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LHC Injectors Upgrade: Ready for installation

Malika Meddahi and Giovanni Rumolo

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LIU beam parameters and beam commissioning: H. Bartosik, V. Kain

Outline

LHC Injectors Upgrade

- LIU in a nutshell
- Performance of the LHC injectors
  - LIU performance target for protons
  - Highlights from 2018 (protons)
  - LIU performance target for Pb ions vs. current performance
- LIU equipment installation readiness and planning in LS2

- **LIU in a nutshell**

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Goals of LIU upgrades

LHC Injectors Upgrade

- Performance:
  - **Deliver the beam parameters** at LHC injection with HL-LHC target for protons and heavy ions
  - Define and deploy **means** to overcome **performance limitations** in all injectors

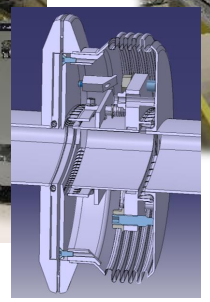
Proton beam properties @LHC injection

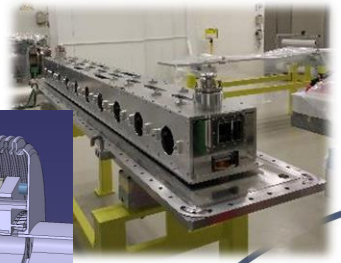
	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)	Bunch spacing	Bunches
HL-LHC target	**2.3**	**2.1**	**25 ns**	**4x72 per injection**
Present	1.3	2.7	25 ns	4x72 per injection

- Sustainability/availability:
  - Ensure and improve injectors' availability/reliability well into the HL-LHC era by upgrading sensitive/ageing equipment, improve radioprotection and services (CONSolidation)

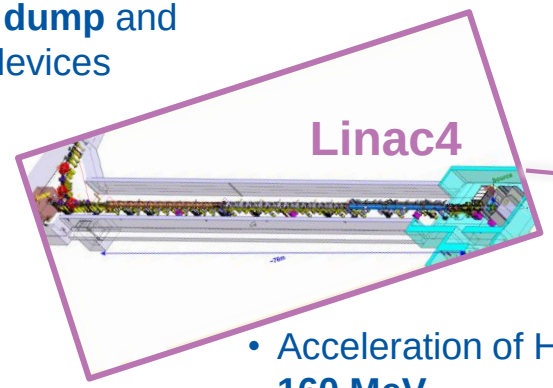
Overview on LIU

LHC Injectors Upgrade

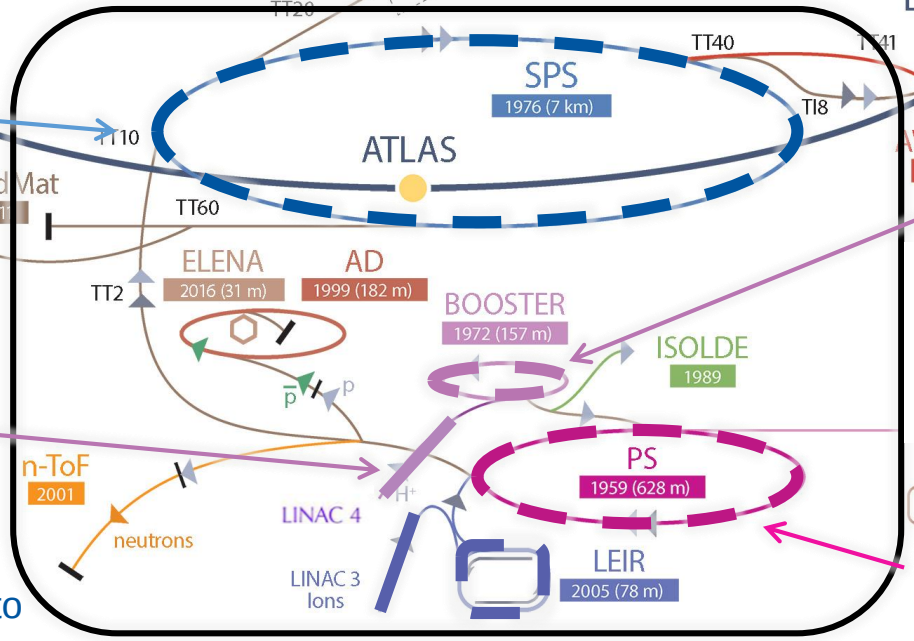


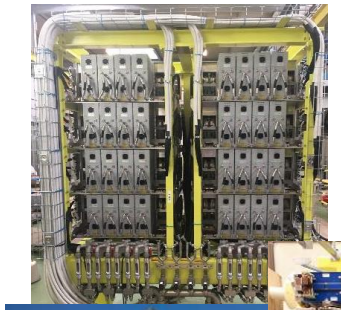


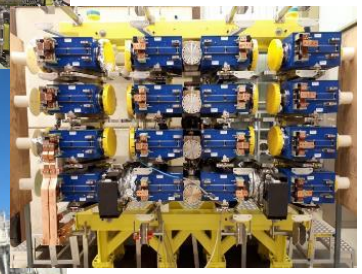
- Main **RF** system (200 MHz) upgrade
- Longitudinal **impedance** reduction & anti-ecloud coating
- New **beam dump** and protection devices



- Acceleration of H^- to **160 MeV**
- Nominal 40 mA within 0.4 μm

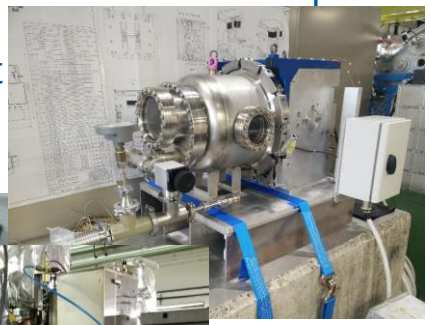






- **160 MeV** H^- charge exchange injection
- Acceleration to **2 GeV** with new main power

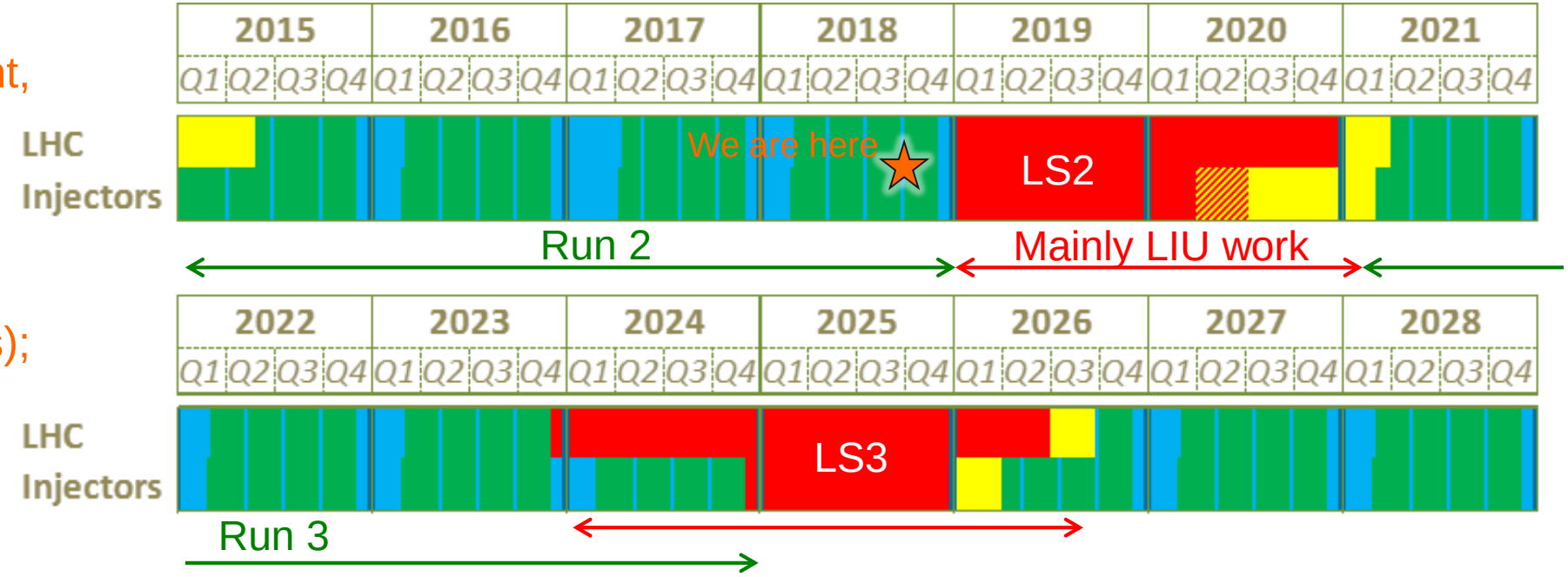
- **2 GeV** injection
- New **RF** equipment including broad-band feedback



General timeline

LHC Injectors Upgrade

- **Up to now**:
  - Equipment design, prototyping, procurement, advanced installation and testing;
  - Cabling and decabling;
  - Beam studies;
  - Surface work (CE, racks);
  - Linac4 commissioning
- **LS2:** Mostly LIU installation work
- **Run 3**: LIU beam commissioning through the injector chain



- LIU in a nutshell

- Performance of the LHC injectors
  - **LIU performance target for protons**
  - Highlights from 2018 (protons)
  - LIU performance target for Pb ions vs. current performance

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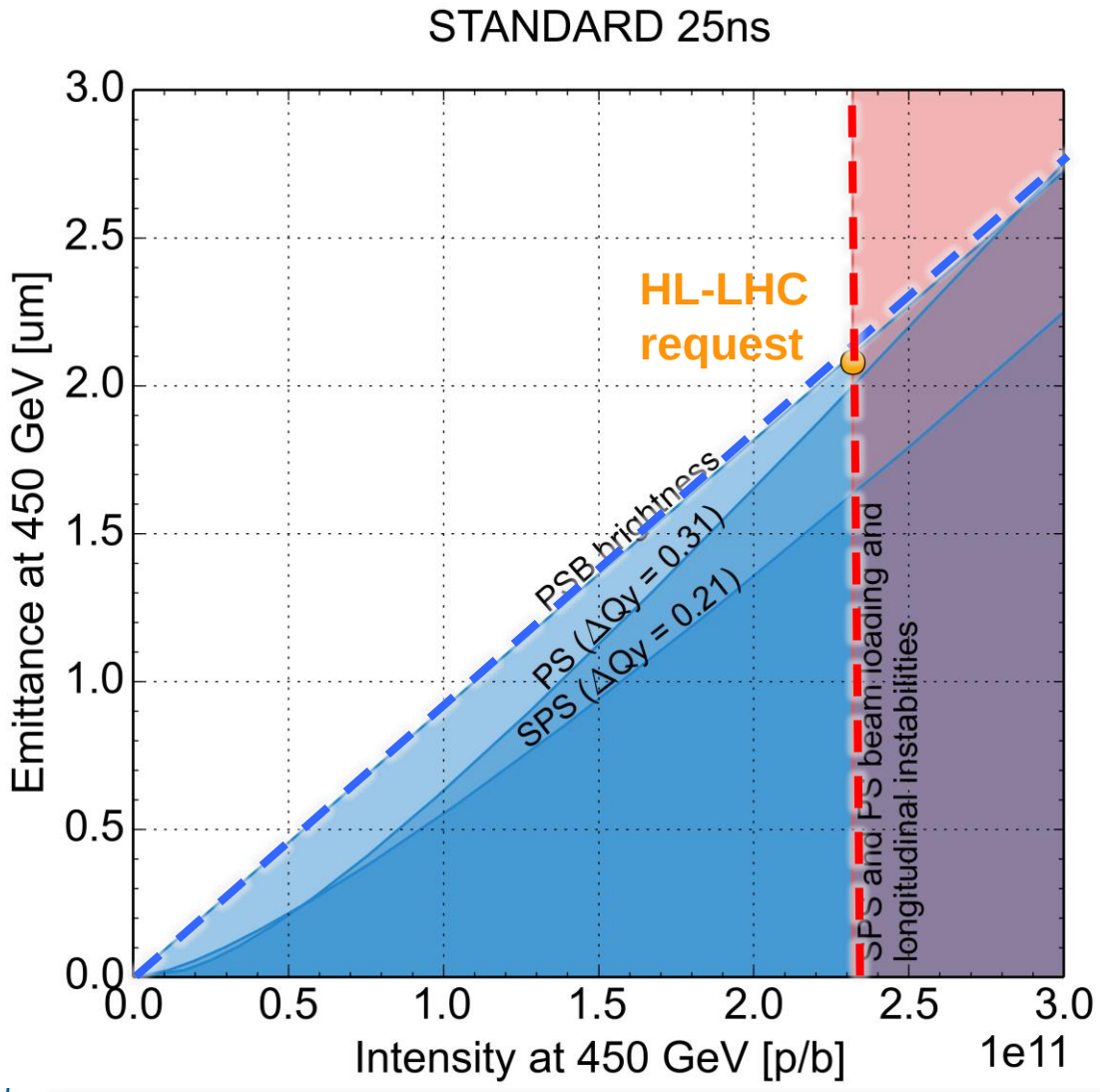
LIU performance reach for protons

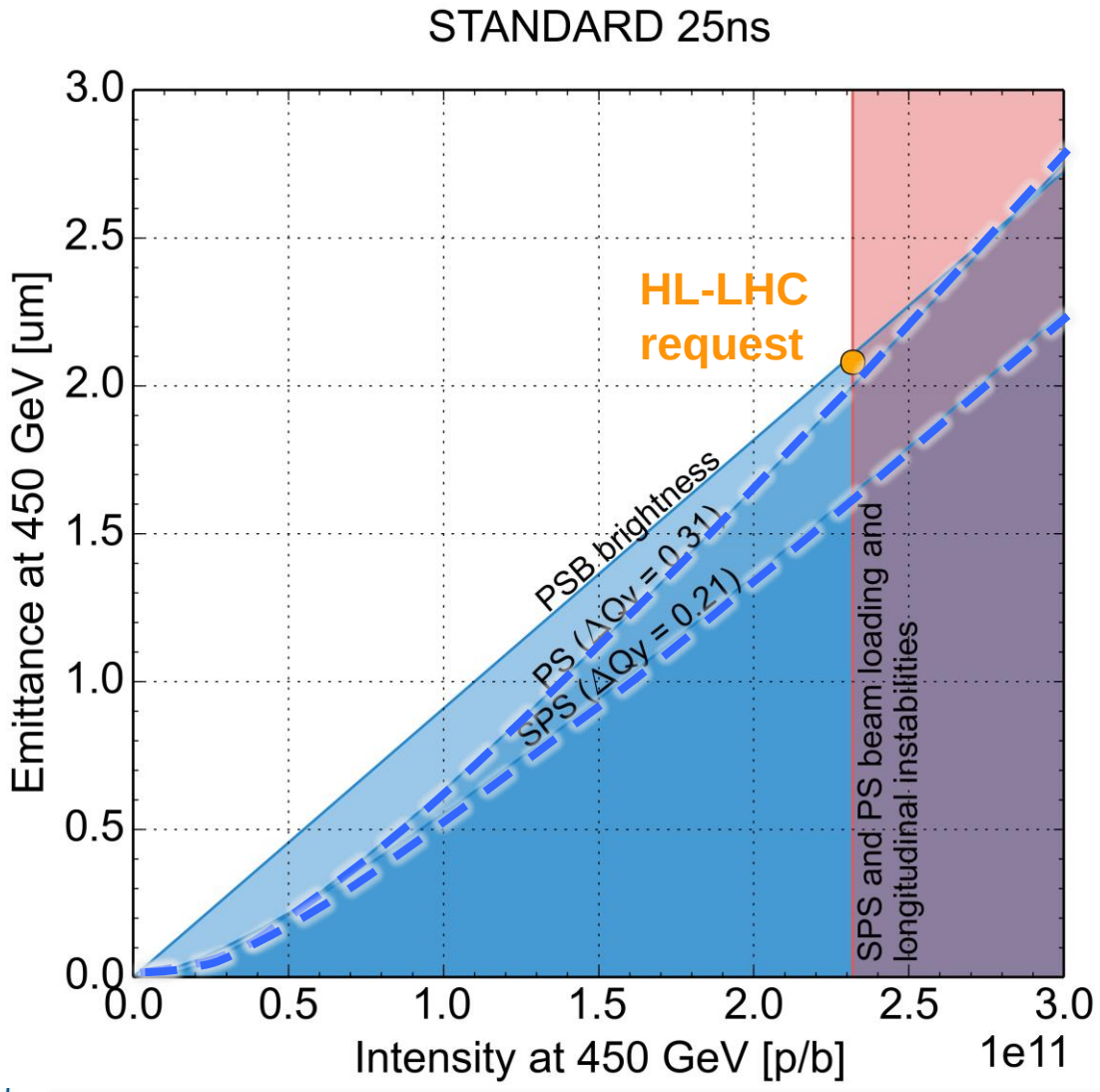


- Beam loss and emittance blow up budgets

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



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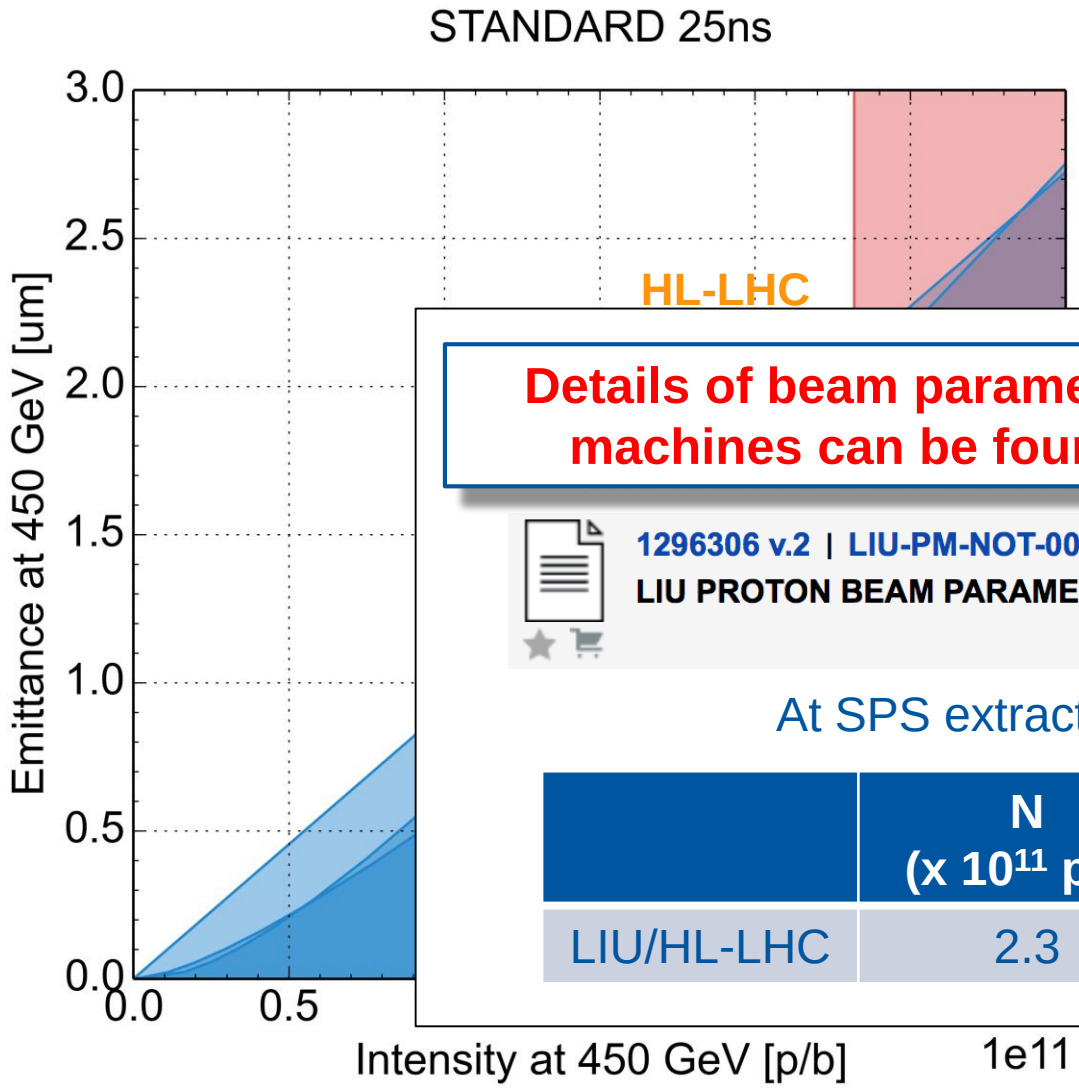
- PSB brightness + intensity limitations in PS and SPS inferred from simulations
- Space charge limitation curves in PS and SPS based on assumed tune spreads and optimised beam parameters at transfers

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

LIU performance reach for protons



Details of beam parameters at injection in all machines can be found in this document

1296306 v.2 | LIU-PM-NOT-0011 v.2 — Released — Public access

LIU PROTON BEAM PARAMETERS — *by Giovanni Rumolo*

At SPS extraction:

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

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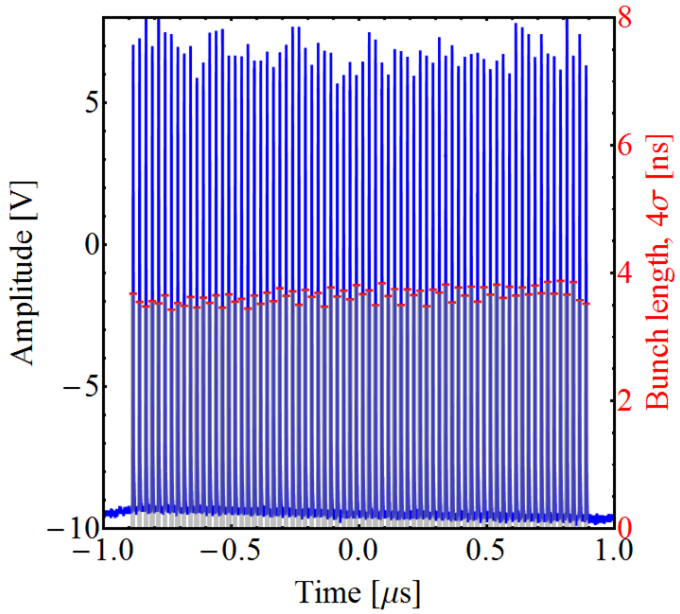
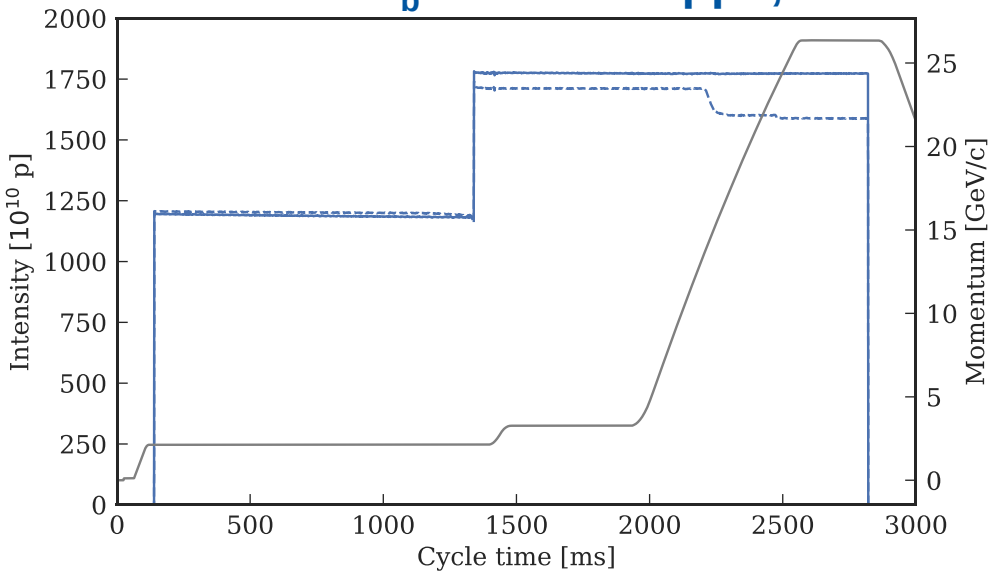
Highlights from 2018

- **PS intensity reach**
  - Longitudinal broadband feedback system installed in LS1 and commissioned in 2015-17
  - New power supplies for 40/80 MHz cavities and for power amplifiers of Finemet cavity installed in YETS 2017-18
  - Multi-harmonic feedback system on 40/80 MHz + use of 40 MHz system as Landau cavity for part of the cycle in 2018
  - Transverse optimisation along the cycle



N_b = 2.6 · 10^{11} ppb, ΔN/N < 5%



H. Damerau, A. Huschauer, A. Lasheen,
in LIU Beam Performance meeting, 20/09/2018

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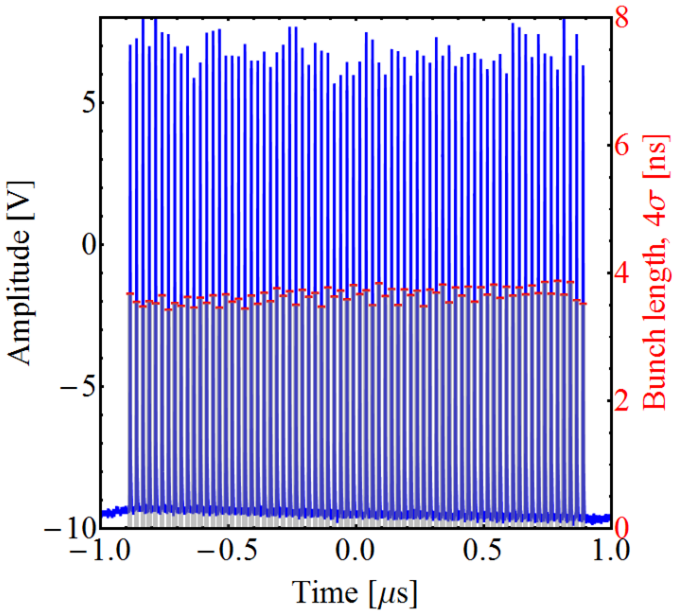
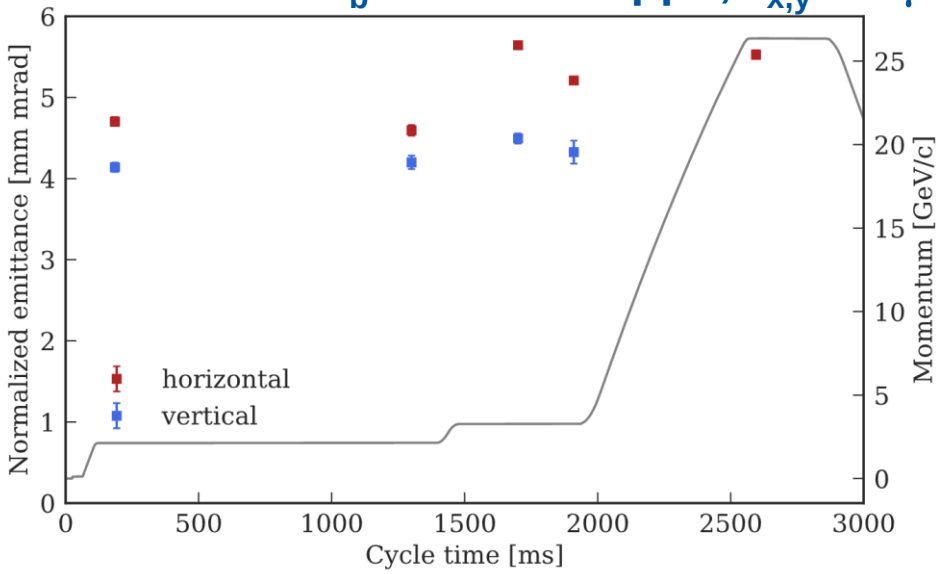


N_b = 2.6 · 10^{11} ppb, $\varepsilon_{x,y}$ ≈ 5 μm



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LHC Injectors Upgrade

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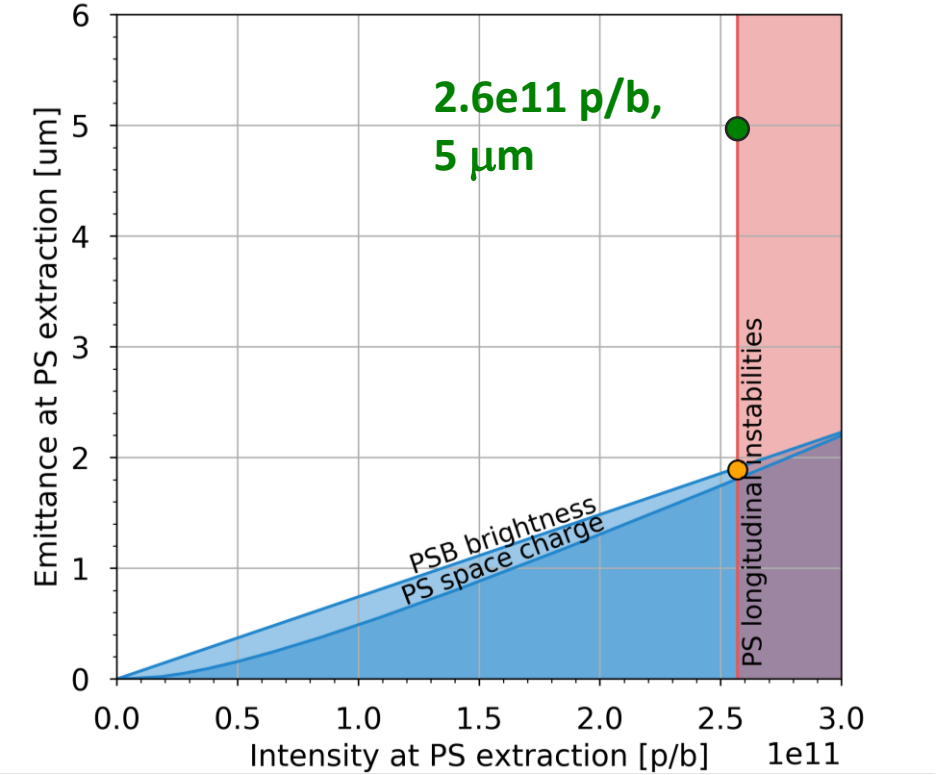


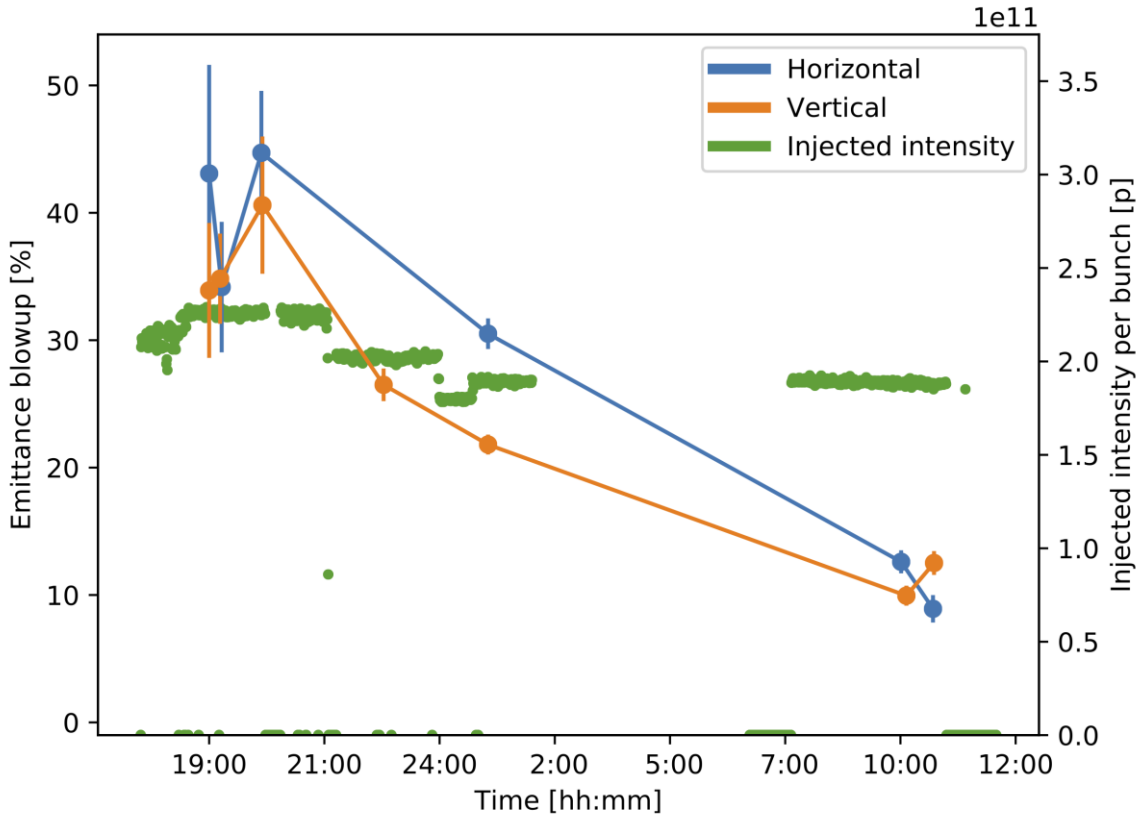
⇒ **Target intensity (2.6e11 p/b) achieved** out of the PS – a successful combination of already installed LIU equipment and intensive beam studies

⇒ Additional studies ongoing, e.g. on reproducibility

Highlights from 2018

LHC Injectors Upgrade

- **High intensity in the SPS**
  - Extensive studies at 26 GeV with **>2e11 p/b** to gain a deeper insight into beam stability and lifetime
  - Visible beam induced scrubbing with ~2e11 p/b → Baseline for e-cloud mitigation after LS2 in combination with QD coating



H. Bartosik, M. Carlà

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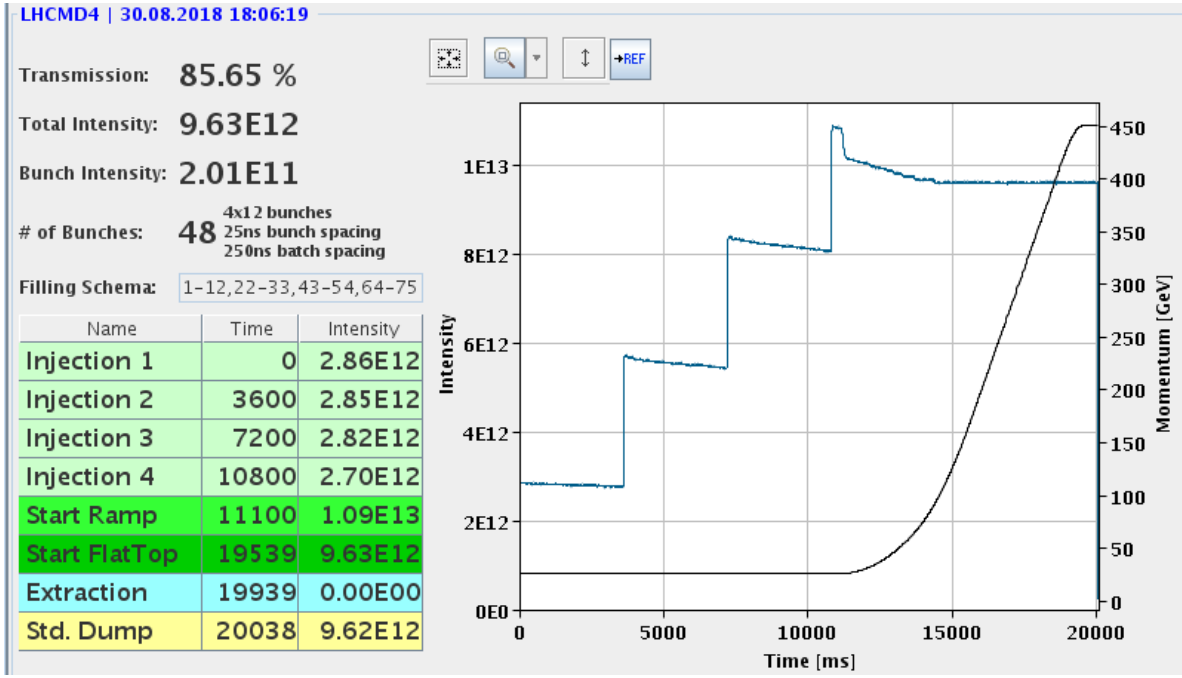
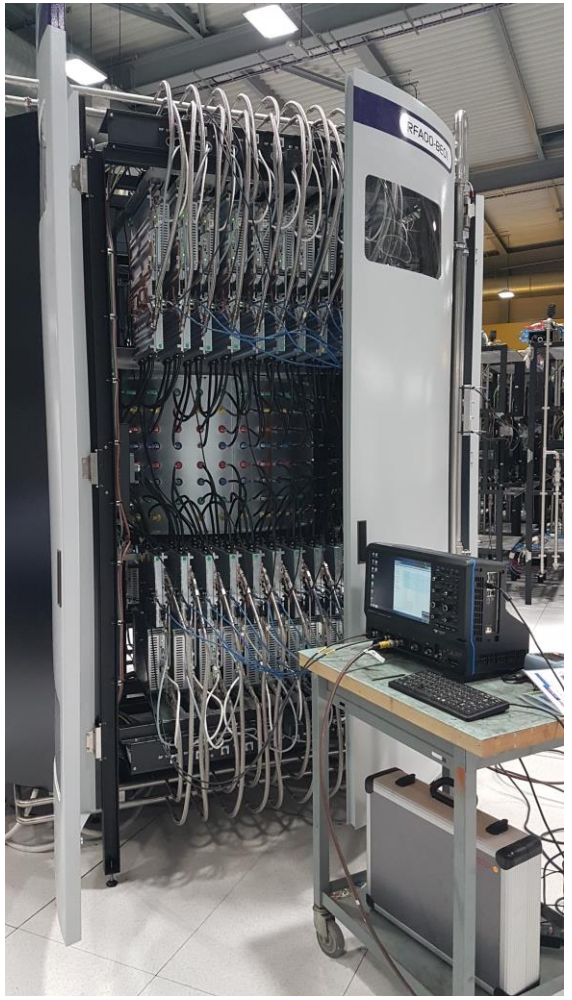
  - Visible beam induced scrubbing with ~2e11 p/b → Baseline for e-cloud mitigation after LS2 in combination with QD coating
  - Acceleration to 450 GeV of trains of 12 bunches with >2e11 p/b
    - One train up to 2.3e11 p/b
    - Four trains with 2e11 p/b extractable to LHC → Unique opportunity for LHC MDs **to sneak a peek into HL-LHC-like intensities**!



H. Bartosik, E. Shaposhnikova,
in LIU Beam Performance meeting, 20/09/2018

Highlights from 2018

- **Problems overcome with SPS 200 MHz RF system upgrade**
- Upgraded version of the Solid State Power Amplifiers in 80 module tower successfully passed the 1000 hours and short-circuit tests by end of August 2018
- Module series production launched
  - Now emphasis on quality assurance and control
- Firmly on track for **baseline installation** of the new power plant based on SSPA **during LS2**
  - According to present planning installation will finish at the end of 2019



E. Montesinos, C. Julie and BE/RF teams

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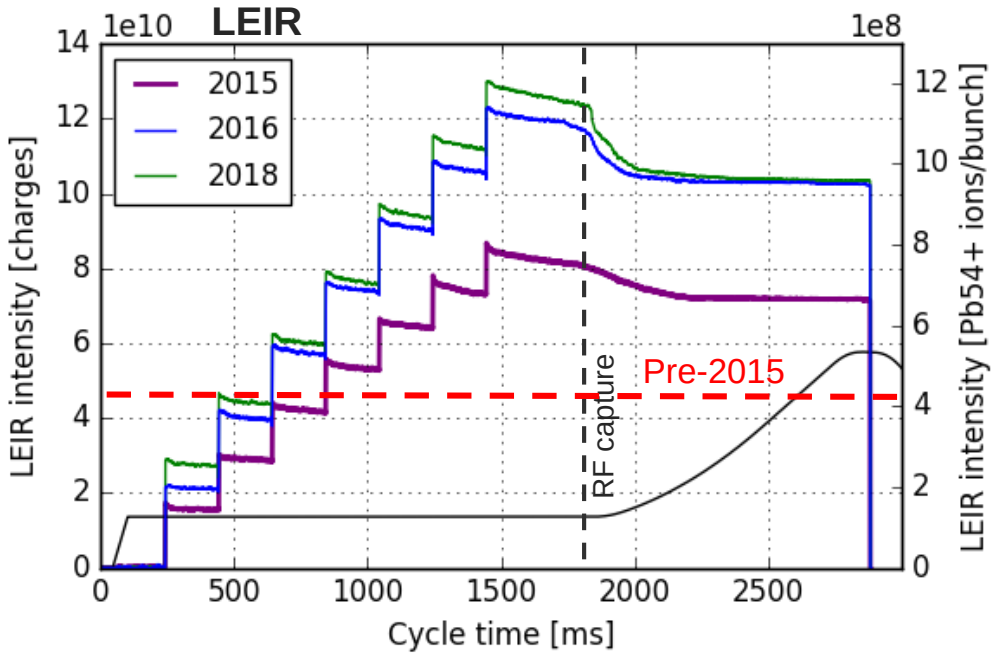
LIU performance reach for Pb ions

LHC Injectors Upgrade

- Intensive study program in 2015-16 across injector chain
  - Performance in **2015** outstanding thanks to improved LEIR performance
  - Performance in **2016** further improved thanks to continued work on Linac3 + LEIR
  - **2018**: Same performance as 2016 + significant progress in beam availability/reproducibility



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  - **2018**: Same performance as 2016 + significant progress in beam availability/reproducibility
- Baseline LIU Pb ion parameters compliant with HL-LHC request
  - Single bunch parameters at SPS extraction in 2016 match requested ones when including additional losses in SPS due to **longer injection plateau** and **slip stacking**
  - **Number of bunches** only achievable with slip stacking in the SPS (post-LS2)
  - 60% of integrated lumi target without slip stacking – even up to 70% if using 3 bunches with 75 ns spacing from PS

	N (x 10^8 ions/b)	ε (mm)
Achieved (2016)	2.2	1.5
LIU/HL-LHC	1.9	1.5

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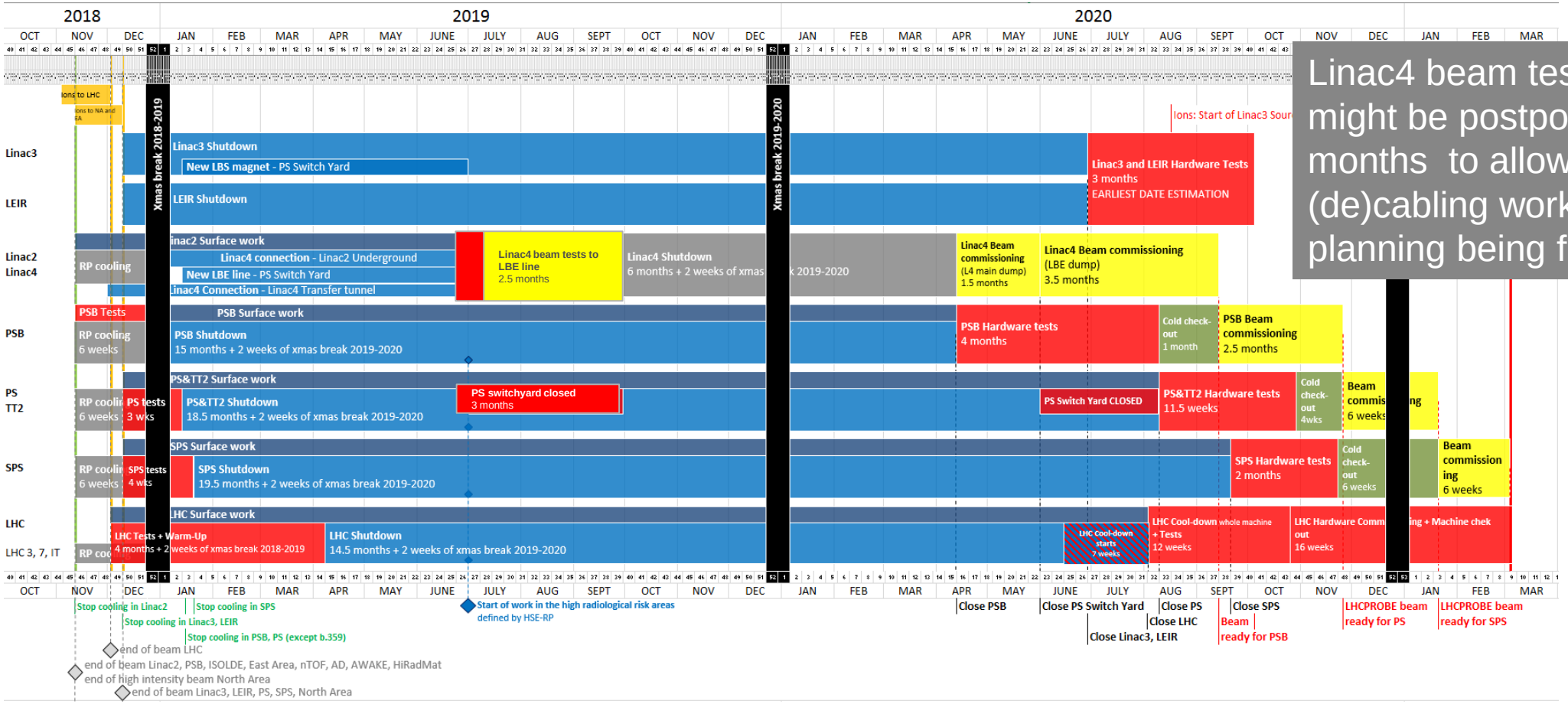
LS2 master schedule

J. Coupard, LS2 Days,
9-10 October, 2018

LHC Injectors Upgrade

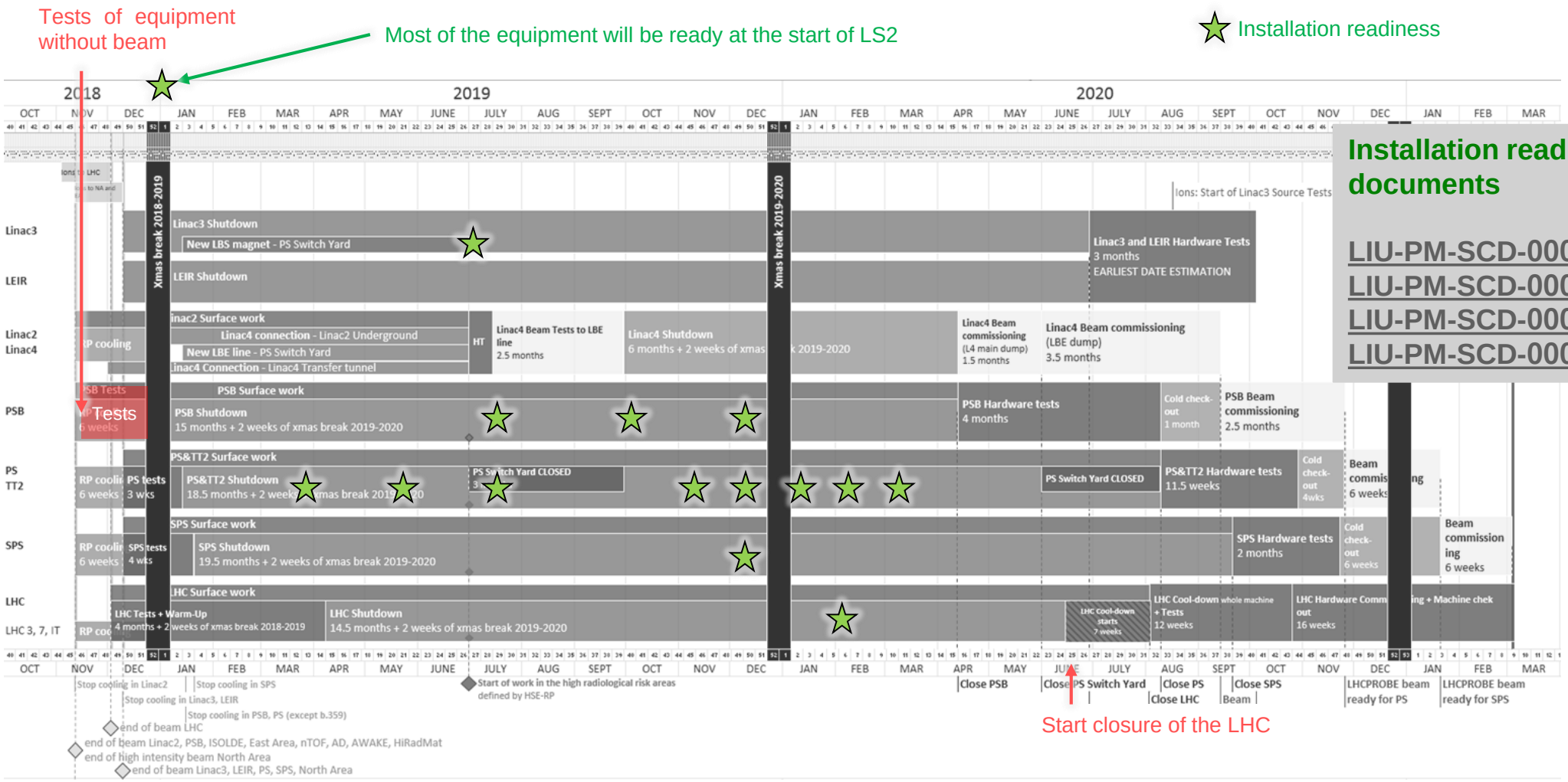
1687788 v.1.2 | ACC-PM-MS-0002 v.1.2 Released



Linac4 beam tests in 2019 might be postponed by two months to allow for (de)cabling work → New planning being finalised

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)

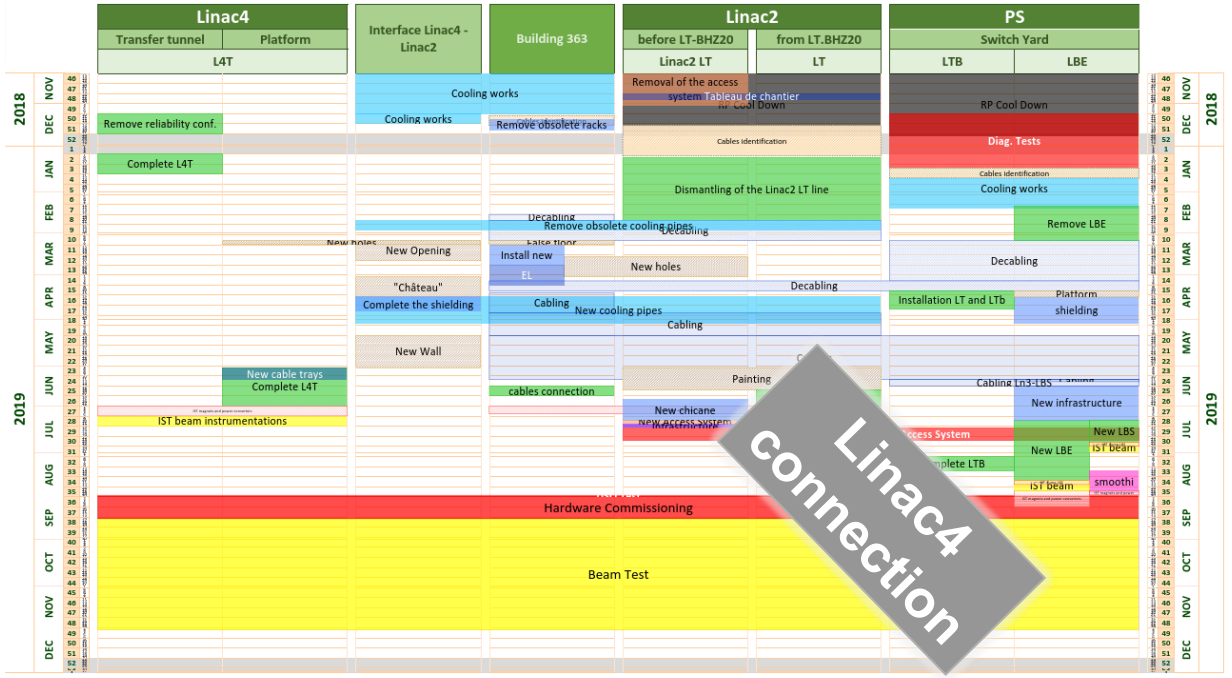
LIU installation during LS2

LHC Injectors Upgrade

- LIU schedule
  - LIU project globally on time, individual delays not expected to impact on completion date
  - LS2 linear schedules for all machines under work to correctly include resources and coactivity in some areas (within project and with other projects)

J. Coupard, EDMS documents

EDMS1892837 (SPS)
EDMS1421005 (PS & TT2)
EDMS1810496 (PSB)
EDMS2026782 (Linac4 connection)



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- LIU schedule
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- Next steps
  - Complete integration and Engineering Change Requests
  - Update the Installation Readiness dates, as needed, and adjust planning
  - Finalise placement and duration of the Linac4 beam tests in 2019
  - Resolve remaining conflicts due to coactivity or resources in the linear schedules

⇒ Complete **new LS2 schedule by mid November 2018** (start of LS2 for Linac2 and PSB)

Restart after LS2 and beam commissioning

LHC Injectors Upgrade

- Injectors restart in 2020 (Beam Commissioning Working Group)
  - Individual System Tests during the shut-down (will be included in LS2 Master Plan)
  - Hardware commissioning/cold check out preparation
    - **Check-list tool** deployed for all machines and extensively used (and debriefed) for 2018 restart
    - Integration of **LIU equipment** in the operational environment with requirements (e.g. availability of signals, applications to be developed)
  - Beam commissioning planning
    - Inclusion of **beam commissioning steps** in check lists
    - Analysis and development plan of the necessary **commissioning tools**
    - Ensure extensive **beam doc** and **pre-LS2 reference measurements**
    - Draw-up first part of the **Accelerator Schedules** with dates of availability of different beams for the various users in 2021 – year of recovery

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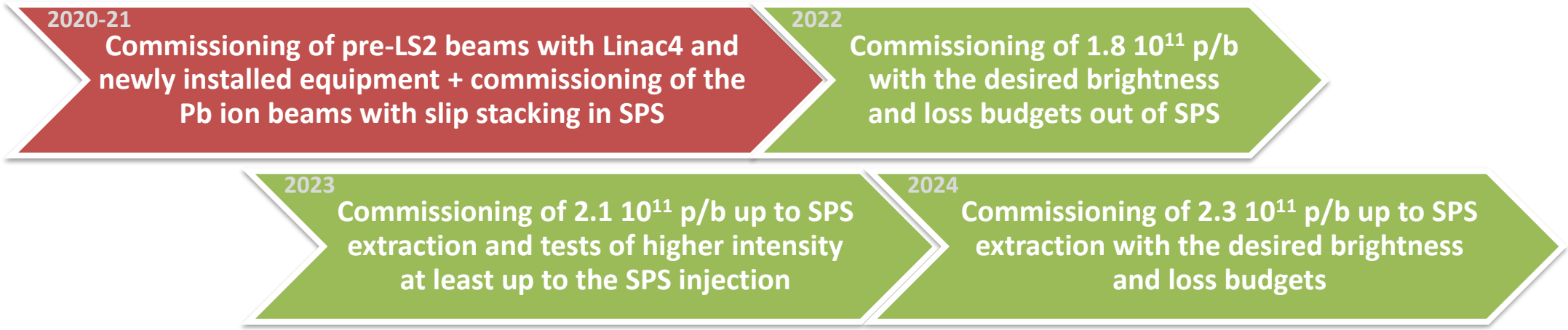
  - Hardware commissioning/cold check out preparation
  - Beam commissioning planning
- LIU beam commissioning plan: a smooth intensity ramp up



Conclusions: LIU ready for installation? Yes!

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

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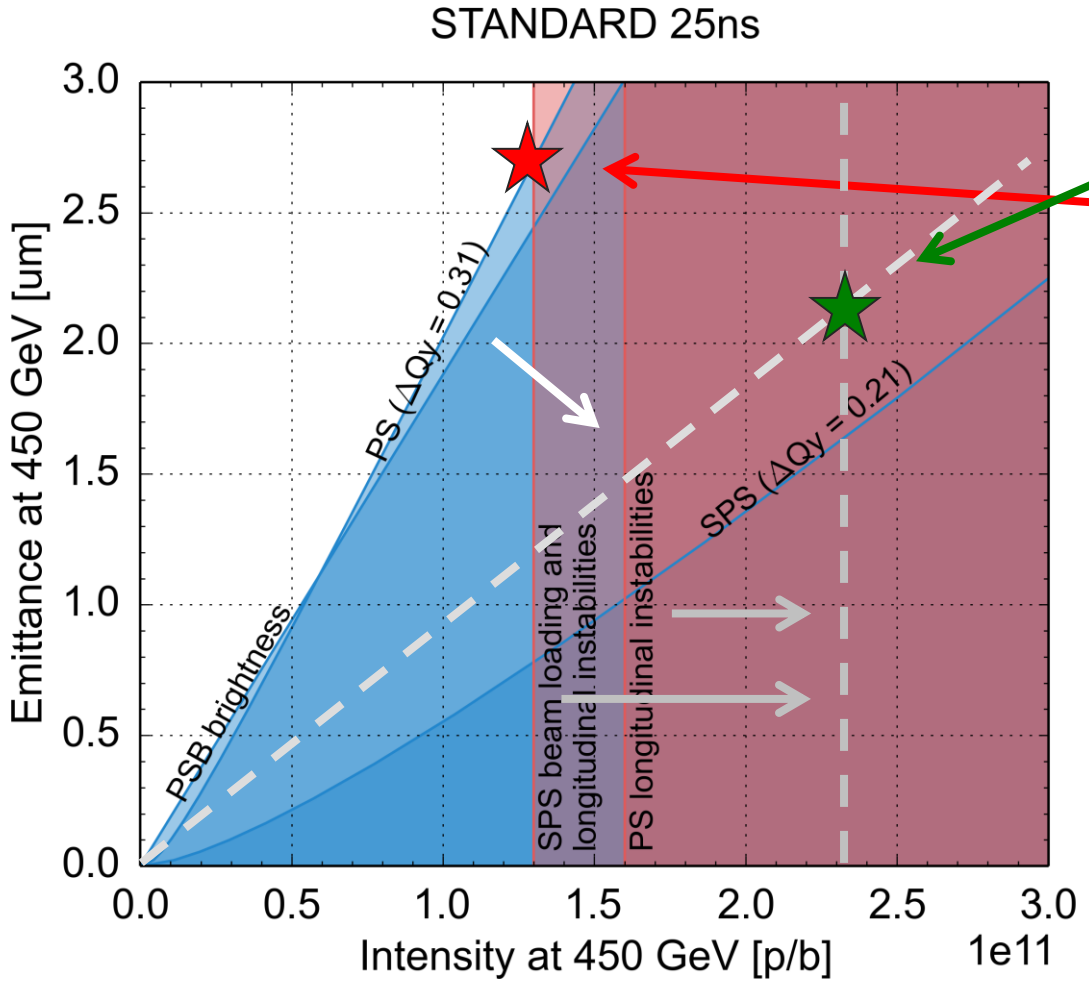
THANK YOU FOR YOUR ATTENTION

Present performance limitations

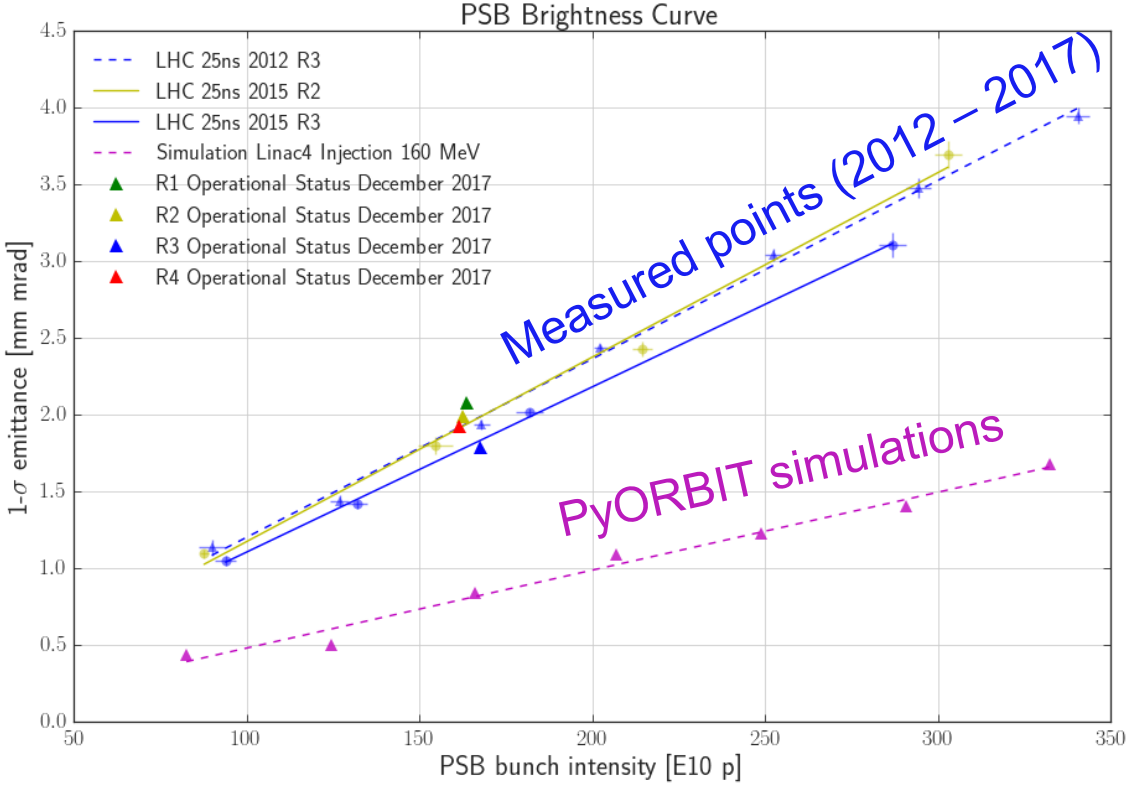


	N_b (x 10^{11} p/b)	$\varepsilon_{x,y,}$ (μm)
HL-LHC target	2.3	2.1
Present	1.3	2.7

- **PSB injection**: Brightness limited by efficiency of multi-turn injection process and space charge effects
- **PS and SPS injection**: Brightness limited by space charge – ΔQ<0.31 (PS) and 0.21 (SPS), to limit beam degradation (**H. Bartosik's talk**)
- **PS cycle**: Bunch intensity limited by longitudinal coupled bunch dipolar instability
- **SPS cycle**: Bunch intensity limited by RF power, longitudinal coupled bunch instability

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



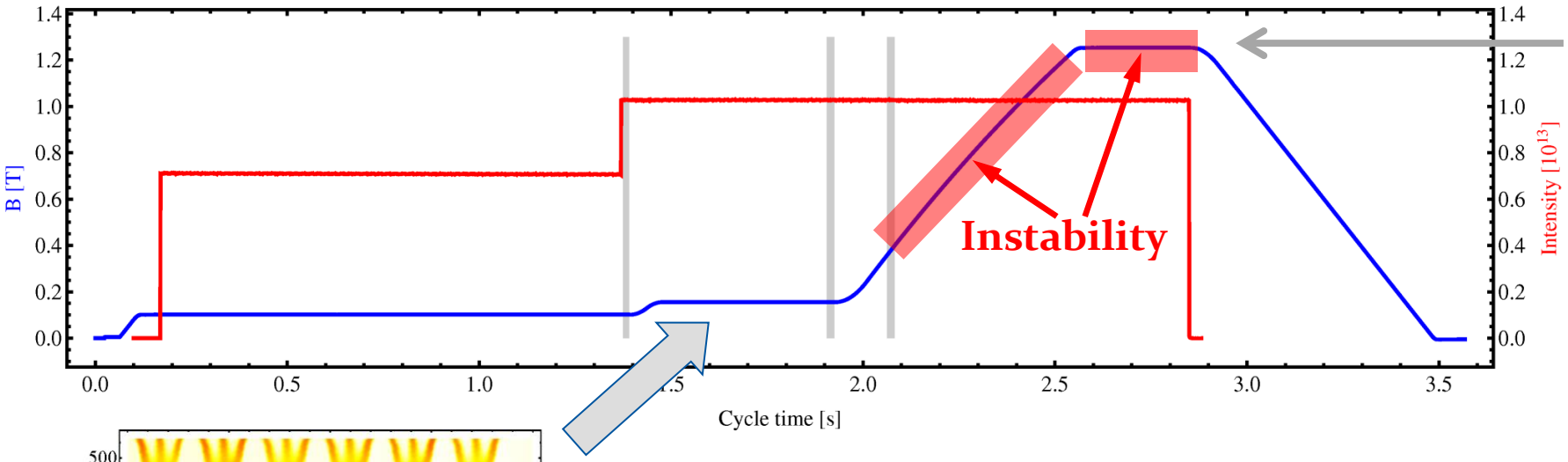
$$\left[\frac{(\beta\gamma^2)_{160\,\mathrm{MeV}}}{(\beta\gamma^2)_{50\,\mathrm{MeV}}}\right] = 2$$

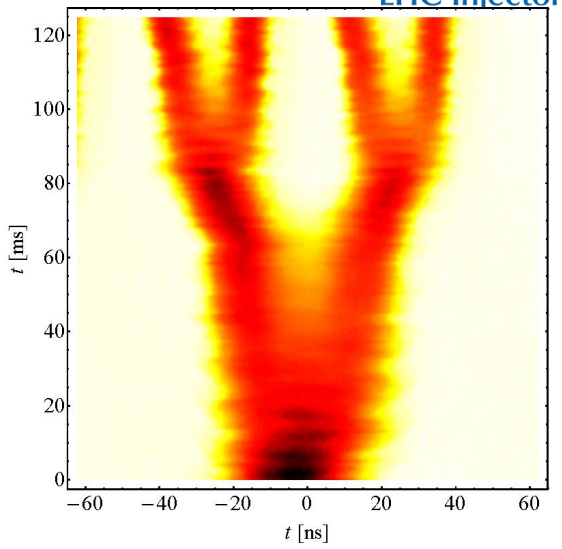
Lifting the brightness limitations

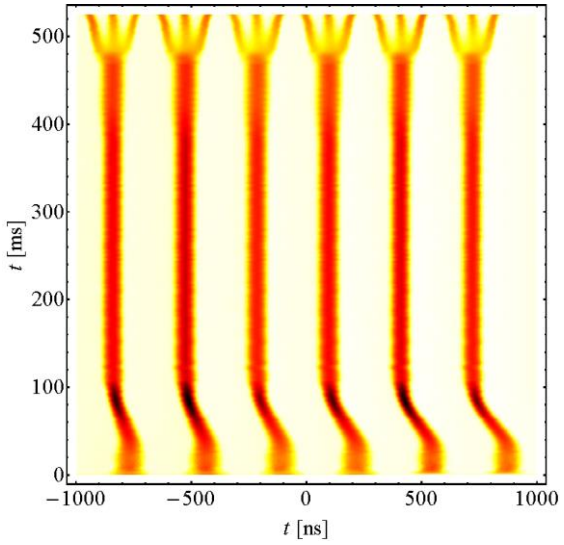
- Halve the slope of the **PSB brightness line**
  - 160 MeV H^- charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2
- Reduce **space charge at PS injection** to accommodate same tune spread as current LHC beam (ΔQ_y=*-0.31*)
  - Increase of PS injection energy from 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





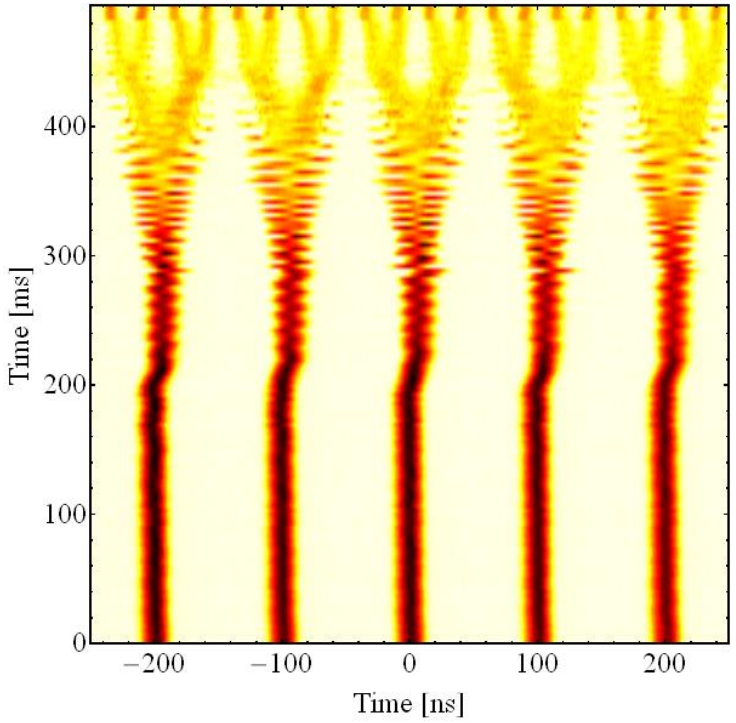


- Bunch current limited to **1.6e11 p/b at extraction**
- Above 1.6e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
  - Dipolar oscillation, caused by **10 MHz RF system impedance** (as found also in simulations)

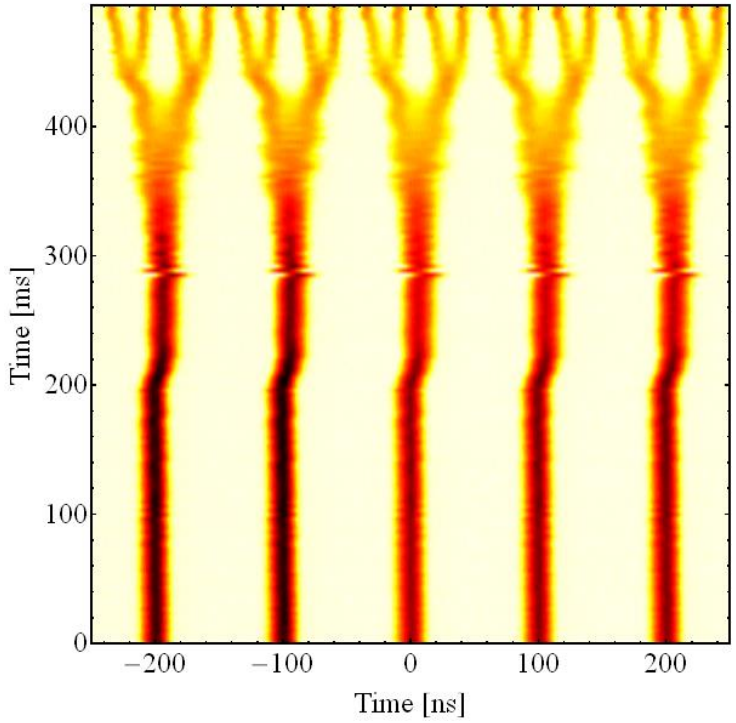
Lifting the PS intensity limitation

- **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)



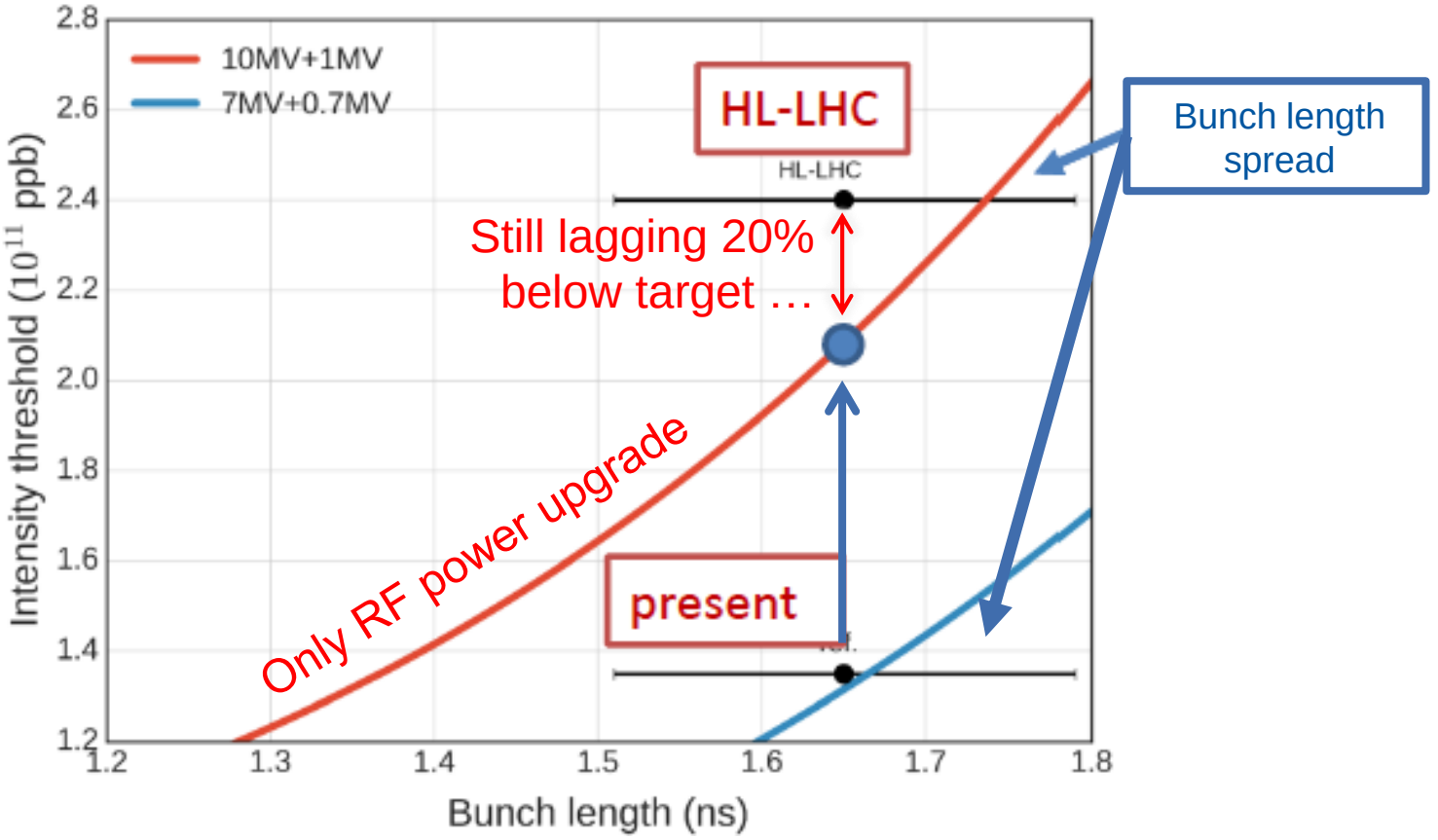
Lifting the PS intensity limitation

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

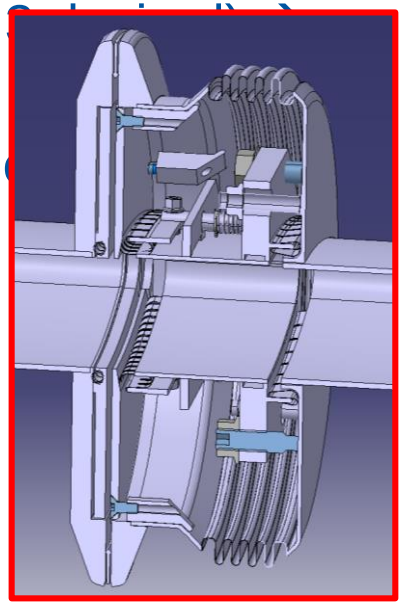
Lifting the SPS intensity limitation

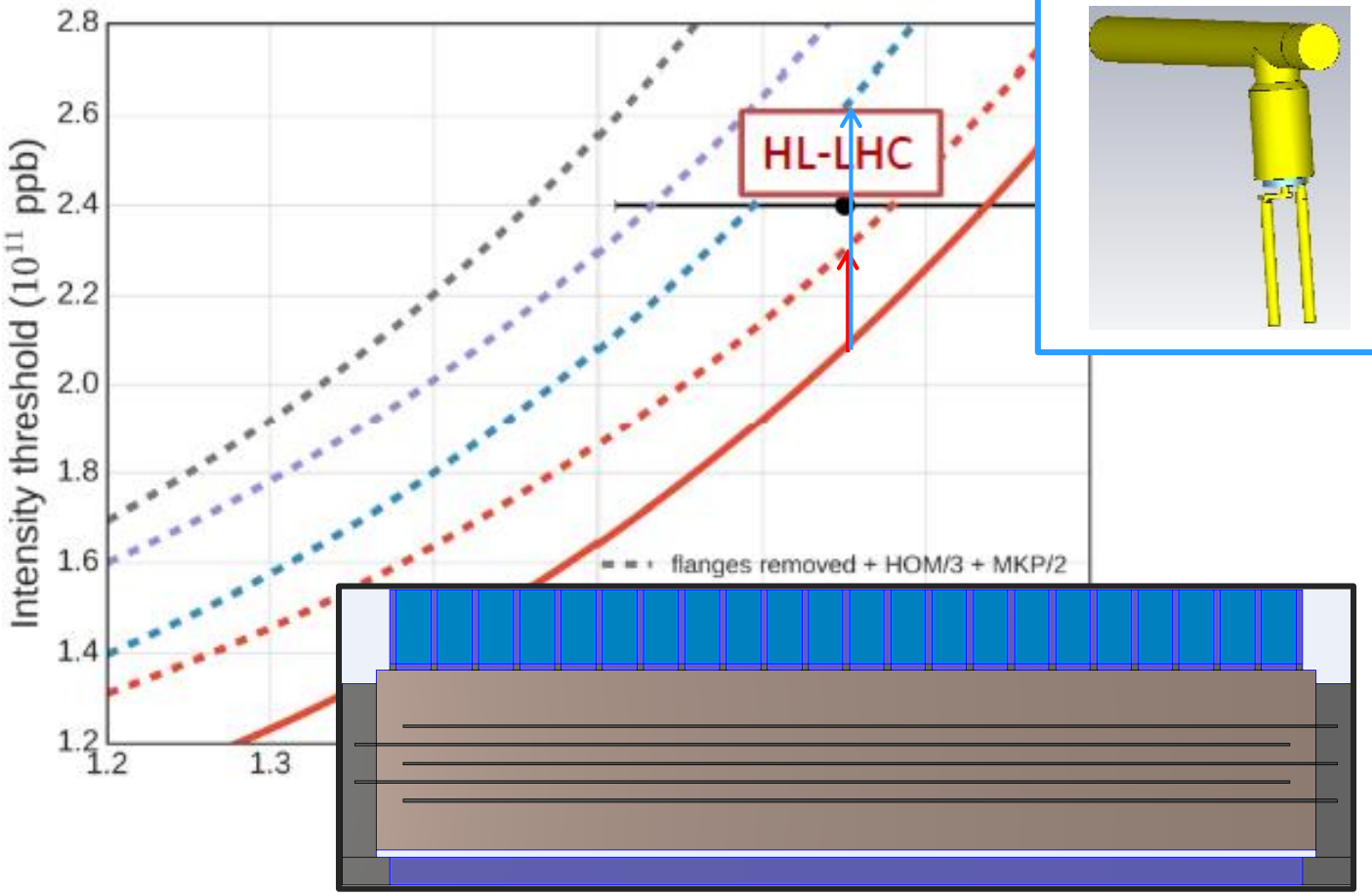
- **Beam loading** in the present 200 MHz TW RF system – intensity limited to about 1.3e11 p/b
- **Longitudinal instabilities** during ramp with very low threshold currently cured by
  - 800 MHz RF system in bunch shortening mode
  - Controlled emittance blow-up (with constraint of 1.7 ns bunch length 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 [illegible]) → baseline for LIU
  - Serigraphy on the kickers MKP



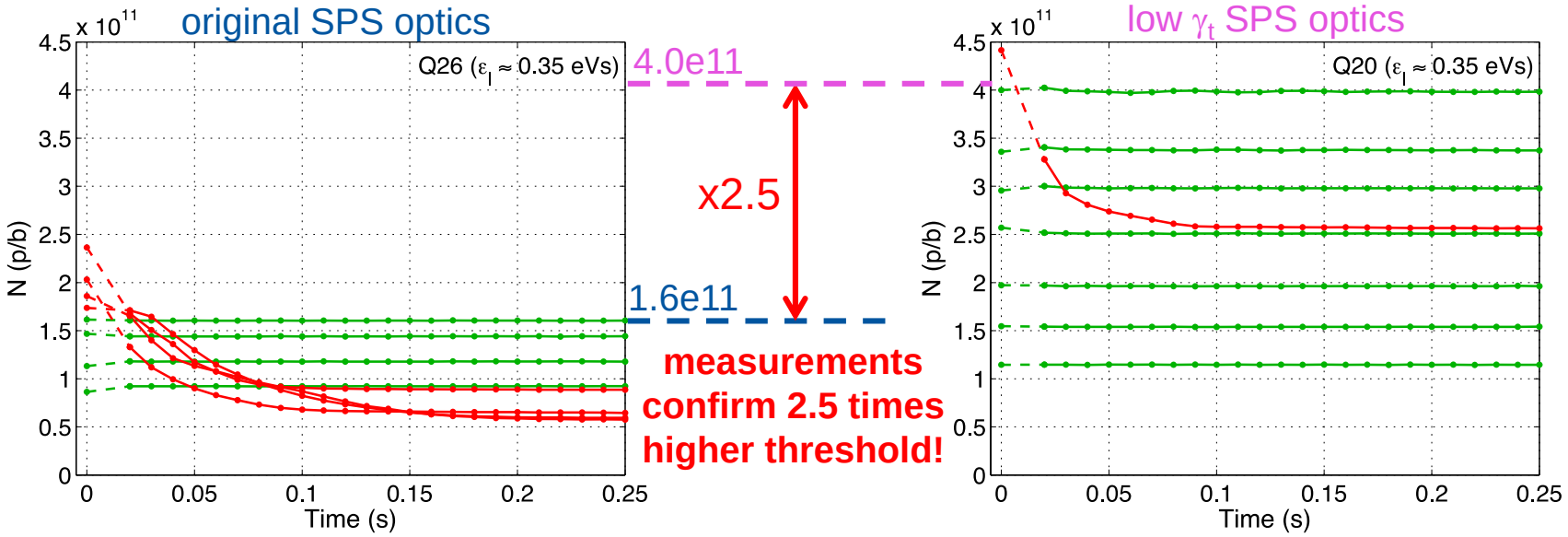


new HOM coupler

Other SPS intensity limitations?

LHC Injectors Upgrade

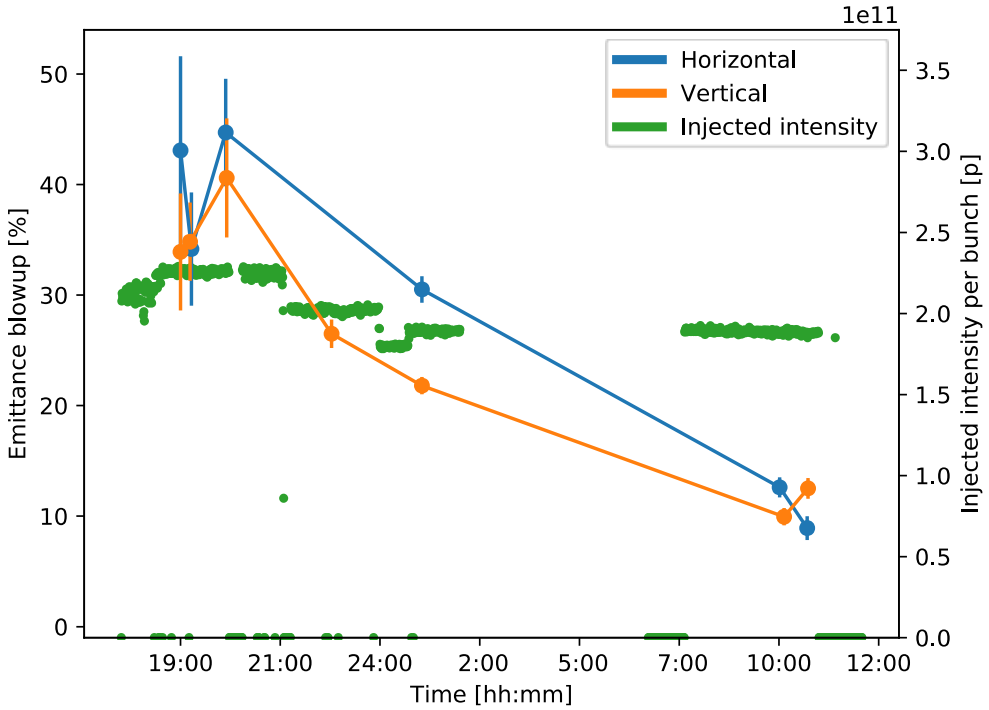
- **Transverse Mode Coupling Instability (TMCI)** threshold was raised from 1.6e11 p/b to 4e11 p/b when switching to a low gamma transition (γ_t) optics

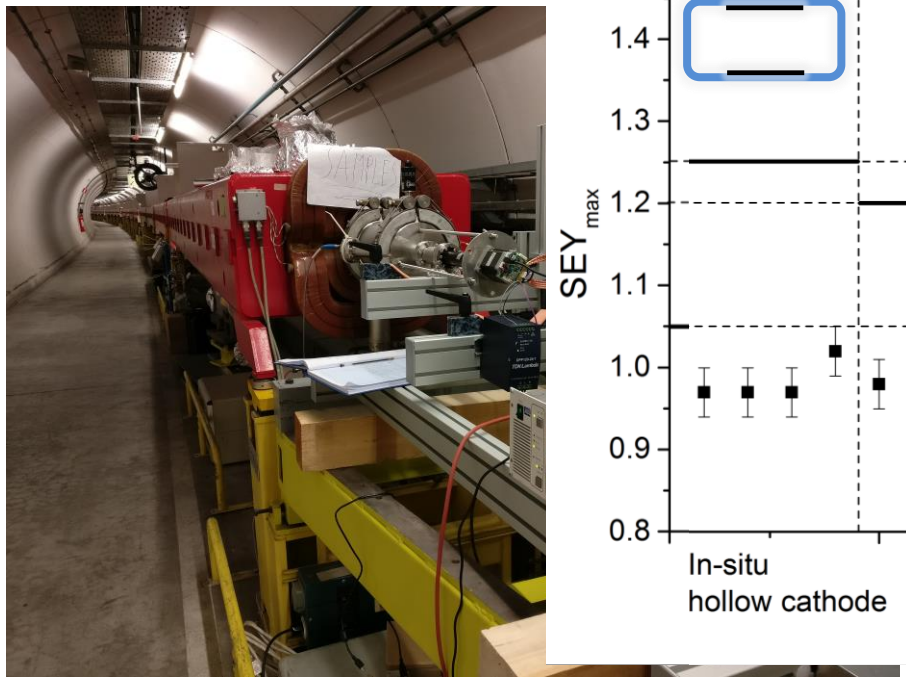


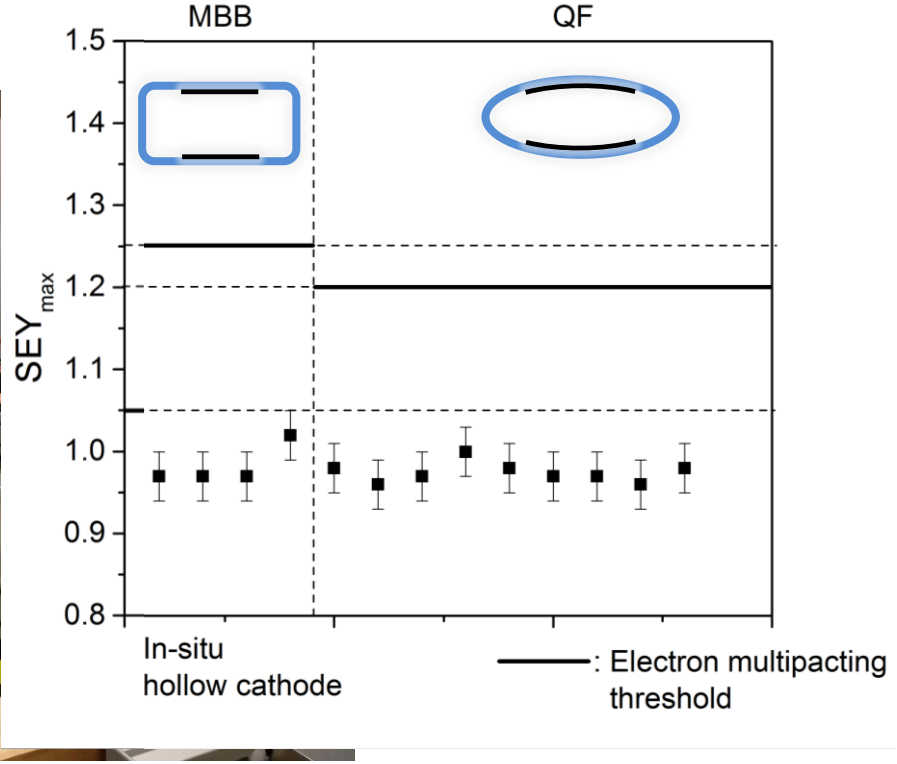
Other SPS intensity limitations?

LHC Injectors Upgrade

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

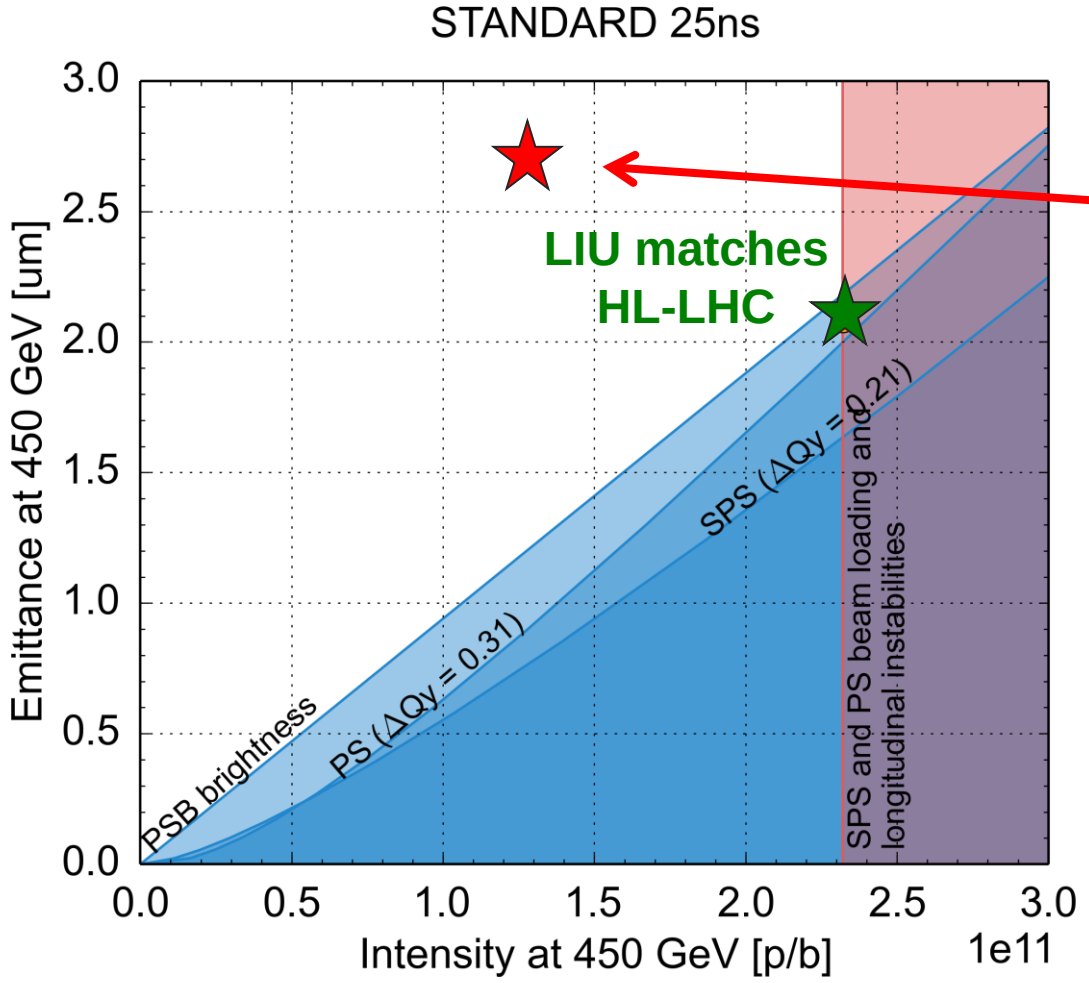






Summary: Future LIU performance

LHC Injectors Upgrade



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

- **PSB injection**: from Linac4
- **PS injection**: 2 GeV, larger longitudinal emittance
- **PS cycle**: Longitudinal coupled bunch feedback system, impedance reduction
- **SPS cycle**: RF power upgrade, longitudinal impedance reduction, beam scrubbing & partial a-C coating, low γ_t optics

LS2 schedule: Critical path

LHC Injectors Upgrade

Tests of equipment without beam