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LHC Injectors Upgrade

LHC Injectors Upgrade Workshop

Montreux, 20-22 January 2020

LHC Injectors Upgrade

LIU beam performance ramping up phase: **PSB and PS**

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Outline

- **Beam performance ramp-up for proton beams during Run 3**
- **The standard beam**
  - Intensity ramp-up
  - Brightness ramp-up
- **The BCMS beam as operational beam during Run 3**
- **Conclusions**

Beam performance ramp-up for proton beams during Run 3

- **Two different beams have to be distinguished during Run 3**
  - **Standard beam with 72 bunches (HL-LHC baseline)**
    - gradual performance increase to be carried out in parallel MDs
      - allocate a **permanent parallel "LIU commissioning" slot** in the PSB and the PS super cycle?
  - **BCMS with 48 bunches**
    - considered to be the operational beam during Run 3
    - performance increase as the work on the standard beam progresses

- **Two main aspects of the LIU beam performance ramp-up of the standard beam**

1) Intensity ramp-up → mainly occurring in the SPS
2) Brightness ramp-up → determined by the PSB and PS performance

Beam performance ramp-up for proton beams during Run 3

- **LIU target beam parameters at injection of the respective accelerator (from EDMS1296306)**

PSB (H^- injection from Linac4)

		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
LIU target	Standard	34.21	1.72	0.16	1.4	650	1.8	(0.58, 0.69)
	BCMS	17.11	1.36	0.16	1.4	650	1.8	(0.35, 0.43)

PS (Standard: 4b+2b – BCMS: 2× 4b)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
LIU target	Standard	32.50	1.80	2.0	3.00	205	1.5	(0.18, 0.30)
	BCMS	16.25	1.43	2.0	1.48	135	1.1	(0.20, 0.31)

SPS (Standard: 4 × 72b – BCMS: 5 × 48b)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
LIU target	Standard	2.57	1.89	26	0.35	4.0 (3.0)	0.9 (1.5)	(0.10, 0.17)
	BCMS	2.57	1.50	26	0.35	4.0 (3.0)	0.9 (1.5)	(0.12, 0.21)

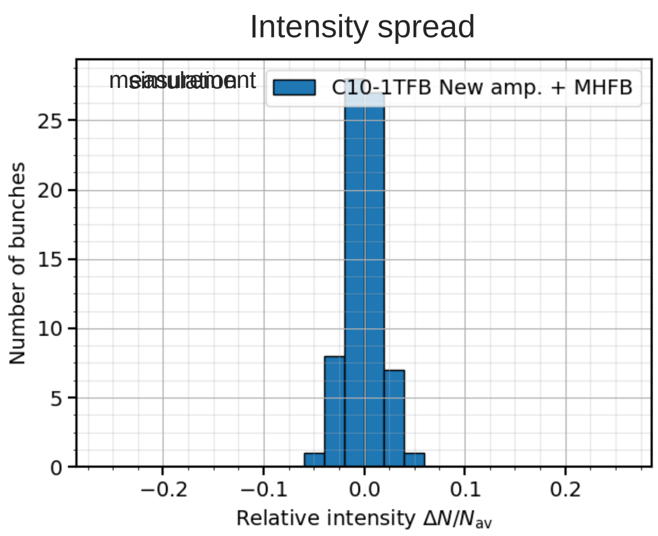
LHC (≈10 injections)

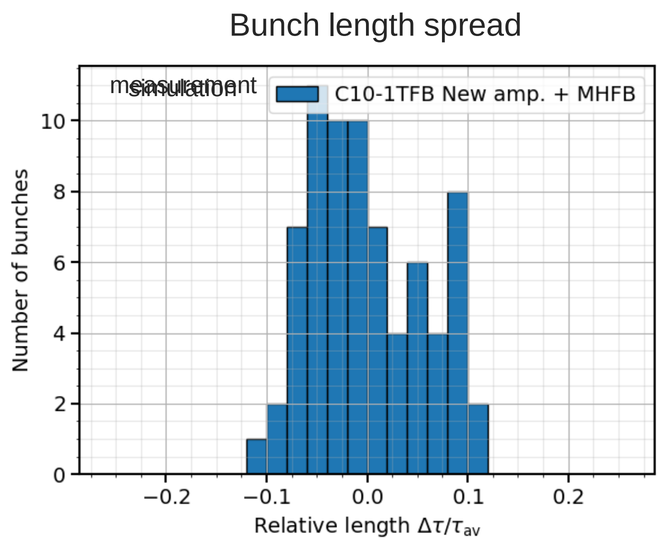
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
LIU target	Standard	2.32	2.08	450	0.56 (0.58)	1.65 (1.24)	288
	BCMS	2.32	1.65	450	0.56 (0.58)	1.65 (1.24)	240

Intensity ramp-up of the standard beam

- **Intensity reach demonstrated at PS extraction pre-LS2**
  - Remaining upgrades of the PS RF systems will further improve the reproducibility and reduce the bunch-by-bunch variability
    - New 10 MHz feedback amplifiers to reduce the impedance and deliver more robust performance
    - Improved reliability of the Finemet cavity
    - No major modifications to the high-frequency cavities (multi-harmonic feedbacks already in place pre-LS2)

- **Simulation results confirm improved beam quality after LS2**
  - Pre-LS2 measurements: bunch-by-bunch variation ≈ ±10%
  - Assuming completely independent triple and double splittings in simulations
  - significantly reduced intensity spread achievable at LIU intensity
  - Further optimization possible to improve bunch length spread at the expense of increased intensity spread
  - Further simulations indicate degradation of the triple splitting in the presence of the Finemet impedance → studies with beam required during Run 3

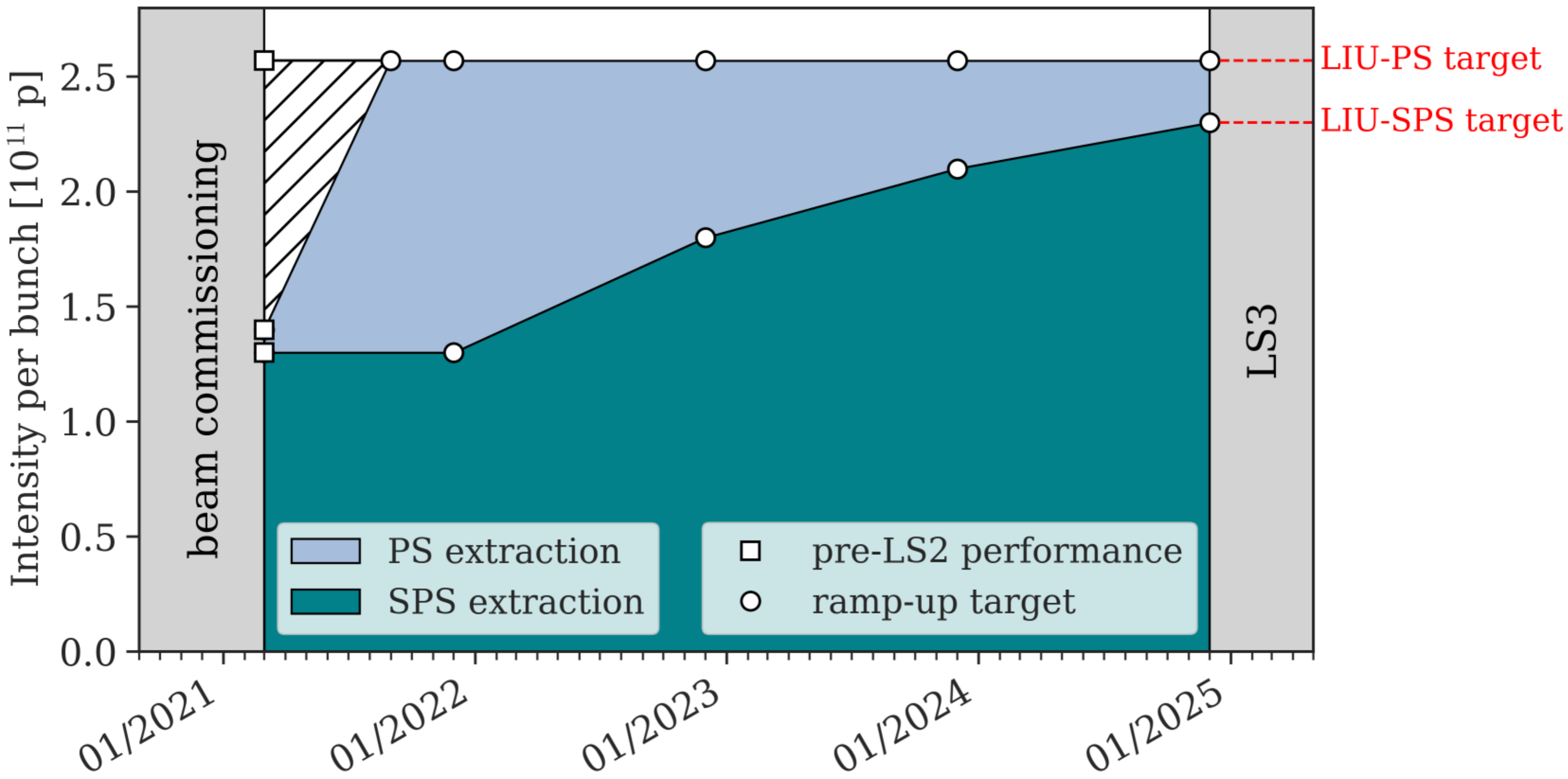




Intensity ramp-up of the standard beam

- **Intensity reach demonstrated at PS extraction pre-LS2**
  - Recovery of high-intensity beams expected by end of summer 2021

- **Gradual intensity ramp-up in the SPS**
  - Ramp-up planned to start from 2022 due to LHC Pb-ion run at the end of 2021
  - LIU-SPS intensity target planned to be reached at the end of 2024

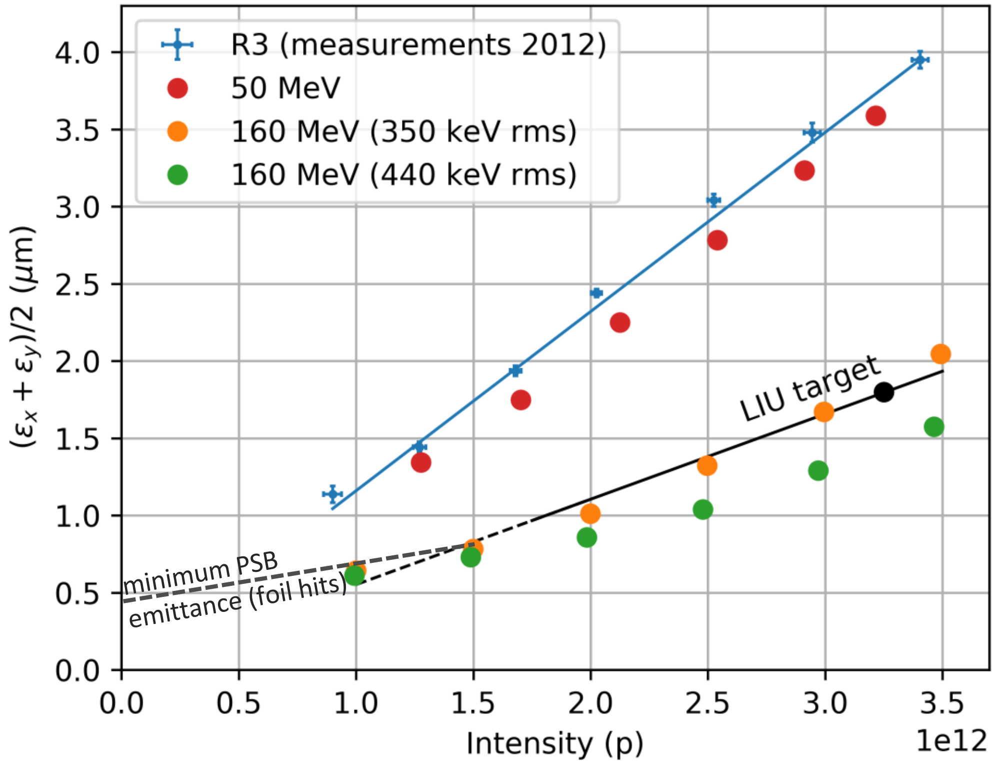


Brightness ramp-up of the standard beam

- **Achievable PSB brightness limited by the injection scheme and acceleration at low energy**
- **PSB space charge simulation studies were performed to reproduce pre-LS2 and investigate LIU performance**

  - **Simulations at 50 MeV (beam from Linac2)**
    - capture of coasting beam (1e-3 dp/p rms) with operational voltage program
    - capture losses of about 15% (as observed in measurements)
    - single turn injection on the ramp (no multi-turn stacking)
    - 1 μm transverse emittance at injection
    - Q_x / Q_y = 4.40 / 4.45
    - **5% beta-beating included**

  - **Simulations at 160 MeV (beam from Linac4)**
    - 25 mA at PSB injection
    - 350 keV rms energy spread with chopping factor 0.6
    - 440 keV rms energy spread with chopping factor 0.7
    - “flat1” cycle and voltage program provided by S. Albright
    - injection on flat bottom, with injection chicane and foil
    - 0.4 μm transverse emittance at injection
    - Q_x / Q_y = 4.40 / 4.45
    - **15% beta-beating included**



➔ **large energy spread (~440 keV rms) from Linac4 required**

Brightness ramp-up of the standard beam

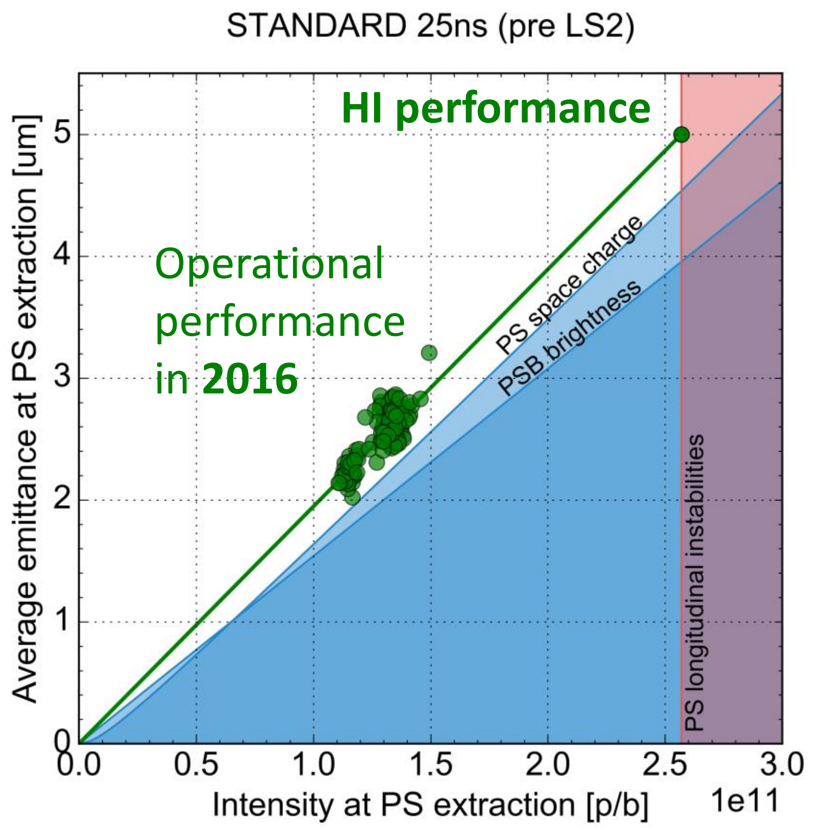
- **Achievable brightness along the chain will be limited by space charge effects on the PS flat bottom**
  - LIU baseline: beams with large longitudinal emittance at PS injection to overcome this limitation
  - → Brightness ramp-up therefore determined by the evolution of the longitudinal emittance at PS injection

- **Longitudinal emittance at PS injection will be gradually increased during Run 3**
  - Brightness ramp-up is foreseen to take place until the end of 2023
  - Limited experience with large longitudinal emittance beams and their impact on transverse emittances
    - Standard procedure from an RF point-of-view
  - → Transverse emittance preservation at PS injection and on the flat bottom is expected to be the most critical aspect
  - → Emittance preservation along the ramp might also become critical and work is ongoing to improve the control of the PFW
  - → Foresee sufficient commissioning time to gain experience

Pre-LS2 performance of the standard beam

- **Experience with the standard beam**
  - Operational experience limited to 2016
  - LIU intensity target achieved in MDs in 2018
    - Reliable beam production at high-intensity achieved after transverse optimization

- **Performance at different intensities followed constant brightness**



Target performance of the standard beam at the end of 2021

- **PSB will deliver beams of significantly increased brightness already in 2021**

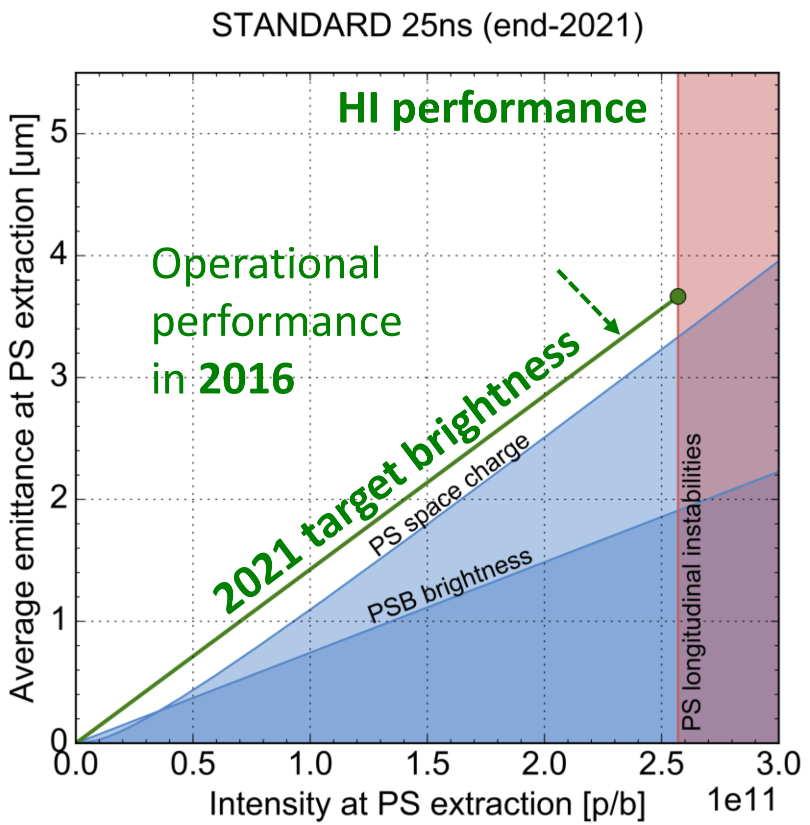
- **Longitudinal parameter target at PS injection in 2021**
  - will require longitudinal blow-up at the end of the PS flat bottom

ε_z [eVs]*	σ_z [ns]*	$\delta p/p$ [10^{-3}]*
1.5	135	1.1

* parameter conventions according to EDMS1296306

→ Achievable brightness will be limited by space charge effects on the PS flat bottom

- **First important brightness increase expected to be achieved at the end of 2021**
  - Including a 10% margin on the transverse emittances with respect to the maximum achievable performance

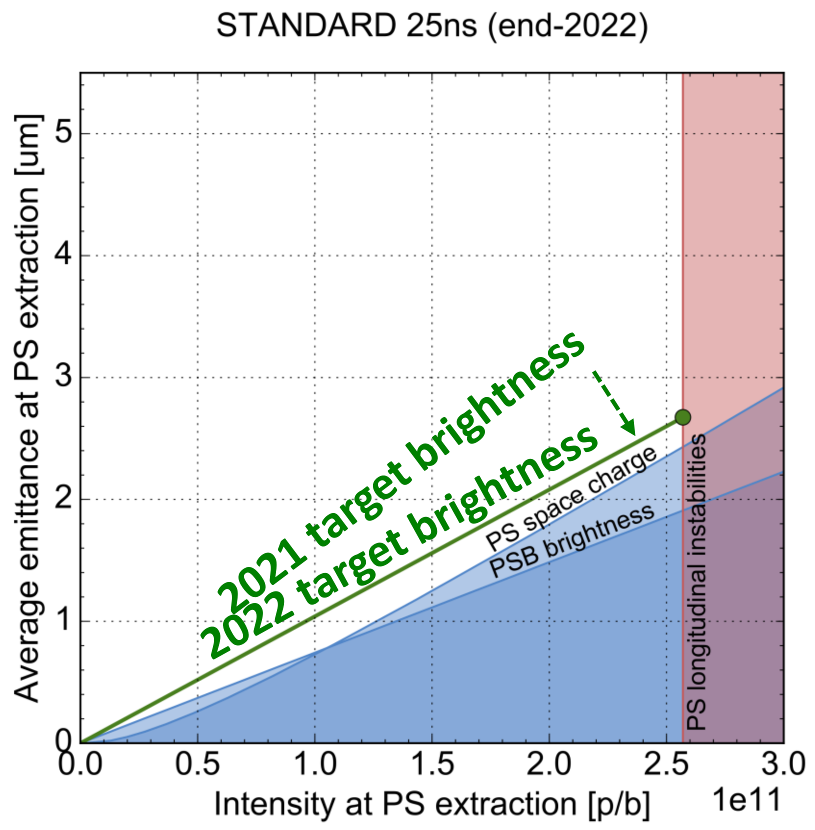


Target performance of the standard beam at the end of 2022

- **Further brightness increase by increasing the longitudinal emittance at PS injection**
  - Longitudinal parameter target at PS injection in 2022

ε_z [eVs]*	σ_z [ns]*	$\delta p/p$ [10^{-3}]*
2.25	170	1.3

* parameter conventions according to EDMS1296306



→ **Achievable brightness will still be limited by space charge effects on the PS flat bottom**

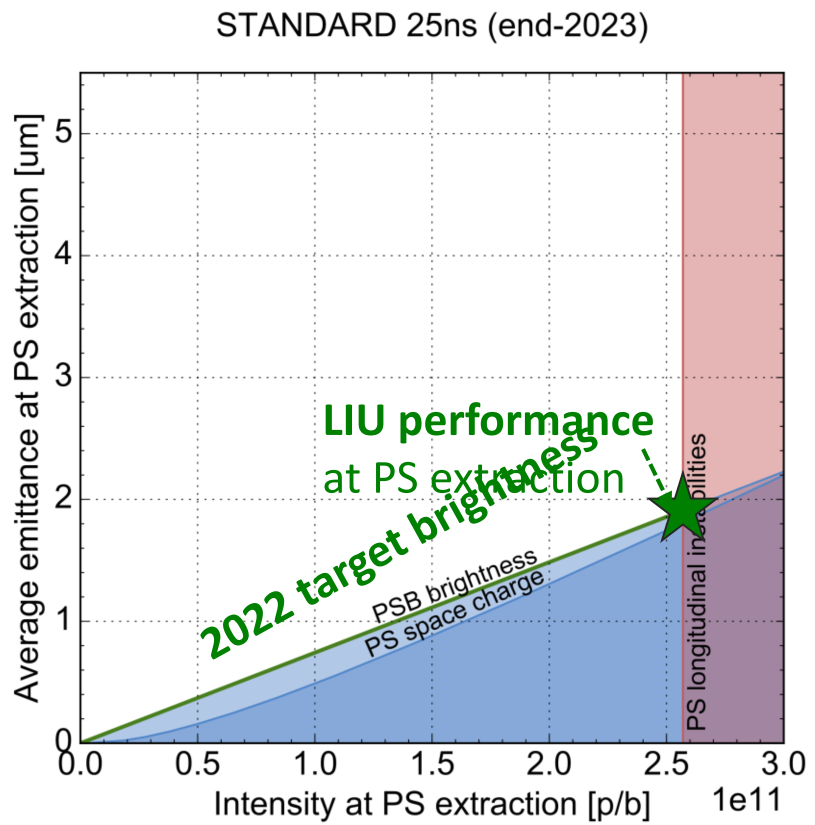
Target performance of the standard beam at the end of 2023

- **Final step in longitudinal emittance foreseen in 2023**
  - Longitudinal parameter target at PS injection in 2023 (**= LIU parameters**)

ε_z [eVs]*	σ_z [ns]*	$\delta p/p$ [10^{-3}]*
3.0	205	1.5

* parameter conventions according to EDMS1296306

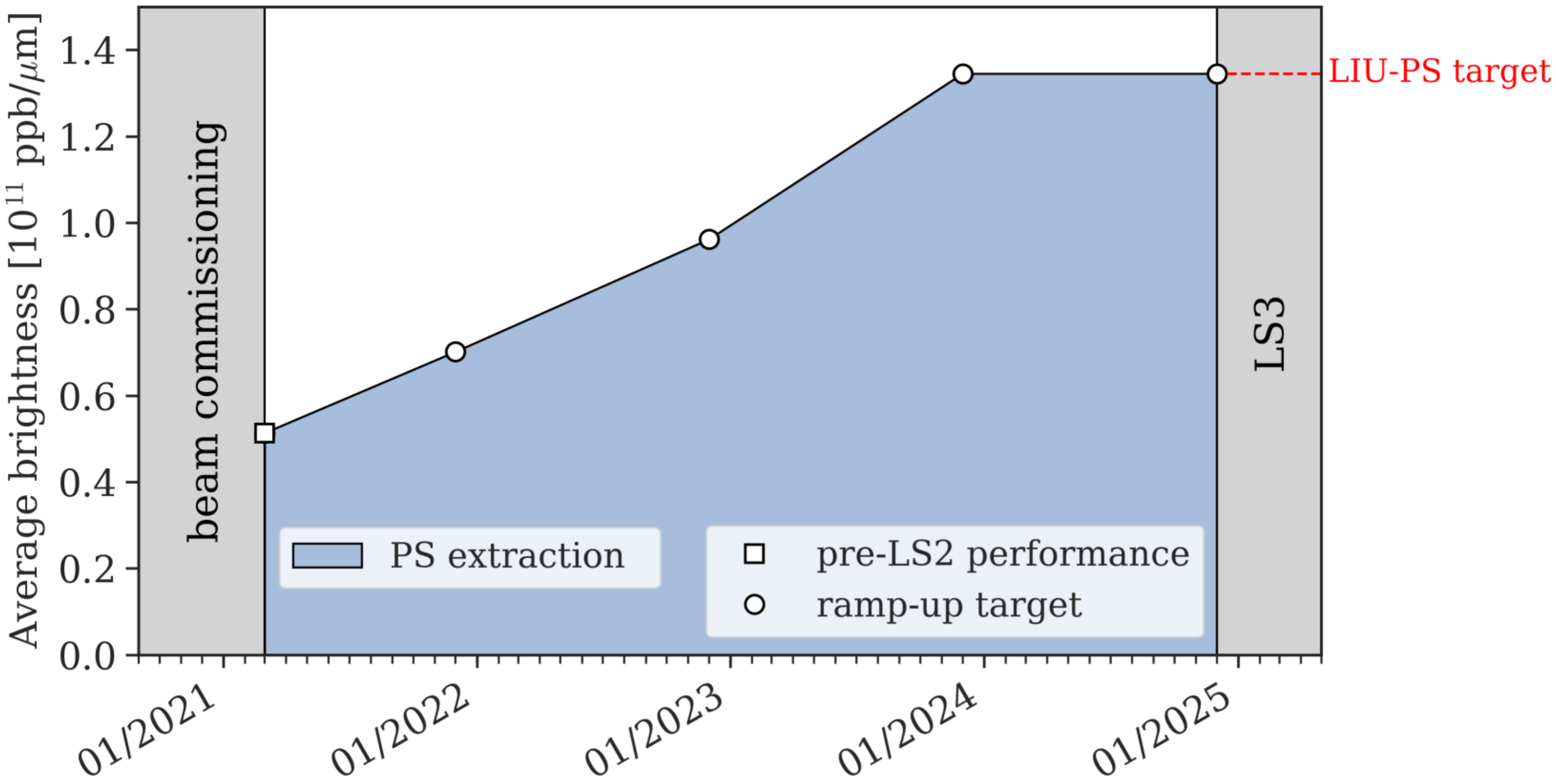
→ **LIU performance at PS extraction planned to be reached at the end of 2023**



Summary of the brightness ramp-up of the standard beam during Run 3

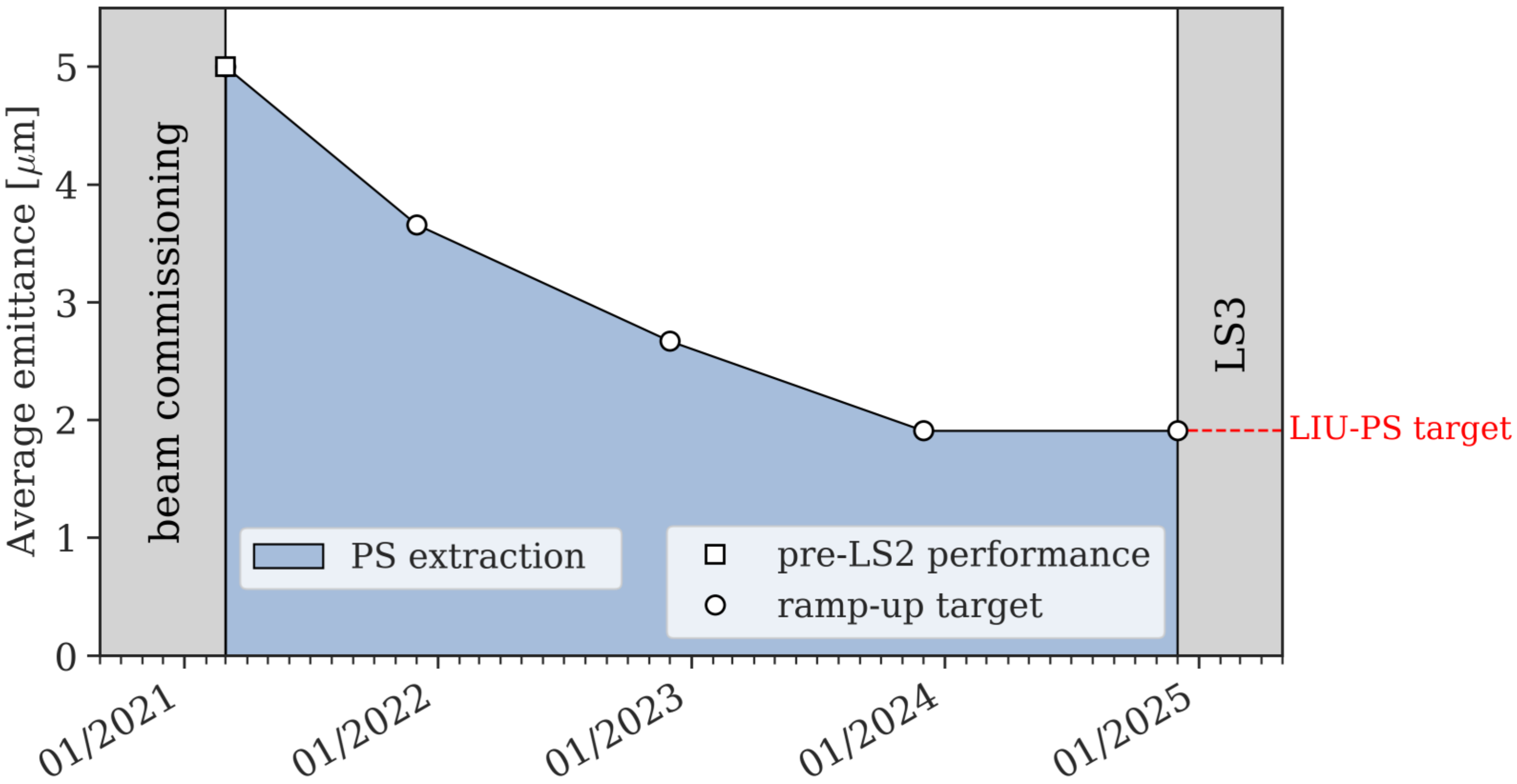
- **Brightness ramp-up determined by the evolution of longitudinal parameters at PS injection**
  - Ramp-up foreseen to gradually occur until the end of 2023

→ **LIU beam performance expected to be available at PS extraction at the end of 2023**
  - SPS performance ramp-up will continue throughout 2024 (see Elena's talk)



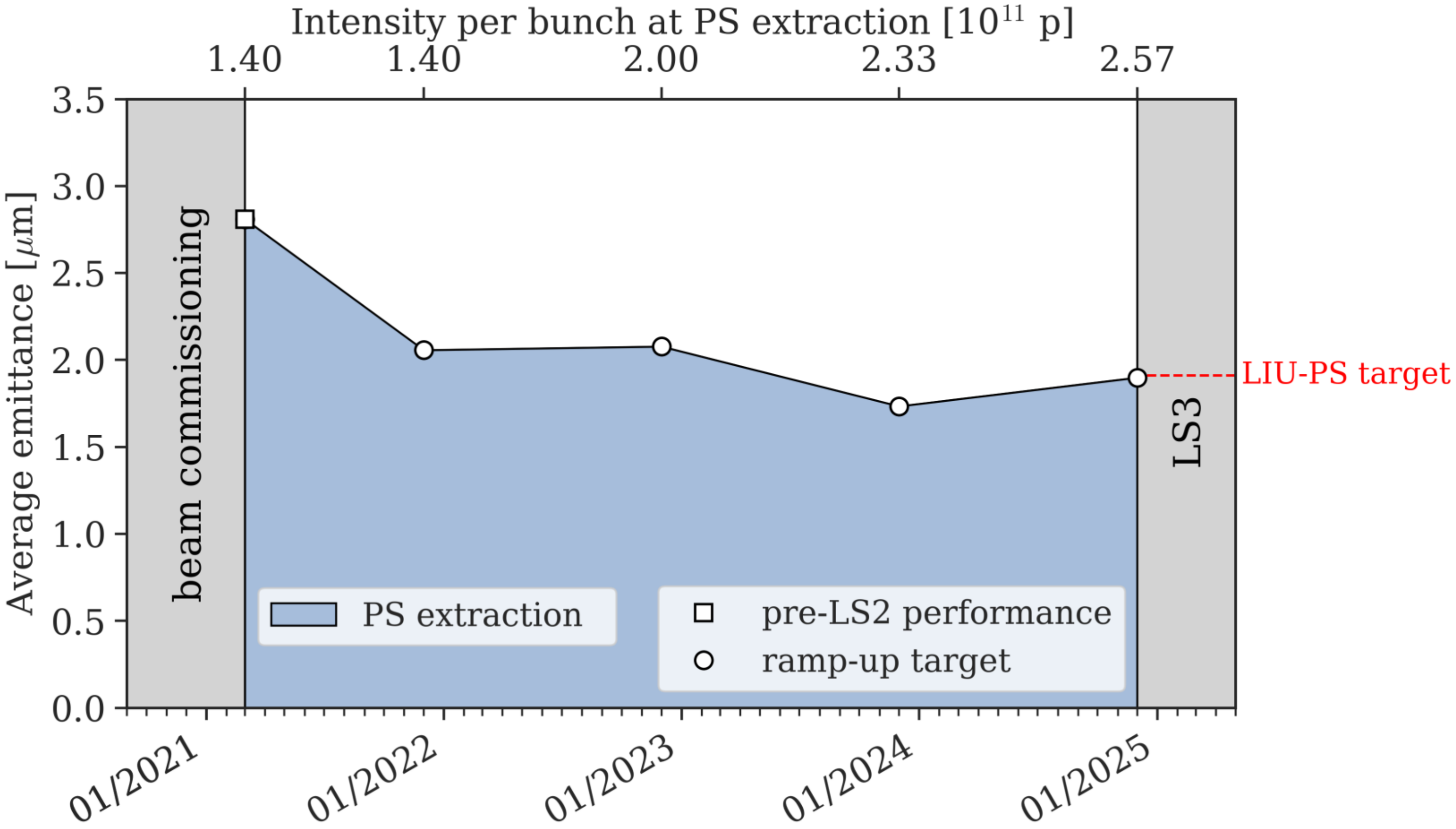
Emittance evolution of the standard beam during Run 3

- **Transverse emittances will gradually decrease during the brightness ramp-up**
- **Figure shows the emittance evolution at PS extraction considering the LIU intensity target of 2.57 x 10^{11} ppb**



Emittance evolution of the standard beam during Run 3

- **Transverse emittances will gradually decrease during the brightness ramp-up**
- **Figure shows the emittance evolution at PS extraction following the projected intensity ramp-up of the SPS**
- **The emittance during 2024 is expected to increase as the last step of the intensity ramp-up occurs at constant brightness**



Summary of the projected beam parameter evolution at PS injection during Run 3

- **Brightness ramp-up of the standard beam during Run 3 determined by the gradual increase of the longitudinal emittance at PS injection**

- **Beams expected to be operationally available according to the table below**
  - LIU performance at PS extraction planned to be reached at the end of 2023

End of year	N [10^{11} ppb]	$\varepsilon_{x,y}$ [μm]*	ε_z [eVs]*	σ_z [ns]*	$\delta p/p$ [10^{-3}]*	$\Delta Q_{x,y}$	Remarks
2021	325	3.49	1.50	135	1.1	(0.23, 0.28)	natural post-LS2 PSB performance for longitudinal parameters
2022	325	2.54	2.25	170	1.3	(0.20, 0.29)	
2023	325	1.80	3.00	205	1.5	(0.18, 0.30)	LIU performance reached in the PS

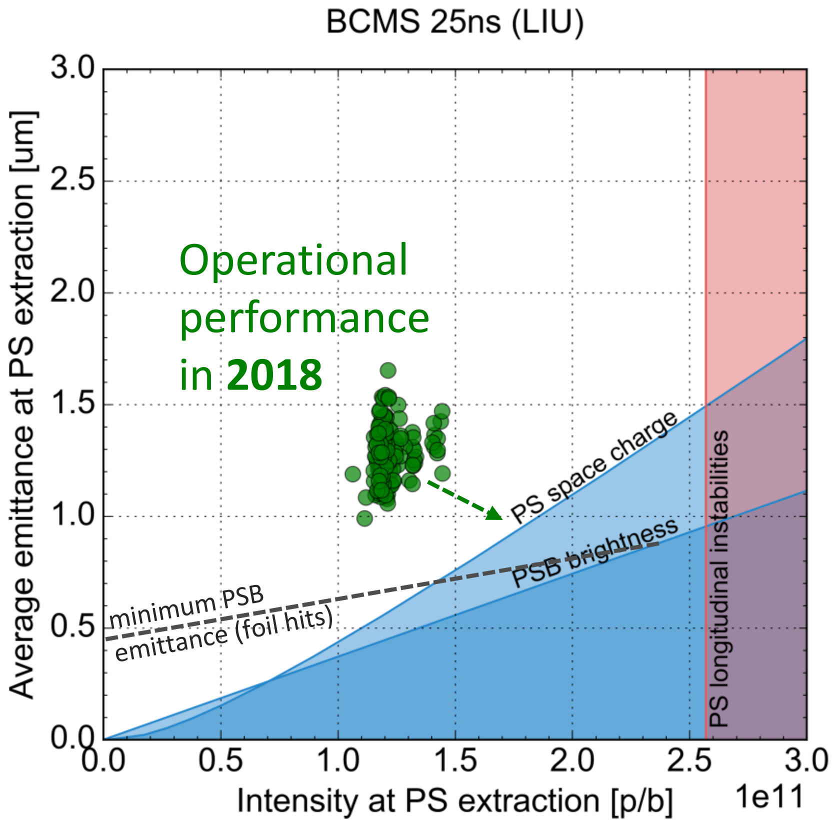
* parameter conventions according to EDMS1296306

The BCMS beam as operational beam during Run 3

- **BCMS beam considered as operational LHC beam during Run3**
  - Based on the report from the Run 3 configuration working group at the 2019 Evian Workshop

- **BCMS beam production expected to be less critical than the standard beam in the PS**

- **LHC will benefit from increased performance as PS brightness and SPS intensity are ramped up**



To be included?

- Choice of future injection energy
- Choice of future intermediate plateau energy
- Microwave instabillity at transition for low-emittance ion beams

Conclusions

- **Two main aspects of the LIU beam performance ramp-up for the standard beam during Run 3**
  - Intensity ramp-up
  - Brightness ramp-up

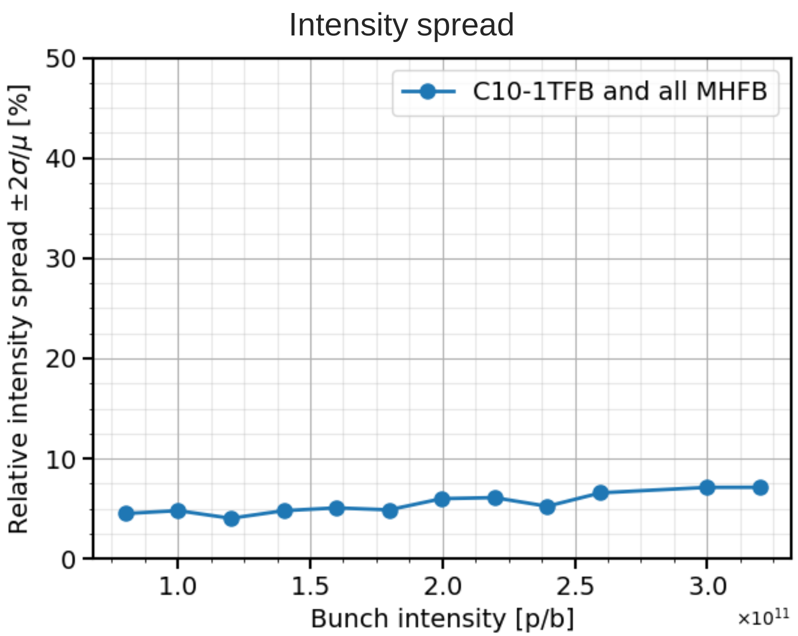
- **Brightness ramp-up determined by the evolution of longitudinal parameters at PS injection**

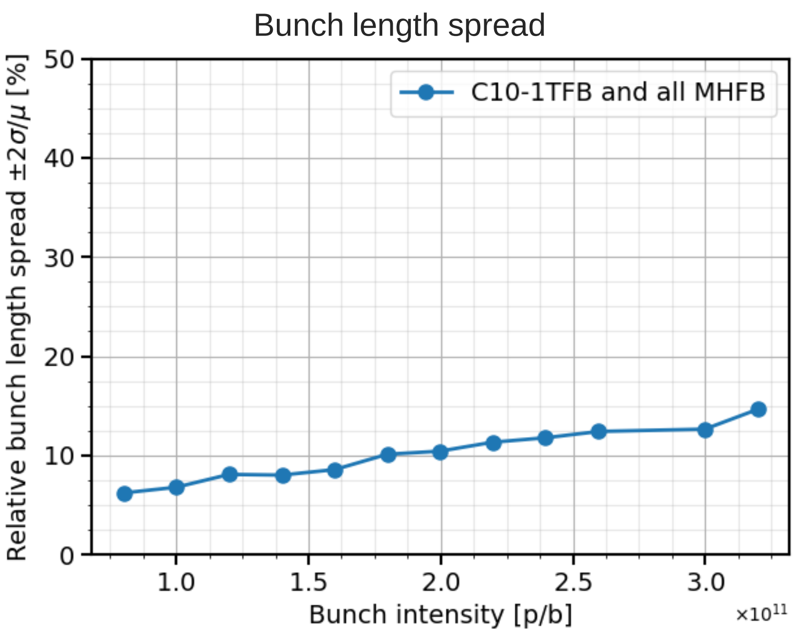
- **LIU beam performance expected to be reached at PS extraction at the end of 2023**
  - One additional year required to achieve LIU performance at SPS extraction

- **BCMS beam considered as operational LHC beam during Run 3**
  - BCMS performance will gradually improve as the performance ramp-up progresses

Backup slides

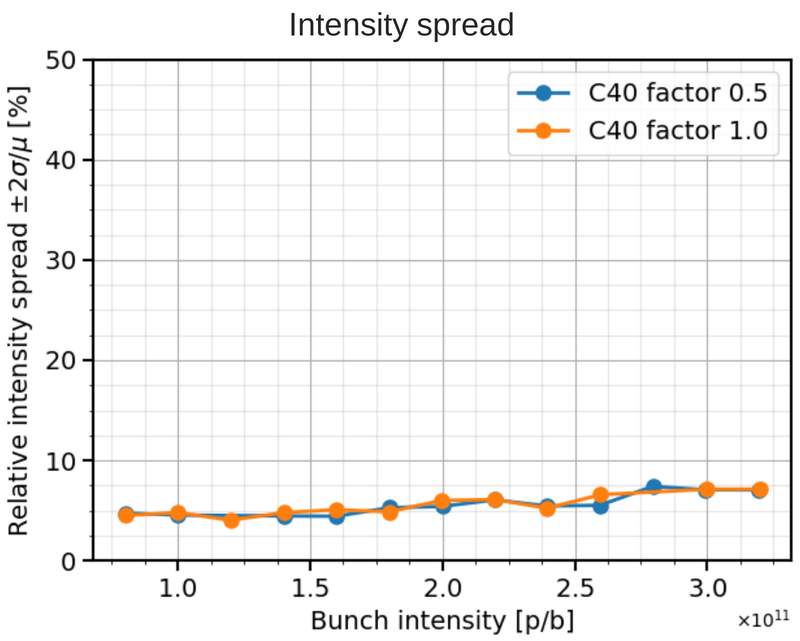
Best achievable double splitting after LS2

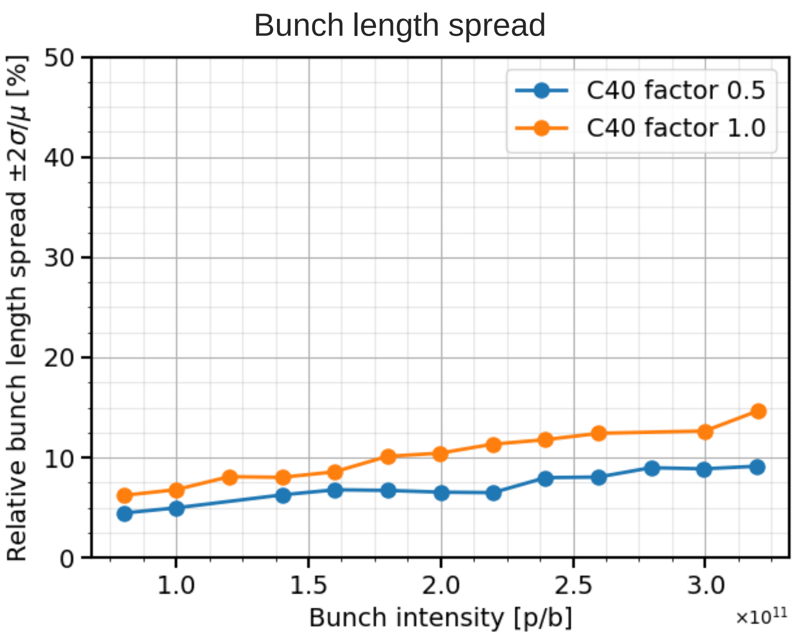




- Assuming no change in impedance due to the fast feedback and adding the MHFB for all high frequency cavities
- New amplifier on C10, reduction of impedance by factor 2
- Acceptable spread even $> 3.0 \times 10^{11}$ p/b, leaving good margin

Benefits of improved fast feedback on C40

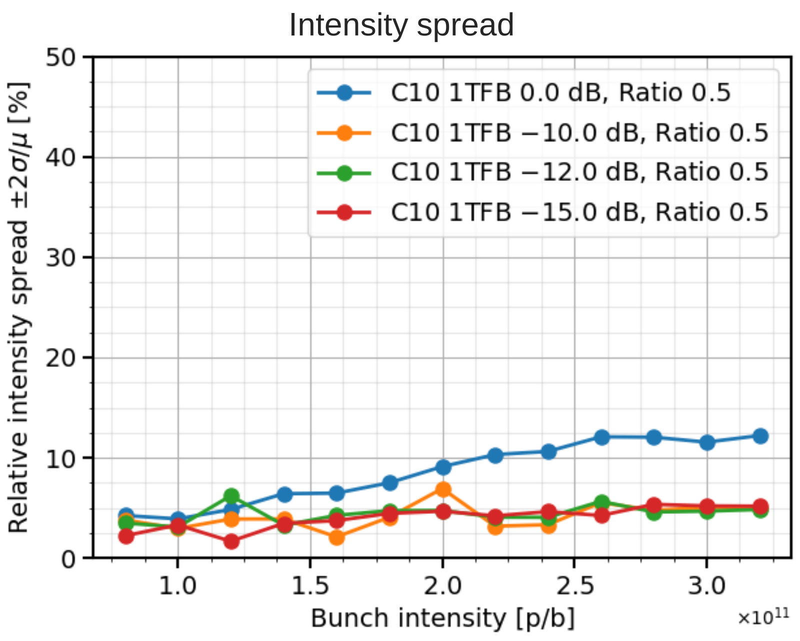


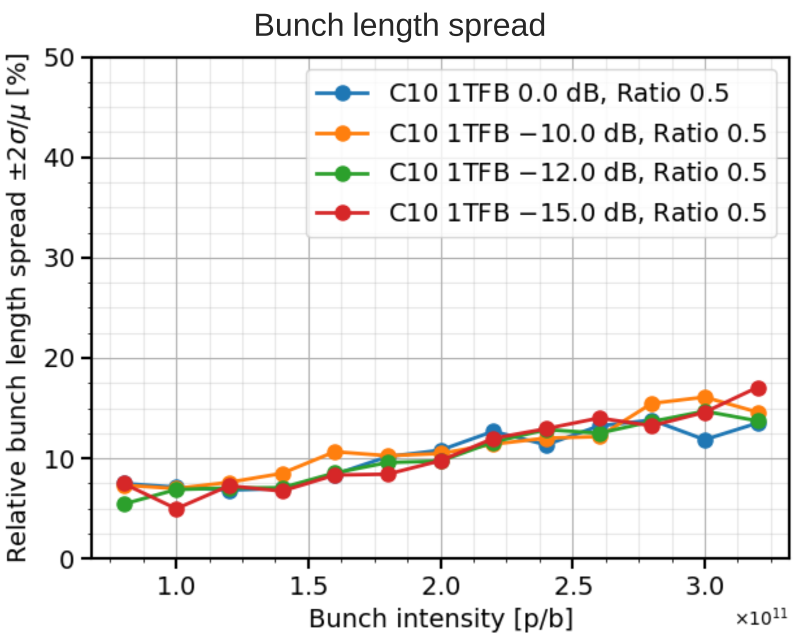


- Improving the fast feedback for the 40 MHz has little influence on the bunch intensity spread but gradually improves the bunch length spread

- The optimal phase setting for bunch length and intensity spread is different, further impedance reduction would allow to reduce the need to find a compromise between intensity/length optimization

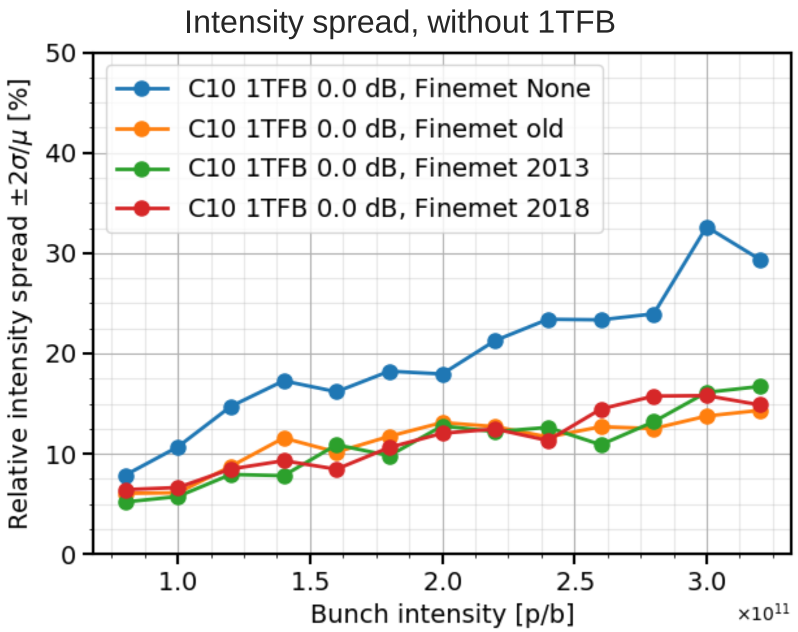
Best achievable triple splitting after LS2

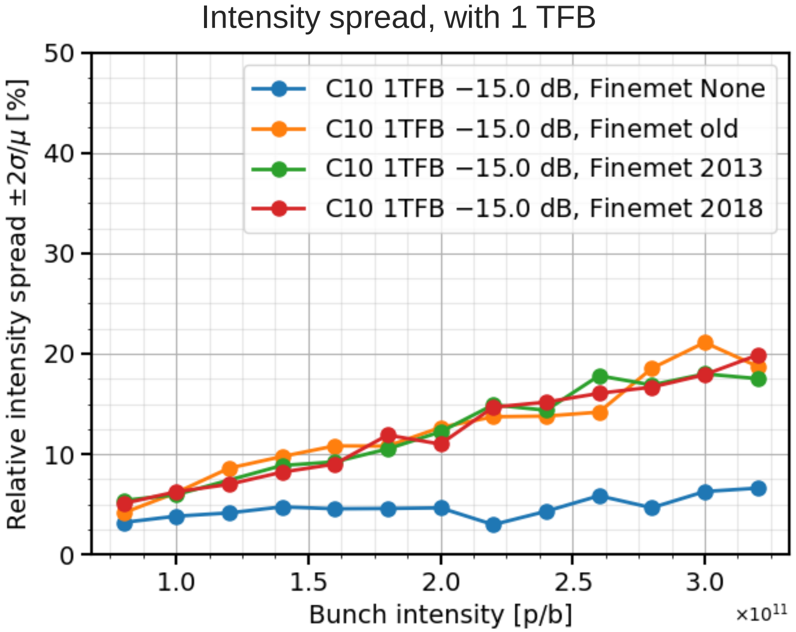




- The upgraded power amplifier on the 10 MHz cavities will reduce the shunt impedance by a factor 2
- The quality of the triple splitting is improved and the spread in bunch length is reduced, with the same justification as the double splittings
- For all intensities, we are below the $\pm 10\%$ variation criterion with sufficient margin

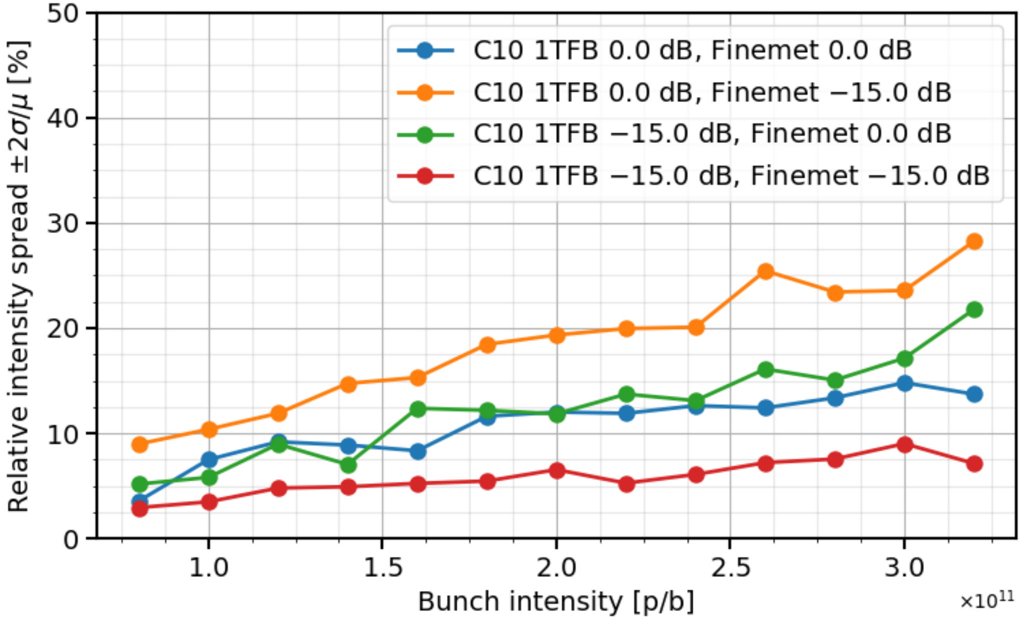
Influence of Finemet model on splittings



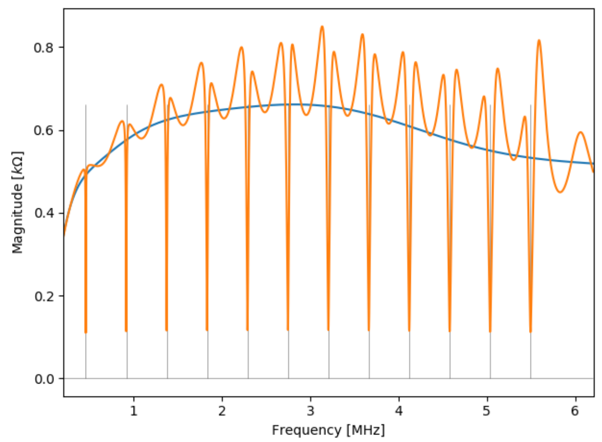


- The different fitting results for the Finemet impedance were included in simulations
- The different models for the Finemet impedance have the same influence on the triple splitting
- There is something more fundamental than the fitting quality or impedance flatness of the Finemet cavity that affects the triple splitting
- *NB: simulations done for pre-LS2 C10 impedance*

Adding a “MHFB” on the Finemet cavity



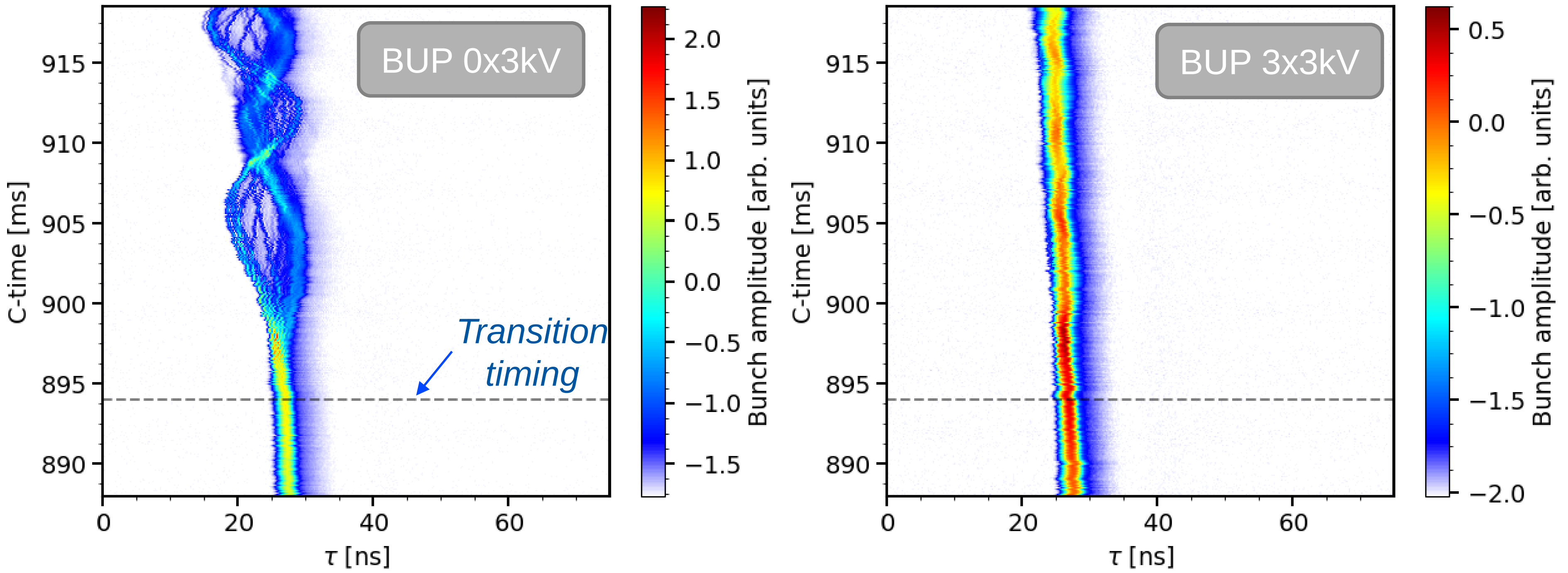
Finemet impedance with “MHFB” (resonator filters)



- The parameters for the “Multi-Harmonic Feedback” model on the Finemet cavity are based on results from 2014 tests:
  - *-15 dB impedance reduction*
  - *Bandwidth of 8 kHZ at +3 dB from minimum*
  - *Notches on h=1 to h=12*

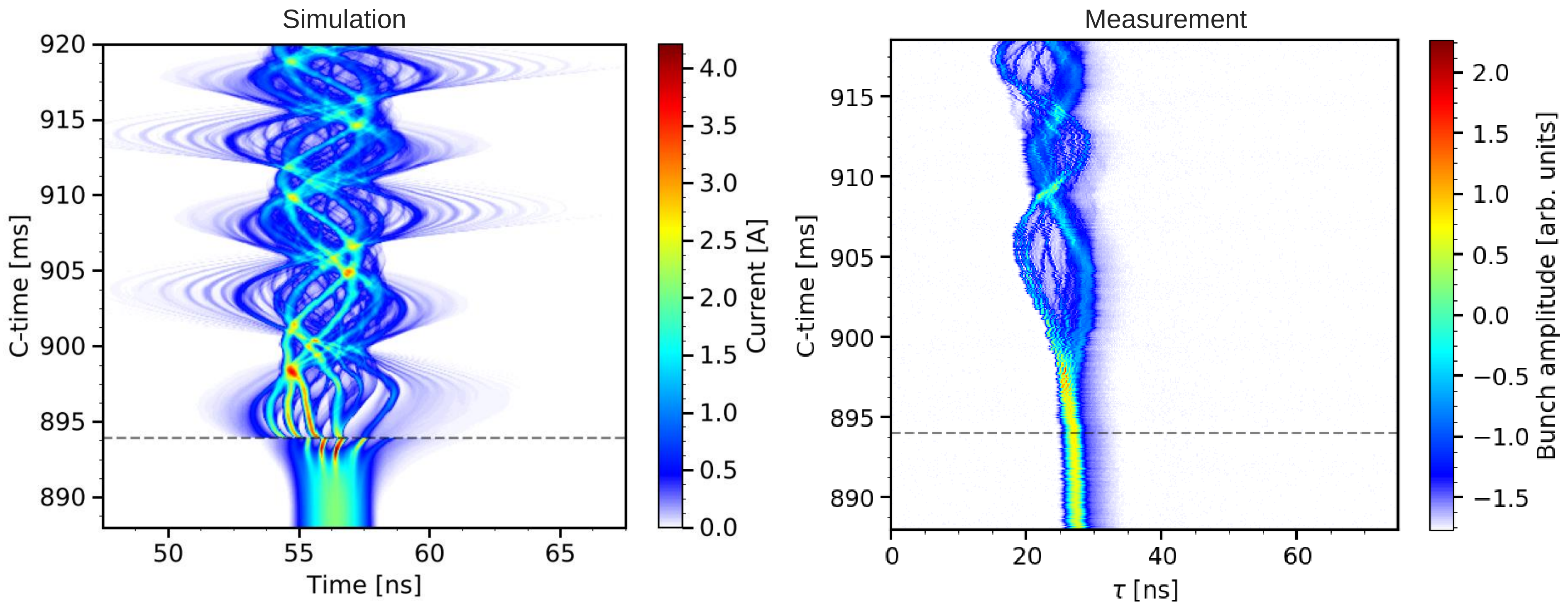
- Enabling both 1TFB on C10 cavities and MHFB on Finemet cavity greatly improves the quality of the triple splitting

Microwave instability at transition crossing for ion beams



- Microwave instability right after transition is responsible for uncontrolled emittance blow-up and generation of tails -> more intensity in satellite bunches
- Occurs with the higher bunch intensity with the 3 bunches beam (same total intensity as the 4 bunches beam), cured with controlled emittance blow-up (BUP) (also measured with Xenon https://indico.cern.ch/event/710562/)
- Study useful for impedance source identification and general benchmark of transition crossing simulations (also beneficial for p+ beams)

Microwave instability at transition crossing - simulation studies



- The gamma jump was removed and the B field increased, without changing the timing of the RF phase jump in simulations (mismatch between $\eta_0 = 0$ crossing and the RF phase jump)
- In all simulations
  - The first synchrotron period is always shorter than in measurements
  - When the bunch is unstable, the amplitude of the quadrupolar oscillation is always bigger in measurements than in simulations
- Explanation for this observation to be determined (reduced RF voltage after transition ? Other impedance source ?)

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