LHC Injectors Upgrade

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An overview on the LHC injector complex and its upgrade

G. Rumolo and M. Meddahi

Acknowledgments: H. Bartosik, E. Benedetto, T. Bohl, J. Coupard, H. Damerau, A. Findlay, A. Funken, R. Garoby, S. Gilardoni, B. Goddard, S. Hancock, K. Hanke, G. Iadarola, V. Kain, L. Kobzeva, A. Lombardi, D. Manglunki, S. Mataguez, B. Mikulec, E. Shaposhnikova, M. Vretenar

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Outline

- Introduction to the injector complex and LHC beam production across the injection chain

- Goals, means and timelines of the LHC Injectors Upgrade (LIU) project
- LIU improvements and impact on performance of LHC beams
  - Linac4
  - PS-Booster
  - PS
  - SPS

- Parameter reach at LHC injection for LIU beams
  - How far we can get
  - Can this be further improved?

- Conclusions

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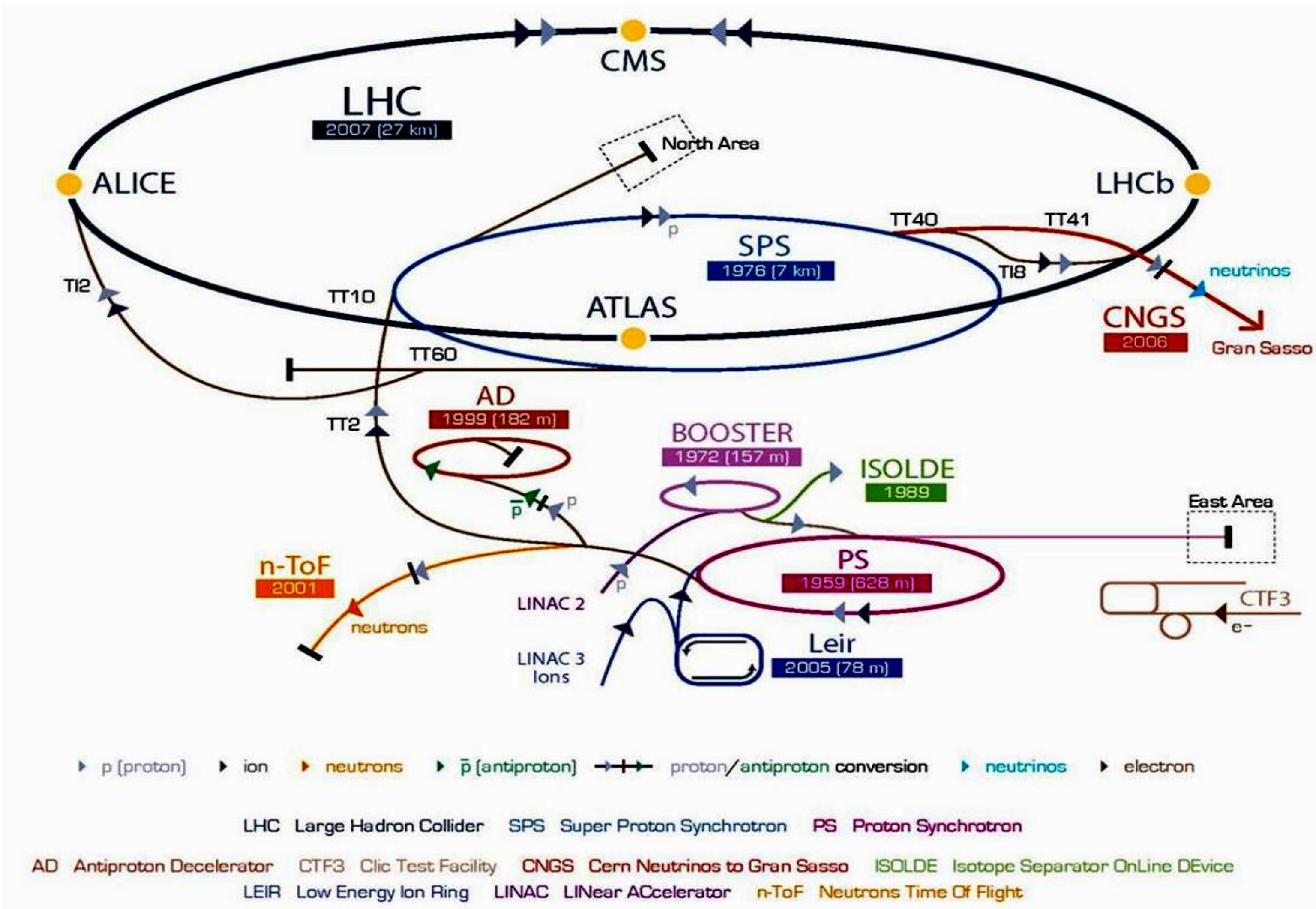
LHC injector complex

The LHC Injectors have to reliably deliver to the LHC the beams required for reaching the LHC luminosity goals

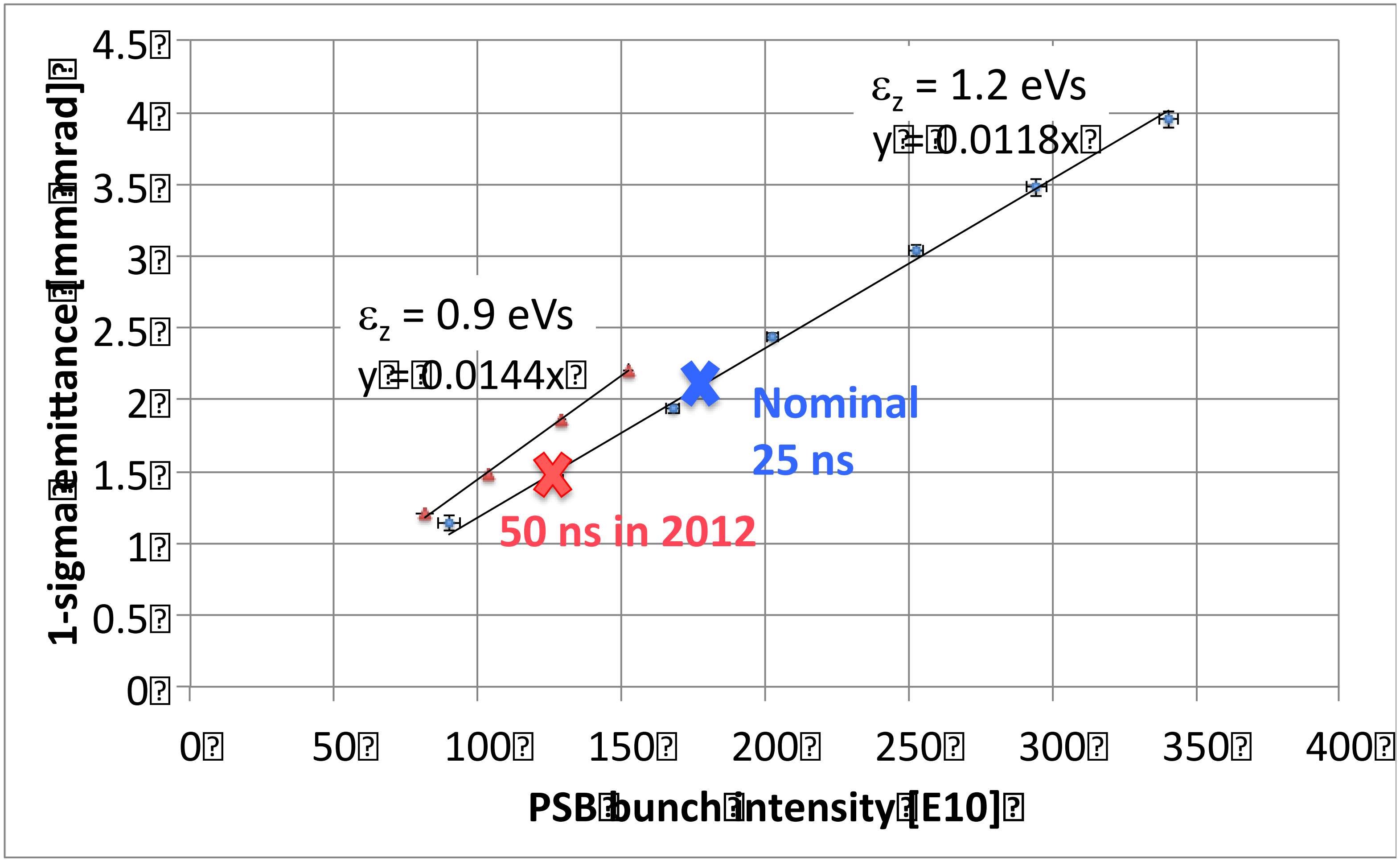


LHC injector complex: Linac2

- **Linac2** injects into the PS-Booster quasi-square pulses of ~150 mA with variable length (tens of us) and transverse emittance of about 1 um
- Nominal **LHC beams are produced injecting ~2.5 turns in all the four rings of the PS-Booster**. High intensity beams rely on injection of up to 13 turns
- Presently a standard multi-turn injection process is used, which determines together with space charge the attainable brightness out of the PS-Booster

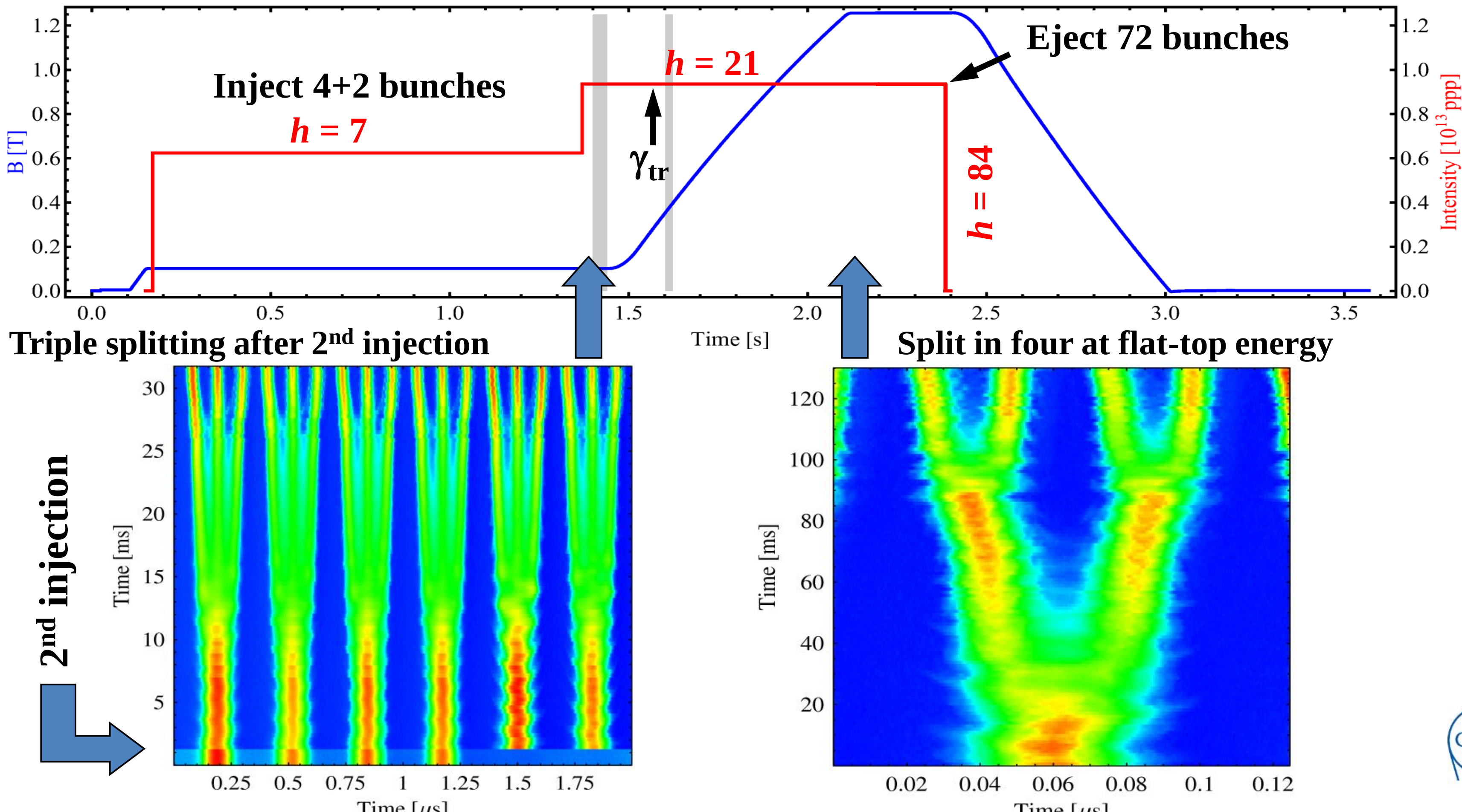
LHC injector complex: PS-Booster

- In each of the four **PS-Booster** rings the beam is bunched (1 bunch/ring) and accelerated from 50 MeV to 1.4 GeV
- Brightness curve at extraction



LHC injector complex: PS

- Six bunches from the PS-Booster are injected into the **PS** in two subsequent injections (4 + 2), spaced by 1.2 s. Acceleration from 1.4 GeV to 25 GeV.
- Triple bunch splitting at low energy and two double bunch splittings at 25 GeV give the beam the final 25 ns structure to be injected into the SPS



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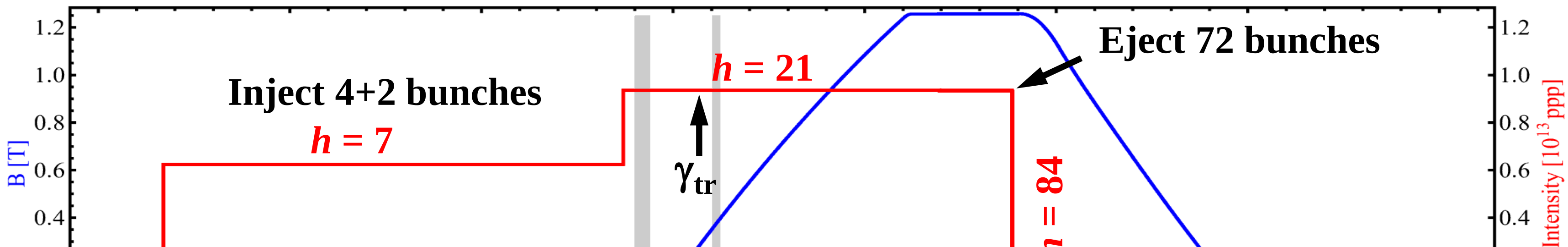
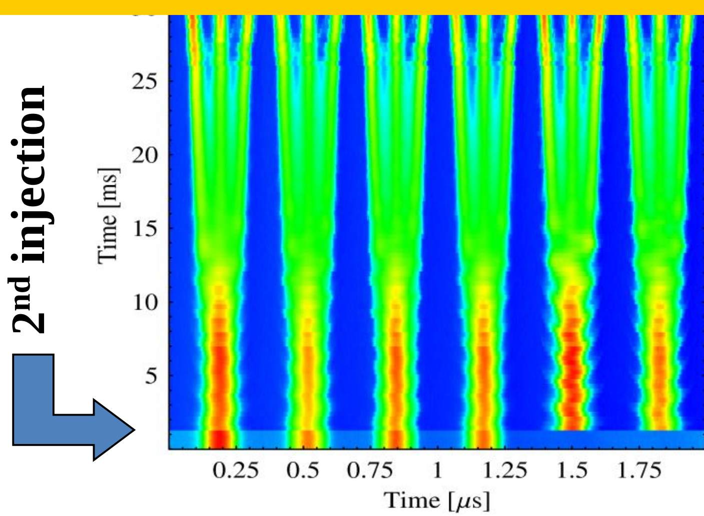
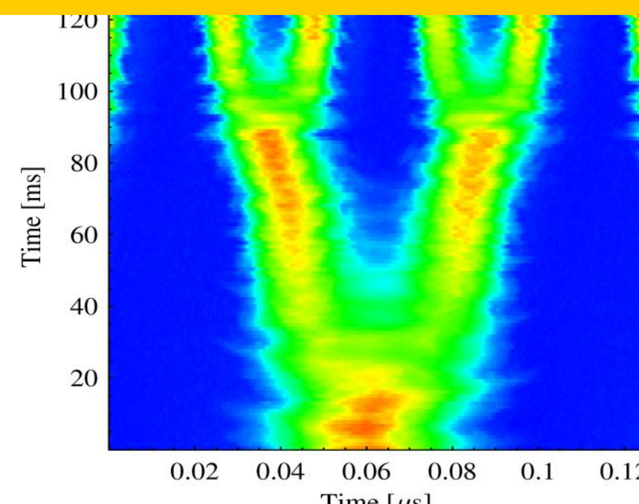


→ **72 bunches with ~ 1.3 · 10^{11} p/bunch sent to the SPS**

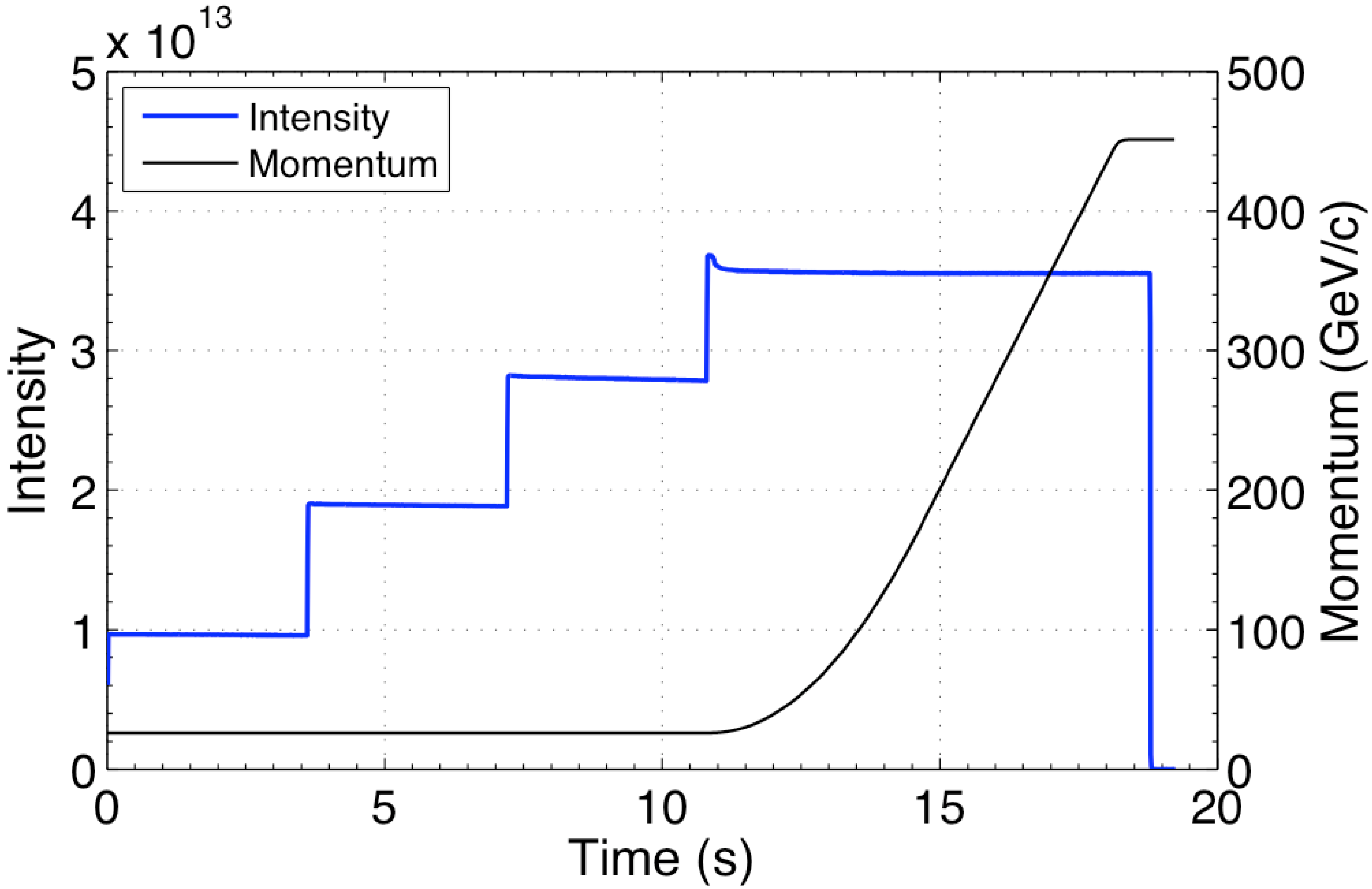
→ **Transverse emittances of about 2.4 um at the PS exit**





LHC injector complex: SPS

- Four trains from the PS are injected into the **SPS** (72 bunches/train) in four subsequent injections, spaced by 3.6 s.
- Acceleration from 25 to 450 GeV, halo scraping at the end of energy ramp and bunch shortening at 450 GeV to send beam to LHC (288 bunches/transfer)



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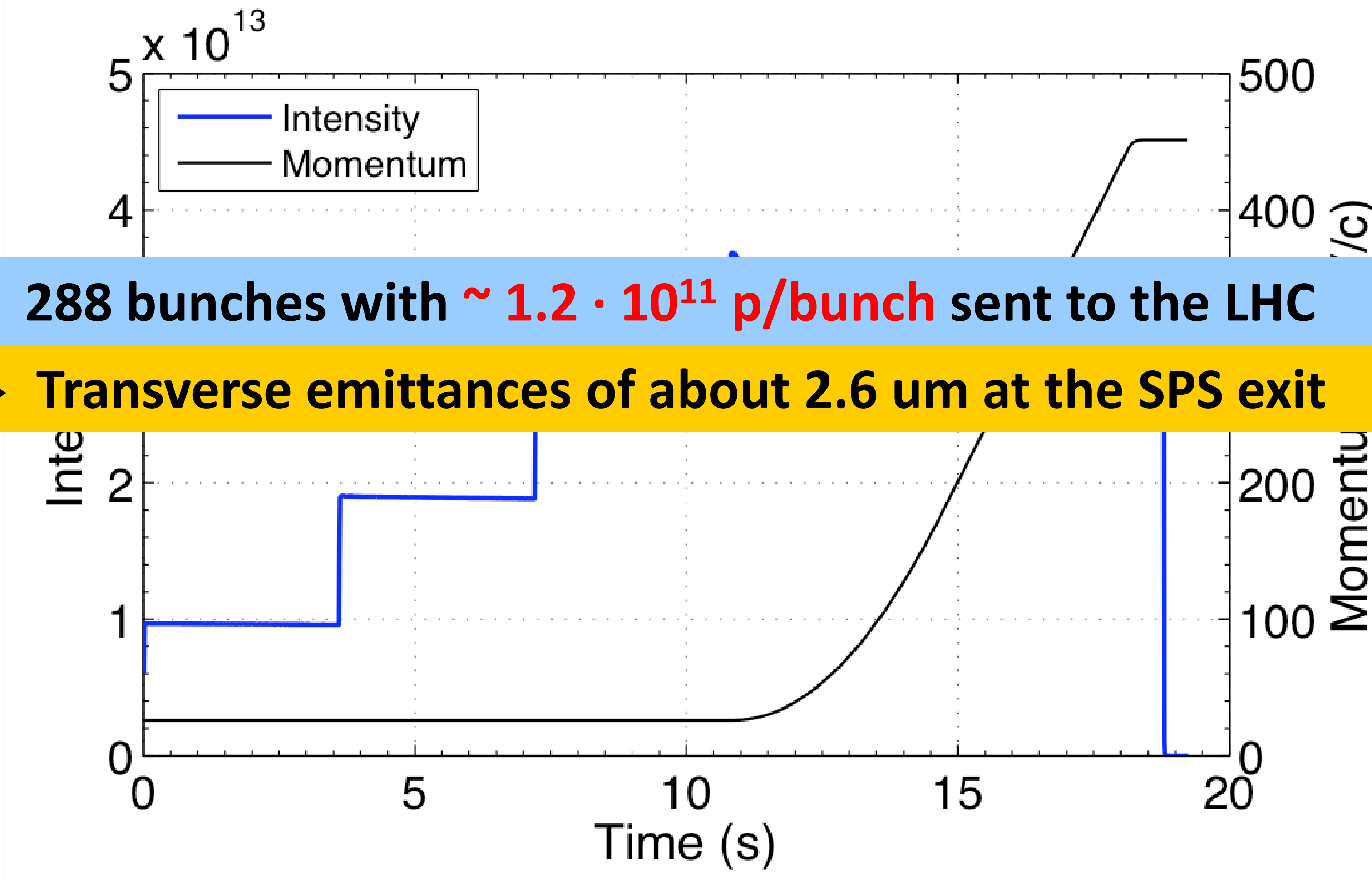

→ **288 bunches with ~ 1.2 · 10^{11} p/bunch sent to the LHC**

→ **Transverse emittances of about 2.6 um at the SPS exit**

LHC injector complex
Summary parameter table

Achieved beam parameters across injector chain

	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)	B_l (ns)	# of bunches
PSB	17.0	2.2	180	6
PS	1.3	2.4	4	72
SPS	1.2	2.6	1.5	288

- Losses and emittance growth are presently in the range of 5% in the PS and 10% in the SPS
- Main performance limitations
  - **PSB**: Space charge and multi-turn injection
  - **PS**: Space charge at injection, longitudinal instabilities (ramp, flat top), transverse instabilities (injection, transition, electron cloud)
  - **SPS**: Longitudinal instabilities along the cycle, RF power, electron cloud, transverse instabilities (mainly at injection)

LHC injector complex
Summary parameter table

Achieved beam parameters compared with desired values for High Luminosity LHC

	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)	B_l (ns)	# of bunches
PSB	17.0	2.2	180	6
PS	1.3	2.4	4	72
SPS	1.2	2.6	1.5	288
SPS for HL-LHC	**2.3**	**2.1**	**1.7**	**288**

Injectors must produce 25 ns proton beams with about double intensity and even more than double brightness

A cascade of improvements is needed across the whole injector chain to reach this target

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Goals and means of the LHC Injectors Upgrade project (LIU)

Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Replace Linac2 with Linac4 and enable the PSB/PS/SPS chain to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedback systems, etc.) targeting the HL-LHC requirement

⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

Increase injectors' reliability and lifetime to cover HL-LHC run (until ~2035!) closely related to CONSolidation project

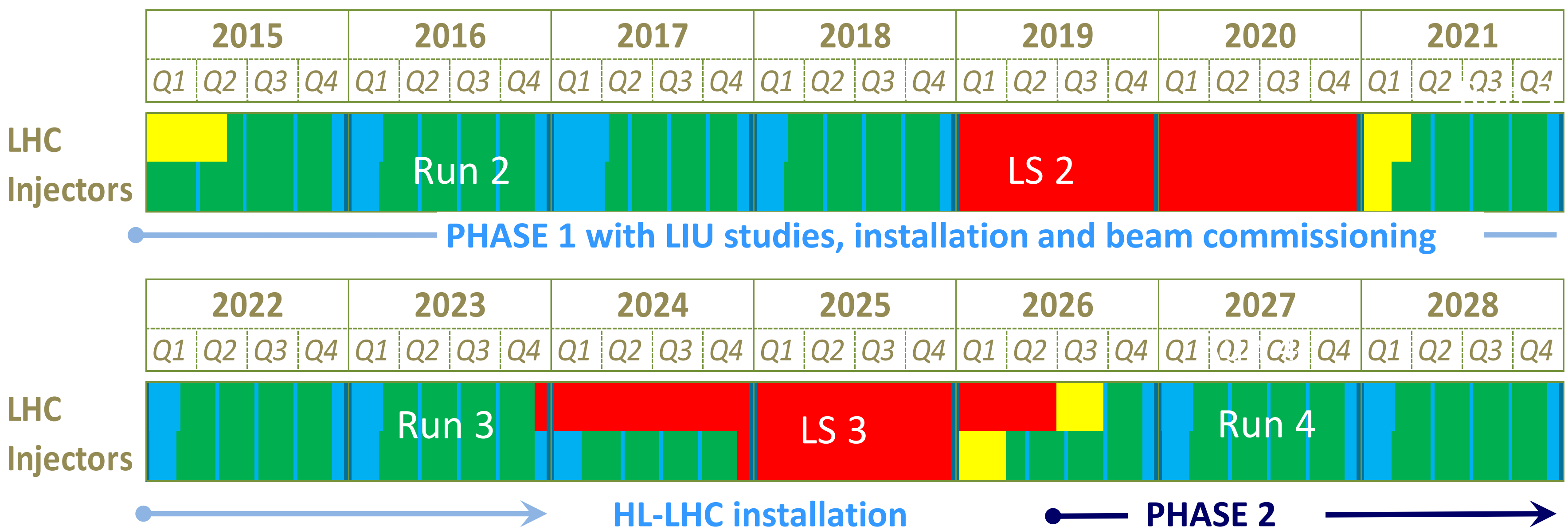
⇒ Upgrade/replace ageing equipment (e.g. power supplies, magnets, RF)

⇒ Improve radioprotection measures (e.g. shielding, ventilation)

** For sake of time, this presentation will cover only the proton injector chain

Timelines of LIU

- LIU (machine and simulation) studies during **Run 2** until **LS2**
  - Key dates for pending decisions until 2016
- LIU installations and hardware work mainly during **LS2**
- Beam commissioning of LIU beams
  - **Pb ion beams** need to be ready by **2021 ion run**
  - **Proton beams** during **Run 3** to be ready after **LS3**



Linac2 → Linac4

- Linac4 will allow production of higher brightness beams in the PS-Booster
  - Higher injection energy (160 instead of 50 MeV) → Weaker space charge
  - H^- injection → Pack more intensity in reduced phase space volume

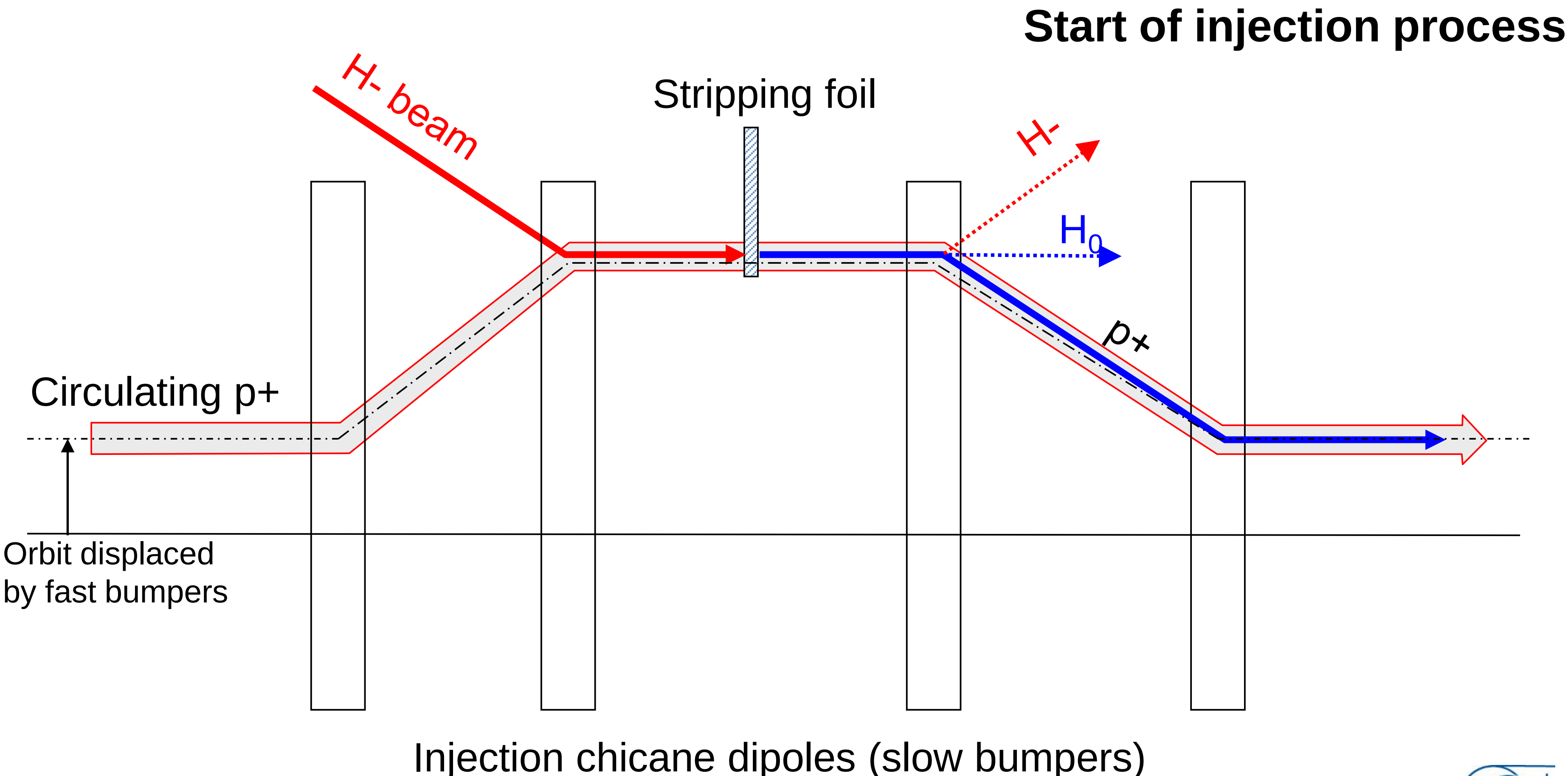
Ion species	H^-
Output Energy	160 MeV
Bunch Frequency	352.2 MHz
Max. Rep. Frequency	2 Hz
Max. Beam Pulse Length	0.4 ms
Max. Beam Duty Cycle	0.08 %
Chopper Beam-on Factor	65 %
Chopping scheme:	215 transmitted /140 empty buckets
Source current	40 mA
Linac pulse current	26 mA
Transverse emittance	0.4 π μm

Maximum repetition frequency of accelerating structures 50 Hz

- HL-LHC goal:
  ~20 turns → 3.4 10^{12} p/Ring in 1.72 μm
- High intensity ISOLDE:
  ~100 turns → 16 10^{12} p/Ring

Linac2 → Linac4

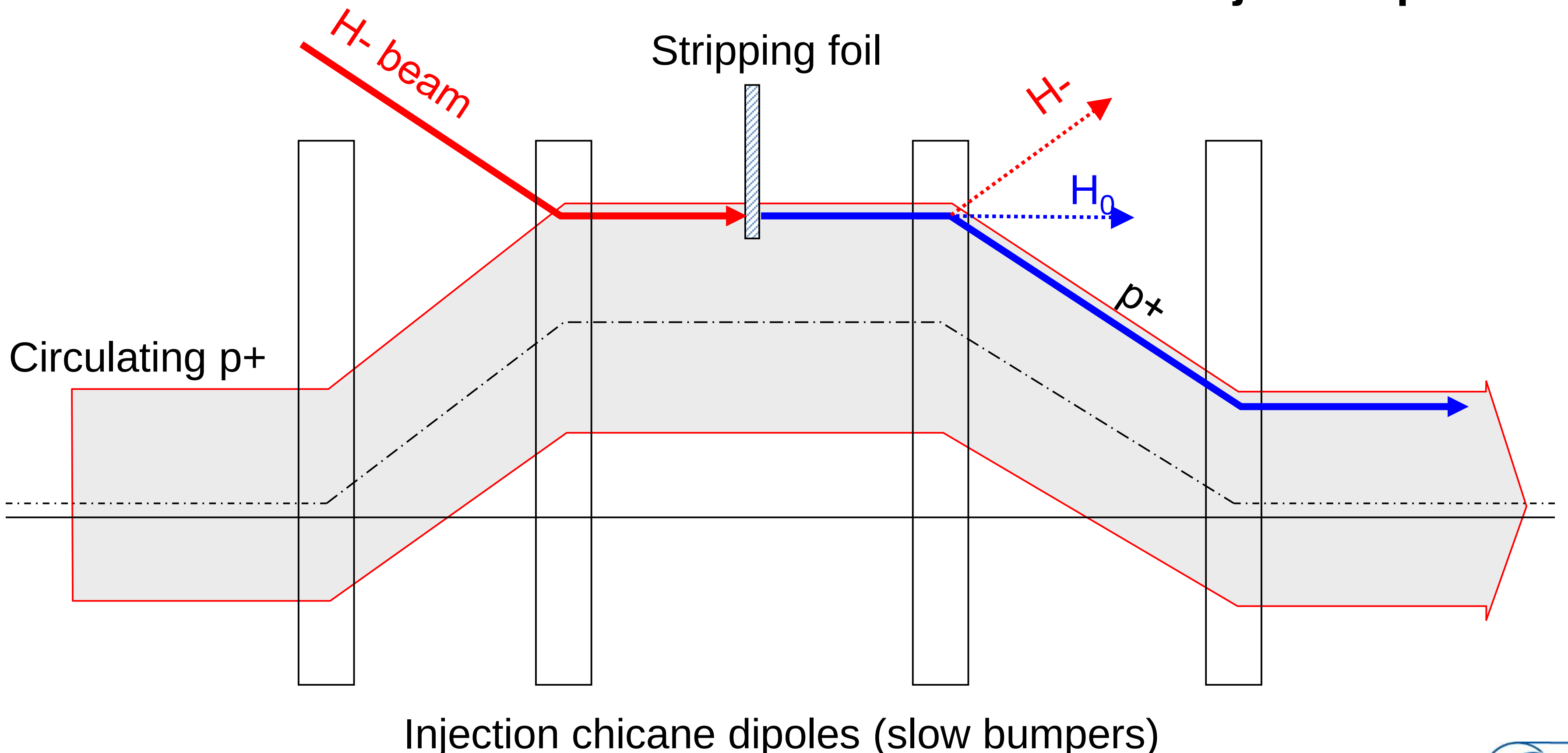
- Charge exchange H^- injection



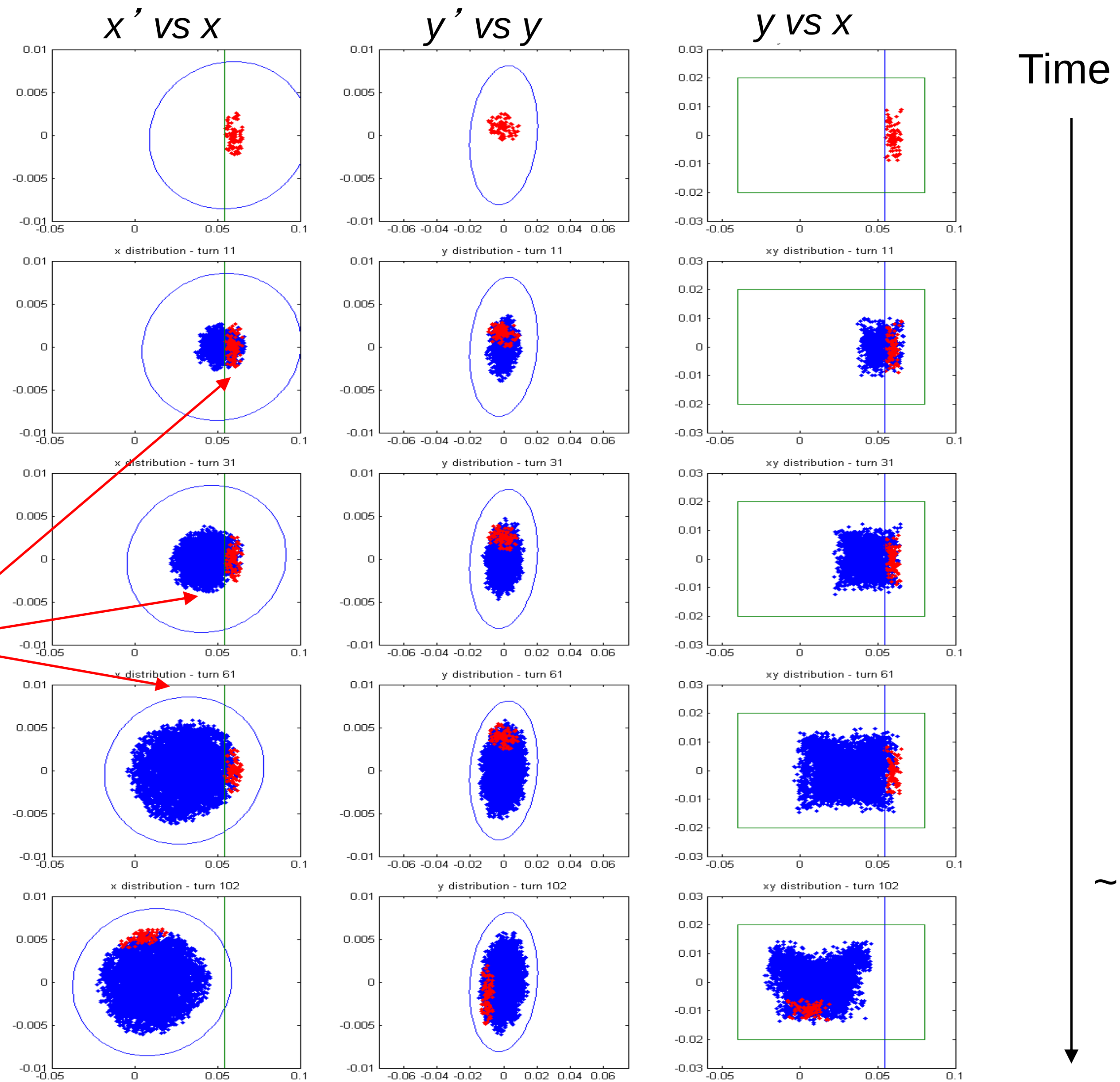
Linac2 → Linac4

- Charge exchange H^- injection

End of injection process



Example of 100 turn injection into PS-Booster



Note injection into same phase space area as circulating beam

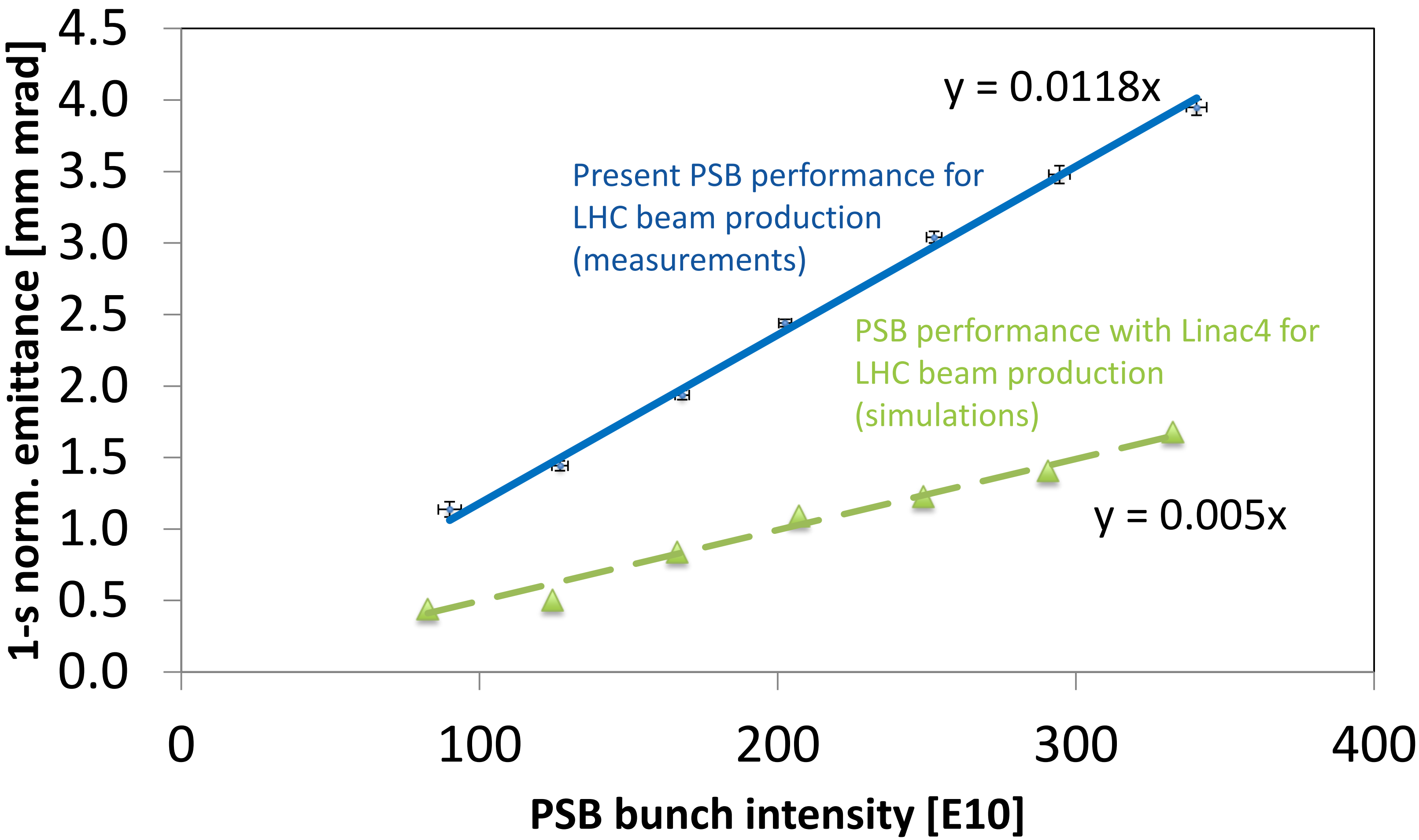
Linac2 → Linac4

- Charge exchange H^- injection
  - Paint uniform transverse phase space density by modifying closed orbit bump and steering injected beam
  - Foil thickness calculated to double-strip most ions (>99%)
    - Carbon foils generally used – very fragile
  - Injection chicane reduced or switched off after injection to avoid excessive foil heating and beam blow up

Linac2 → Linac4: what it will bring

- New brightness curve at PS-Booster extraction has about half slope with respect to old curve (simulations including full H^- injection and space charge)

→ Brightness out of the PS-Booster will be about doubled for LHC beams



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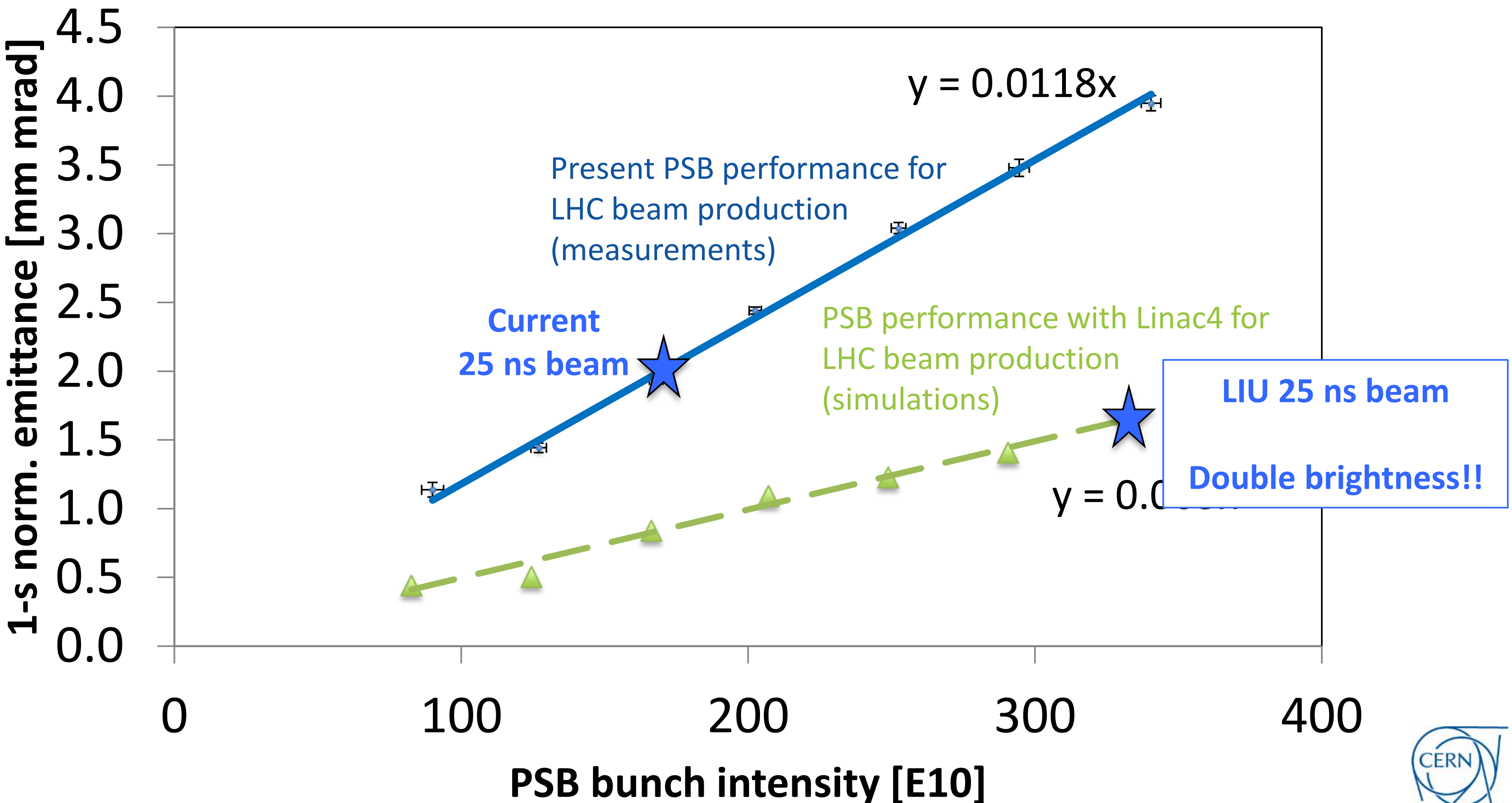
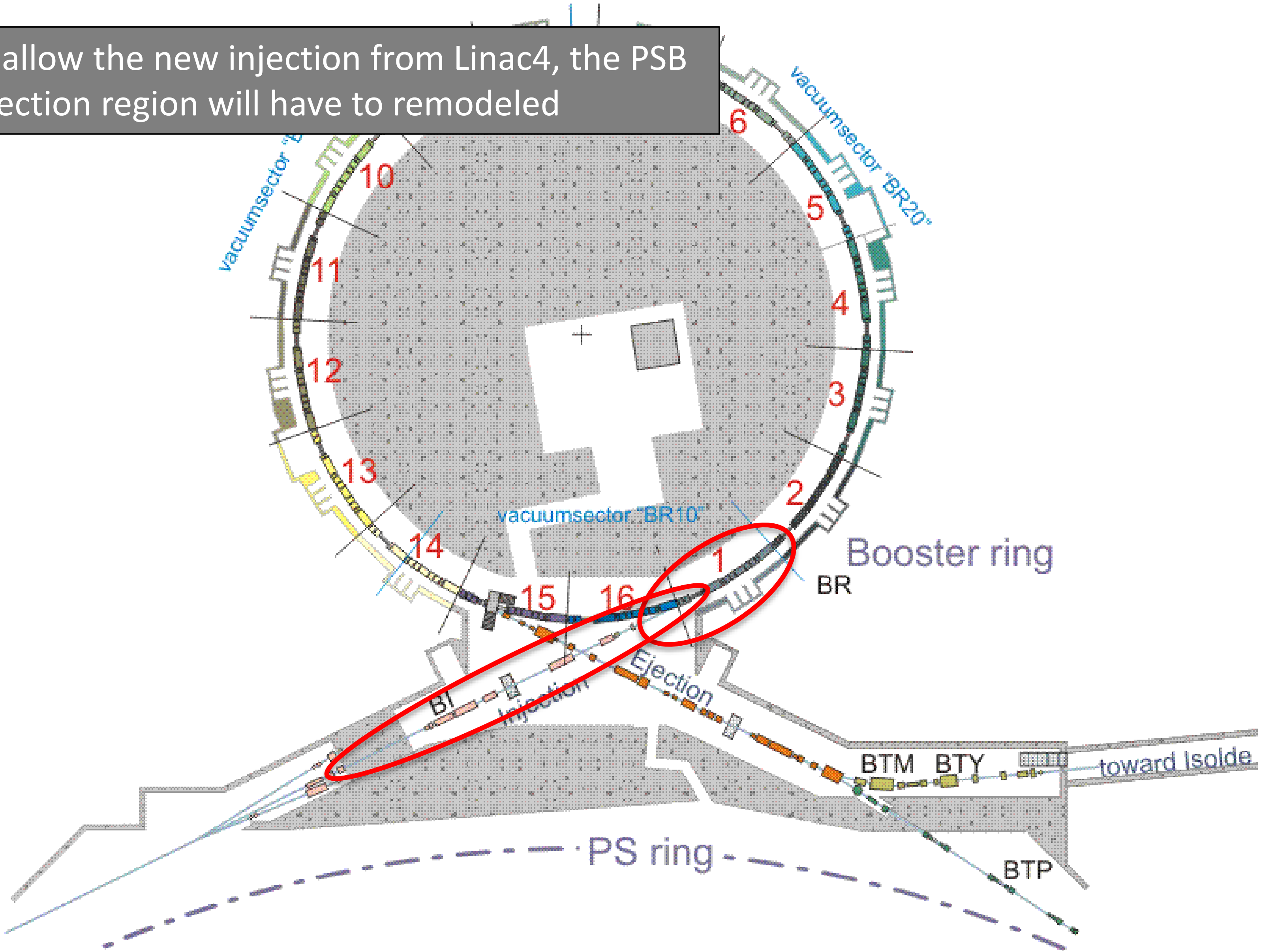


PS-Booster upgrade

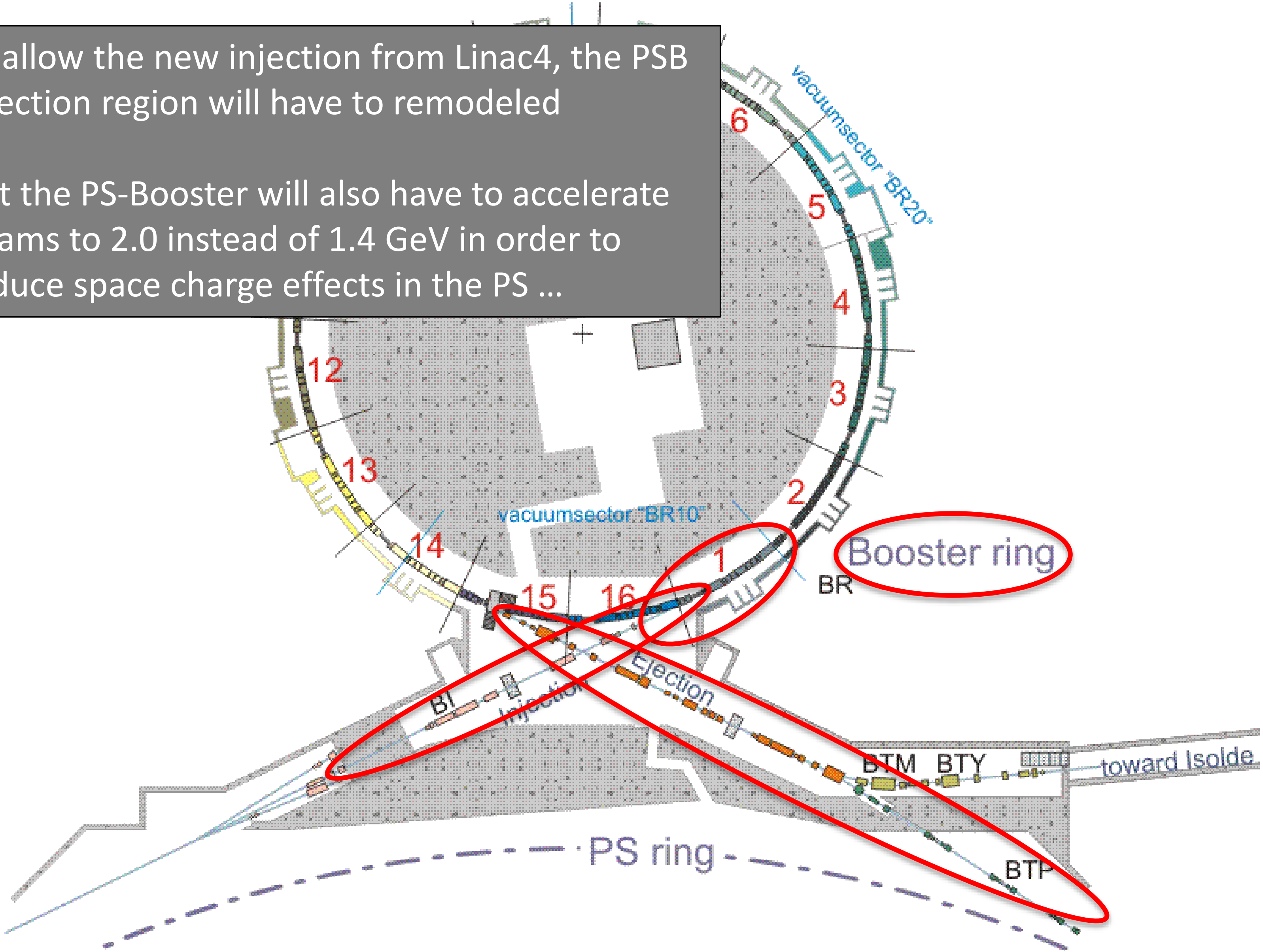
To allow the new injection from Linac4, the PSB injection region will have to remodeled



PS-Booster upgrade

To allow the new injection from Linac4, the PSB injection region will have to remodeled

But the PS-Booster will also have to accelerate beams to 2.0 instead of 1.4 GeV in order to reduce space charge effects in the PS …

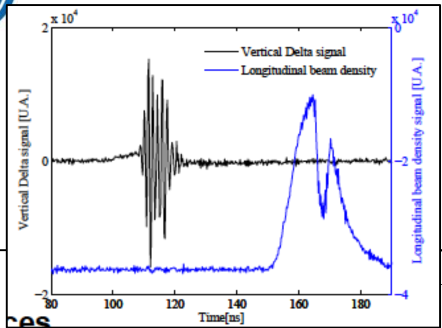


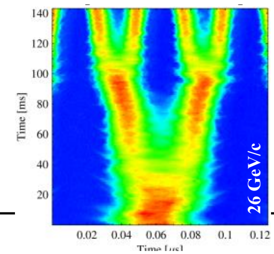
PS-Booster: main upgrade items

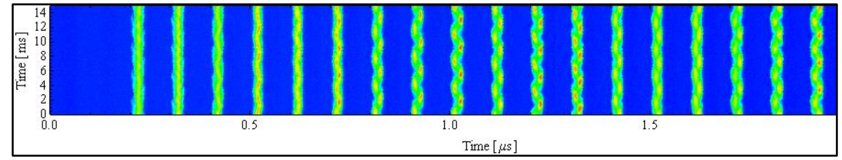
- Implementation of **new H^- charge exchange injection at 160 MeV** from Linac4 (redesign of injection region)
  - Distributor, septa
  - Stripping foil and foil handling system
  - Painting and chicane magnets, correctors
  - New beam instrumentation

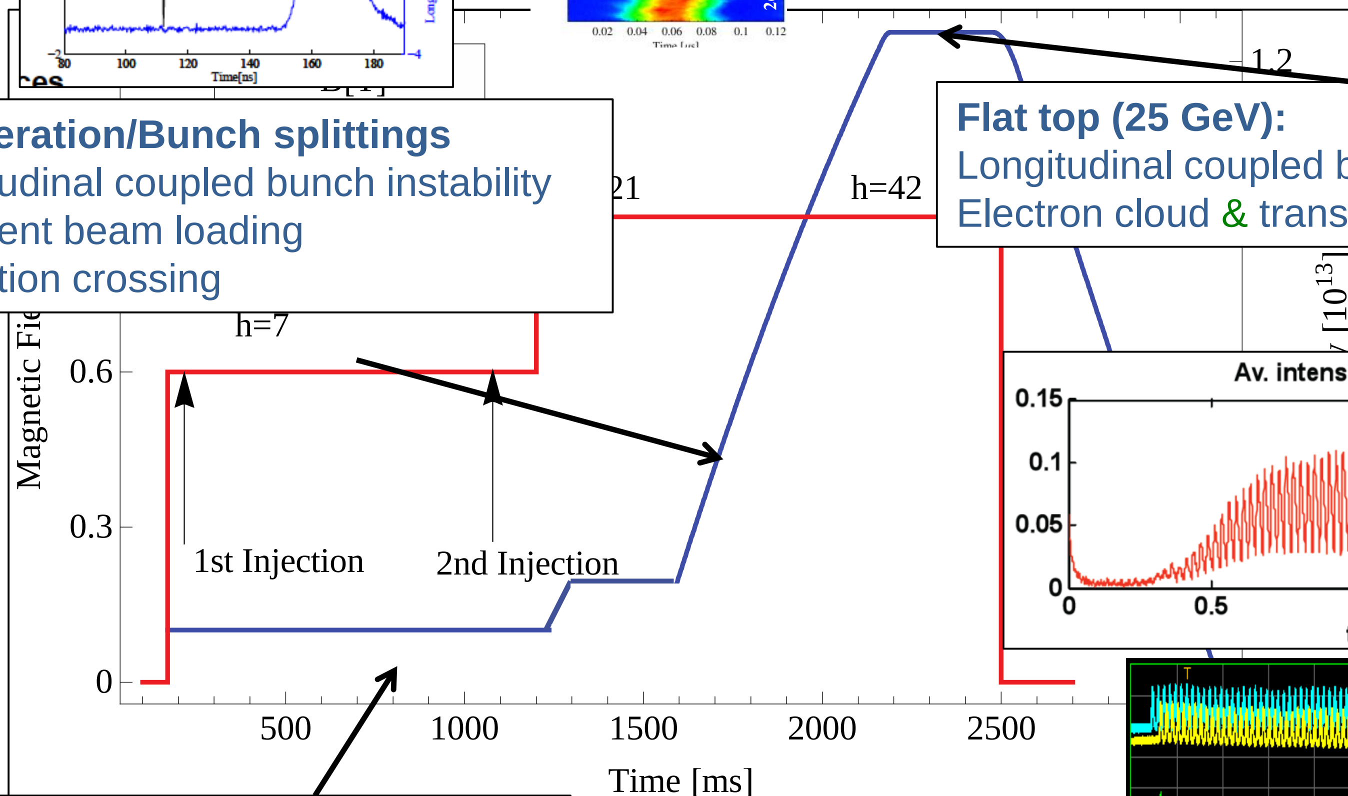
- New extraction energy: **1.4 GeV → 2 GeV**
  - New Main Power Supply (MPS)
  - New RF system to replace current both C02 and C04 systems
  - Modification of main magnet cooling, shimming and saturation layout
  - Extraction/recombination kickers and septa

PS limitations overview



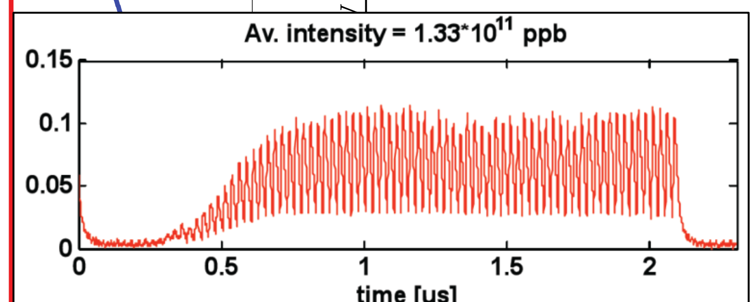


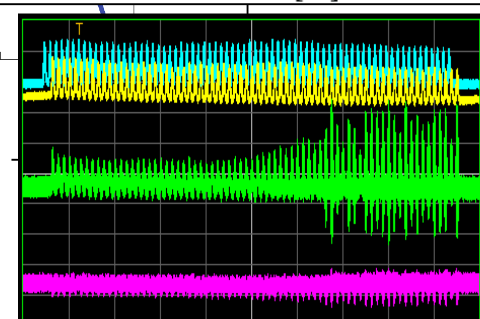


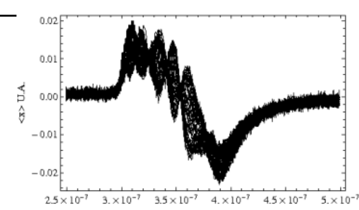


Acceleration/Bunch splittings
Longitudinal coupled bunch instability
Transient beam loading
Transition crossing

Flat top (25 GeV):
Longitudinal coupled bunch instability
Electron cloud & transverse instabilities

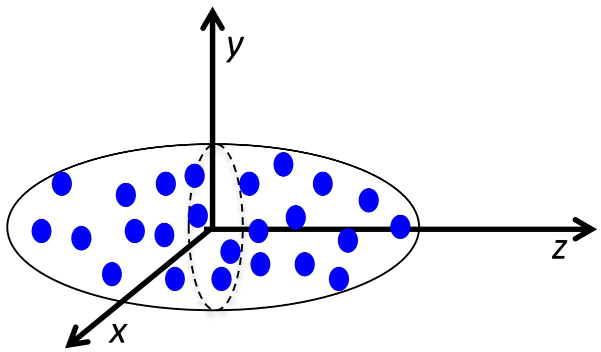






Injection flat bottom (1.4 GeV):
Space charge
Head-tail instability

Space charge: a brief description

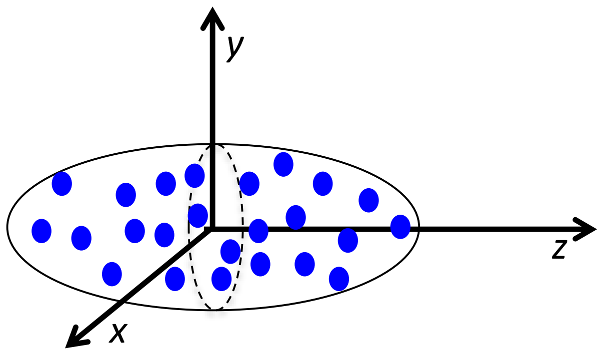


Space charge is the repelling force between same charge particles with one particle bunch

➔ It results into a net defocusing effect felt by each particle and therefore a **tune depression** depending on the beam and machine parameters

$$\Delta Q_{x,y}(z) = -\frac{r_0 \lambda(z) C}{2\pi e \beta \gamma^2 \epsilon_{xn,yn}}$$

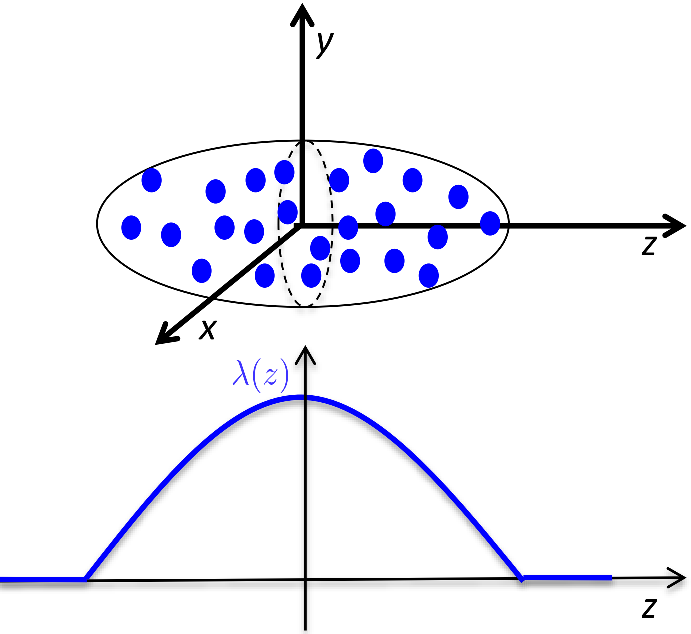
Space charge: a brief description



$$\Delta Q_{x,y}(z) = -\frac{r_0 \lambda(z) C}{2\pi e \beta \gamma^2 \epsilon_{xn,yn}}$$

$\propto \lambda(z)$	Bunches with **higher peak current** suffer larger space charge tune spreads
$\propto 1/\epsilon_n$	**Lower emittance** bunches suffer larger space charge tune spreads
$\propto 1/(\beta\gamma^2)$	**Lower energy** beams suffer larger space charge tune spreads
$\propto C$	**Longer machines** can build up larger space charge tune spreads

Space charge: a brief description



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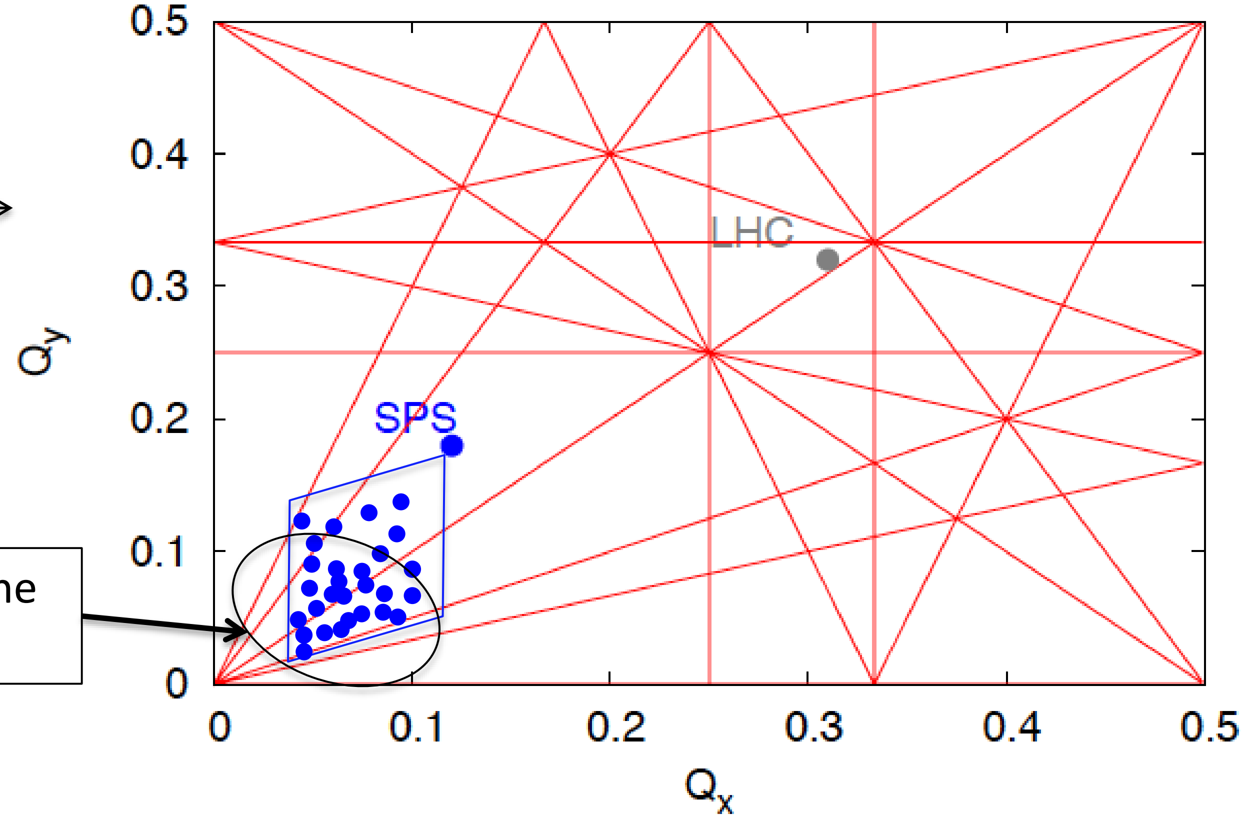
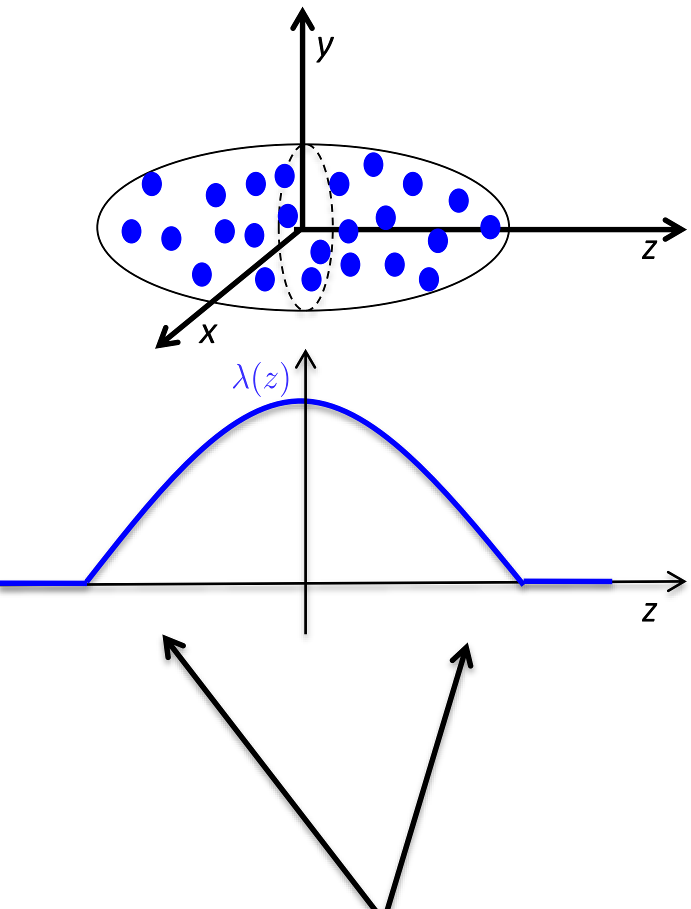


Particles oscillating close to the bunch peak density

Space charge: a brief description



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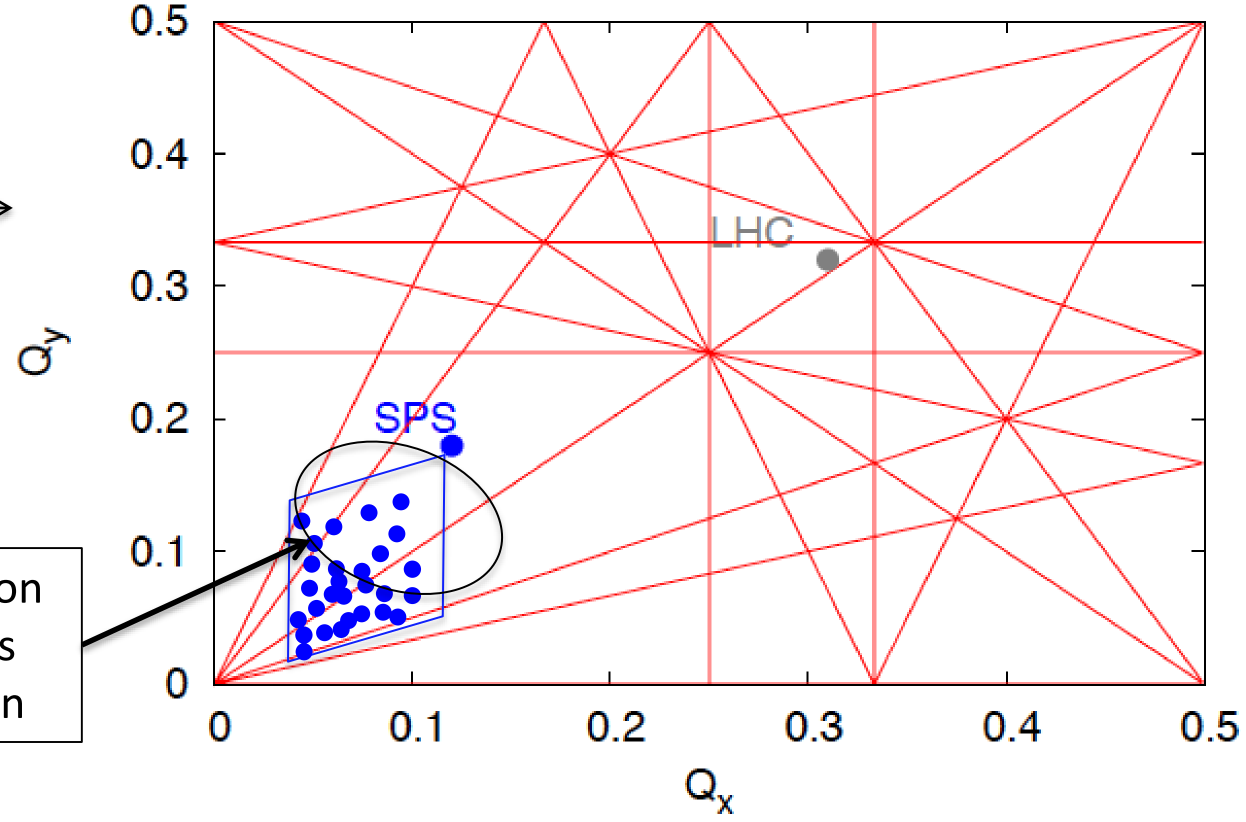
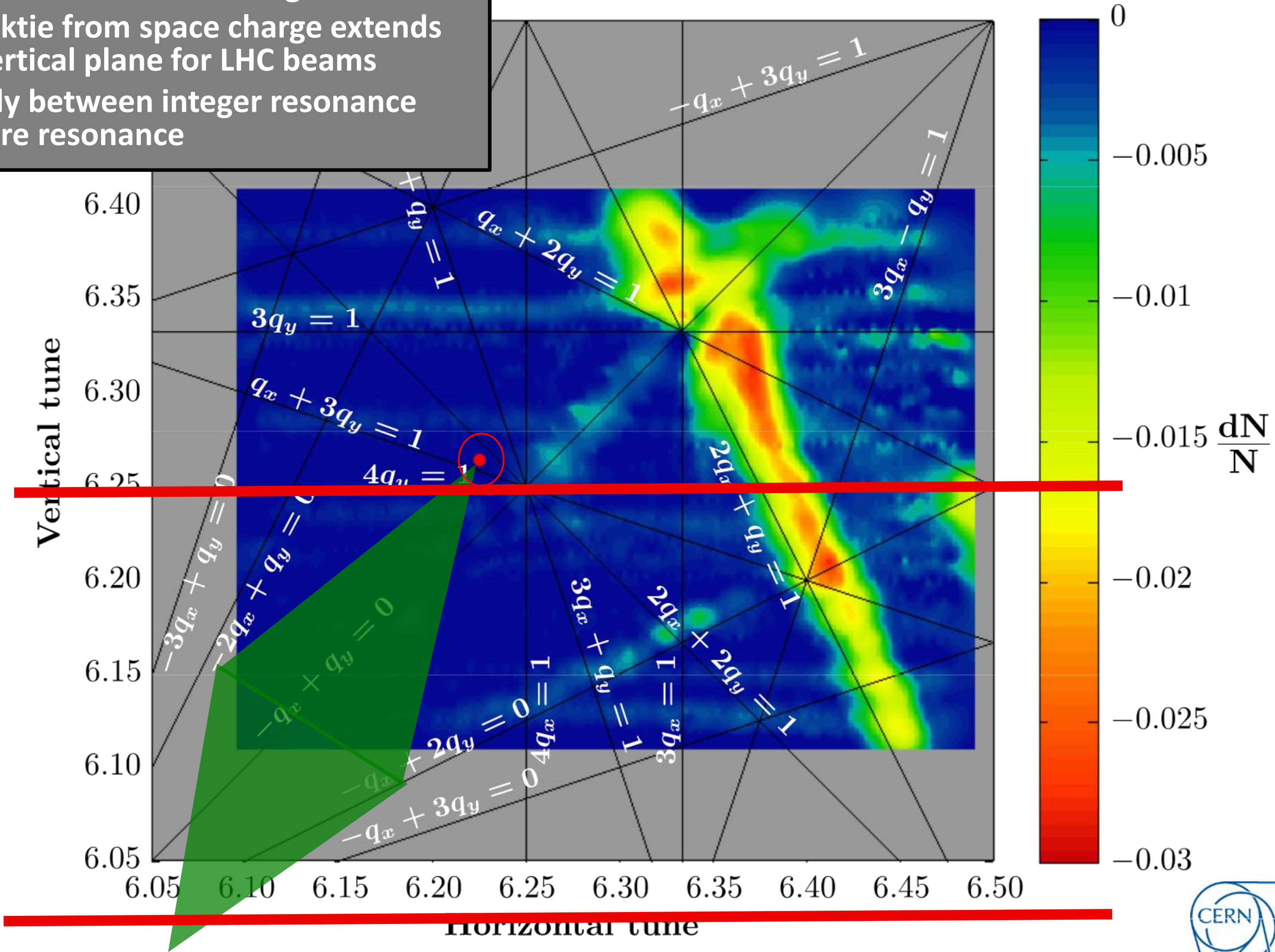


Particles with large synchrotron amplitudes, mainly at the tails of the longitudinal distribution

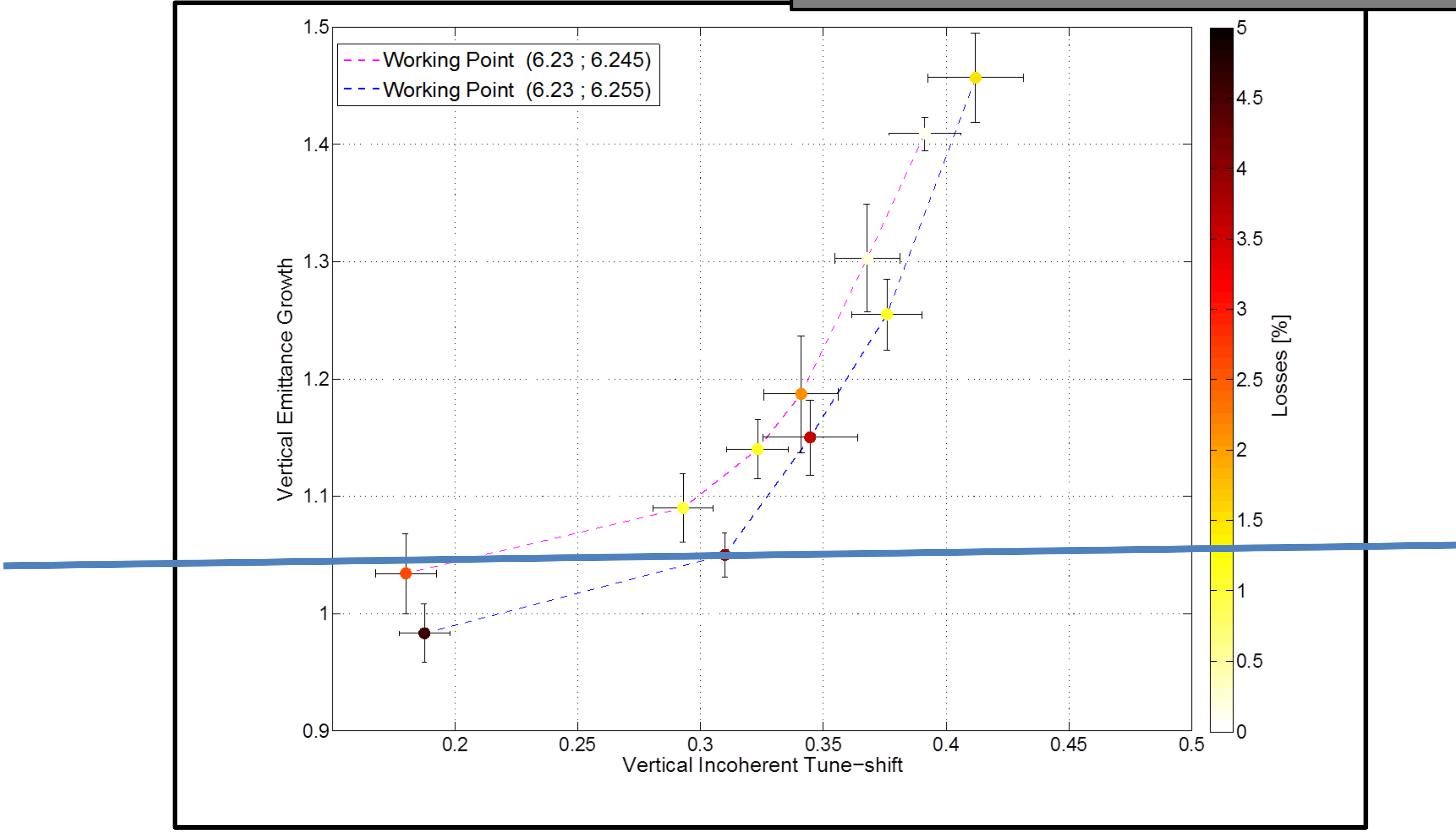
Space charge at PS injection

- Nominal tune in "resonance free" region
- Tune spread necktie from space charge extends by 0.31 in the vertical plane for LHC beams
- Spread fits tightly between integer resonance and 6.25 structure resonance



Space charge at PS injection

- Measurements of losses and emittance growth for different tune spreads reveal the effects of resonance crossing
- To guarantee 5% loss and emittance growth we are limited to 0.31 tune spread with a 'high' working point



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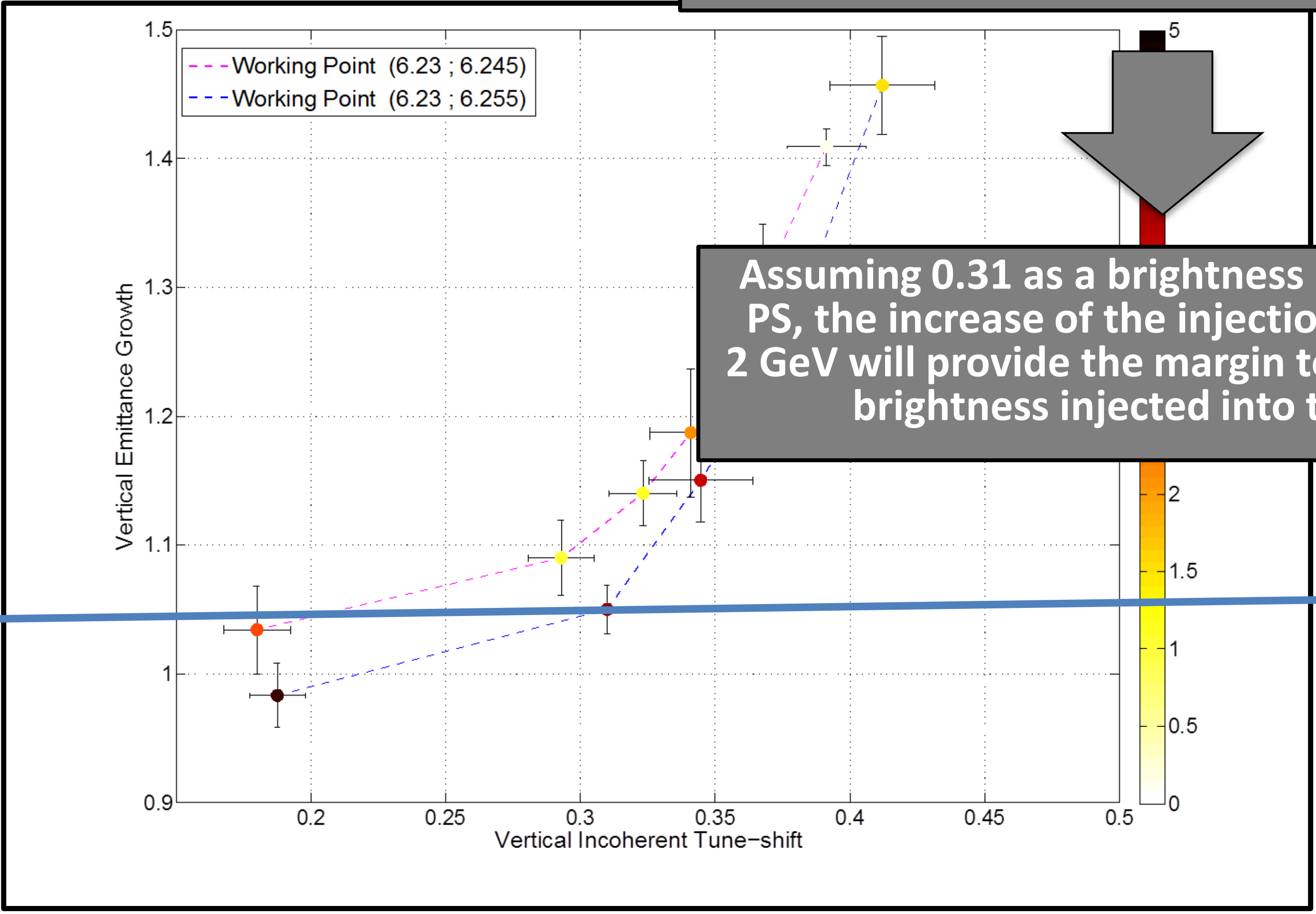

Assuming 0.31 as a brightness limit for the PS, the increase of the injection energy to 2 GeV will provide the margin to double the brightness injected into the PS

PS: main upgrade items

- Implementation of **new 2 GeV injection** from PS-Booster (redesign of injection region)
  - Injection kicker and septum
  - Orbit bumpers at 2 GeV
  - New beam instrumentation

- Upgrades to **accelerate and transfer higher intensities**
  - New longitudinal damper against longitudinal coupled bunch instabilities based on broad-band cavity
  - Transverse feedback system to control transverse instabilities (head-tail, electron cloud)
  - Upgrade of existing RF systems to guarantee RF manipulations and improve transmission to SPS in new intensity regime

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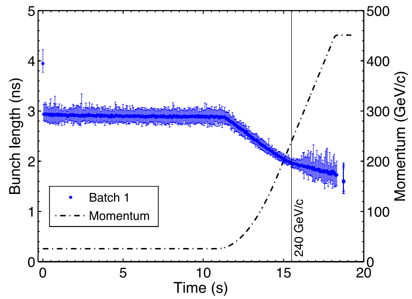
  - Tr d-tail, el
  - Up im

Maximum intensity per bunch @PS extraction mainly due to longitudinal instabilities

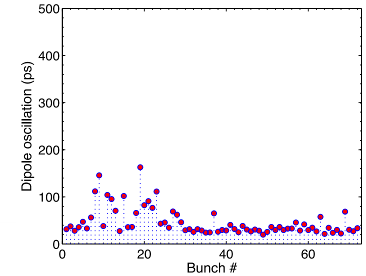
N_b= 2.0 x 10^{11} ppb → 3.0 x 10^{11} ppb after upgrades

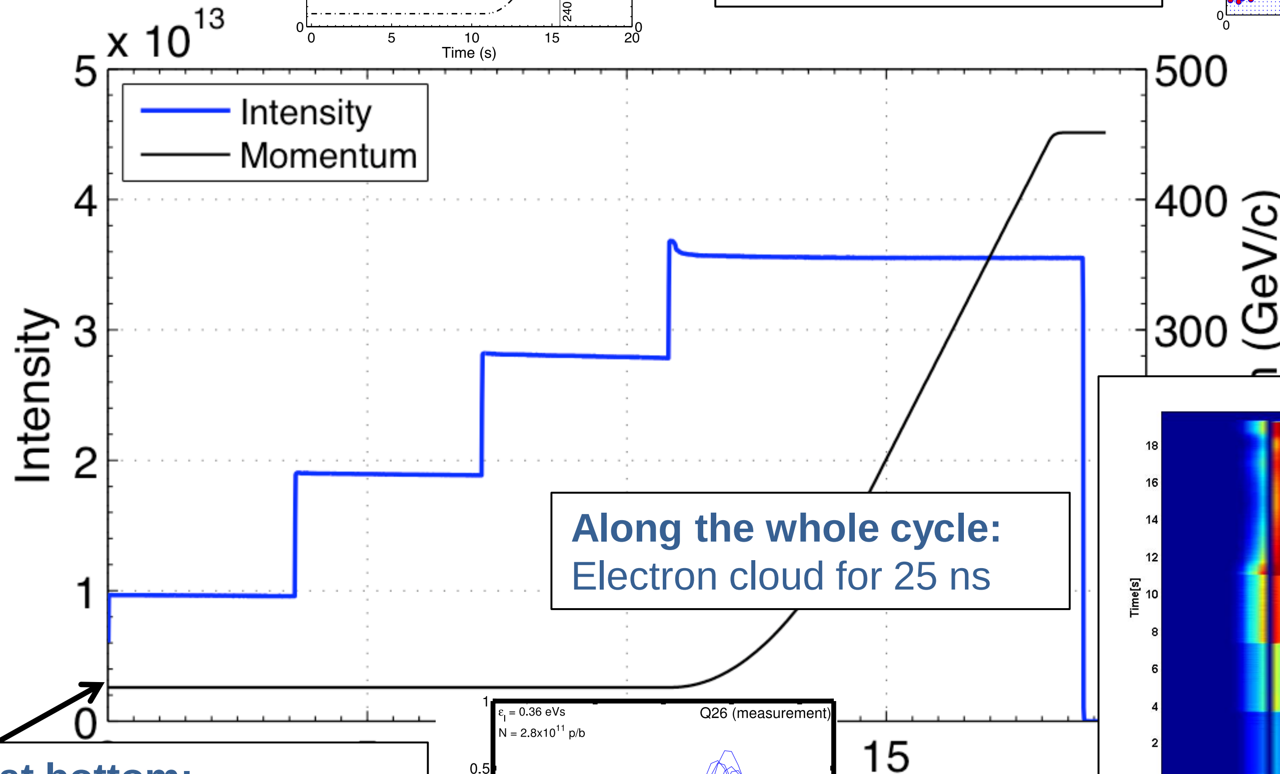
→ Enough to accommodate the LIU targets

SPS limitations overview

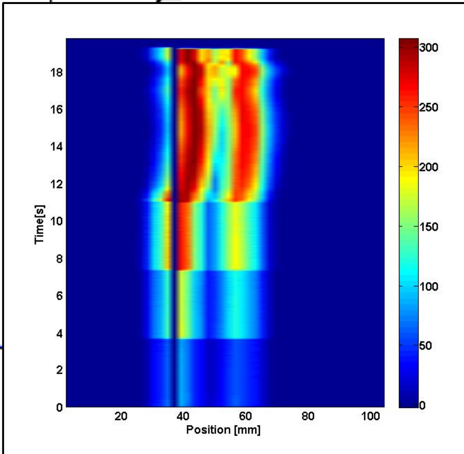


Ramp and flat top:
Longitudinal instability
Beam loading
RF power

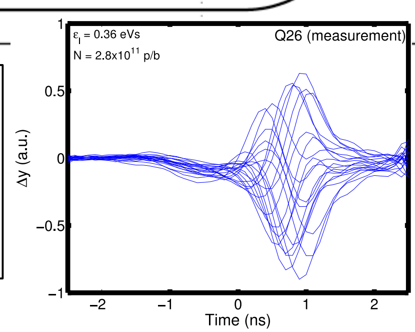




Along the whole cycle:
Electron cloud for 25 ns



Injection flat bottom:
Capture losses, incoherent losses
Space charge
TMCI



Electron cloud: a brief description

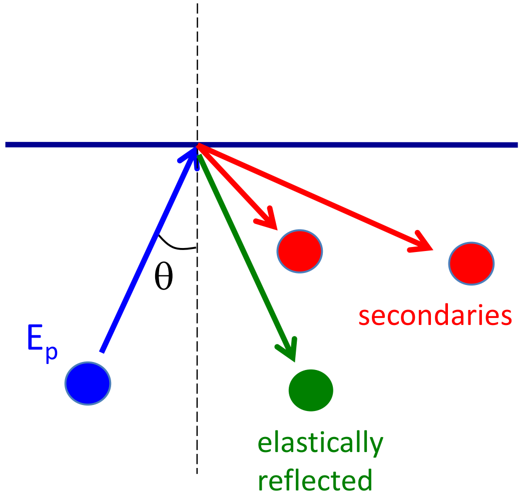
Electrons are created inside the vacuum chamber with circulating beam (primary, or seed, electrons)

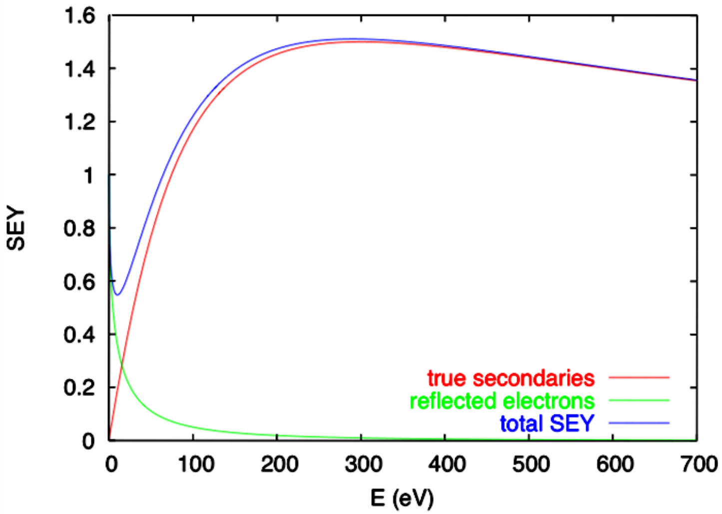
- **Residual gas ionization**
- **Photoelectrons from synchrotron radiation**
- **Desorption from the losses on the wall**

Electron cloud: a brief description

Electrons are created inside the vacuum chamber with circulating beam (primary, or seed, electrons)

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall





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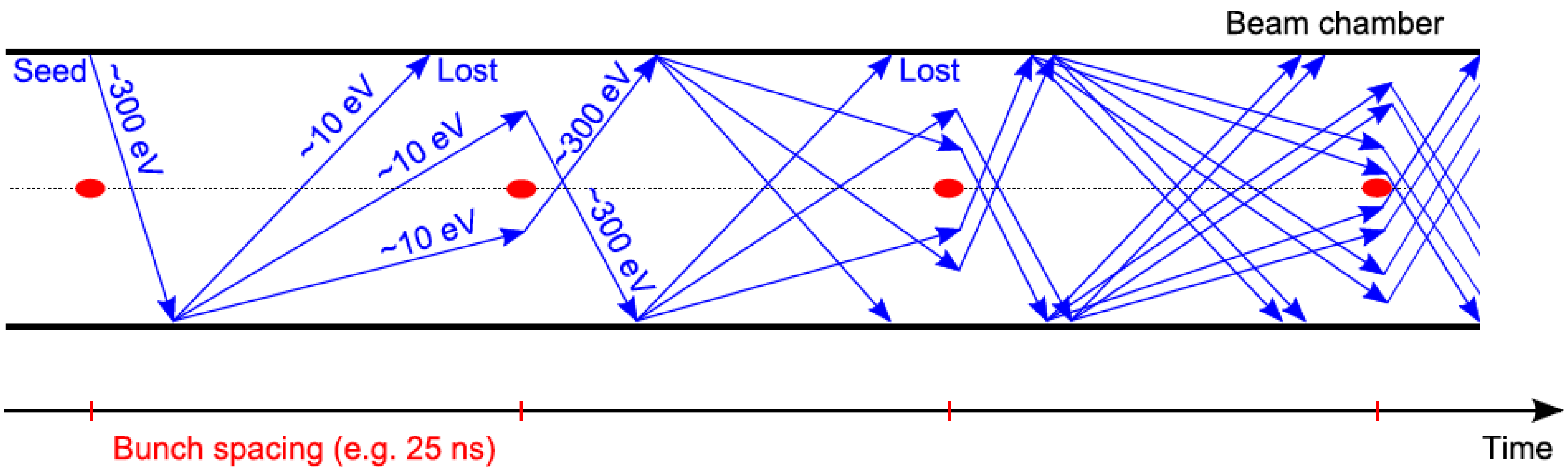
- Avalanche electron multiplication



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Electrons are created inside the vacuum chamber with circulating beam (primary, or seed, electrons)

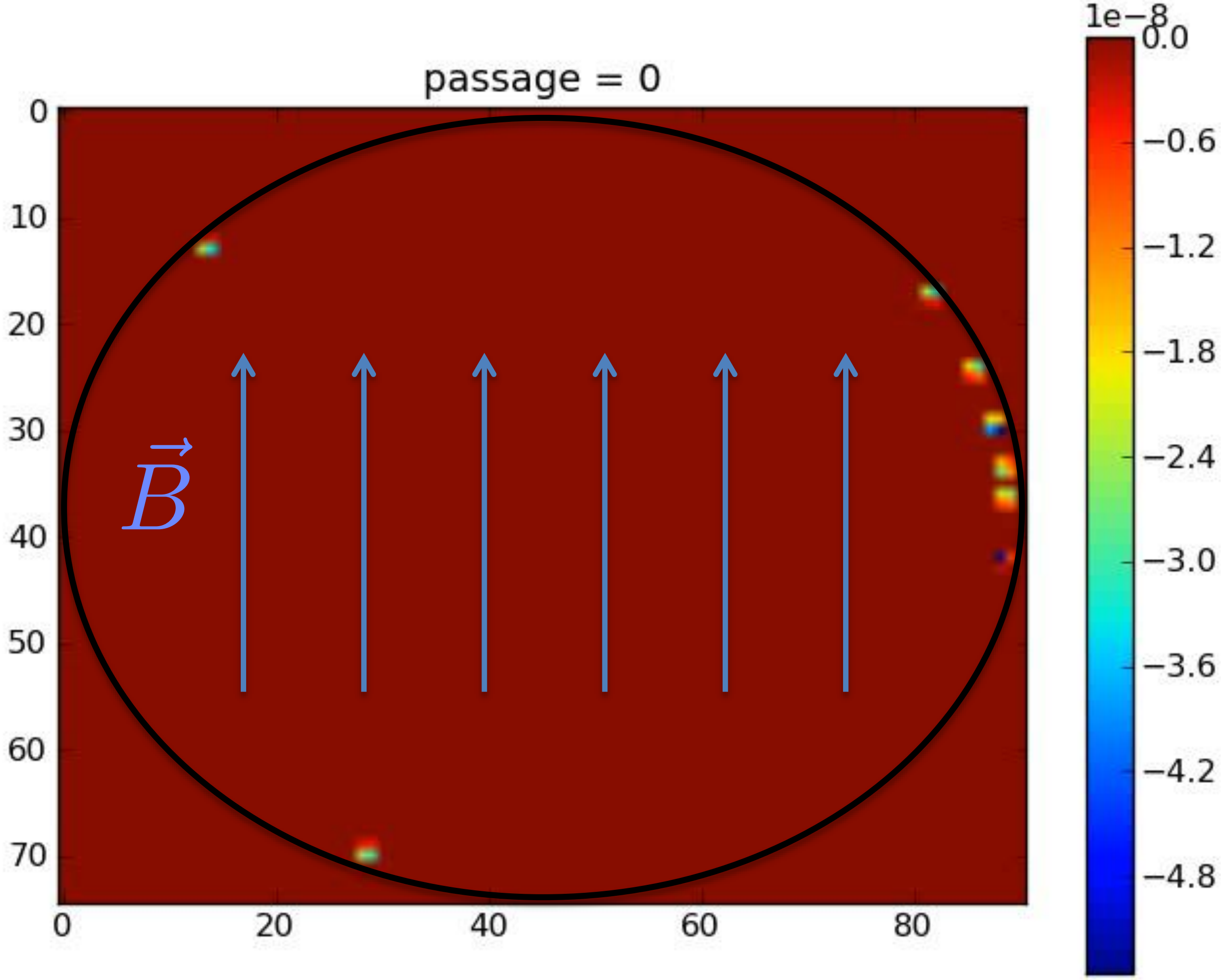
↓

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication

↓

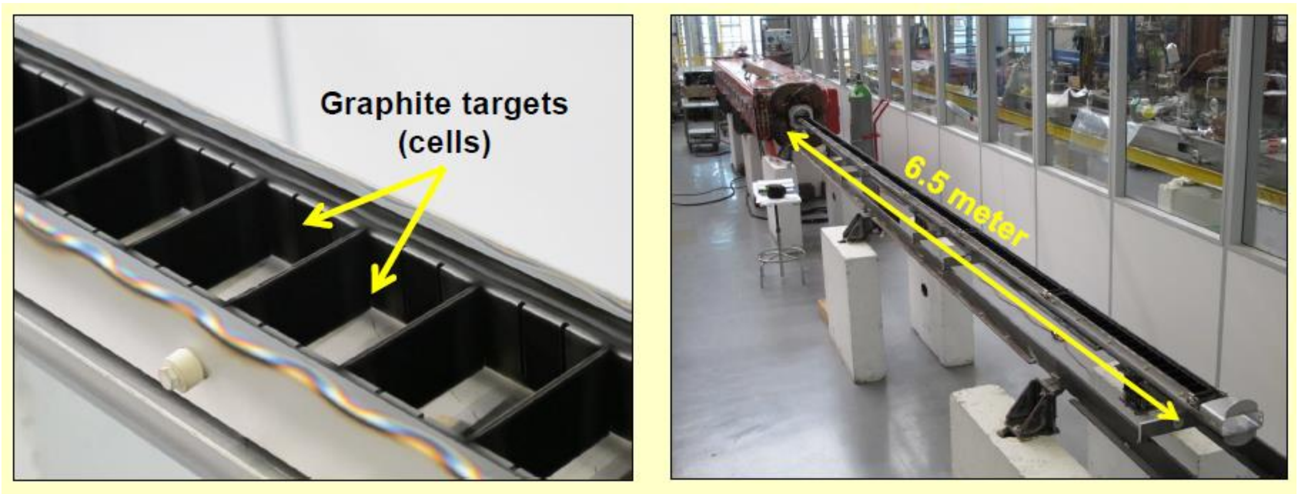
After the passage of several bunches, the electron distribution inside the chamber reaches a stationary state (electron cloud) → Vacuum degradation, beam instability and quality deterioration

Electron cloud: Build up in a dipole



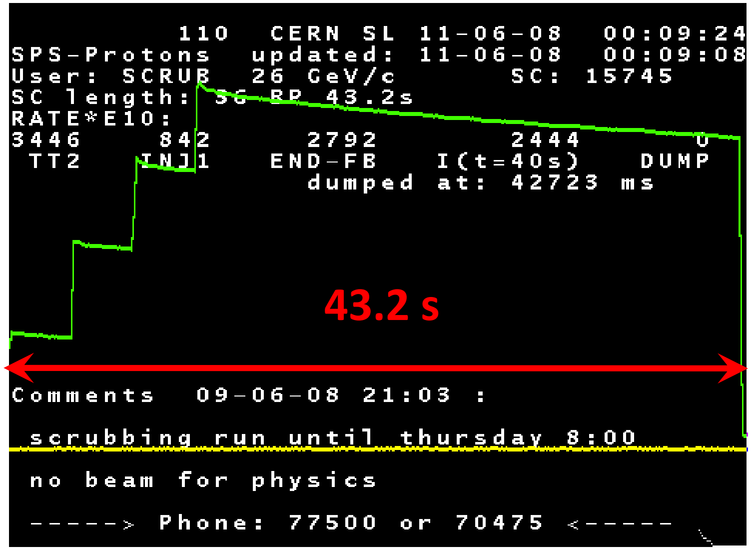
Electron cloud mitigation (a-C coating)

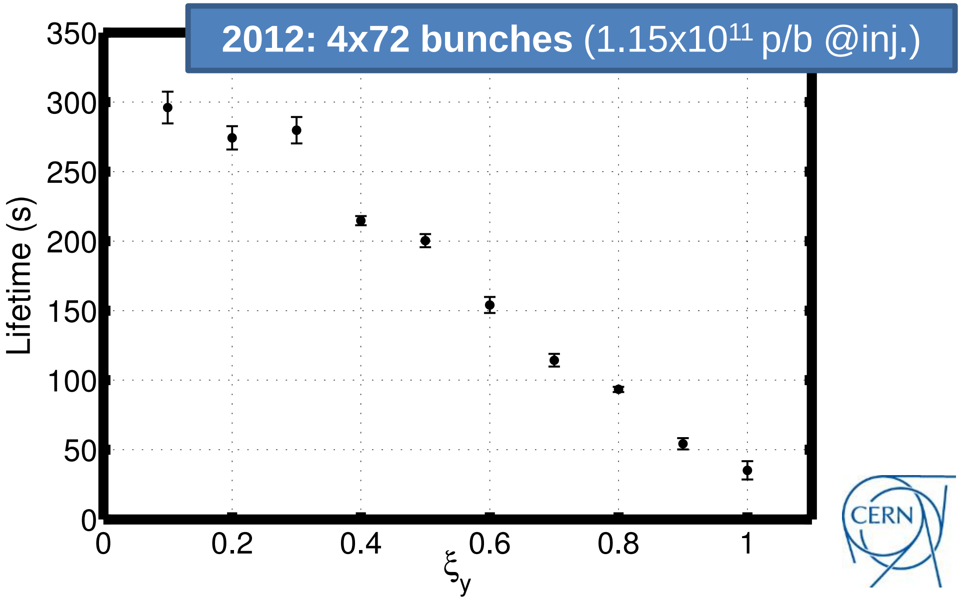
- Thin film of amorphous-C on surface provides low Secondary Electron Yield
  - SEY close to 1.0 guarantees electron cloud suppression in basically all types of chambers for whatever bunch spacing
  - Suppression of electron cloud demonstrated with beam in SPS both in dedicated electron measurement devices and in the main magnets



Electron cloud mitigation (scrubbing)

- Thin film of amorphous-C on surface provides low Secondary Electron Yield
  - SEY close to 1.0 guarantees electron cloud suppression in basically all types of chambers for whatever bunch spacing
  - Suppression of electron cloud demonstrated with beam in SPS both in dedicated electron measurement devices and in the main magnets
- Scrubbing lowers SEY with time
  - Dedicated runs of 1 to 2 weeks performed at injection energy in cycling mode trying to operate in high electron cloud regime (compatibly with beam stability)
  - Beam quality improving with time (usually very fast improvement at the beginning, followed by a phase of very slow improvement)





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  - Ded … trying to c…
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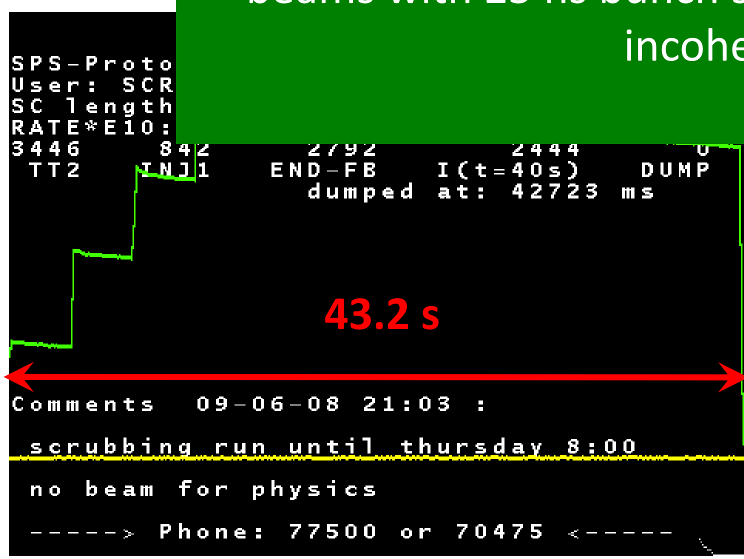
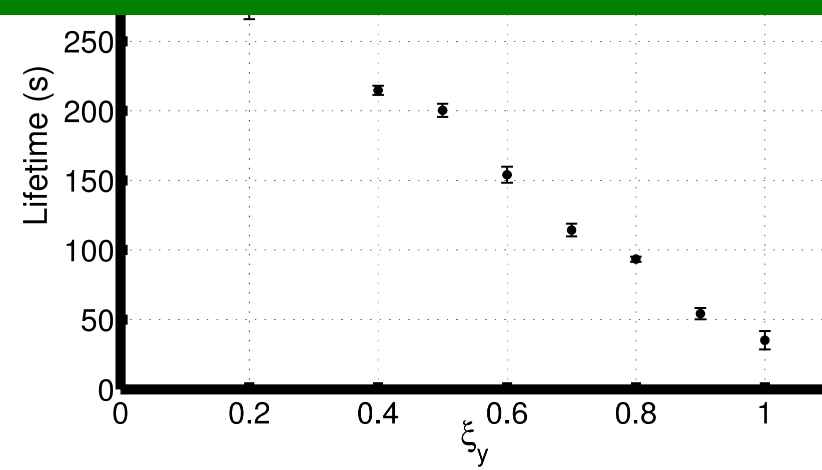
Electron cloud suppression in the SPS (through a-C coating or scrubbing at every start up) is necessary to enable production of more intense beams with 25 ns bunch spacing without transverse instabilities and incoherent emittance growth

…@inj.)





SPS: main upgrade items

- Electron cloud mitigation
  - Scrubbing or a-C coating or combined solution
- Main RF (200 MHz) upgrade
  - Rearrangement of cavities and power upgrade
  - Renovation of control system
- Upgrade of beam dump and protection devices for high intensity and brightness

SPS: main upgrade items

- Electron cloud mitigation
  - Scrubbing or a-C coating or combined solution
- Main RF (200 MHz) upgrade
  - Rea
  - Re
- Upgra
  intensity and brightness

Due to electron cloud, longitudinal instabilities and RF power limitation, the SPS intensity at extraction with 25 ns beams is presently limited to 1.3×10^{11} p/b

With RF power upgrade and electron cloud mitigation → 2.0×10^{11} p/b

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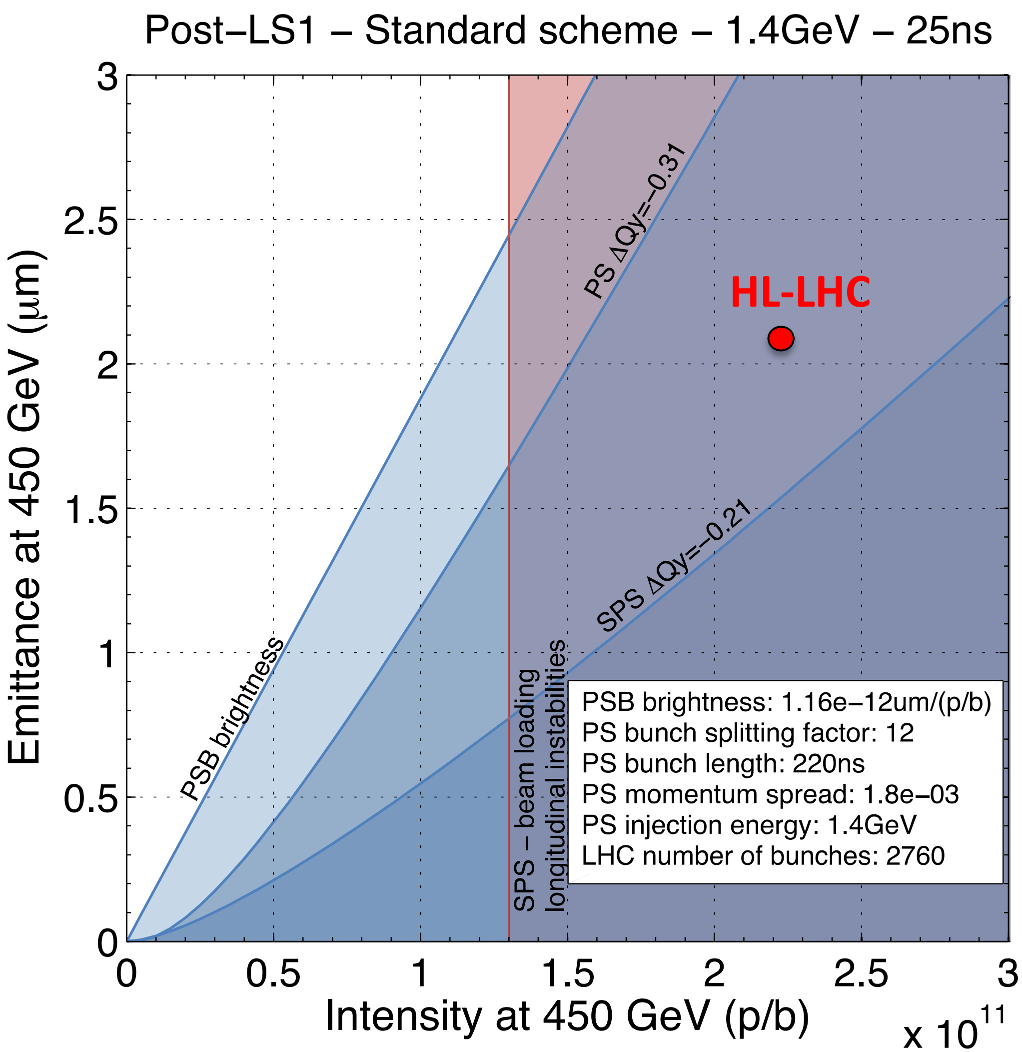
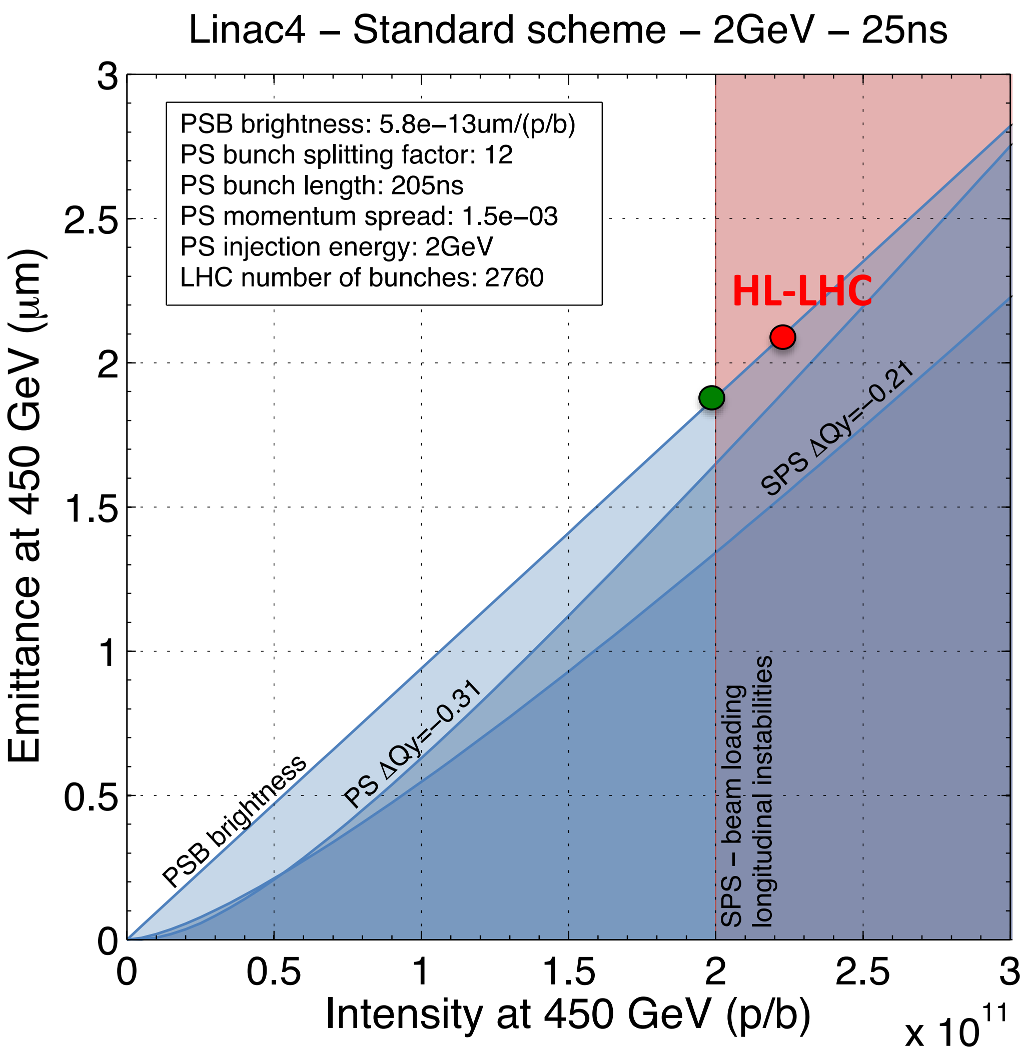
Outline

- Introduction to the injector complex and LHC beam production across the injection chain
- Goals, means and timelines of the LHC Injectors Upgrade (LIU) project
- LIU improvements and impact on performance of LHC beams
  - Linac4
  - PS-Booster
  - PS
  - SPS
- Parameter reach at LHC injection for LIU beams
  - How far we can get
  - Can this be further improved?
- Conclusions

Standard scheme (72b trains) after LS2



Standard scheme (72b trains) after LS2



- With Linac 4
- LIU upgrades
  - PS longitudinal damper
  - SPS 200 MHz upgrade
  - SPS e-cloud mitigation
  - PSB-PS transfer at 2 GeV

- Limitations standard scheme
  - SPS: longitudinal instabilities + beam loading
  - PSB: brightness

- Performance reach
  - 2.0×10^{11} p/b in 1.9 μm (@ 450GeV)
  - 1.9×10^{11} p/b in 2.3 μm (in collision)

Can we better match the HL-LHC target?

- Higher bunch current from the SPS (larger longitudinal

But LHC can also help if it accepts longer bunches from the SPS with 200 MHz RF system

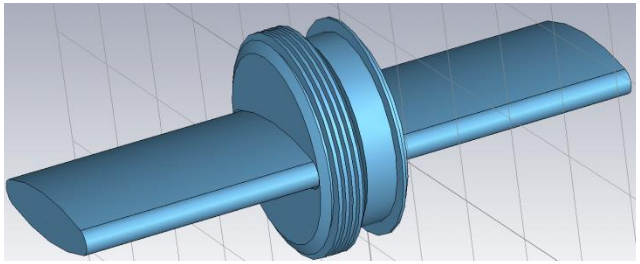
CI

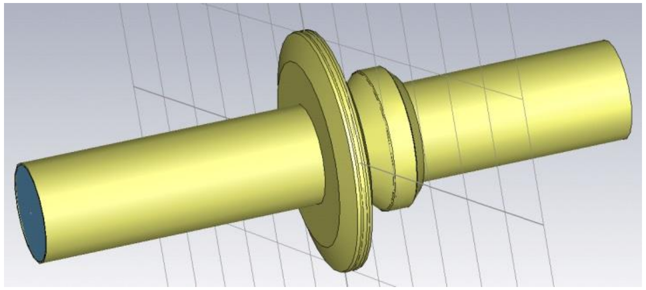
  - Impedance identification and reduction
- Higher number of bunches into LHC
  - Inject trains of 80 bunches into the SPS
    - Based on injecting 7 bunches from the PSB into PS
    - One out of 21 bunches is kicked out with transverse damper before acceleration
- Higher brightness from injectors
  - Alternative production schemes for LHC beams (e.g. BCMS)
    - Trains of 48 bunches into SPS
    - High damage potential for beam intercepting devices in the SPS, transfer lines and LHC

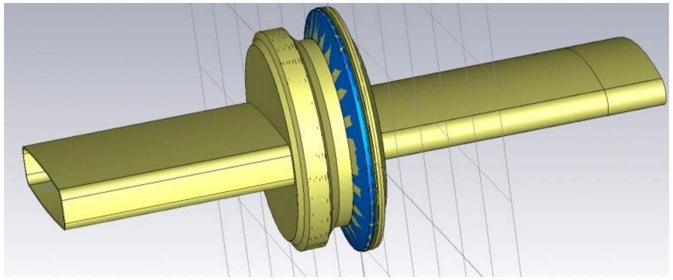
SPS impedance identification and reduction

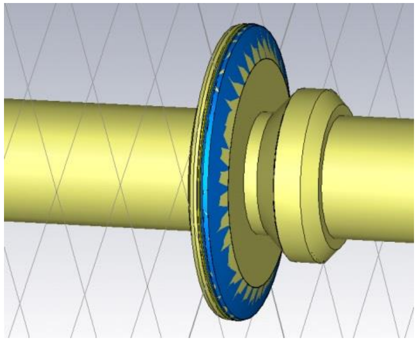
- Vacuum flanges at chamber transitions (≈550)
  - **Particle tracking simulations** show that intensity threshold for longitudinal instabilities can **increase up to a factor of 2** without the impedance of vacuum flanges

- High Order Modes (HOMs) in RF cavities

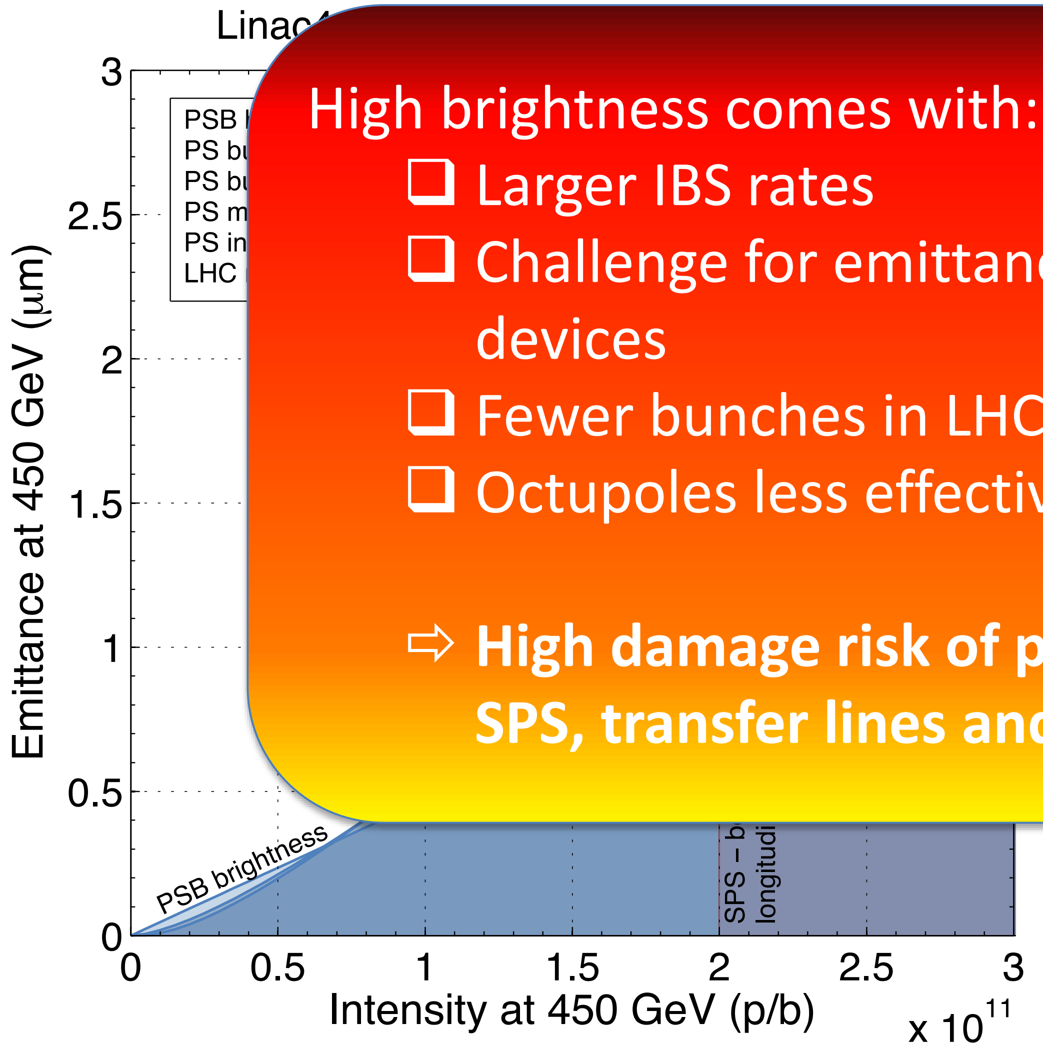








BCMS scheme (48b trains) with LIU



High brightness comes with:

- ❑ Larger IBS rates
- ❑ Challenge for emittance measurement devices
- ❑ Fewer bunches in LHC (~5%)
- ❑ Octupoles less effective to stabilize beam

⇨ **High damage risk of protection devices in SPS, transfer lines and LHC**

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– 2.0x10 p/b in 1.4μm (@ 450GeV)
– 1.9x10^11p/b in 1.7μm (in collision)

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  - PS
  - SPS

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Conclusions

- Protons:
  - **LHC Injectors Upgrade baseline program established** to ensure production of LHC proton beams with parameters close to HL-LHC request
    - Right brightness, ~15% lower intensity per bunch
  - **Promising options identified and under study** to increase intensity and/or brightness of LIU beams delivered to LHC and meet the HL-LHC goals
    - Need additional studies & define action planning/cost estimates
    - Side effects to be evaluated

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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