LHC Injectors Upgrade

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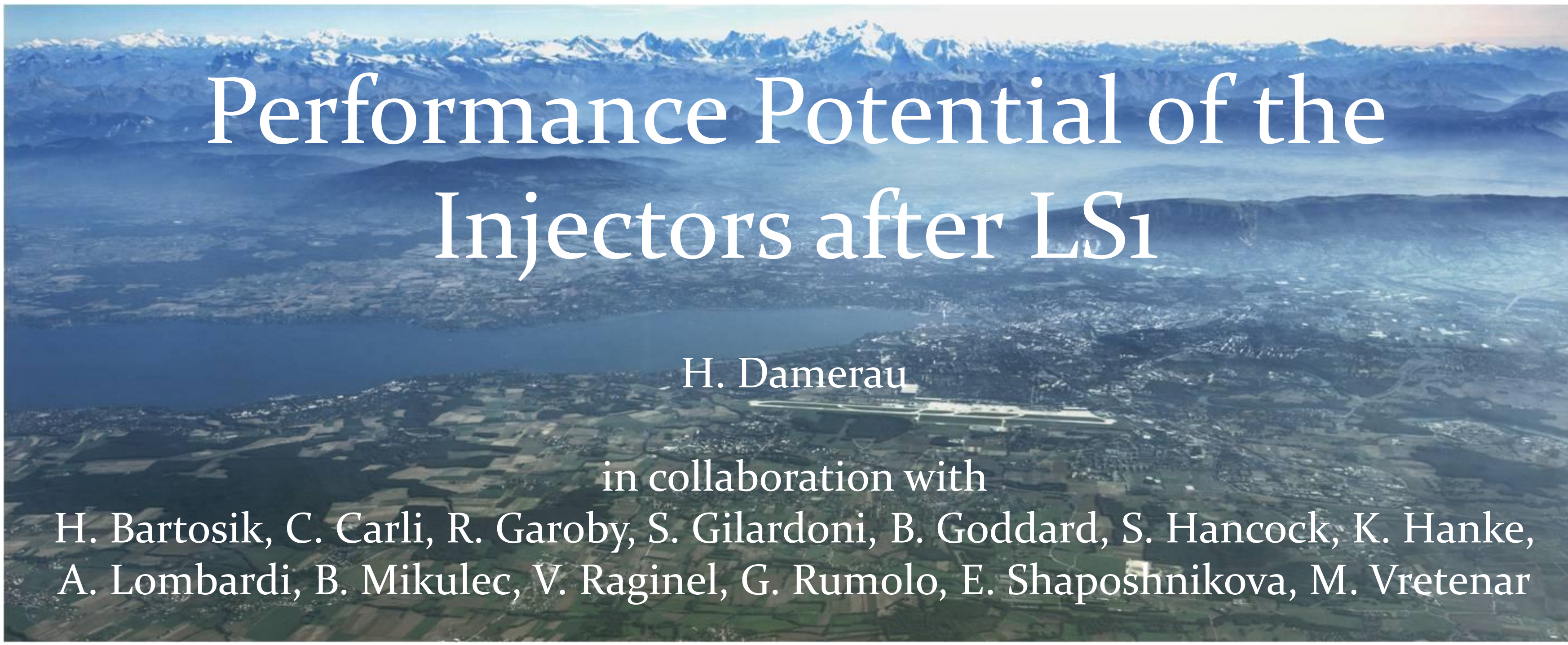

Performance Potential of the Injectors after LS1

H. Damerau

in collaboration with
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Overview

- Introduction
- Injection into PS Booster
  - Protons from Linac2-PSB or Linac4-PSB
  - Linac4-PSB with H^- injection
- Performance reach of PS/SPS
  - PS limitations and present production scheme
  - Batch compression in PS for low emittance
  - SPS performance after LS1
- Conclusions

Introduction

Situation at the end of 'injector LS1' (03/2014)

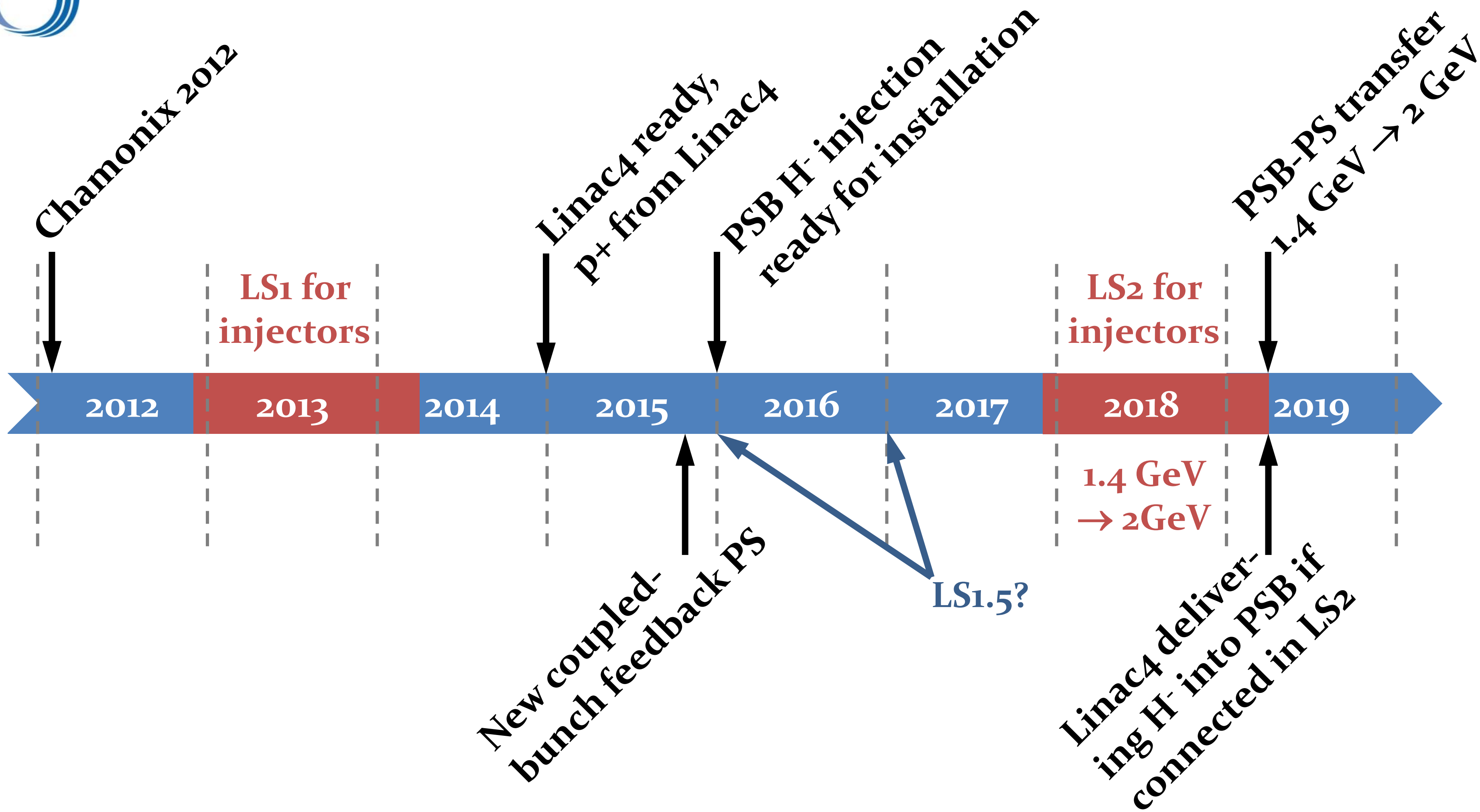
- Linac4 being commissioned, proton operation possible from Q4/2014
- PSB injection for H^- not yet available (baseline: Q4/2015)
- PSB → PS transfer energy: 1.4 GeV

- Major upgrades within LIU project, including increase of PSB-PS transfer energy only during LS2

→ Keep brand-new Linac4 just as a hot spare for more than 3 years?
→ Partially profit from H^- injection already before 2019?
→ What to expect for the period 2014-2017?

2014 is already close!

Timeline (present baseline)



- 2 GeV upgrade of PSB + increase of PS injection energy excluded for LS1

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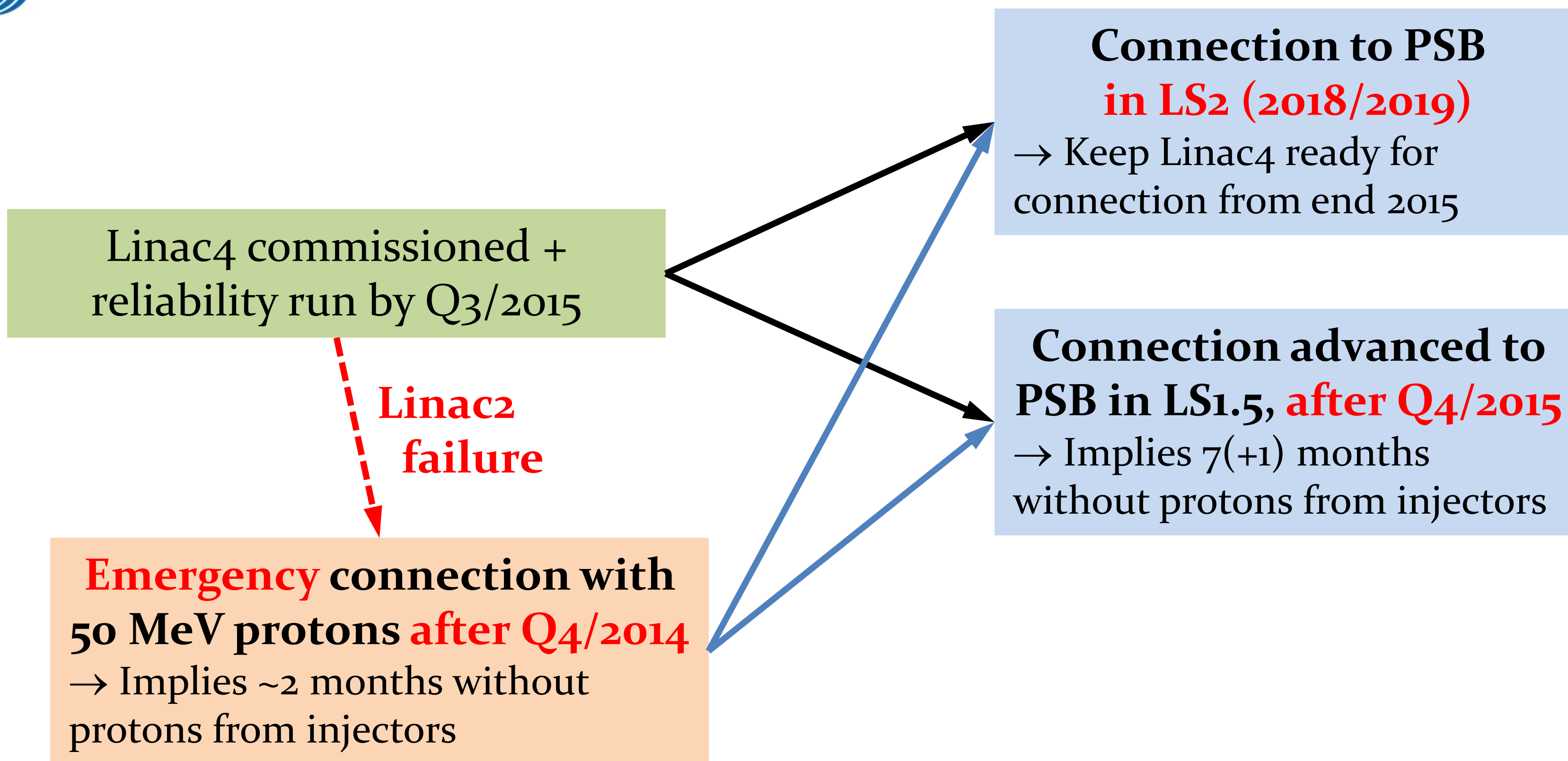
Options for Linac4 connection

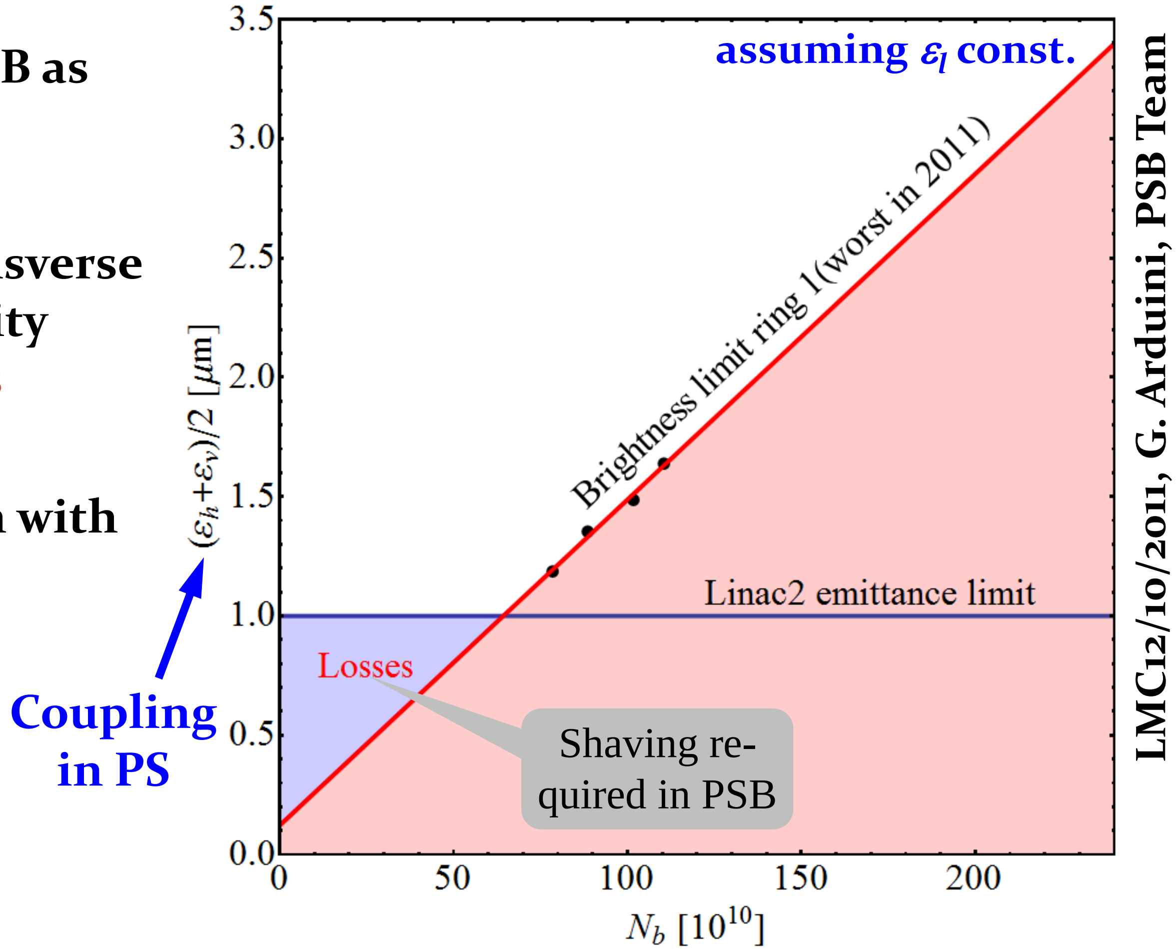


- **Emergency connection with protons does not save time for H$^-$ connection**

→ **Potential benefits of an early LS1.5 connection of Linac4 to PSB?**

Linac2/PSB performance for LHC

- Brightness reach of PSB as measured in 2011
- Linear increase of transverse emittance with intensity → constant brightness
- Emittances below 1 μm with transverse shaving



Emergency – protons from Linac4

- **Major, un-repairable vacuum failure of Linac2 tank → Connect L4 with p+**

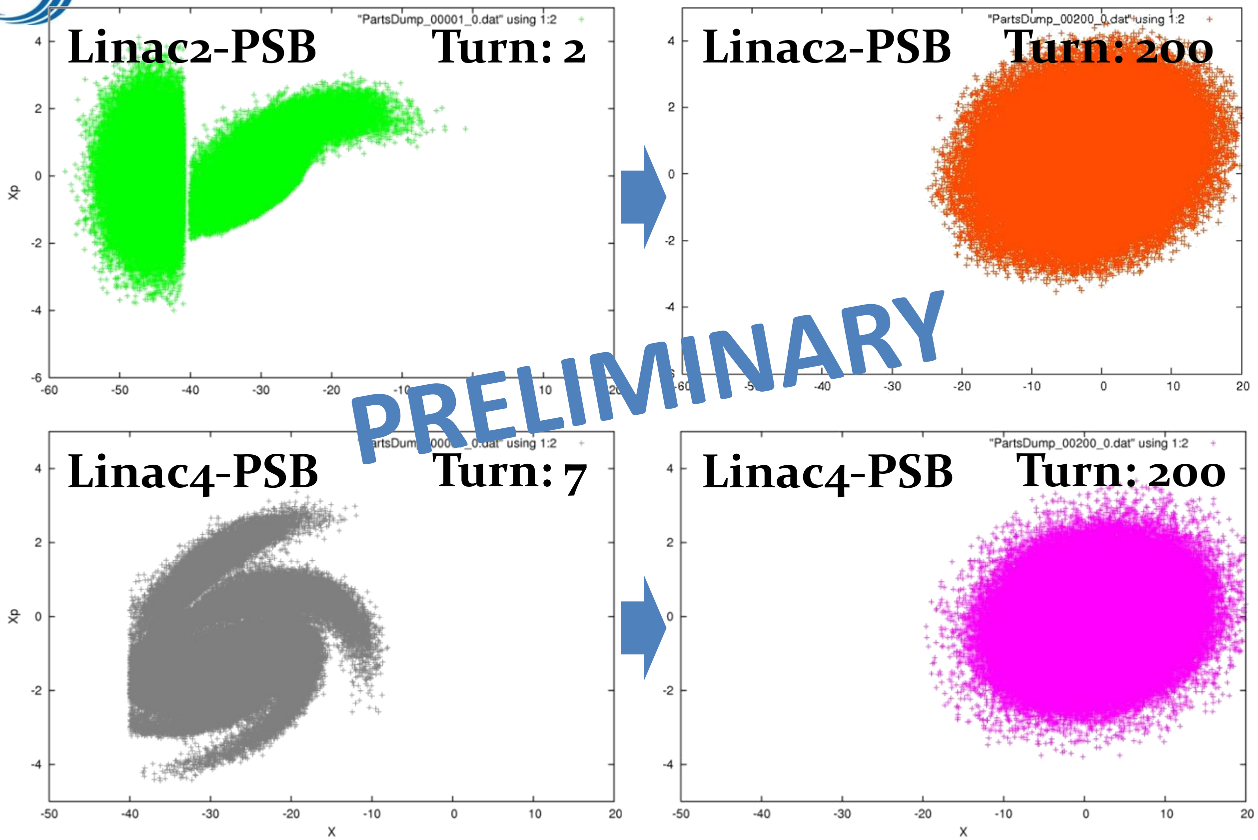
Assumption: $I_{H-} = I_p$

	Linac2 (achieved)	Linac4 (design)
Particle energy at exit (kinetic)	50 MeV	50 MeV
Pulse current	**160 mA**	**40 mA**
Transv. emittance at exit	**1 π mm mrad**	**0.4 π mm mrad**
Maximum beam pulse length	200 μs	400 μs
Bunch frequency	202.56 MHz	352.2 MHz
Relative brightness	**1**	**0.625**

- **Switch off and detune RF structures beyond E_{kin} > 50 MeV to accelerate protons up to only 50 MeV**

→ **Less brightness from Linac4 (no issue with H^- since recovered during stripping injection)**

Simulations of PSB injection @ 50 MeV



Linac2
2 turns injected
$N_b = 2.2 \cdot 10^{12}$ ppb
$\varepsilon_h \approx 2.23\ \pi\ \mu m$

Linac4
7 turns injected
$N_b = 1.6 \cdot 10^{12}$ ppb
$\varepsilon_h \approx 2.55\ \pi\ \mu m$

C. Carli, V. Raginel

- **Only ~60% of today's brightness and ~45% of luminosity for LHC**
- **Very degraded operation for fixed target experiments**
- **~2 months commission L4 with protons and bring them to PSB**

→ **Still 7(+1) months needed to exchange PSB injection for H^- operation**

Linac4 + H^- injection into PSB

Early connection in LS1.5	Connection during LS2
• Allows commissioning of H^--injection without extra complexity from 2 GeV	• PSB: H^--injection + 2 GeV to be commissioned simultaneously
• LHC-type beams: Full brightness benefit from Linac4 in PSB	• New Linac4 unused until 2018
• High-intensity beams need new transverse FB + RF upgrade	• PS: 2 GeV injection energy upgrade allows to profit from improved PSB performance
	• SPS: Coating + RF upgrade ready
→ Brightness cannot be swallowed by the PS at 1.4 GeV	→ Whole injector chain can profit from higher brightness

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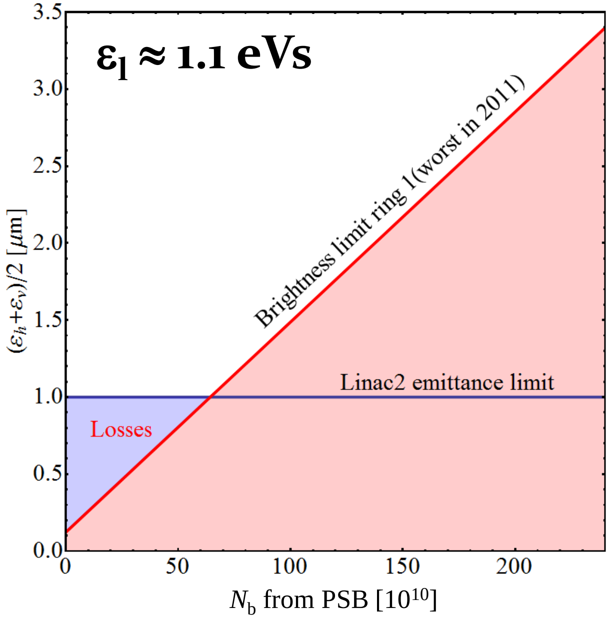
Towards PS: Brightness vs. intensity

- **Per bunch to LHC: Scaling of horizontal axis depends on split-factor in PS**



- **The smaller the splitting ratio the better, but**
- **Price to pay:**
  - → **Shorter batches at PS extraction**
  - → **Longer filling time + less bunches in LHC**

Intensity per bunch to SPS/LHC (no losses in PS/SPS):

PS RF manipulation scheme	25 ns bunch spacing	50 ns bunch spacing
1. Triple splitting	$N_b/12$	$N_b/6$
2. Batch comp. *h*9…h21	$N_b/8$	$N_b/4$
3. Batch comp. + merging + triple split	$N_b/6$ ($N_b/4$)	$N_b/3$

Tune spread at 1.4 GeV PS flat-bottom

Laslett formula:

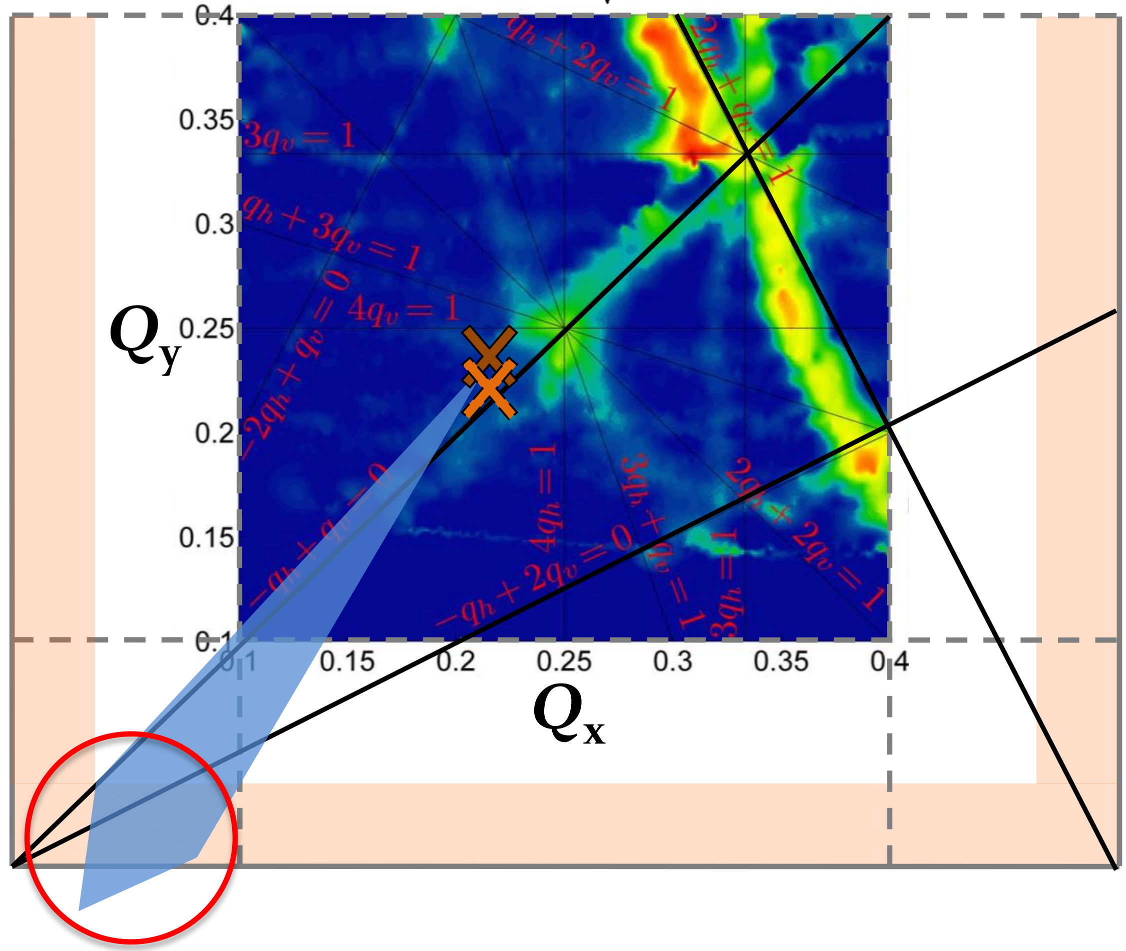
$$\Delta Q_y = \frac{r_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z}\frac{1}{\sqrt{\varepsilon_y}}\oint \frac{\sqrt{\beta_y(s)}}{\sqrt{\beta_y(s)\varepsilon_y}+\sqrt{\beta_x(s)\varepsilon_x+\sigma^2_{\Delta p/p}D_x^2(s)}}\,ds$$

→ Extensive measurement campaign in 2011

- 50 ns/25 ns pushed to PSB brightness limit:

→ Nominal working point $Q_{x/y}$=0.21/0.24

→ Incoherent tune spread $\Delta Q_{x/y}$=-0.21/-0.26

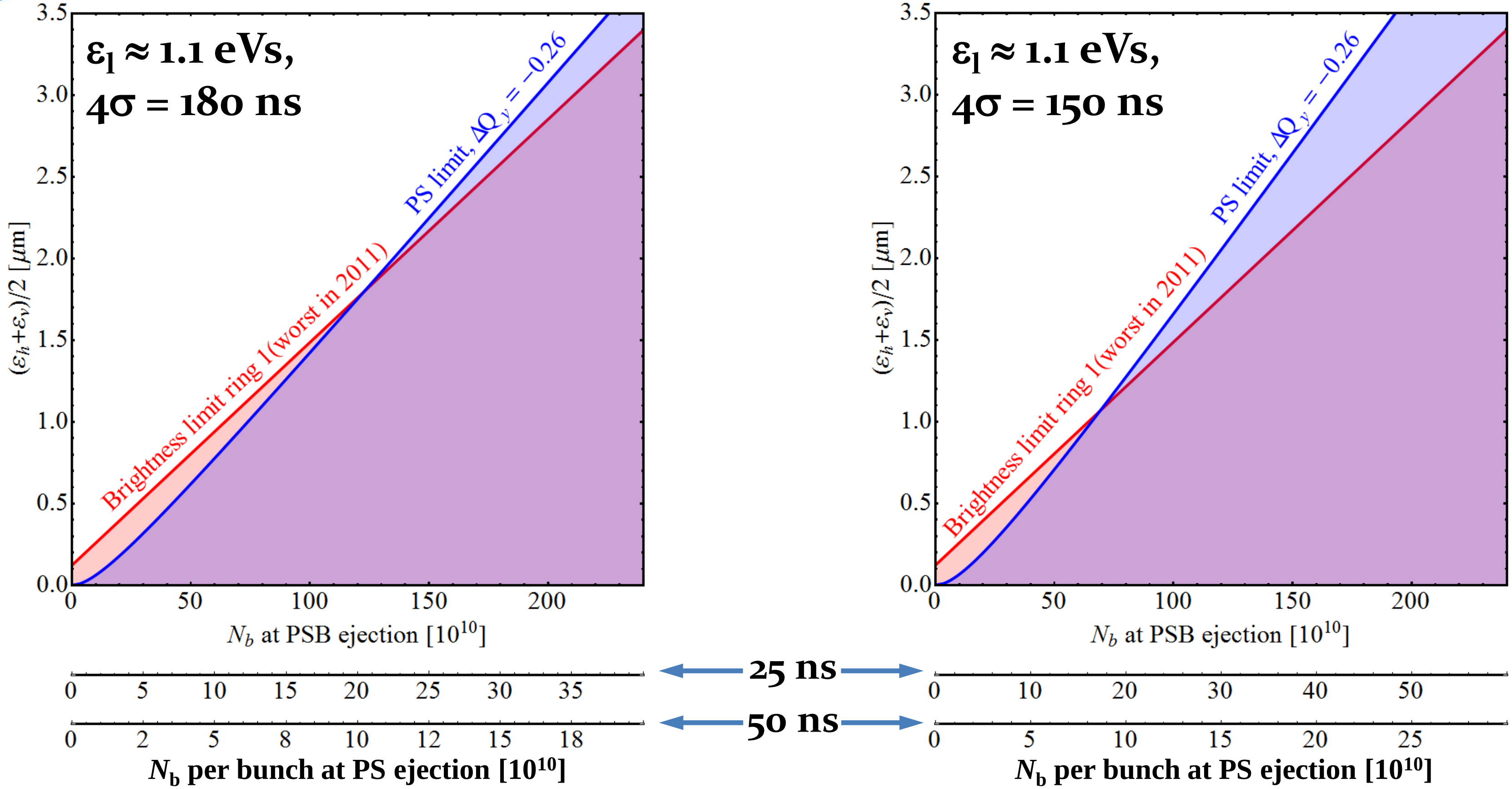


S. Aumon, E. Benedetto, A. Huschauer

→ Adopted maximum tune spread of ΔQ_y = -0.26 for further analysis

PS space charge vs. PSB brightness

PS injection, h = 7 **PS injection, h = 9**



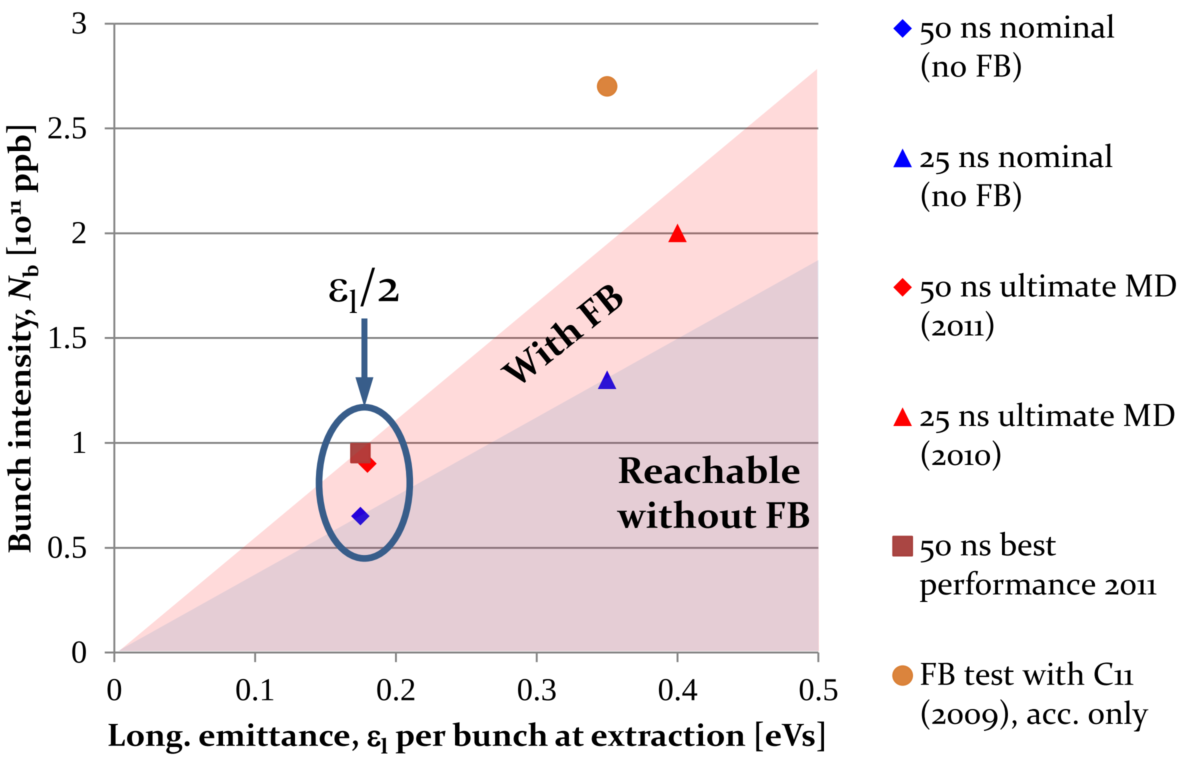
- **Maximum PSB brightness and PS space charge pose similar limitation**

→ **Linac2-PSB and PS at 1.4 GeV are well matched**

→ **PS cannot profit from brightness of Linac4/PSB without 2 GeV upgrade**

Long. coupled-bunch instabilities

- **Coupled-bunch oscillations observed after transition crossing in the PS**
- **Feedback system using RF cavities as longitudinal kickers**



→ **Empiric scaling with longitudinal bunch density, N_b/ε_l**

→ **MDs in 2012**

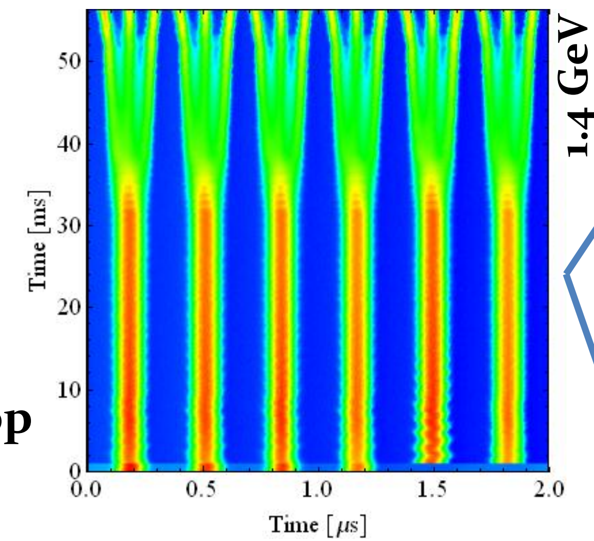
→ **With present system coupled-bunch limit (25/50 ns) at about $1.9 \cdot 10^{11}$ ppb**

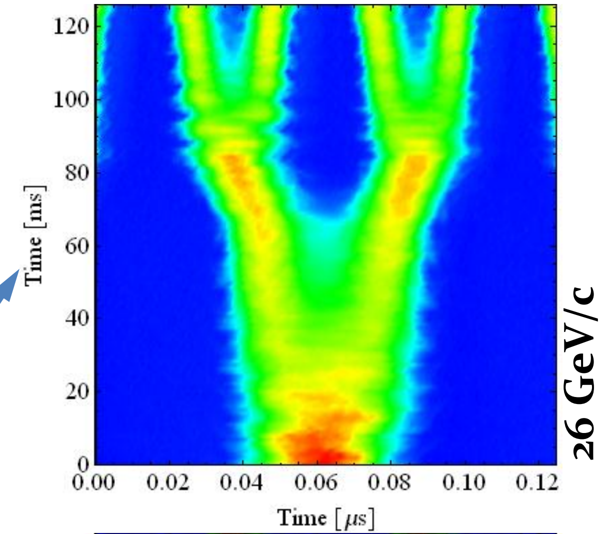
→ **Developed of dedicated wideband kicker (PS-LIU), could be ready in 2015**

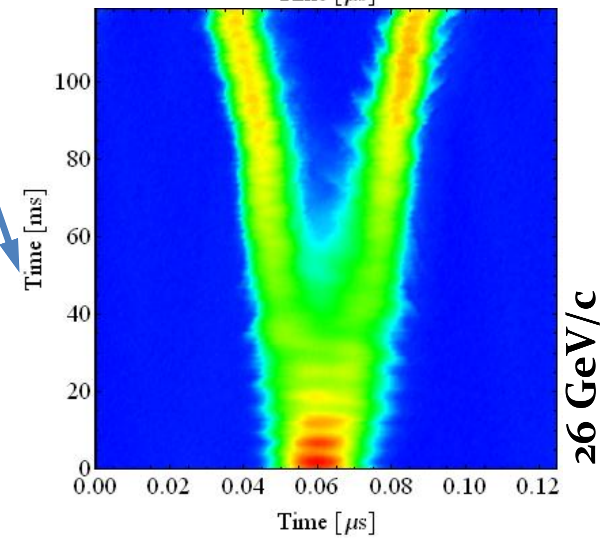
Operational beams: triple split $h = 7 \rightarrow 21$

- **Established LHC beam generation scheme since 2000**

1. **Triple splitting on flat-bottom**
2. **Acceleration on *h* = 21**
3. **Double (50 ns) or quadruple (25 ns) splitting on flat-top**







	25 ns	50 ns
Splitting ratio PS ejection/injection	12	6
Batch length from PS	72	36

Performance with triple split $h = 7 \rightarrow 21$

Operational production scheme		50 ns early 2011	25 ns ~nominal	50 ns CBI-limit
PS injection	Bunch intensity	$0.8 \cdot 10^{12}$ ppb	$1.6 \cdot 10^{12}$ ppb	$1.2 \cdot 10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.2 µm	2.4 µm	1.8 µm
	Vert. tune spread, ΔQ_y	-0.24	-0.26	-0.25
PS ejection	Bunch intensity	$1.27 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$1.90 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.3 µm	2.5 µm	1.9 µm
	Bunches per batch	36	72	36
Brightness limit PSB		X	X	X
Space charge limit PS		X	X	X
Coupled-bunch limit PS				X
SPS ejection	Bunch intensity	$1.15 \cdot 10^{11}$ ppb	$1.15 \cdot 10^{11}$ ppb	$1.71 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.4 µm	2.8 µm	2.1 µm
Relative intensity/luminosity in LHC		0.67/0.67	1.33/0.67	**1.0/1.0**

→ **Achieved performance ≈ expected performance from assumptions**

→ **Insignificant gain expected from Linac4/PSB without 2 GeV upgrade**

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- **Conclusions**

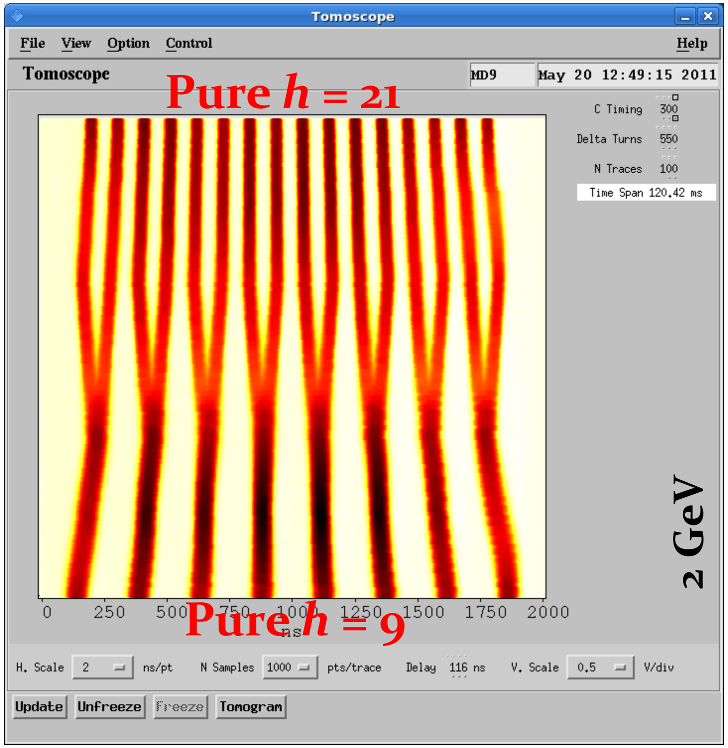
Batch compression $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$

- Suggested in Chamonix 2011 as option to produce higher intensity or higher brightness per bunch for LHC

- Beam tests of RF manipulation in 2011, but splittings on flat-top impossible for hardware reasons
- Full implementation in PS in 2012

→ Expected delivery to SPS in Q3/2012

	25 ns	50 ns
Splitting ratio PS ejection/injection	8	4
Batch length from PS	64	32



Performance reach $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$

Tests with SPS/LHC in 2012		50 ns high intens.	25 ns high intens.	25 ns low $\varepsilon_x/\varepsilon_y$
PS injection	Bunch intensity	$0.8 \cdot 10^{12}$ ppb	$1.07 \cdot 10^{12}$ ppb	$0.64 \cdot 10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.3 µm	1.8 µm	1.0 µm
	Vert. tune spread, ΔQ_y	-0.26	-0.26	-0.26
PS ejection	Bunch intensity	$1.90 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$0.76 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.3 µm	1.9 µm	1.0 µm
	Bunches per batch	32	64	64
Brightness limit PSB				X
Space charge limit PS		X	X	X
Coupled-bunch limit PS		X		
SPS ejection	Bunch intensity	$1.71 \cdot 10^{11}$ ppb	$1.15 \cdot 10^{11}$ ppb	$0.68 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.5 µm	2.1 µm	1.1 µm
Relative intensity/luminosity in LHC		1.0/1.4	1.3/0.9	0.8/0.6

(expected performance)

→ **Insignificant gain expected from Linac4/PSB without 2 GeV upgrade**

Batch compression + bunch merging

- Similar schemes as shown in Chamonix 2011; option for high-intensity LHC-type bunches:

h = (7 → 8 →) 9 → … → 14 ↗ 7 → 21 ↘ 15 → 16 → … → 21

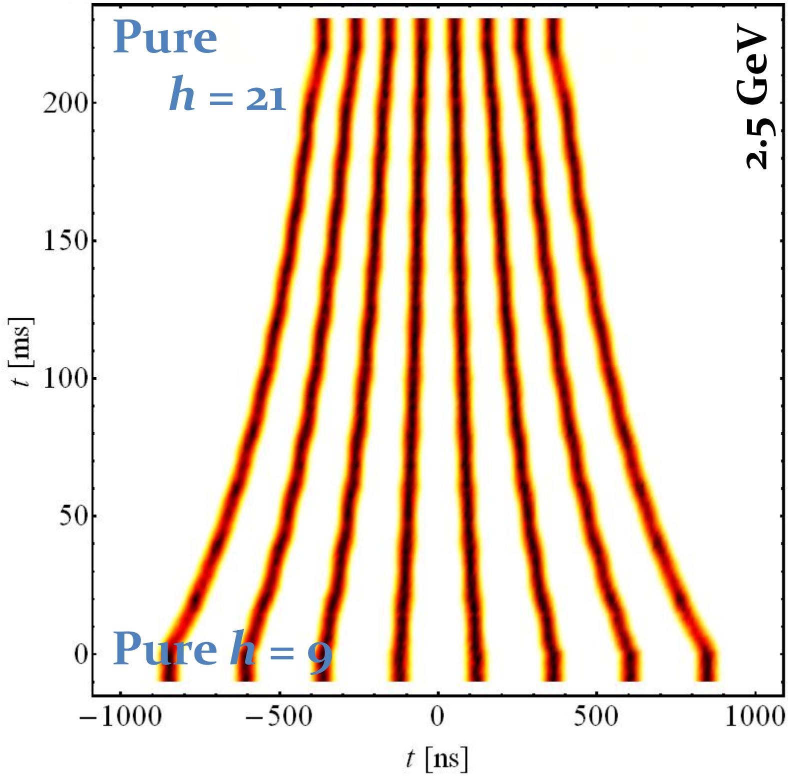
- Several manipulations proposed to achieve very low emittance

- First MDs in 2012
- Splittings on the flat-top not possible in 2012 due to hardware limitations

→ Decision on implementation Q4/2012

→ Could become operational for Q2/2014

	25 ns	50 ns
Splitting ratio PS ejection/injection	4	n/a
Batch length from PS	32	n/a



Performance reach h = 7 or 9 → … → 21

First PS studies in 2012		50 ns high int.	25 ns low $\varepsilon_x/\varepsilon_y$	25 ns ultra-bright
PS injection	Bunch intensity	$0.6 \cdot 10^{12}$ ppb	$0.8 \cdot 10^{12}$ ppb	$0.65 \cdot 10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.0 μm	1.2 μm	1.0 μm
	Vert. tune spread, ΔQ_y	-0.21	-0.24/-0.26	-0.26
PS ejection	Bunch intensity	$1.90 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$1.54 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.1 μm	1.3 μm	1.1 μm
	Bunches per batch	18/24	36/**48**	32
Brightness limit PSB		X	X/-	X
Space charge limit PS			-/X	X
Coupled-bunch limit PS		X		
SPS ejection	Bunch intensity	**Beyond SPS reach**	$1.15 \cdot 10^{11}$ ppb	**Beyond SPS reach**
	Emittance, $\beta\gamma\varepsilon$		1.4 μm	
Relative intensity/luminosity in LHC		(1.0/1.8)	**1.3/1.3**	(1.63/2.38)

(expected performance)

More than present luminosity with 25 ns and slightly higher total current

Emittance conservation for small $\varepsilon_{x/y}$

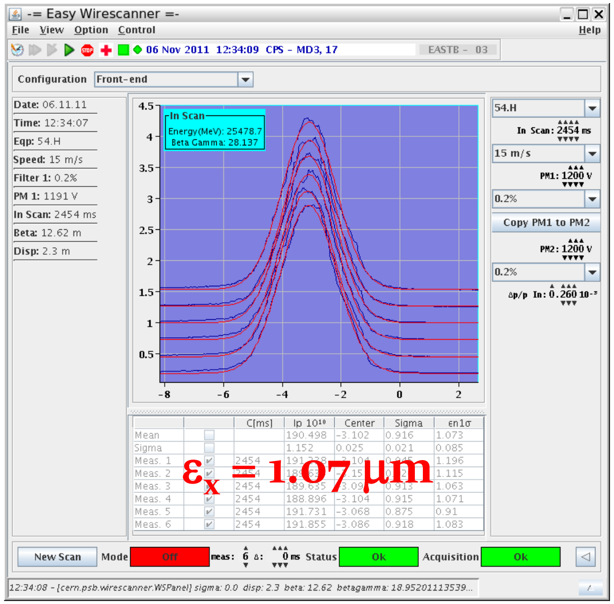
- **First test with low intensity high-brightness beam in 2011:**

→ **~5 · 10[11] ppb from Linac2/PSB with minimum $\varepsilon_{x/y}$**

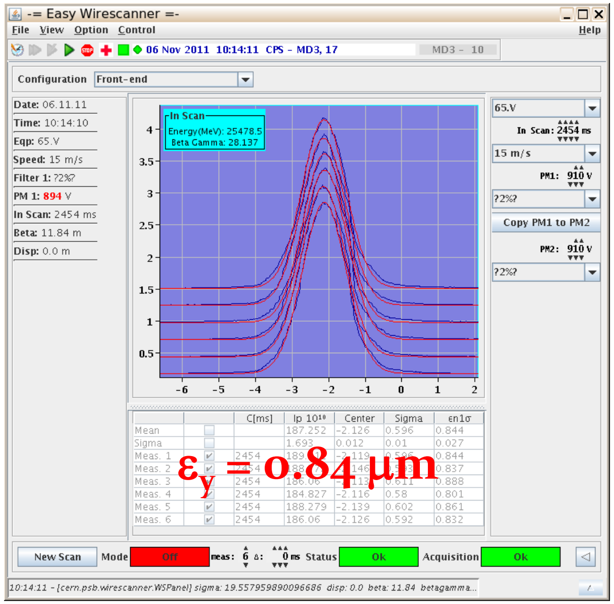
	Ring 1	Ring 2	Ring 3	Ring 4
Emittance average, $(\varepsilon_x + \varepsilon_y)/2$ [μm]	0.88	0.74	0.72	0.8
Longitudinal emittance, ε_l [eVs]	0.93	1.0	1.06	1.05

A. Findlay

→ **Small transverse emittance seems well conserved to PS flat-top**



$N_b = 1.5 \cdot 10^{11}$ ppb @ 26 Gev



P. Freyermuth, S. Gilardoni

→ **To be injected into the SPS in 2012**

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SPS performance after LS1

- Major LIU upgrades in the SPS during LS2
  - E-cloud coating, RF upgrade 200 MHz (4 → 6 cavities), etc.

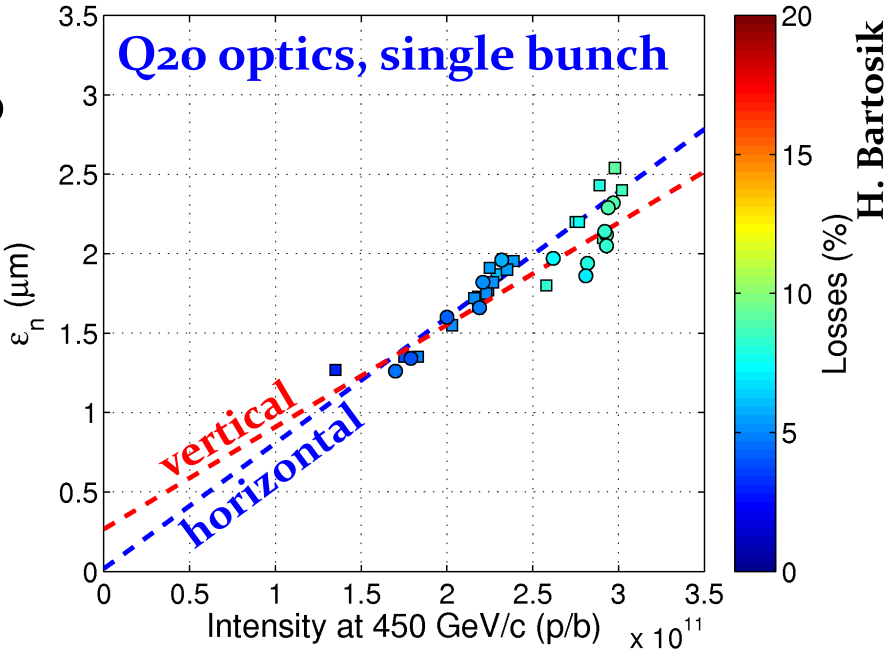
- After LS1, brightness improvements expected from
  - Q20 optics for LHC-type beams (minor hardware changes)
  - Upgrade of SPS 800 MHz RF system → feedbacks + more voltage
  - Shielding of last MKE kicker → impedance reduction

- Assuming that scrubbing helps (?)
  - Suppress e-cloud effects for higher intensity and/or smaller $\varepsilon_{x/y}$

- Recommissioning after LS1 to recover from interventions
  - SPS well scrubbed now, initial conditions after LS1 may not be as good

SPS brightness and injection schemes

- **2011 performance on flat-top achieved during MD with Q20 optics**
  - → Further optimization?
  - → Multi-bunch limit?
  - → MDs in 2012 to explore



- **More injections into SPS to recover from shorter PS batches**

PS RF manipulation	Transfers PS-SPS	# bunches in LHC		Min. fill time
Triple splitting	2/3/4 · 72 bunches	2808	1.0	8 min 38 s
$h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$	up to 4 · 64 bunches	2688	0.96	~ 9 min 20 s
$h = 7...14 \rightarrow 7 \rightarrow 21$	up to 7 · 36 bunches	2520	0.90	~ 13 min
$h = 9...14 \rightarrow 7 \rightarrow 21$	2/4/5(/6) · 48 bunches	2592	0.92	10 min 5 s
$h = 9...21$ (pure batch comp.)	up to 8 · 32 bunches	~2450	~0.87	~14 min 20 s

→ **Consequences in the LHC** → Werner's talk

Conclusions

- Little improvement from Linac4 with PSB-PS transfer at 1.4 GeV
  - Linac2/PSB brightness and PS space charge limit match very well
  - With Linac4/PSB space charge at PS flat-bottom is bottleneck
- Potential performance improvements by low-emittance beams
  - First results with transport of such beams up to PS flat-top
  - Feasibility of $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$ manipulation shown in PS in 2011, fully tested with SPS and LHC in Q3/2012
  - Feasibility test of PS RF manipulation $h = 7 \ldots 14 \rightarrow 7 \rightarrow 21$, acceleration and beam to SPS/LHC only after LS1
- SPS performance improvements expected from Q20 optics, 800 MHz RF upgrade and MKE shielding

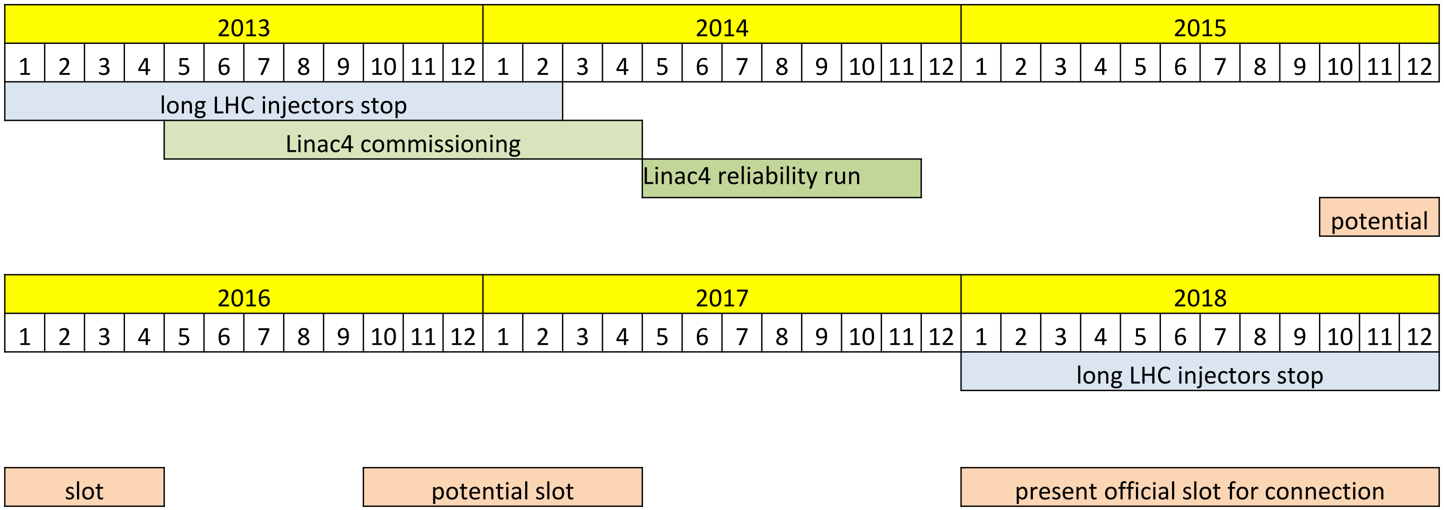
→ Need upgrade of transfer energy PSB-PS to 2 GeV to profit from Linac4!

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN

Booster Injection: Planning



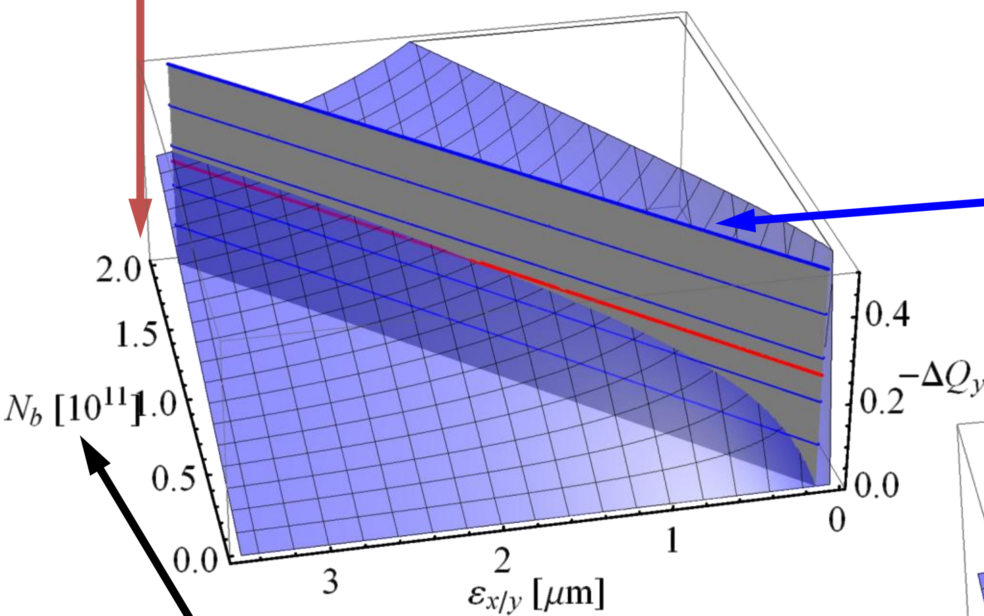
1. Connection of Linac4 to the PSB during LS1 ruled out
2. Connect to the PSB during an intermediate length shut-down (2015/16 or 2016/17)
3. Connect to the PSB during LS2 (assumed 2018)
4. Depending on the physics results, there is still a (minor) possibility that LS1 could move

K. Hanke

PSB + PS at 1.4 GeV flat-bottom

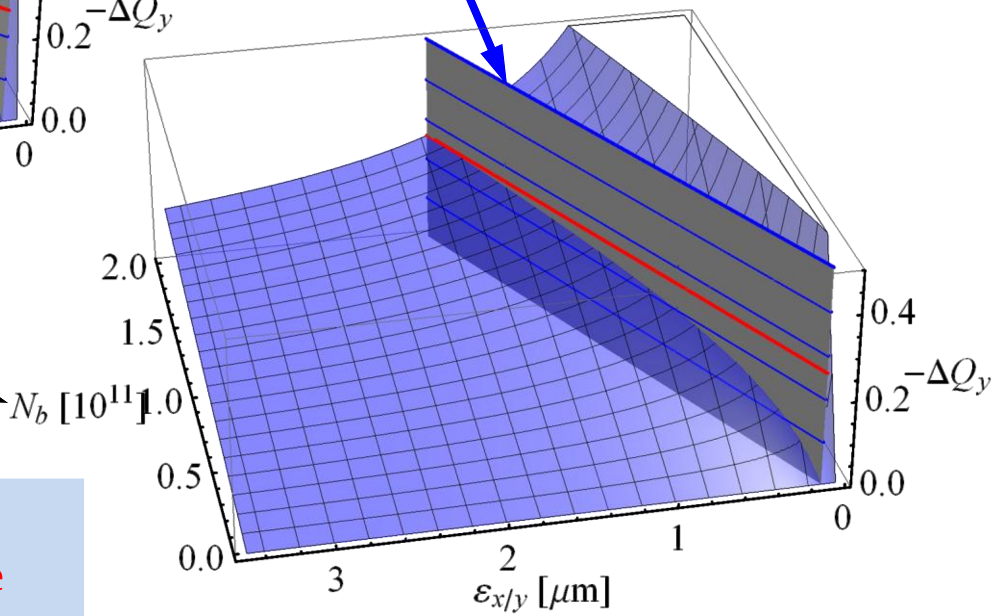
25 ns, split factor: 12

PS coupled-bunch limit



PSB brightness limit

50 ns, split factor: 6



Intensity per LHC bunch at PS injection

→ **Maximum PSB brightness surface cuts PS space charge close to $\Delta Q_y \approx -0.26$**