LHC Injectors Upgrade

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Status of the LHC Injectors Upgrade Project

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Outline

- Introduction:
  - Goals and means of the LIU project
  - Timelines of LIU

- Baseline LIU improvements and their impact on performance of LHC injector synchrotrons
  - Ion chain
  - Linac 4
  - PSB
  - PS
  - SPS

- Can we do it better?
  - Higher intensity
  - High brightness challenges

- Outlook

Goals and means of the LIU project

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

⇒ Inject H^- into the PSB at 160 MeV (replace Linac2 with Linac4, re-design injection into PSB)

⇒ Raise injection energy in PS to 2 GeV (increase field in PSB magnets, replace main power supply, change transfer equipment, re-design PS injection)

⇒ Double RF power in SPS (new 200 MHz power plant, rearrange 200 MHz system, power 2nd 800 MHz cavity, new low-level)

⇒ Enable PSB/PS/SPS to accelerate and manipulate higher intensity beams (electron cloud mitigation, impedance reduction, feedbacks, etc.)

⇒ 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

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)

⇒ Improve radioprotection measures (shielding, ventilation…)

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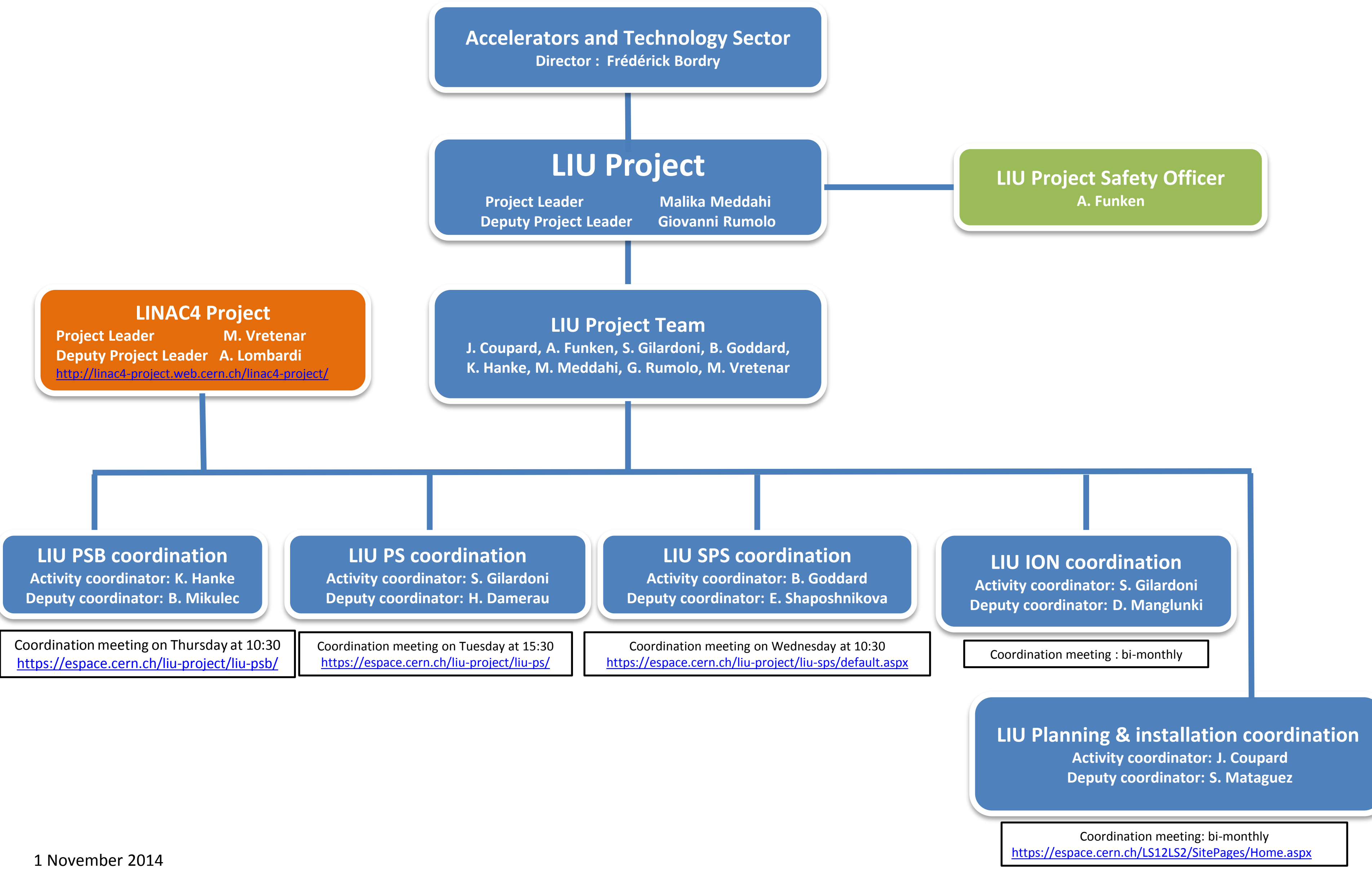

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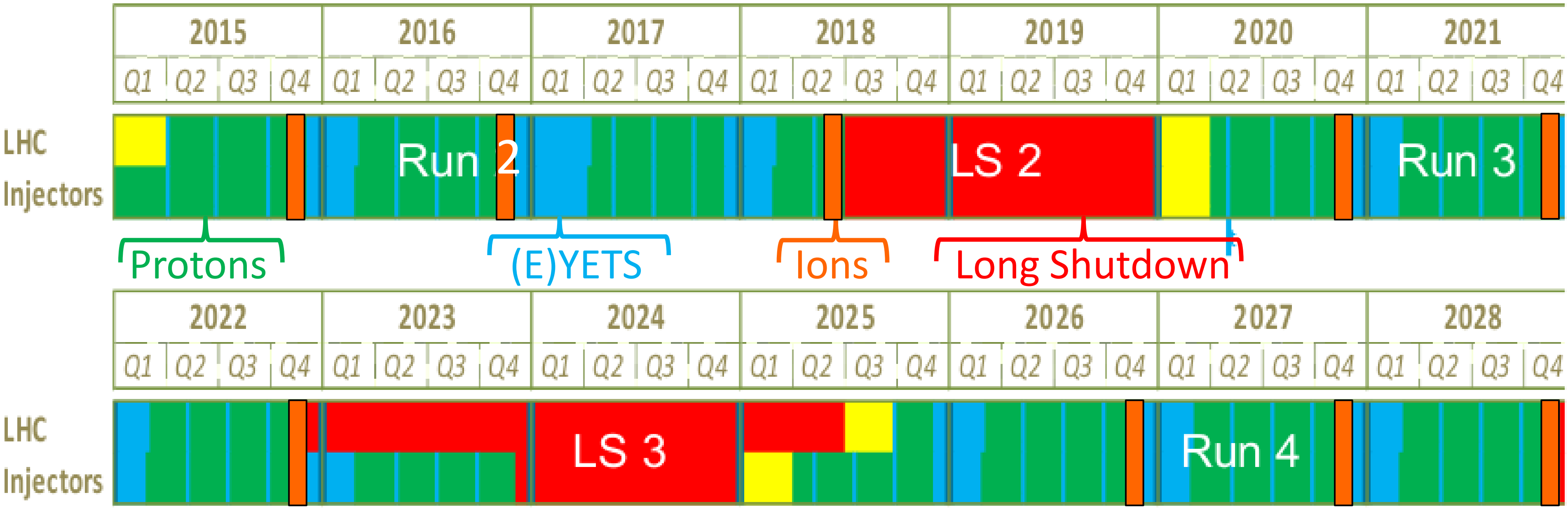
Complete LIU Work Breakdown Structure @ EMDS Id 1146814 - LIU-PM-QA-0007

Timelines of the LIU project

- LIU (machine and simulation) studies during **Run 2** until **LS2**
  - Key dates for pending decisions until 2016
- LIU installations and hardware works mainly during **LS2**
- Beam commissioning of LIU beams
  - **Pb ion beams** need to be ready by **2020 ion run**
  - **Proton beams** during **Run 3** to be ready after **LS3**



LIU-IONS target: 7x nominal peak luminosity!

	$\mathcal{L}_{\text{peak}}$	**Beam energy**
Achieved in 2011	$5\text{x}10^{26}$ Hz/cm^2	3.5 *Z* TeV
LIU-IONS	**$7\text{x}10^{27}$ Hz/cm^2**	7 *Z* TeV

IBS & space-charge already at the limit on SPS flat bottom …

We need to pack **a larger number** of only **slightly less intense (compared to 2013)** bunches in LHC

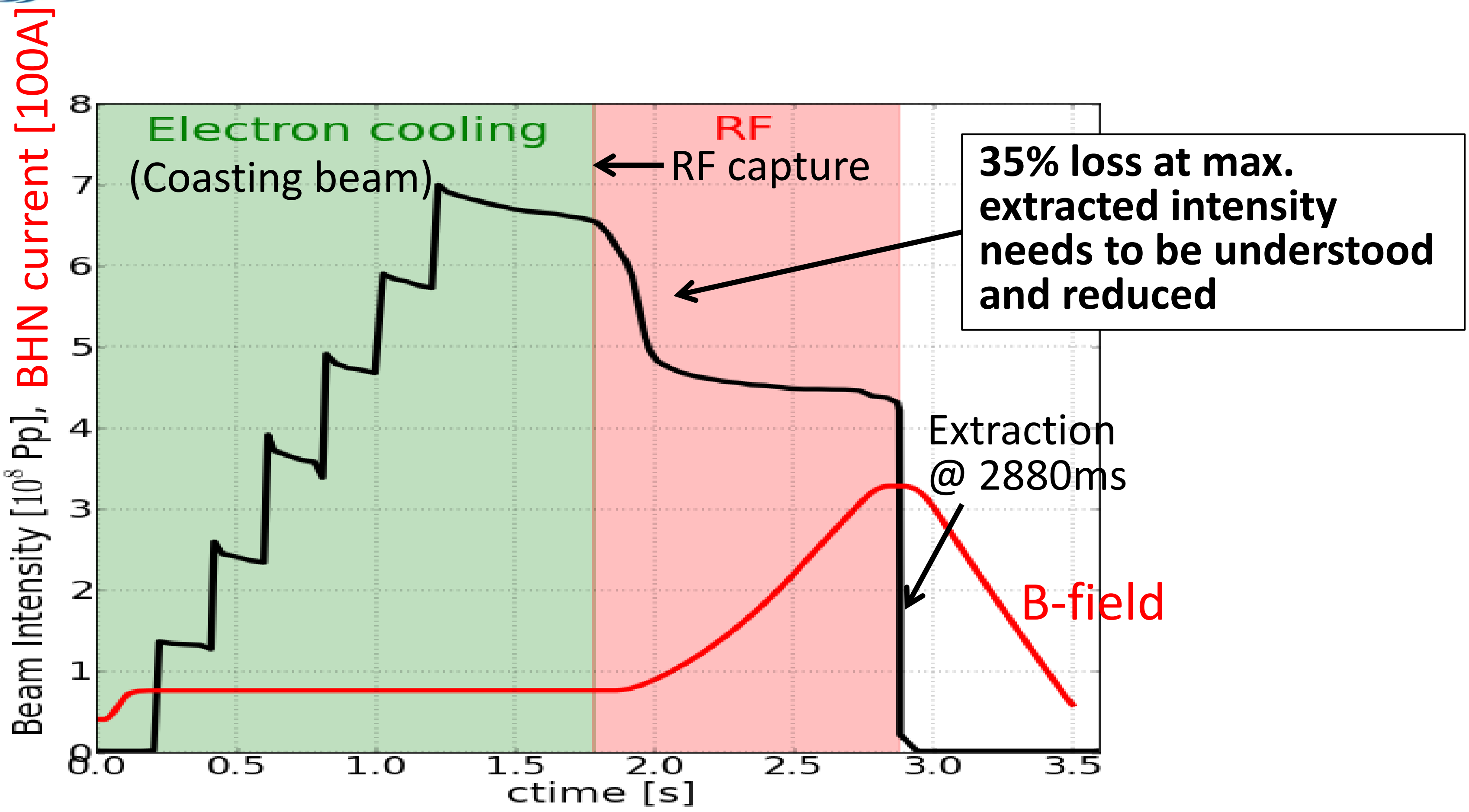
Means to achieve target luminosity

- Source & Linac3:
  - Increase beam current by improving Low Energy Beam Transport (LEBT)
  - Injection rate: 5 Hz → 10 Hz
- LEIR:
  - Increase number of injections
  - Understand and mitigate large beam losses at RF capture
- PS:
  - Bunch splitting to produce 4 bunches with 100 ns bunch spacing
- SPS:
  - Mitigate beam degradation at flat bottom
  - Upgrade SPS injection system with 100 ns rise time
  - Longitudinal slip-stacking → 50 ns bunch spacing

Means to achieve the target luminosity

- Source & Linac3:
  - Increase beam current by improving Low Energy Beam Transport (LEBT)
    - Identify and remove bottlenecks (simulation & diagnostics needed)
  - Injection rate: 5 Hz → 10 Hz
- LEIR:
  - Increase number of injections
  - Understand and mitigate large beam losses at RF capture
    - More advanced modeling and MDs needed
- PS:
  - Bunch splitting to produce 4 bunches with 100 ns bunch spacing
- SPS:
  - Mitigate beam degradation at flat bottom
    - Reduction of RF noise, Q20 optics
  - Upgrade SPS injection system with 100 ns rise time
  - Longitudinal slip-stacking → 50 ns bunch spacing

LEIR challenges



LIU proton target → HL-LHC beam parameters

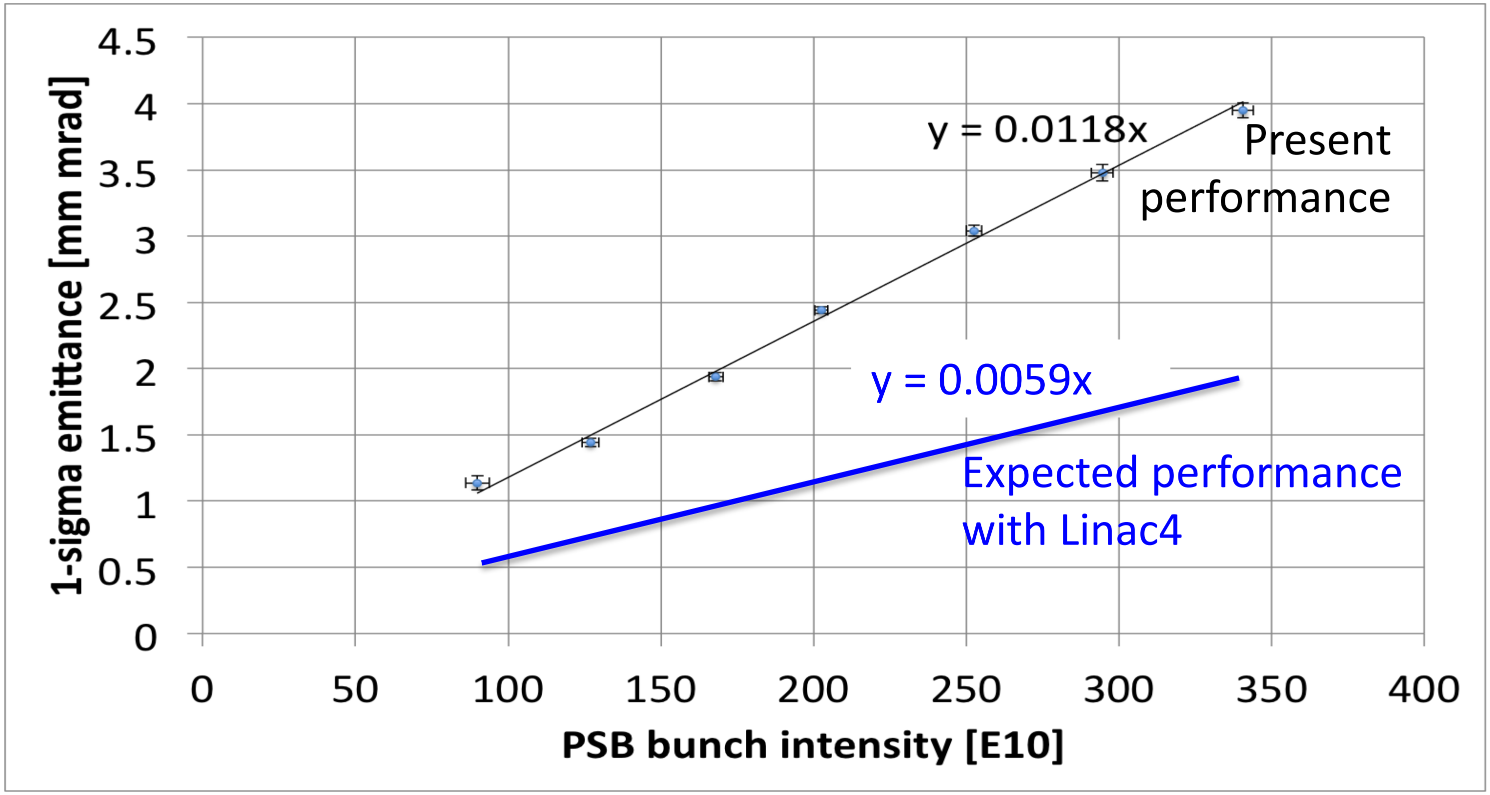
25 ns	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)	B_l (ns)
Achieved in 2012	1.2	2.6 (std)	1.5
HL-LHC	**2.3**	**2.1**	**1.7**

Injectors must produce 25 ns proton beams with about double intensity and higher brightness

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

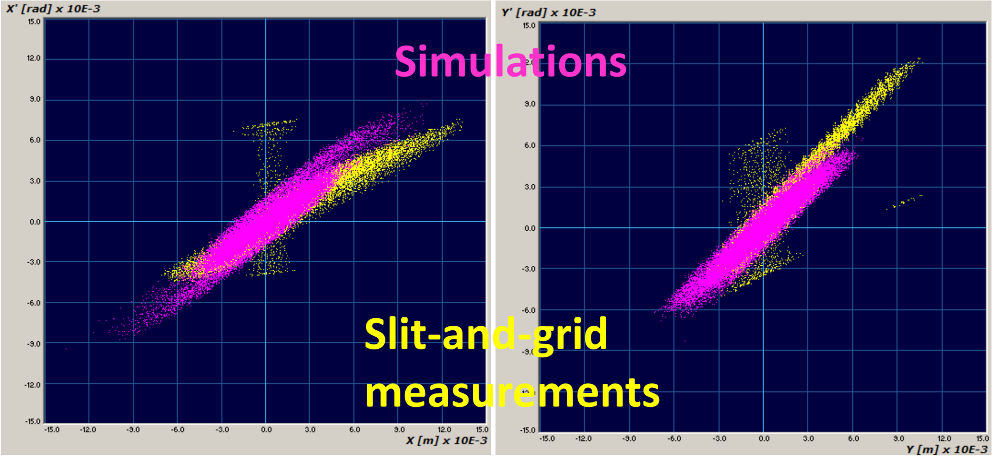
Linac2 → Linac4

- Linac4 will replace Linac2
  - H^- injection into PSB at 160 MeV
  - Expected double brightness for LHC beams out of the PSB



Linac2 → Linac4

- Linac4 is being commissioned stage by stage with a temporary source
  - Acceleration to 12 MeV is validated
    - RFQ and chopper behave correctly
    - DTL tank1 accelerates the beam without losses
  - Emittance measurements agree with code predictions (PARMTEQ, PATH, TRACEWIN)
    - Reconstruction methods for transverse and longitudinal emittances are also validated!



Linac2 → Linac4

- New caesiated source ready for use
  - Will provide 40 mA within 0.35 μm
    - > 20 turns injection for future LHC beams → simulations ongoing to establish future emittance vs. intensity curve
    - ~100 turns for future ISOLDE beams → attainable maximum injected intensity to be assessed
- Half-sector test planned for June 2016 to “simulate” injection into PSB with the real equipment

Main means to achieve the target HL-LHC proton beam parameters

- PSB:
  - Double brightness with injection from Linac4
  - Acceleration to 2 GeV with upgraded main C02+C04 RF systems or replacement by Finemet cavity based RF system, and new main power supply
- PS:
  - Injection at 2 GeV
  - Beam production schemes
  - Feedback systems:
    - Newly installed wide-band longitudinal feedback against CBI
    - Transverse feedback against headtail and e-cloud instabilities
- SPS:
  - Power upgrade of the main 200 MHz RF system (plus double available 800 MHz voltage, and new LL RF system)
  - Electron cloud mitigation through a-C coating (baseline) or beam induced scrubbing, possibly with doublets (decision mid-2015)
  - High Bandwidth (intra-bunch) transverse feedback system (CERN-USLARP collaboration): fighting ecloud instabilities; better beam quality during scrubbing runs – Good first results in 2013 to be continued.

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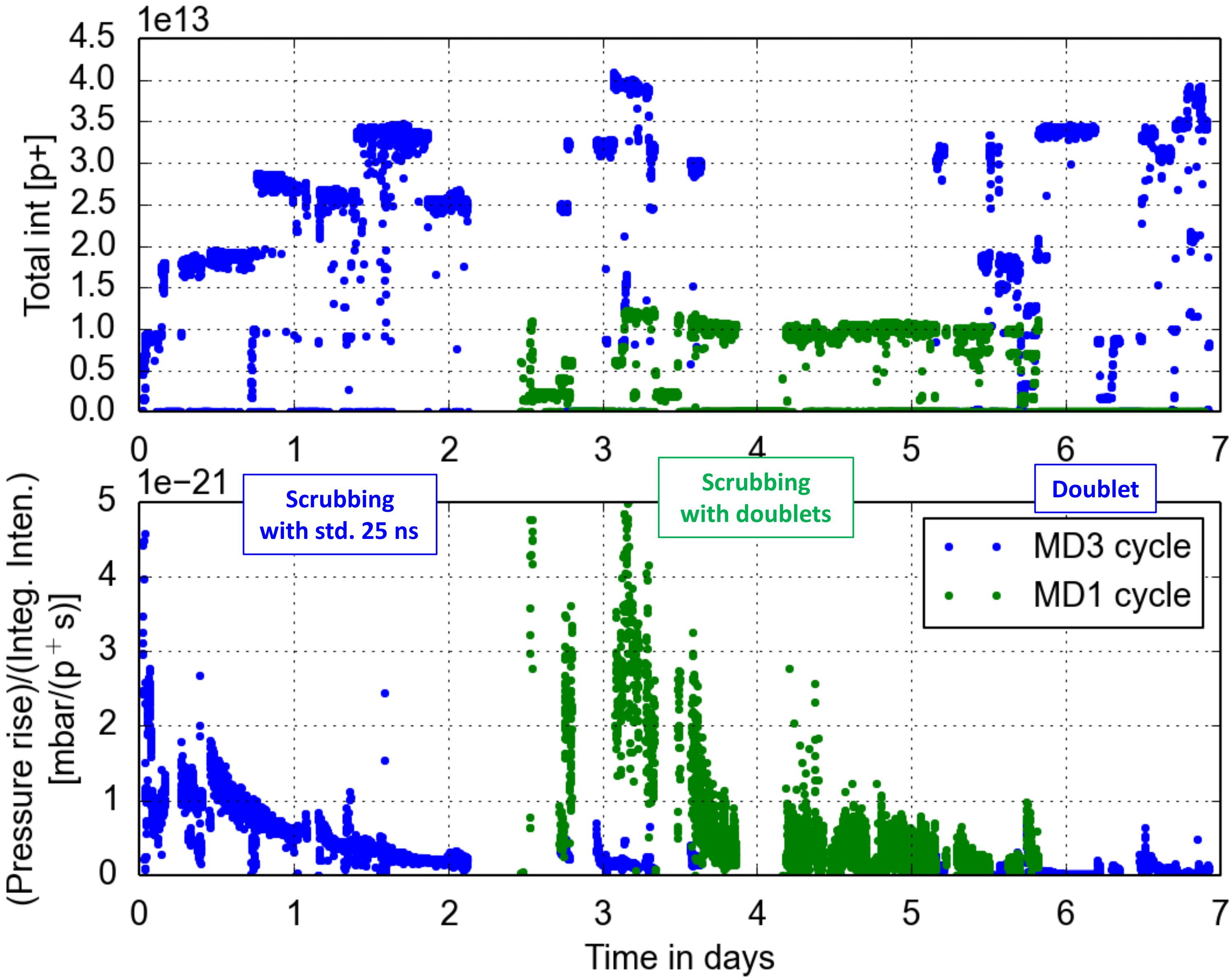
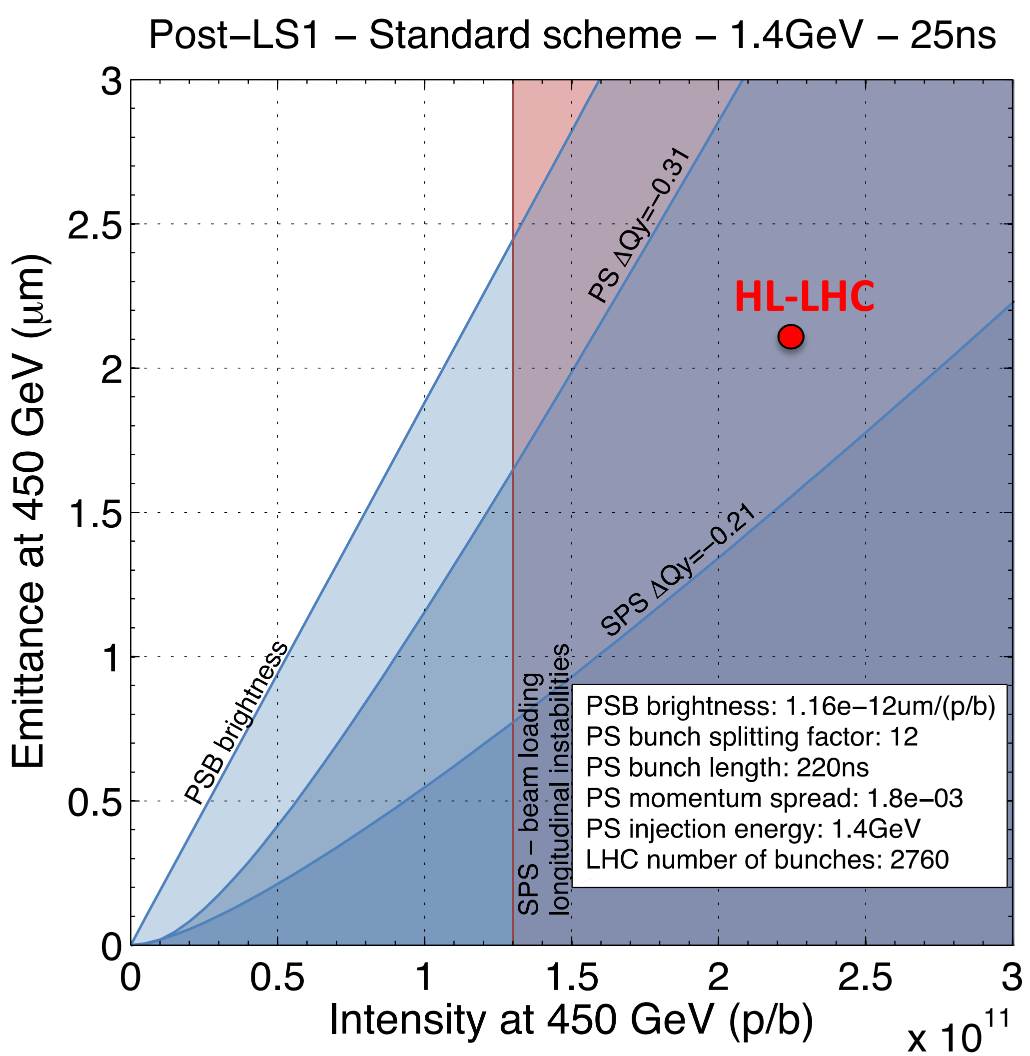
SPS scrubbing run 3-9/11/2014

- 1 week high efficiency scrubbing with very good beam availability
  Scrubbing with both standard LHC 25 ns and doublet beams
- Recovered nominal LHC beam (4 batches 72b) at 450 GeV/c
- Successfully deployed doublet beam (up to four batches at 26 GeV/c)
  - Enhanced ecloud in high-field non a-C coated regions and none in a-C coated regions and field free regions
  - Lower heating of sensitive elements, as expected from impedance models, which allowed scrubbing while recovering conditions (vacuum, cooling)
- Electron cloud instability only affecting doublets, thanks to Q20.
- Scrubbing limited essentially by newly installed elements, not pressures in arcs
- Next steps: 3 days of scrubbing week 50: accelerated doublets and higher intensity

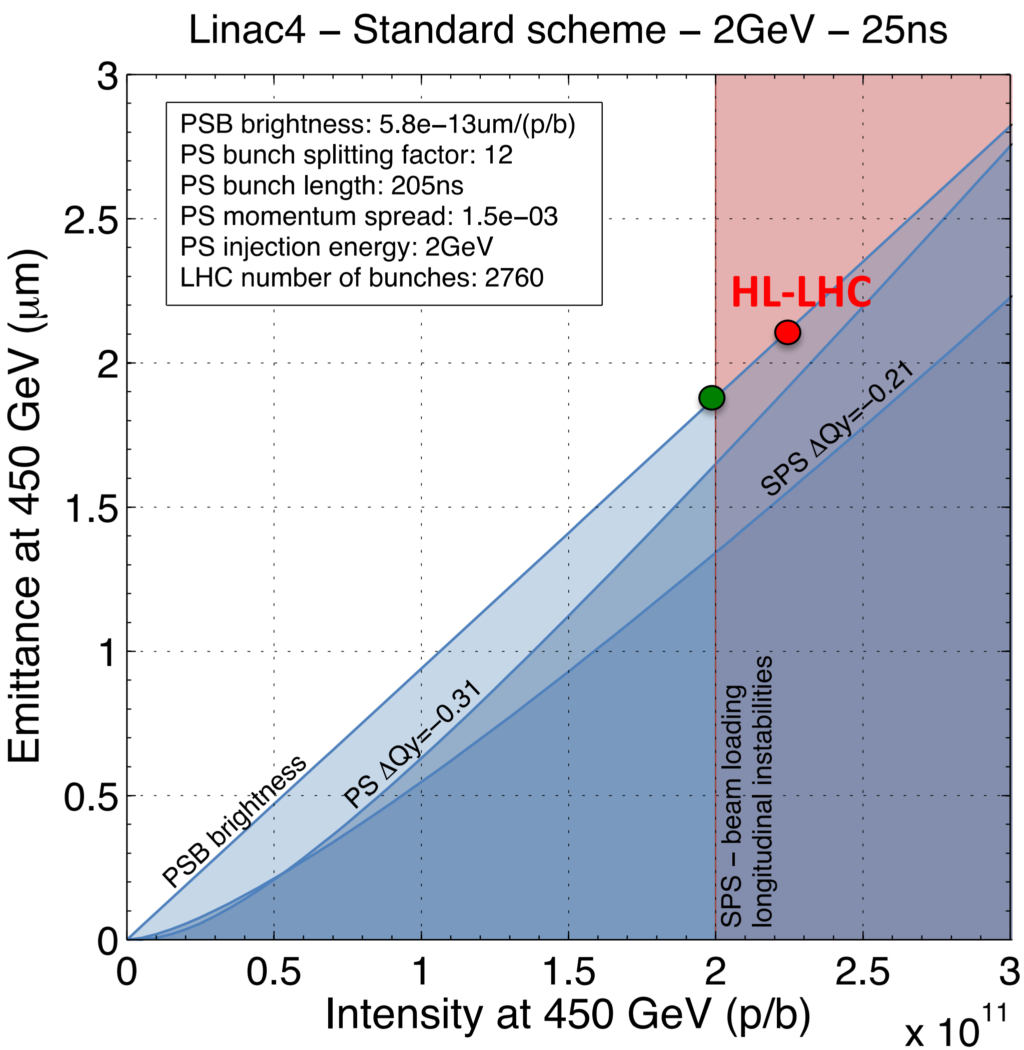
Pressure evolution: Arc 5



Standard scheme (72b trains) presently



Standard scheme (72b trains) after LIU



- With Linac 4
- LIU upgrades
  - 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 1.9µm (@ 450GeV)
  - 1.9×10^{11}p/b in 2.3µm (in collision)

Can we do it better for HL-LHC?

- Higher bunch current from the SPS (larger longitudinal

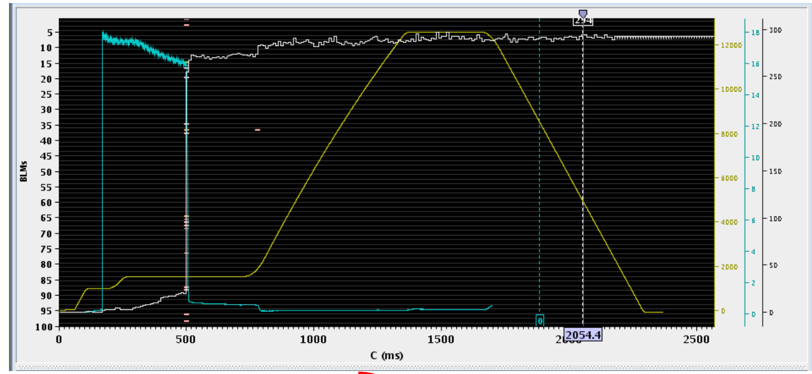
... can LHC also help and accept longer bunches from the SPS with 200 MHz RF system?

  – 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
  – BCMS beams
    - Trains of 48 bunches into SPS
    - High damage potential for beam intercepting devices in the SPS, transfer lines and LHC

80 bunches from PS

Remove 1 bunch with transverse feedback:
21 → 20 bunches

Use of TFB to kick out single circulating bunch validated in MD !



triple splitting
7 => 21 bunches

2 double splittings

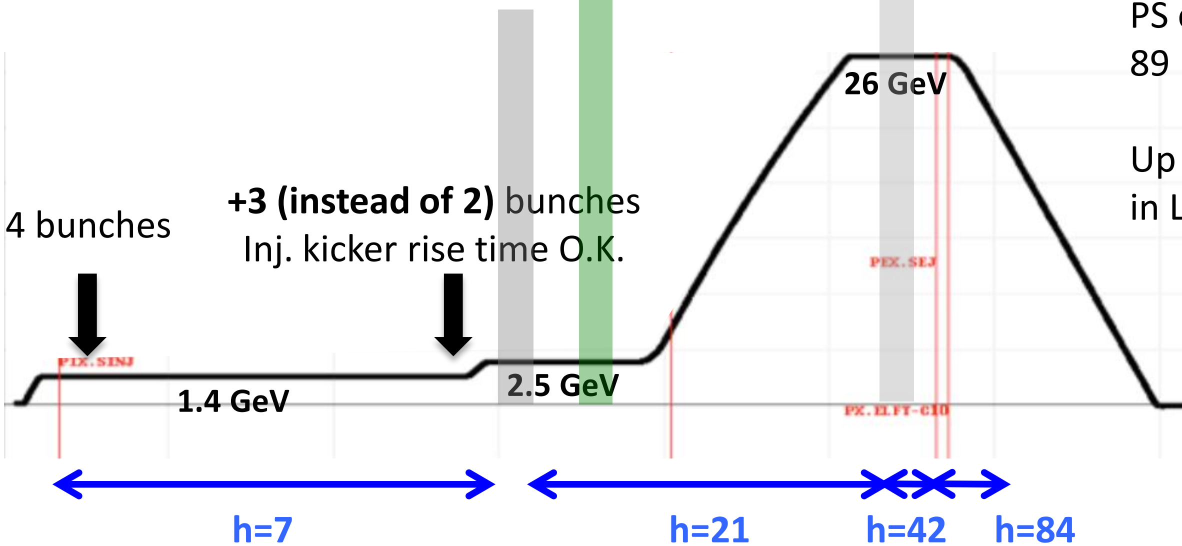
20 => 40 =>
<u>**80 bunches instead of 72**</u>

PS extr. kicker rise time
89 ns (1-99%) => **O.K.**

Up to **5% more bunches** in LHC

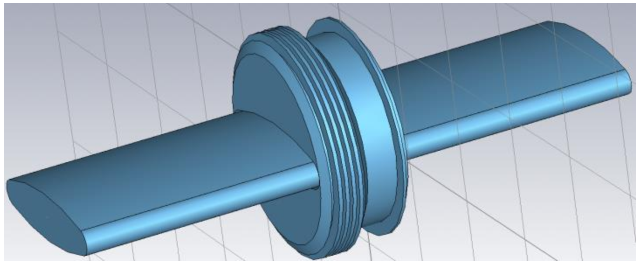
4 bunches

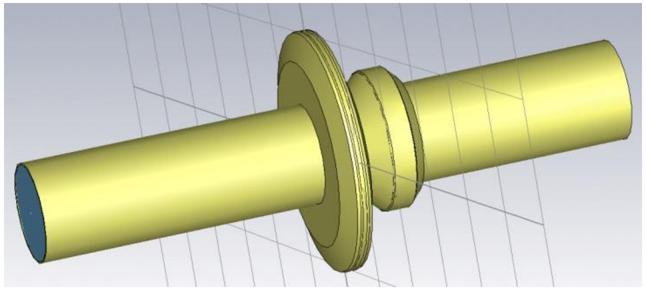
+3 (instead of 2) bunches
Inj. kicker rise time O.K.

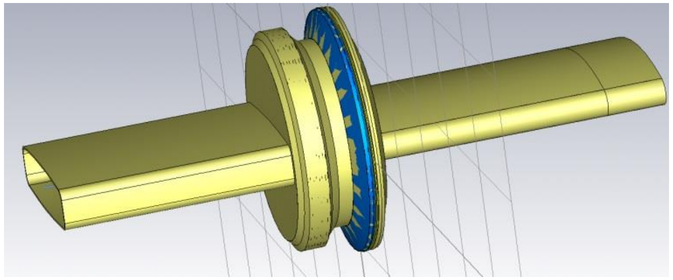


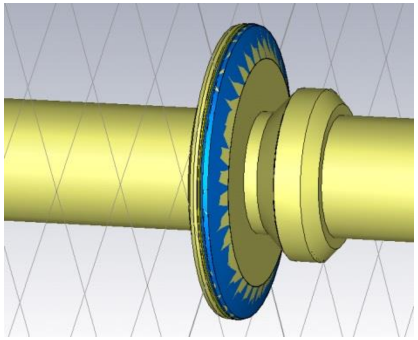
SPS impedance identification and reduction

- Vacuum flanges (≈550) are the likeliest candidate
  - **Particle tracking simulations** show that intensity threshold **increases by a factor of 2** without the impedance of vacuum flanges









SPS impedance identification and reduction

- Vacuum flanges (≈550) are the likeliest candidate
  - **Particle tracking simulations** show that intensity threshold **increases by a factor of 2** without the impedance of vacuum flanges

- **Preliminary** suggestions to reduce the impedance of the SPS vacuum flanges (both requiring **15 – 30 weeks of work**)

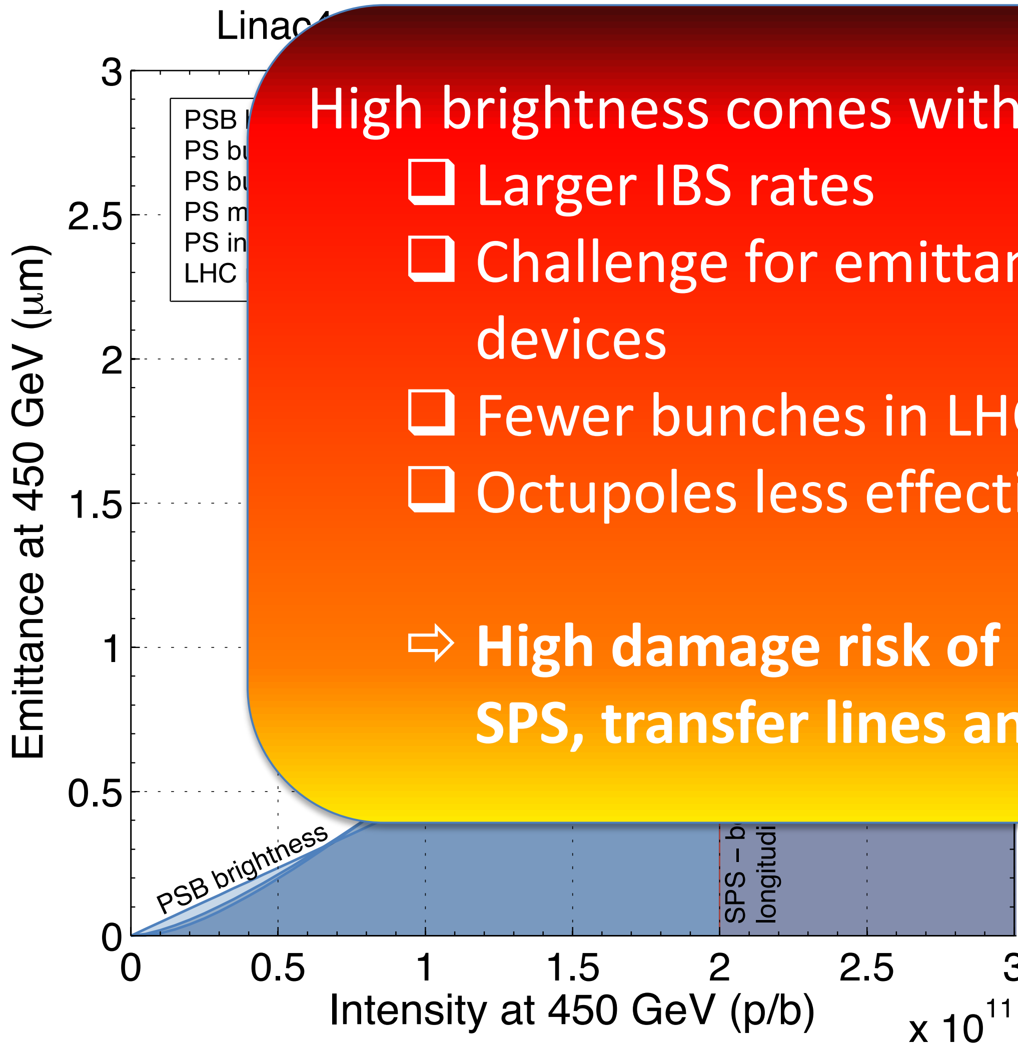
  - **Partial shielding + damping**
    - **R/Q reduction factor 8** could be achieved
    - **Only half of the flanges** could be modified

  - **Flange redesign**
    - **Minimum impedance**. R/Q reduction factor 20
    - **All flanges** could be changed
    - **Higher cost** (new elliptical bellows, …)

- Conceptual design work launched

- **Major extra activity to be possibly added to baseline**, decision needed in 2015 to be able to prepare for LS2

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 GeV

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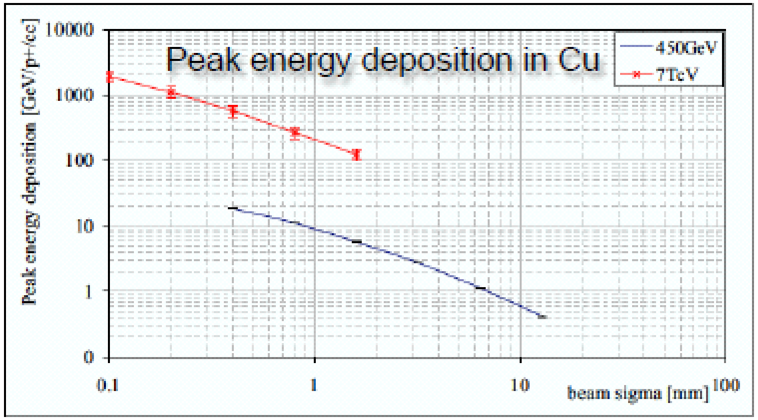
nstabilities

– 2.0x10 p/b in 1.37μm (@ 450GeV)
– 1.9×10^{11}p/b in 1.65μm (in collision)

Dangers of high brightness (I)

Energy deposition depends on total intensity as well as spot size



$$\Delta E \propto \frac{I_{beam}}{\sigma_x \cdot \sigma_y}$$

$$\Delta E \propto \frac{I_{beam}}{\varepsilon}$$

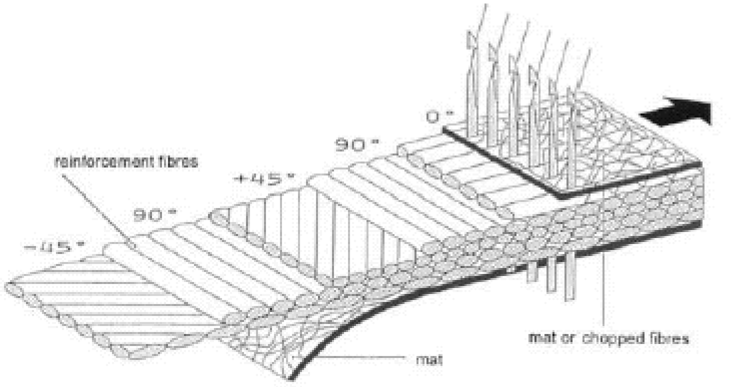
	Bunch intensity	Normalized emittance	Number of bunches	(N_b/ε) / $(N_{ultimate}/\varepsilon_{ultimate})$
nominal	1.15×10^{11}	3.5 μm	288	**0.68**
ultimate	1.7	3.5 μm	288	**1**
standard run 2	1.2	2.6 μm	288	**0.95**
BCMS run 2	1.3	1.39 μm	288 = 6 x 48	**2.1**
HL 25 ns	2.3×10^{11}	2.1 μm	288	**2.3**
BCMS LIU	2×10^{11}	1.3 μm	288 = 6 x 48	**3.1**

Protection devices in LIU era might need to attenuate 100-200% more than present design !!

Dangers of high brightness (II)

- Choice of material is challenging
  - Stresses in case of impact of high brightness beams are estimated to be beyond the strength of materials presently used in passive protection absorbers (even standard HL-LHC can pose problems)
  - R&D needed to possibly find suitable materials for new absorbers post LS2.

- HiRadMat facility will use SPS beam at 450 GeV to test
  - Material properties (used as input for simulations)
  - Robustness against "simulated" future beams
  - New promising materials (e.g. 3D Carbon-Carbon)



Conclusions

- Protons:
  - **LIU baseline program established** to ensure production of LHC proton beams with parameters close to HL-LHC request
    - Right brightness, ~15% lower intensity per bunch
    - Very dense machine and simulation study program until 2016 to
      - Further improve our parameter estimates
      - Take decisions latest 2015 for few remaining pending items
  - **Promising options identified and under study** to increase intensity and/or brightness of LIU beams delivered to LHC
    - Need additional studies & define action planning/cost estimates
    - Brightness may clash with safety of machine protection devices
- Ions:
  - **List of actions defined** to achieve the target ion beam parameters at LHC injection to fulfil the luminosity goals
    - However, big challenges ahead
      - Increase beam current into and out of LEIR
      - Reduce beam degradation along chain (e.g. SPS flat bottom)
      - ⇨ First in line to require beam after LS2 …

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THANK YOU FOR YOUR ATTENTION!

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