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LHC Injectors Upgrade

LHC Injectors Upgrade Workshop

Montreux, 13-15 February 2019

LHC Injectors Upgrade

LIU beam performance reach

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Acknowledgements: R. Alemany, M. E. Angoletta, F. Asvesta, P. Baudrenghien, E. Benedetto. G. Bellodi, F. Bertin, A. Blas, T. Bohl, K. Cornelis, G. P. Di Giovanni, A. Findlay, V. Forte, B. Goddard, S. Hancock, K. Hanke, S. Hirlander, W. Höfle, A. Huschauer, G. Iadarola, V. Kain, G. Kotzian, D. Küchler, K. Li, E. Mahner, M. Meddahi, B. Mikulec, J. Molendijk, Y. Pappaphilippou, G. Papotti, J. Repond, A. Saa Hernandez, M. Schwarz, R. Scrivens, G. Sterbini, F. Tecker, H. Timkó, F. Velotti and the Operations Teams of Linac3, LEIR, PSB, PS, SPS

Overview

- Beams for HL-LHC
- LIU baseline for protons
  - Removing the present limitations
  - Sensitivity of HL-LHC luminosity to beam parameters
- Performance with protons
  - Linac4, PSB, PS and SPS
- Performance with lead ions
  - Linac3, LEIR, PS and SPS
- Conclusions
  - Main challenges
  - Progress summary

Menu of beams for HL-LHC

	Beam type	
1.	72b standard	• Nominal beam with up to 4 × 72b from SPS
2.	72b + 24b mixed	• Optimized version with more bunches in LHC • Mixed 24b + 72b + 72b from SPS ( )
3.	48b BCMS	• Up to 5 × 48b, no advantage for 6 × 48b
4.	8b+4e mixed with BCMS	• Mixed 2 × 56b + 3 × 48b and 1 × 56b + 1 × 48b • Reduce electron cloud heat load
5.	80b + 32b	• 4 × 80b and 1 × 32b + 1 × 80b ( )

Back-up

→ Mixed schemes might require improving operational flexibility of injectors

→ Shorter fills have impact on injector operation

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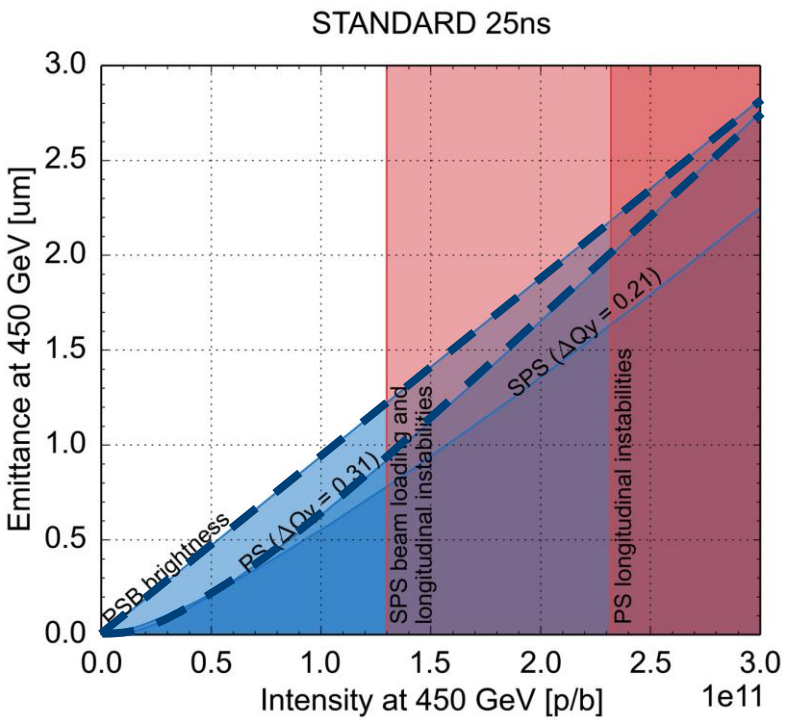
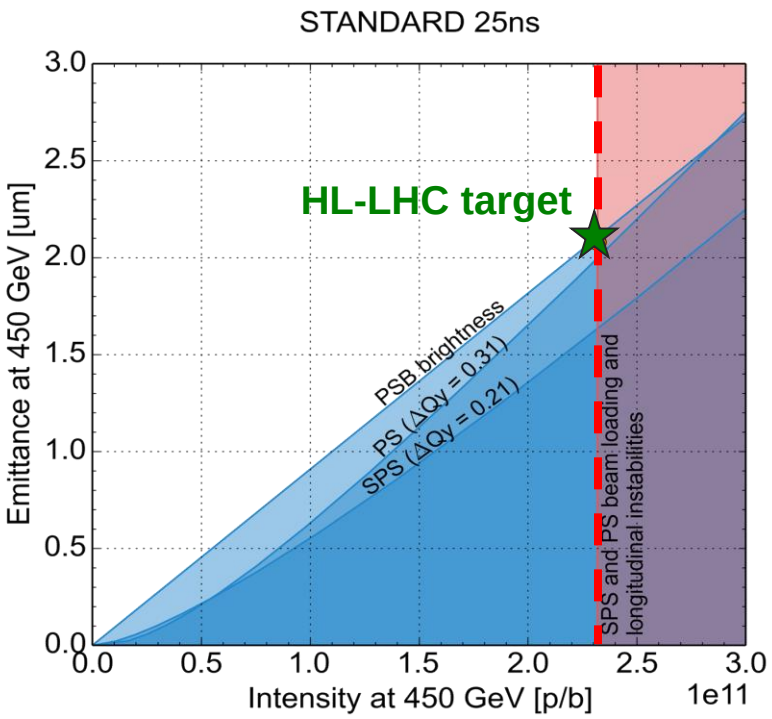
LIU performance reach for protons



- **Linac4-PSB connection**
  - → Reduced space charge, double PSB brightness
- **PS upgrade**
  - → 2 GeV injection + large longitudinal emittance transfer from PSB
  - → RF feedbacks to suppress longitudinal instabilities and reduce transient beam loading

LIU performance reach for protons



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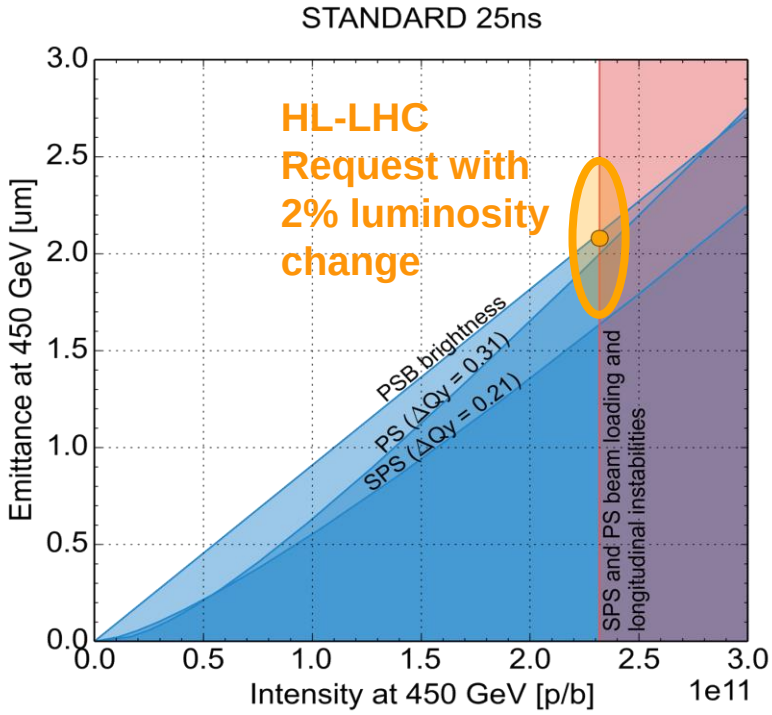
- **PS upgrade**
  - → 2 GeV injection + large longitudinal emittance transfer from PSB
  - → RF feedbacks to suppress longitudinal instabilities and reduce transient beam loading
- **SPS upgrade**
  - → 200 MHz RF power upgrade and new LLRF
  - → Q20, scrubbing + partial (staged) SPS aC coating
  - → New beam dump & transfer line collimators
  - → Longitudinal impedance reduction (flange shielding and HOM reduction)

Parameter sensitivity of HL-LHC



- 2% luminosity loss of nominal can be caused by

Injectors

→ $0.13 \cdot 10^{11}$ p/b less at constant brightness

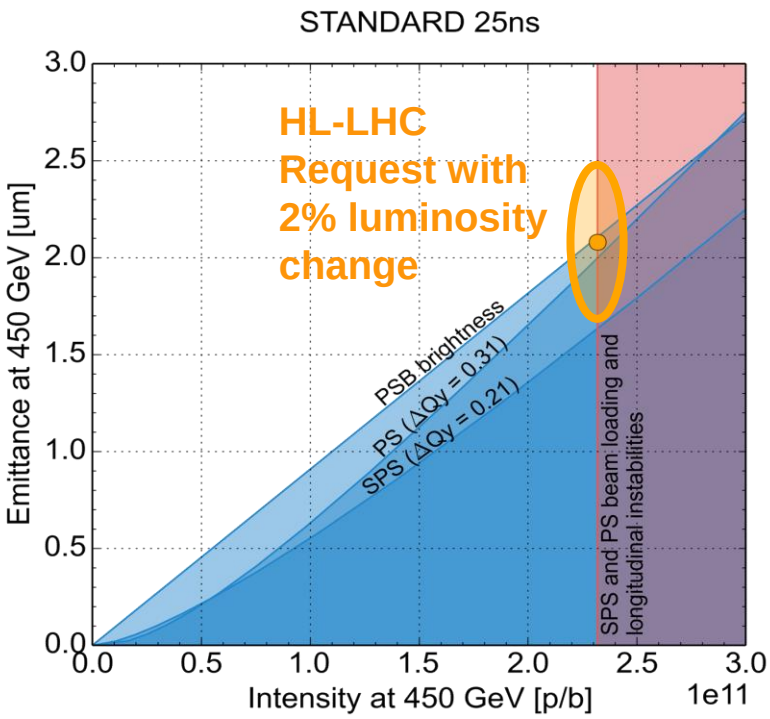
→ 0.4 μm larger emittance at constant intensity

→ 14 minutes turn around time

→ β^* increase by 8 cm

→ 1% efficiency reduction

Parameter sensitivity of HL-LHC



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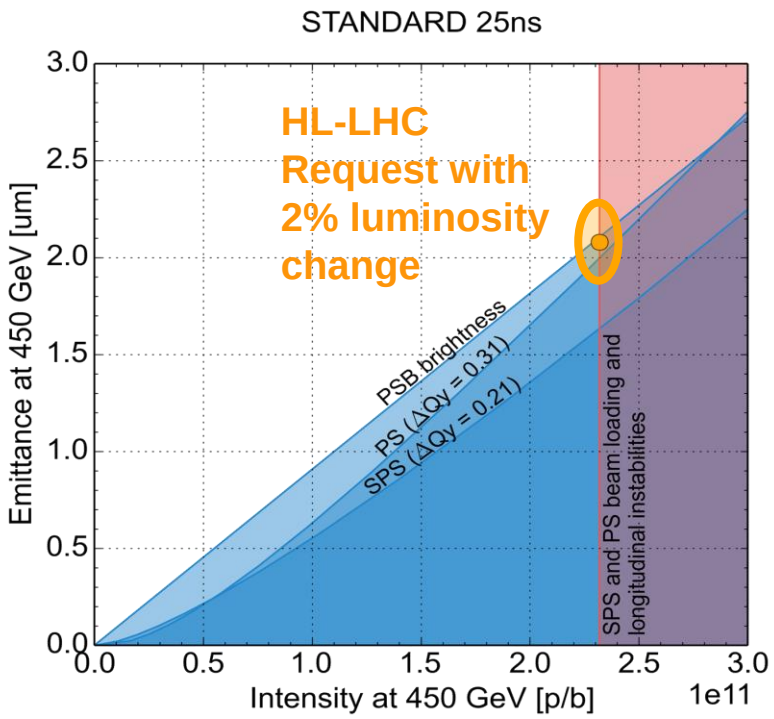
Trade off performance with speed to serve LHC?

Parameter sensitivity of HL-LHC



- 2% luminosity loss of ultimate can be caused by

Injectors

→ $0.09 \cdot 10^{11}$ p/b less at constant brightness

→ 0.2 μm larger emittance at constant intensity

→ 10 minutes turn around time

→ β^* increase by 4 cm

→ 1% efficiency reduction

Trade off performance with speed to serve LHC?

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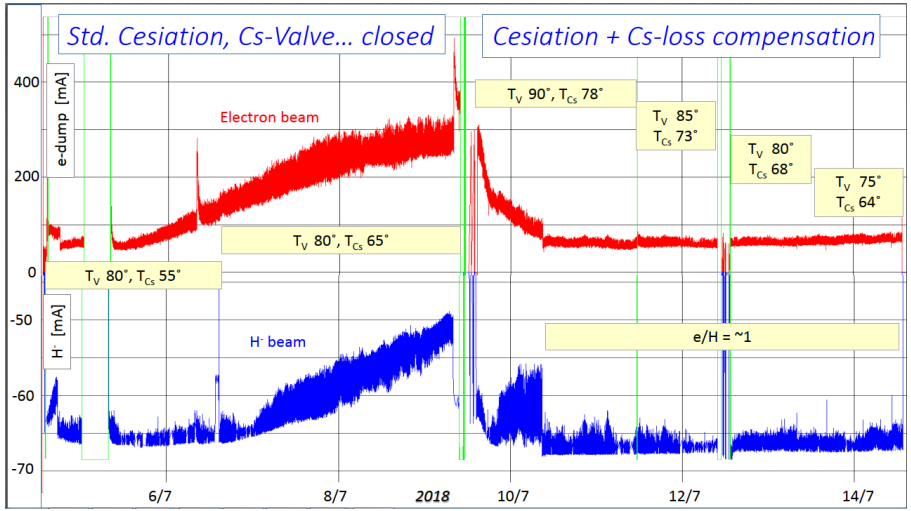
Linac4

- ✓ Reliable operation with 25 mA current after RFQ ensures 1.25 · 10^{13} p/ring
  - → All pre-LS2 beams can be reproduced
  - → Reproducible transmission between 3 MeV and 160 MeV
  - → Continuous source cesiation demonstrated to improve source stability



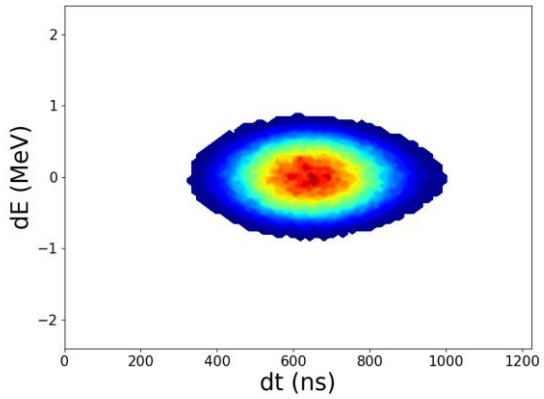
Challenges

- → Position and energy variations along the pulse → LLRF regulation
- → Current flatness and shot-to-shot reproducibility → Further tests during LBE run
- → Make 45 mA from available by 2023

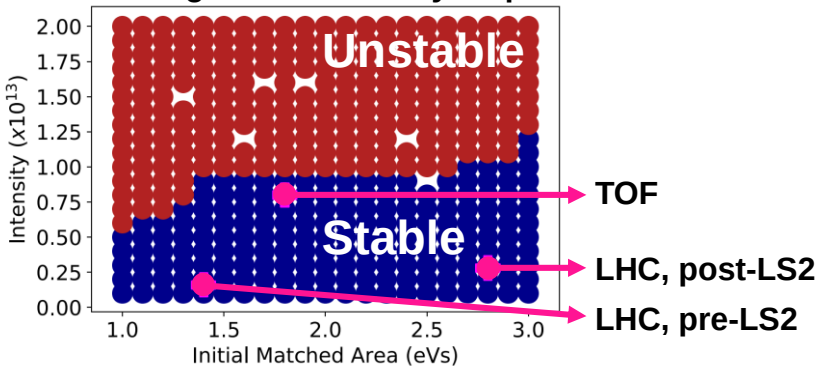
PSB longitudinal

- Finemet technology fully demonstrated before LS2
  - → Reliability runs since 2015
- Blow-up technique based on phase noise validated and well understood
  - → Improved control of final distribution
  - → Reliability run in 2018
- Impedance of new Finemet RF no issue for LHC-type beams
- Potential concerns with
  - → Very high-intensity beams
  - → Operational complexity of multi-harmonic feedback

Blow-up with phase noise

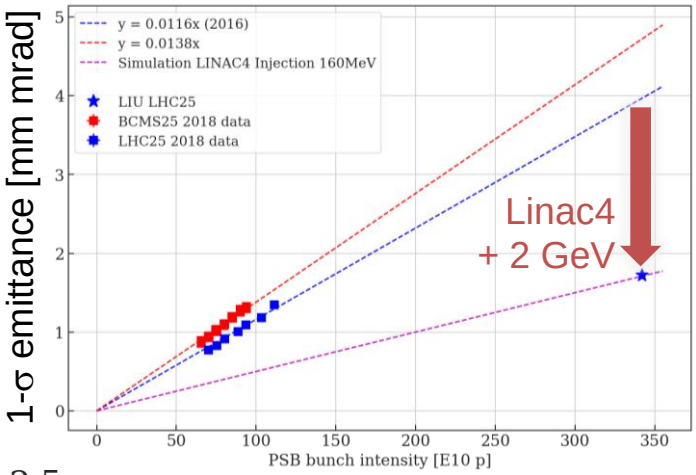


Longitudinal stability map

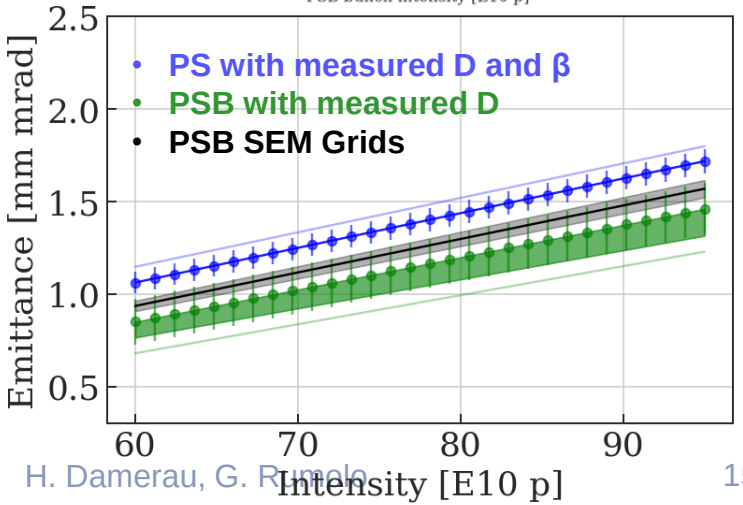


PSB transverse

- **Brightness curves** with Linac2 well reproducible during run 2
  - → Doubled brightness with Linac4 + 2 GeV confirmed with simulations



- Progress with understanding of emittance
  - → Measured β and D, beta beating
  - → **Deconvolution for large ε_l beams**
- Prototype wire scanner validated
- Detailed studies of H^- injection

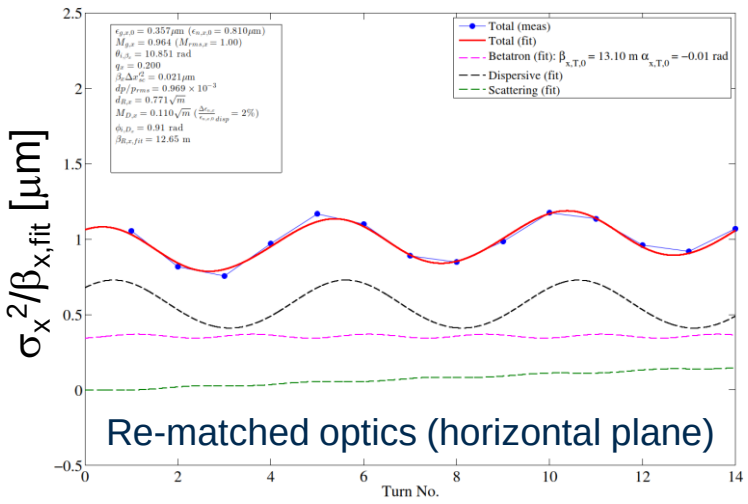


Key studies in PSB

	Activity	Timeline
Transverse	Conclude on transverse emittance measurements as input for brightness curve	Q2/2019
	Establish common model for space charge simulations, including imperfections, to define optics choices at injection	Q3/2019
	Study impact of unmatched termination of extraction kicker (horizontal instability)	Q3/2019
	Prepare tool to optimize alignment of all rings after LS2	Q1/2019
Longitudinal	Controlled longitudinal blow for longitudinal shaving	Q3/2019
	Definition of longitudinal parameter sets for all beams	Q3/2019
	Renovation and possible upgrade of longitudinal Tomography	Q1/2020
	Longitudinal emittance model after LS2	2020

PS injection

- Mismatch in PSB-PS transfer line
  - → Important dispersion mismatch
  - → Almost no betatronic mismatch
- Studies of systematic errors
  - → Measured optics functions (β and D)
- Deployment of turn-by-turn SEM grids
  - → Turn-by-turn beam size essential
  - → Electronics and software ready in 2018
- Extensive kicker pulse measurements
  - → Ripple in expected range

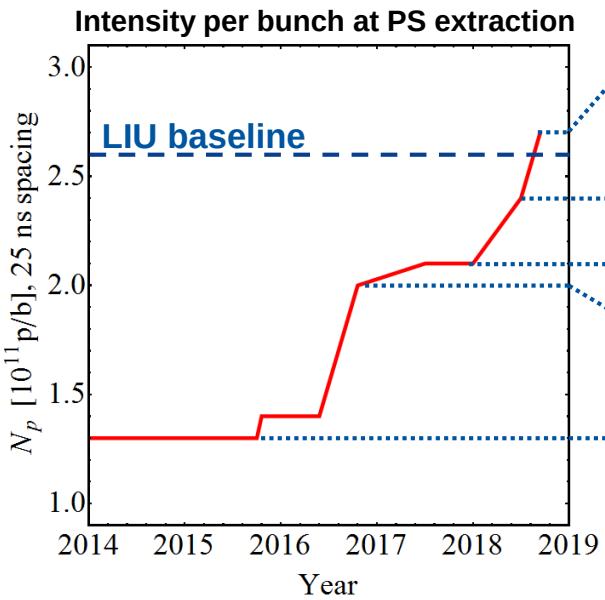


Beam type	OP optics $\Delta\varepsilon$ abs. [mm mrad]		Rematched optics $\Delta\varepsilon$ abs. [mm mrad]	
	Expected	Measured	Expected	Measured
BCMS OP	0.15	**0.33 ± 0.06**	0.011	**0.30 ± 0.09**
BCMS 1.5 eVs	0.36	**0.43 ± 0.06**	0.027	**0.35 ± 0.09**

PS Intensity reach

- LIU target intensity reached at nominal ε_l = 0.35 eVs
- Large transverse emittance: ~5 μm
- Excellent transmission of ~98% even at highest intensities

- Transverse stability
  - → Careful tune and chromaticity adjustment
  - → Transverse damper



Multi-harmonic feedbacks
40 MHz RF as Landau system

Suspected feedback saturation

Optimization 2017

Finemet dipole-mode coupled-bunch feedback

Reach with C10-86/96 coupled-bunch feedback (2005)*

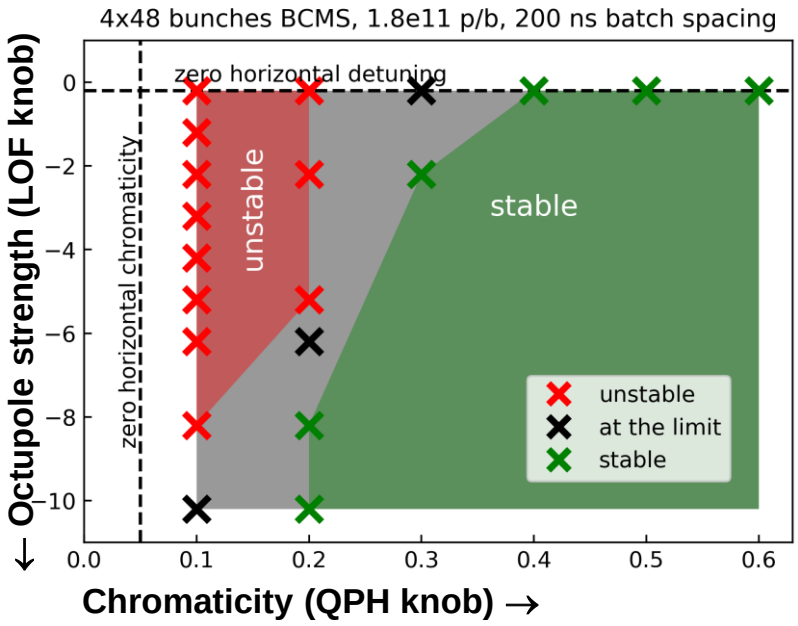
*Intensities >1.3 · 10^{11} p/b were delivered <2016, but not with sufficient quality for LHC

Key studies in PS

	Activity	Timeline
Transverse	Analysis of KFA45 field measurements	Q2/2019
	Conclude on emittance blow-up measurement (systematic errors)	Q2/2019
	PSB-PS transfer line matching using turn-by-turn acquisitions	Q4/2019
	Simulations to understand relevance of space charge after injection	Q4/2019
Longitudinal	Identify impedance source exciting longitudinal instabilities	Q2/2019
	Performance predictions for RF upgrades during LS2	Q2/2019
	Review longitudinal parameters at PS-SPS transfer	Q4/2019
	Longitudinal impedance model after LS2	Q4/2019

SPS transverse

- Horizontal instability $N_b > 1.8 \cdot 10^{11}$ p/b
  - → Cured by either chromaticity, octupoles or combination at present intensities
- Coherent tune shift at 26 GeV will be on the order of $\Delta Q_y \sim 0.04$ with LIU intensities
  - → Wide tune acceptance of damper shown with beam in 2018
  - → Implications on working point choice to be studied in simulations

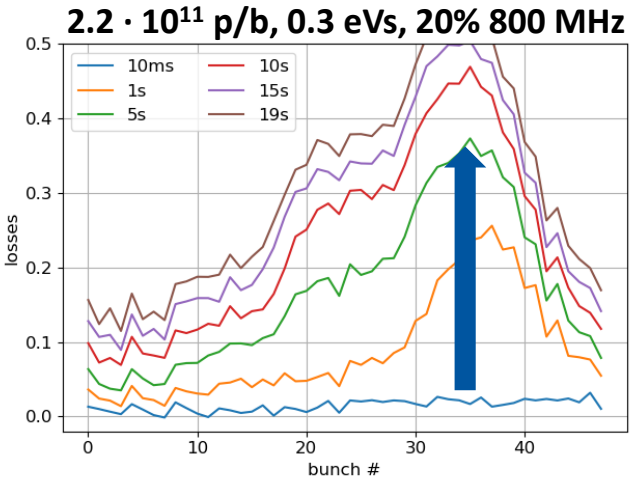


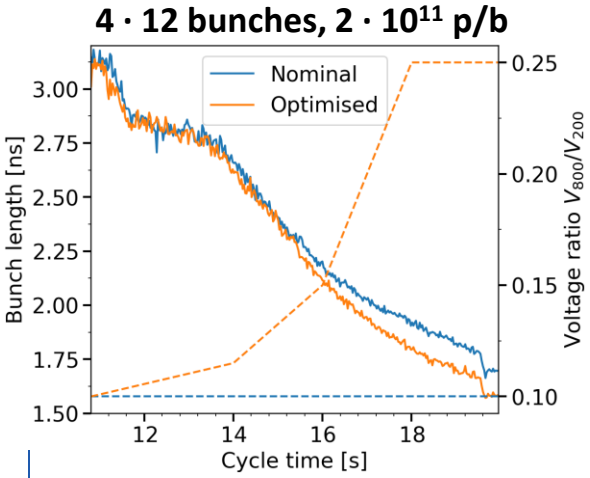
- Electron cloud
  - → Mini scrubbing run in 2018 demonstrated emittance growth reduction to 10-15% at around $2 \cdot 10^{11}$ p/b

SPS intensity reach

- Insufficient RF power with pre-LS2 SPS
  - → Losses increasing with total beam intensity
  - → Limited to $1.4 \cdot 10^{11}$ p/b in long batches

→ Advance beam studies using 12 bunches





- Measurements and simulation agree well for 12 bunches and single harmonic case
- Stability improvement with 800 MHz
  - → Measured with high-intensity in 2018
  - → BLonD simulations for post-LS2

SPS longitudinal, what to expect after LS2

- Simulations of stability at flat-bottom in SPS (48b, 25ns, Q20)

	Nominal emittance	15% less	30% less
$2.6 \cdot 10^{11}$ p/b 800 MHz off →	unstable	unstable	unstable
800 MHz on 10% ratio →			

→ Stabilisation by 800 MHz RF system with 0.1 voltage ratio

→ 15% smaller longitudinal might be possible from PS

- Little interest in Q22 optics (beam loading, long. stability)

Key studies in SPS

	Activity	Timeline
Transverse	Removal of momentum aperture restrictions (MBB-SSS), decision on installation	Q1/2019
	Benchmarking of bunch-by-bunch tune shift measurement with impedance model	Q2/2019
	Horizontal instability at SPS injection, identification of source	Q4/2019
	Impact of bunch-by-bunch tune shift on incoherent tune footprint of different bunches for working point optimization	2020
Longitudinal	630 MHz HOM damper (shift of fundamental mode), decision on installation	Q2/2019
	Beam loss at flat-bottom and beginning of ramp, smaller longitudinal emittance	Q3/2019
	Impact of smaller longitudinal emittance during acceleration	Q4/2019
	Impact of installing 200 MHz cavities for eSPS (for PBC and CLIC)	Q4/2019

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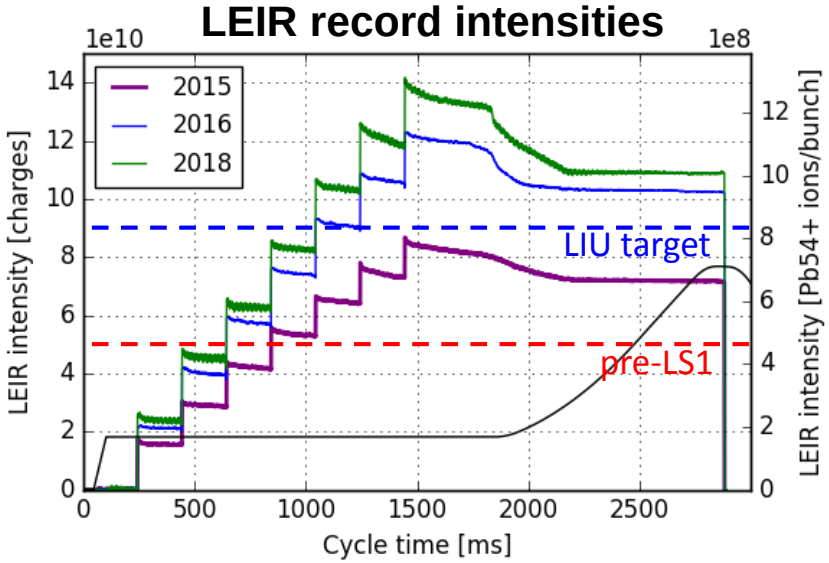
Linac3 and LEIR

Pb source and Linac3

- ✓ Source autopilot
- ✓ Continuous support during LHC run
- ✓ **30 uA golden value for LIU reached**

LEIR

- **Improved accumulation and reduced losses in LEIR**
  - ✓ Careful tuning and understanding
  - ✓ RF capture with frequency modulation
  - ✓ Elimination of tune ripple
- **Improved reliability**
  - ✓ Automatic tools and optimizers
  - ✓ Improved beam instrumentation

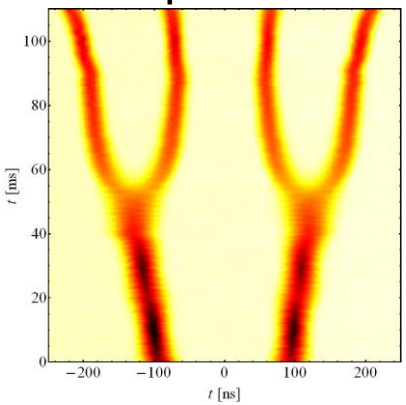


→ Linac3/LEIR ready to operationally deliver LIU target parameters

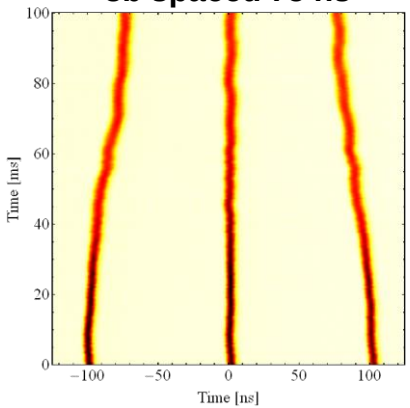
PS

- LIU baseline
  - → Split 2 bunches from LEIR at intermediate plateau into 4 bunches spaced 100 ns
- Alternative
  - → 3 bunches, 75 ns
- Potential issues
  - → Instability after transition crossing for N_b > ~5 · 10^8 ions/b
  - → Cured by controlled blow-up, but satellite bunches at ±12.5 ns

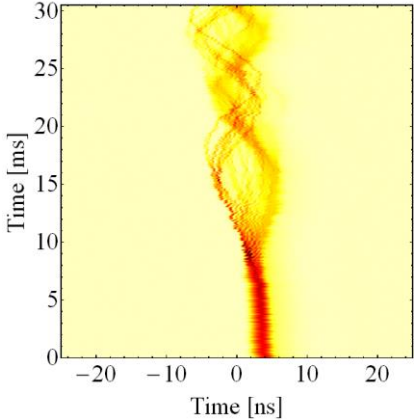
4b spaced 100 ns



3b spaced 75 ns



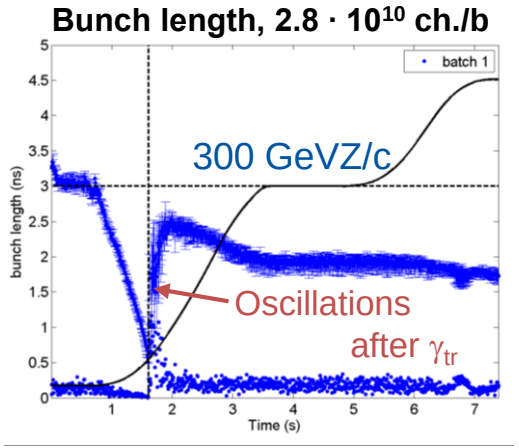
Transition > 5 · 10^8 ions/b



→ Little margin, but PS reaches LIU target ✔

SPS

- Longitudinal instability after transition crossing
  - → Instability often starts at energy of plateau for future slip stacking

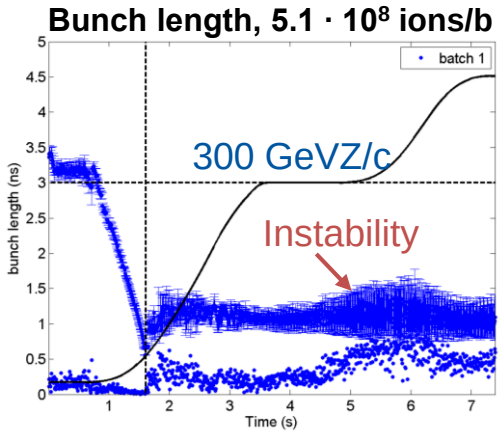


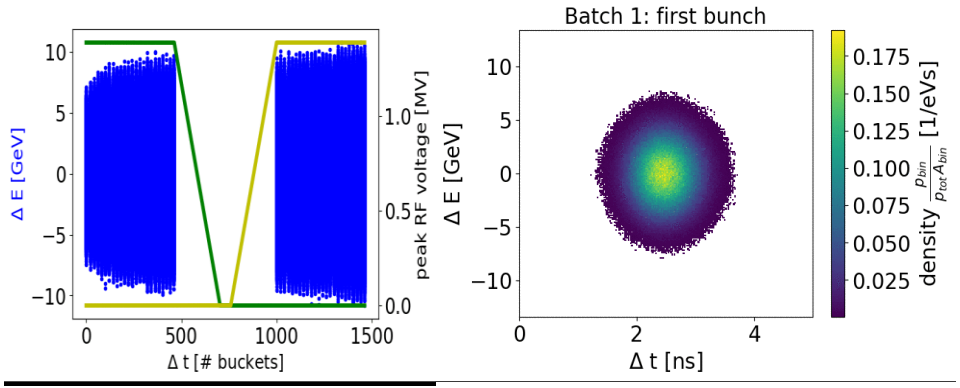
SPS

- Longitudinal instability after transition crossing
  - → Instability often starts at energy of plateau for future slip stacking

- Simulation of slip-stacking with intensity effects
  - → Instability often starts at energy of plateau for future slip stacking

→ Slip-stacking challenging

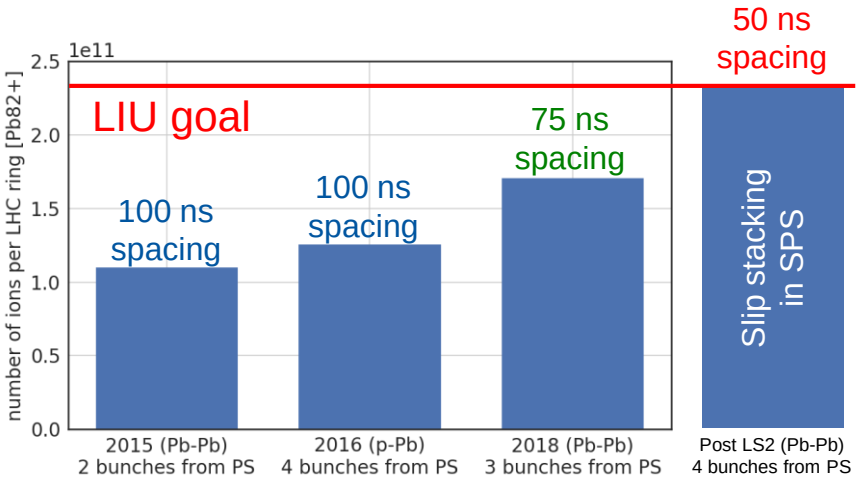




Ions

- Achievements
  - ✓ 2 bunches at LEIR-PS transfer
  - ✓ RF manipulations in PS
  - ✓ 4 bunches spaced by 100 ns at PS-SPS
  - ✓ Multiple injections (~14) into the SPS
- Alternative
  - ✓ 3 bunches with 75 ns spacing
- Challenges
  - → Longitudinal instabilities SPS
  - → Slip stacking: 100 ns → 50 ns spacing in SPS

} → Beam studies in 2018
→ LLRF upgrade



Key studies with ions

	Activity	Timeline
Transverse	Space charge and IBS studies of capture beam losses	Q2/2019
	Maximum accumulated intensity in LEIR (injection process, cooling)	Q4/2019
	Analyse beam stability versus intensity in LEIR (impedance and cooling)	2020
	Injection optics to reduce losses from Linac3 to LEIR	2020
Longitudinal	Optimum longitudinal emittance from LEIR	Q4/2019
	Microwave instability at PS transition crossing, impedance source identification	Q4/2019
	Simulate longitudinal ion instability in SPS and propose mitigation	Q3/2019
	Definition of scenario for slip-stacking in SPS	2020

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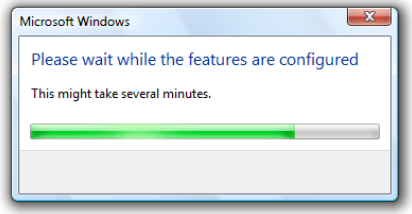
Challenges on the path to LIU performance

Protons	Mitigation	Activity
Large momentum spread transfer PSB-PS	Matched transfer line optics	In depth analysis of 2018 data and simulations
PS-SPS transfer	Smaller longitudinal emittance from PS	Simulation studies of transfer and long. stability in SPS
Transverse stability and e-cloud in SPS	Landau damping, wideband feedback system, scrubbing	Identification of instability source
Beam losses at SPS injection	Lower longitudinal emittance from PS, enlarge momentum aperture	Analysis of efficiency and margins, lift momentum aperture restrictions

Ions	Mitigation	Activity
Longitudinal stability in SPS (for slip-stacking)	Controlled emittance blow-up before transition	Simulation studies

Progress summary



Protons

Linac4 → PSB → PS → SPS

Intensity

Brightness
(studied with BCMS)

Ions

Linac3 → LEIR → PS → SPS

→ HL-LHC parameters reached with lead ion at PS extraction

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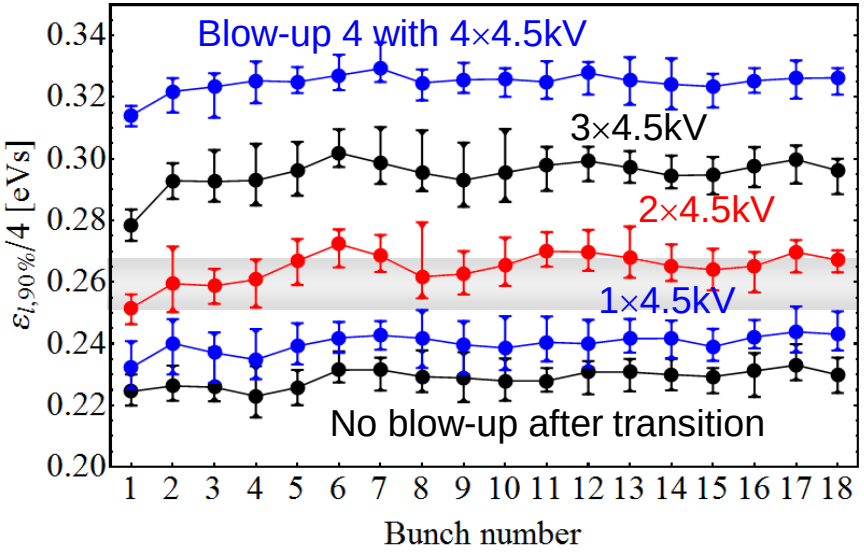
Smaller longitudinal emittance from PS for transfer?

ε_l (90%) at start of flat-top, per bunch at ejection versus controller blow-up after transition, 2.6 ·10^{11} p/b



Corresponds to nominal ε_l at extraction

→ Margin to deliver longitudinal emittance of 15% below nominal

→ **How low can we go in longitudinal emittance?**

PS-SPS smaller emittance at transfer

- 2.0 GeV, post-LS2, LIU baseline, **0.35 eVs**

→ **Large momentum spread required** for $\Delta Q_y = 0.31$

→ Corresponds to

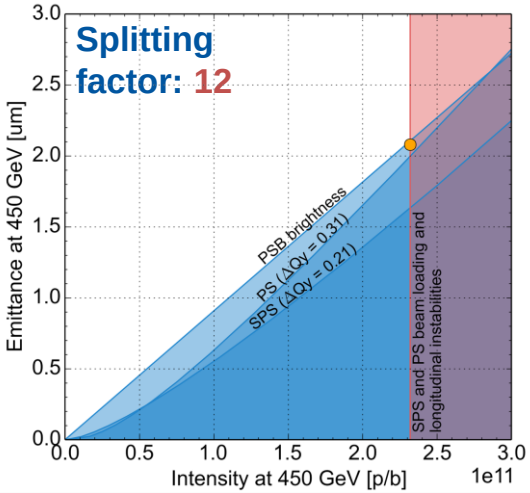
→ ε_l = 3 eVs/12 (standard)

→ ε_l = 1.5 eVs/6 (BCMS)

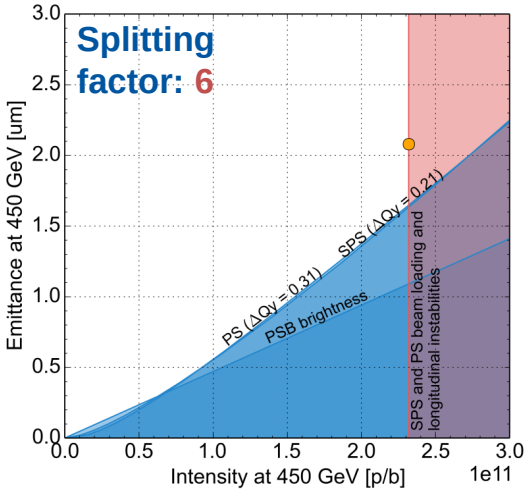
at PS flat-bottom

→ Little margin for RF manipulations in PS

Standard, 72b → 2.1 μm



BCMS→ 1.6 μm



→ **Gain margin by reducing longitudinal emittance already from PSB?**

PS-SPS smaller emittance at transfer

- 2.0 GeV, post-LS2, **0.25 eVs** at PS ejection (if stable)

→ **Large momentum spread required** for $\Delta Q_y = 0.31$

→ Corresponds to

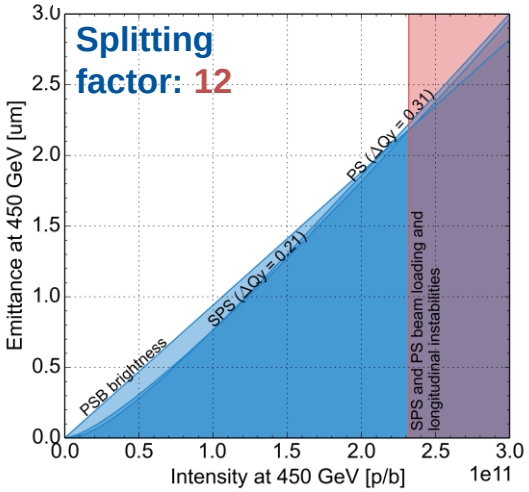
→ ε_l = 3 eVs/12 (standard)

→ ε_l = 1.5 eVs/6 (BCMS)

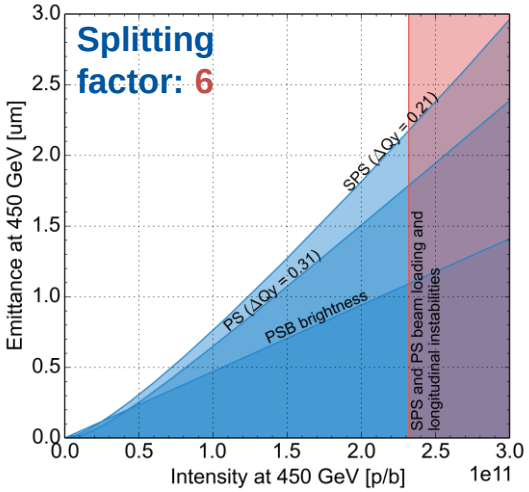
at PS flat-bottom

→ Little margin for RF manipulations in PS

Standard, 72b → 2.2 μm

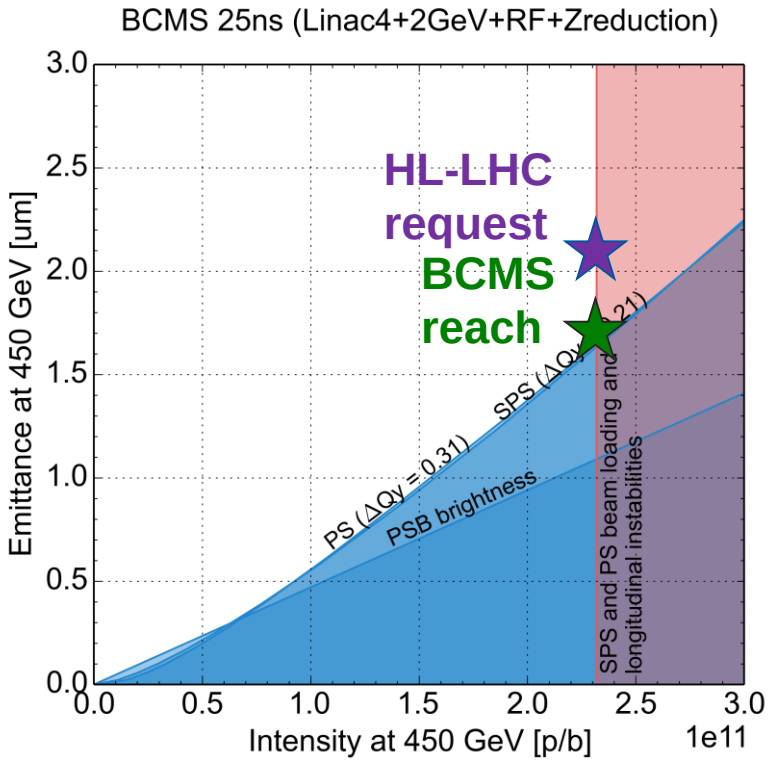


BCMS→ 2.1 μm



→ **Interesting for standard (72b) beam, but not BCMS**

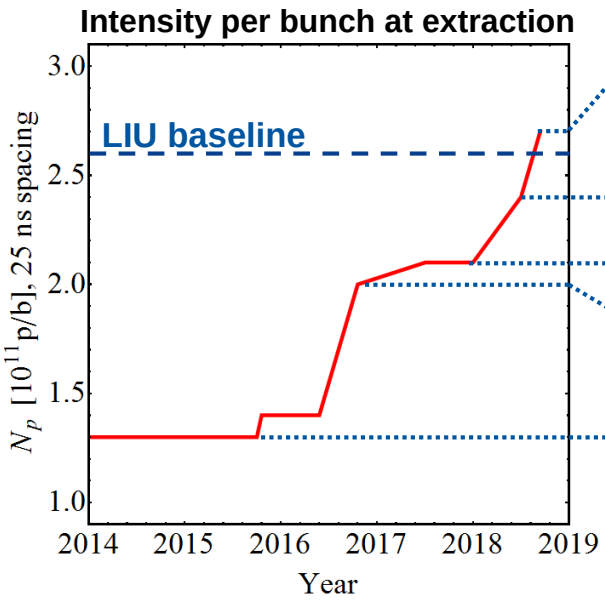
High brightness variant (BCMS)



- For the **BCMS** beam
  - Same bunch intensity reach as standard 25 ns
    - Due to SPS intensity limitation
    - Extraction/transfer/injection protection devices validated for this brightness
  - 25% higher brightness in trains of 48 bunches
    - Almost same number of bunches in LHC
    - Shorter trains are usually easier in injectors and lead to lower e-cloud effects
    - Brightness gain limited by hitting space charge limit in both PS and SPS

Intensity reach of PS, 25 ns standard

- LIU target intensity reached at ε_l = 0.35 eVs



Multi-harmonic feedbacks
C40-78 as Landau RF system

Suspected feedback saturation

Optimization 2017

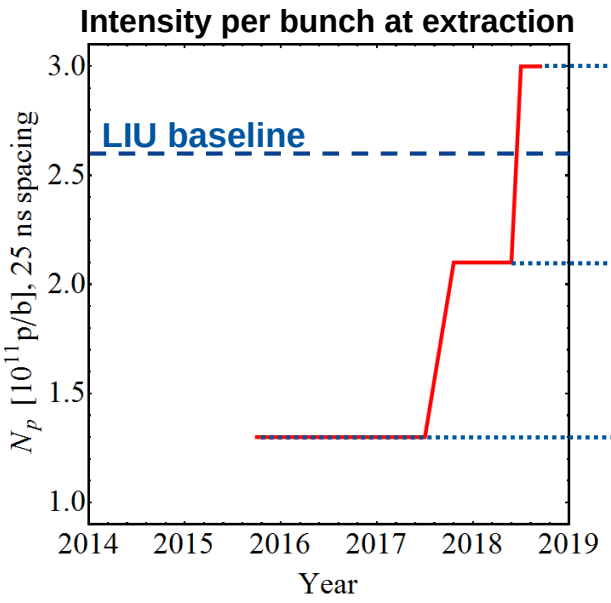
Finemet dipole-mode coupled-bunch feedback

Reach with C10-86/96 coupled-bunch feedback (2005)*

*Intensities >1.3 · 10^{11} p/b were delivered <2016, but not with sufficient quality for LHC

Intensity reach of PS, 25 ns standard and BCMS

- LIU target intensity reached at ε_l = 0.35 eVs



Longitudinally more stable than in 2017

- Suspected feedback saturation
- Not systematically checked

Finemet dipole-mode coupled-bunch feedback

No systematic beam tests to push intensity before 2017

Bunch-by-bunch variations (protons)

- Transverse variations
  - Differences between PSB rings (emittance and intensity)
  - First and second transfer PSB-PS (blow-up in PS)
  - Multiple transfers PS-SPS (blow-up in SPS)
- Longitudinal variations
  - Differences between PSB rings (emittance and intensity)
  - Longitudinal emittance from PS due to splitting

Protons

- Baseline
  - ○ Linac4 injection and H- injection at 160 MeV
  - ○ 2 GeV PSB-PS transfer (large ε_l = 3.0/1.5 eVs)
  - ✓ Triple splitting (standard) or BCMS and controlled long. blow-up
  - ✓ Up to 288 bunches accelerated in SPS, controlled long. blow-up
- Alternatives
  - ✓ 8b4e, 80b
  - ○ None of them validated up to $2.6 \cdot 10^{11}$ p/b

Linac4

- Short term goal (2018)
  - 25mA peak current after the RFQ (acceptance 2.6 mm mrad total normalised)
  - Pulse length of 600µs
  - Stability shot-to-shot of 2%
  - Pulse flatness over
    - 600µsec : 5%
    - 120µsec : 2%

Intensity can be compensated (to a certain limit) with injection turns
In-Stability cannot be compensated
Reliability is key

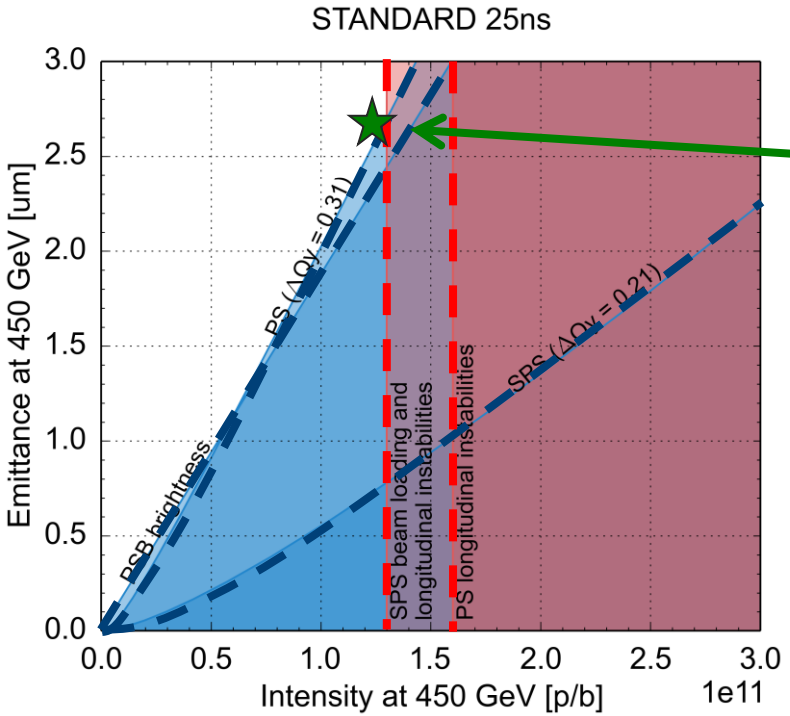
- Long term goal (2023)
  - 45mA peak current after the RFQ (acceptance 2.6 mm mrad total normalised)
  - Pulse length of 600µs
  - Stability shot-to-shot of 2%
  - Pulse flatness over
    - 600µsec : 5%
    - 120µsec : 2%

Charge questions

Wrap up of Session 1: LIU beam performance reach, Giovanni + Heiko (20'+10')

- Keywords: LIU target performance, risks, mitigations, challenges for post-LS2 and LIU beam commissioning, protons and ions
- Questions to be answered:
  - What are the baseline beam parameters for LIU and the alternative production schemes (protons and ions)?
  - What are the assumptions, do we need to review any of the assumptions based on 2018 experience or gained knowledge on some other items?
  - What we can definitely tick out from Run 2 experience and what we still need to study in LS2 and prove in Run 3 (simulation and post-LS2 MDs)?
  - ~~How to balance pushing performance for protons and ions after LS2?~~
  - Bunch-by-bunch variations within trains?

LIU performance reach for protons



	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
- **PS cycle**: Bunch intensity limited by longitudinal coupled bunch dipolar instability
- **SPS cycle**: Bunch intensity limited by RF power, longitudinal coupled bunch instability