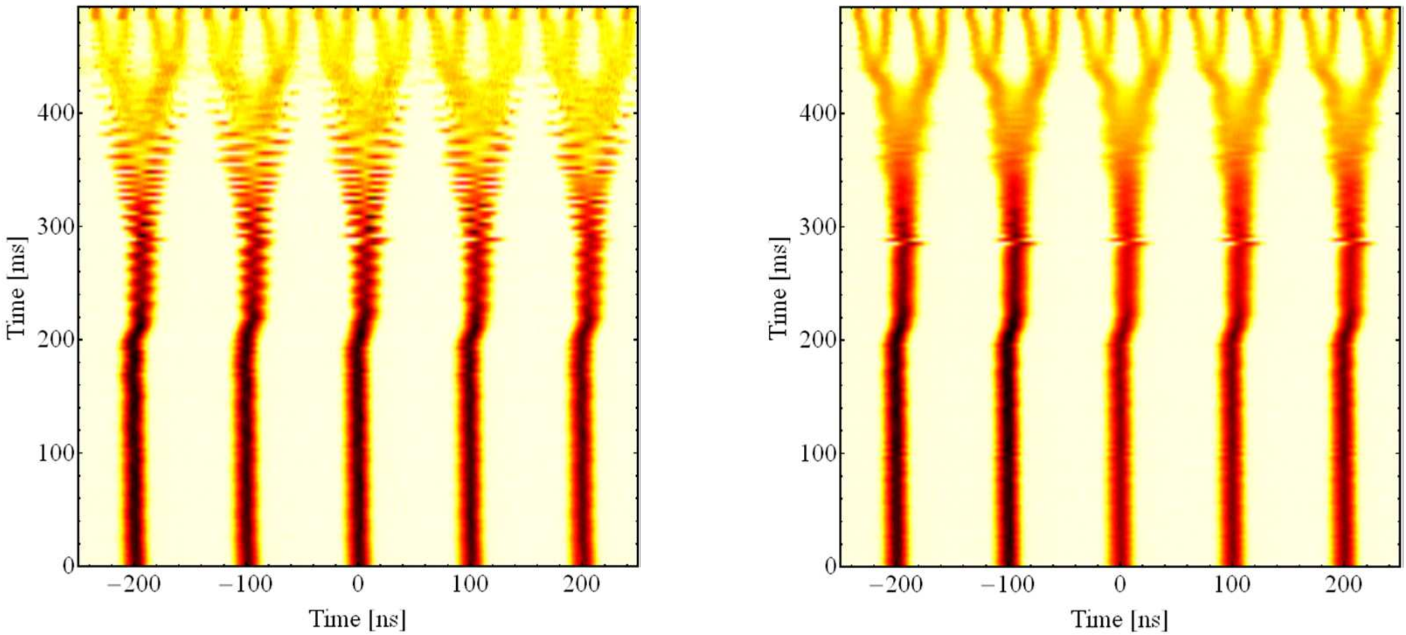
- Bunch current limited to **1.6e11 p/b at extraction**
- Above 1.6e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
  - Dipolar oscillation, caused by **10 MHz RF system impedance** (as found also in simulations)

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

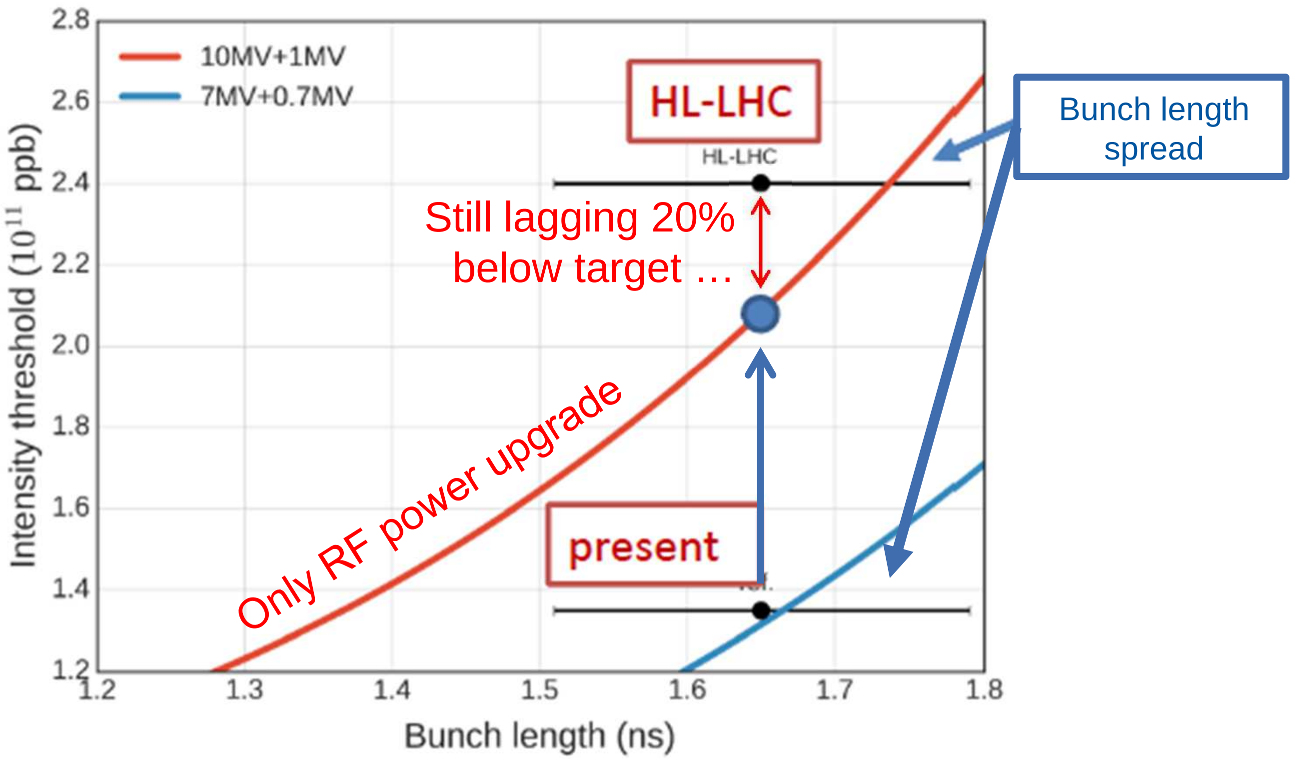
LHC Injectors Upgrade

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

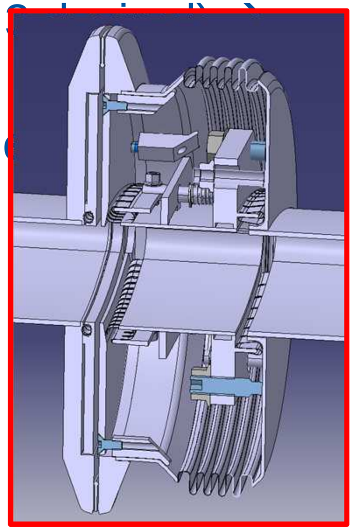
LHC Injectors Upgrade

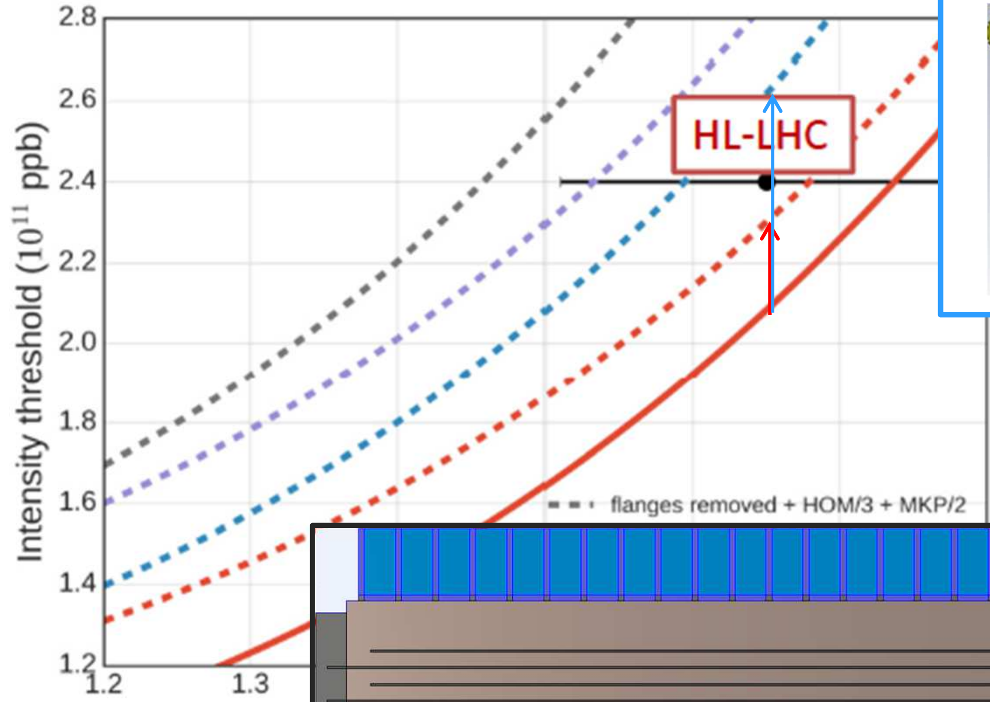
- **Beam loading** in the present 200 MHz TW RF system – intensity limited to about 1.3e11 p/b
- **Longitudinal instabilities** during ramp with very low threshold currently cured by
  - 800 MHz RF system in bunch shortening mode
  - Controlled emittance blow-up (with constraint of 1.7 ns bunch length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

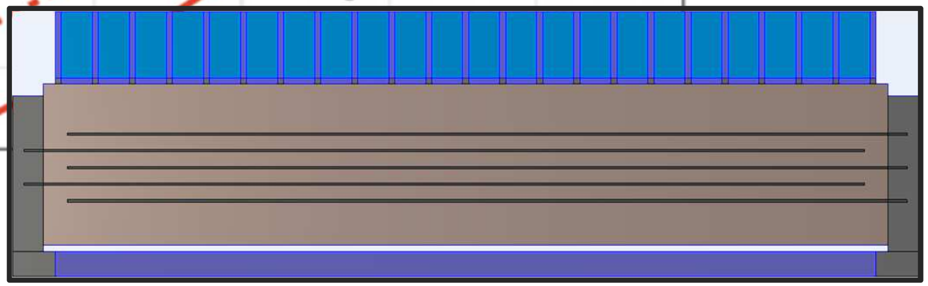


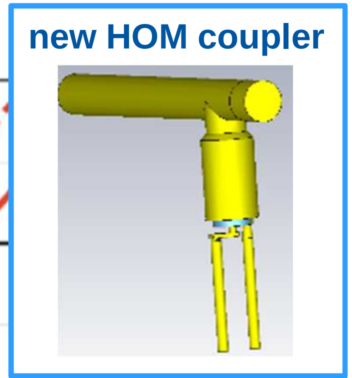
Lifting the SPS intensity limitation

- **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





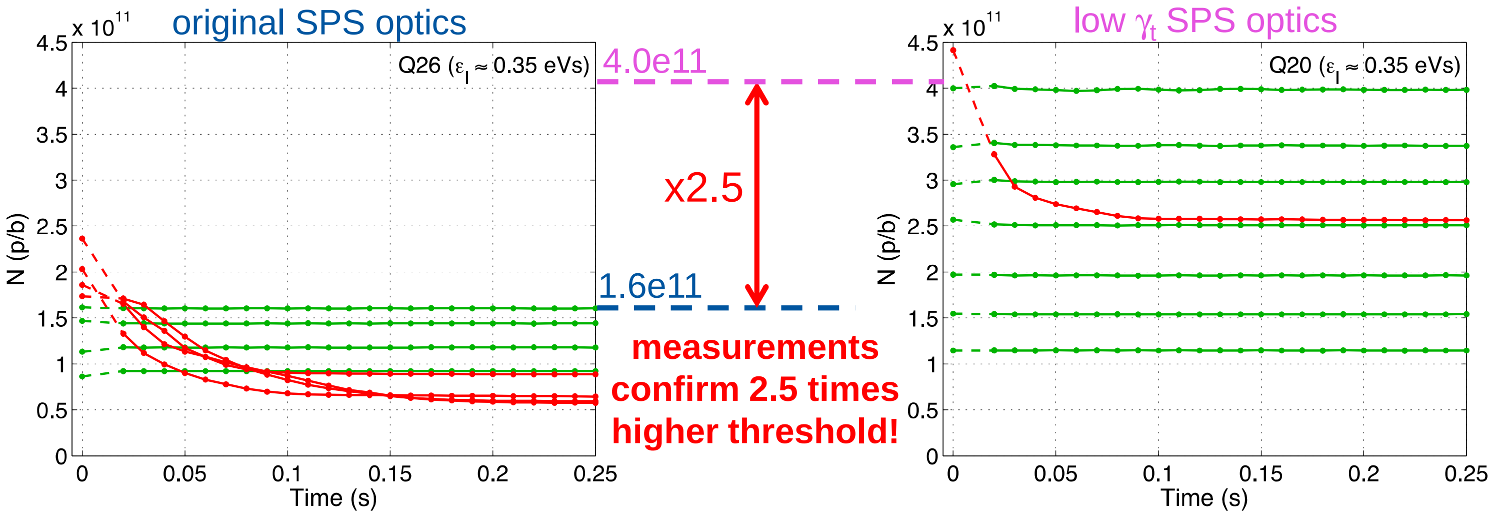




Other SPS intensity limitations?

LHC Injectors Upgrade

- **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



Injectors restart after LS2

LHC Injectors Upgrade

- Injectors restart in 2020-21 (Commissioning Coordination & Working Groups)

  - Individual System Tests during shutdown period
  - Hardware commissioning/cold check out including new equipment
  - Stand-alone beam commissioning
    - **Beam commissioning** steps outlined and added to check lists