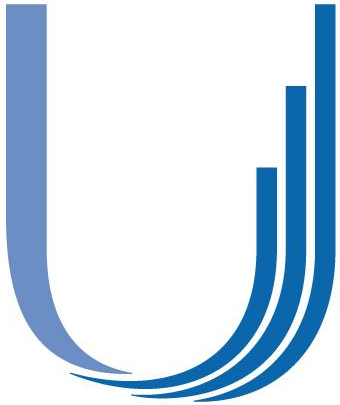

LHC Injectors Upgrade

LHC Injectors Upgrade

Low Emittance Options from the PS

H. Damerau, A. Findlay, S. Hancock

in collaboration with

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CERN

Overview

- Introduction
- Alternative RF schemes in PSB and PS
  - Achieved performance
  - Limitations in PSB and PS
  - Further alternatives
- Potential performance reach from injectors
  - Before LS1
  - Between LS1 and LS2
- Conclusions

Introduction

Present production of 50 ns beams for LHC:

Accelerator	Effect	Limit on
1. PSB	• Quasi at constant brightness: $N_b/(\varepsilon_h+\varepsilon_v) \sim$ const.	→ Transverse emittances
2. PS	• Longitudinal density during acceleration: max. $N_b/\varepsilon_l \sim$ const.	→ Intensity per bunch to LHC
3. SPS	• Longitudinal stability during acceleration	→ Intensity per bunch to LHC

- Major upgrades of the injector chain within LIU only during LS2

→ Before LS2: higher brightness beams from the injectors

a) Fill PS with moderate intensity bunches from PSB
b) Compress the batch in the PS + RF manipulations
→ High intensity but low transverse emittance bunches from injectors at cost of shorter PS batches

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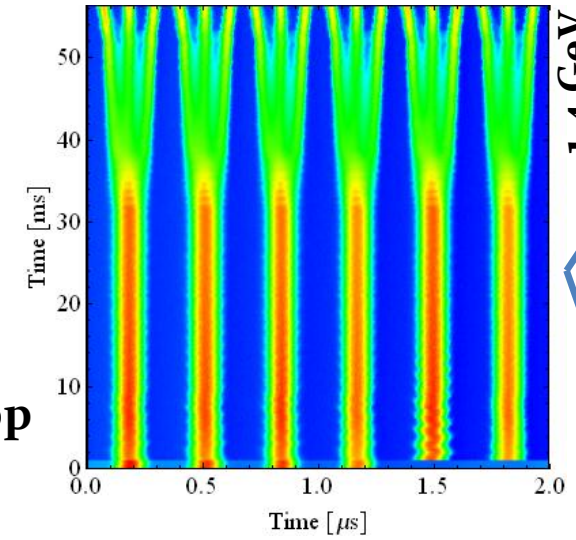
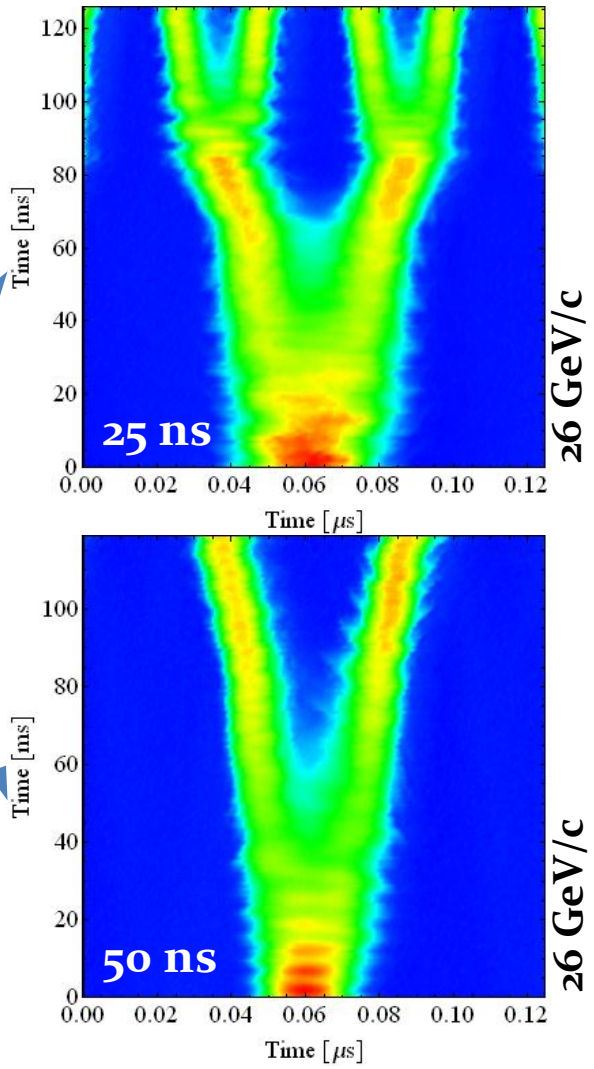
Operational beams: triple split $h = 7 \rightarrow 21$

- **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**

Key harmonic for acceleration $h = 21$, as bunch rotation cavities at $h = 84/168$

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PSB/PS: Brightness vs. intensity

- **Ideas for schemes with increased brightness in 2003** (Garoby et al.)
- **Chamonix 2011: alternative RF manipulations** (Carli, Garoby)
  http://indico.cern.ch/getFile.py/access?contribId=26&sessionId=8&resId=3&materialId=slides&confId=103957
- **Chamonix 2012: first measurements and expected performance**
  https://indico.cern.ch/getFile.py/access?contribId=41&sessionId=6&resId=1&materialId=slides&confId=164089
- **140th LMC: First higher brightness 50 ns variant ready for LHC**
  https://espace.cern.ch/lhc-machine-committee/Presentations/1/lmc_140/lmc_140g.pdf

Bunch intensity to SPS/LHC (no losses in PS/SPS) per bunch from PSB:

PS RF manipulation scheme	25 ns bunch spacing	50 ns bunch spacing
1. Triple splitting	N_{PSB}/12 in 72 b	N_{PSB}/6 in 36 b
2. Batch compression + double split	N_{PSB}/8 in 64 b	N_{PSB}/4 in 32 b
3. Batch comp. + merge + triple split	N_{PSB}/6 in 48 b	N_{PSB}/3 in 24 b
4. Pure batch compression	N_{PSB}/4 in 32 b	N_{PSB}/2 in 16 b

Higher brightness

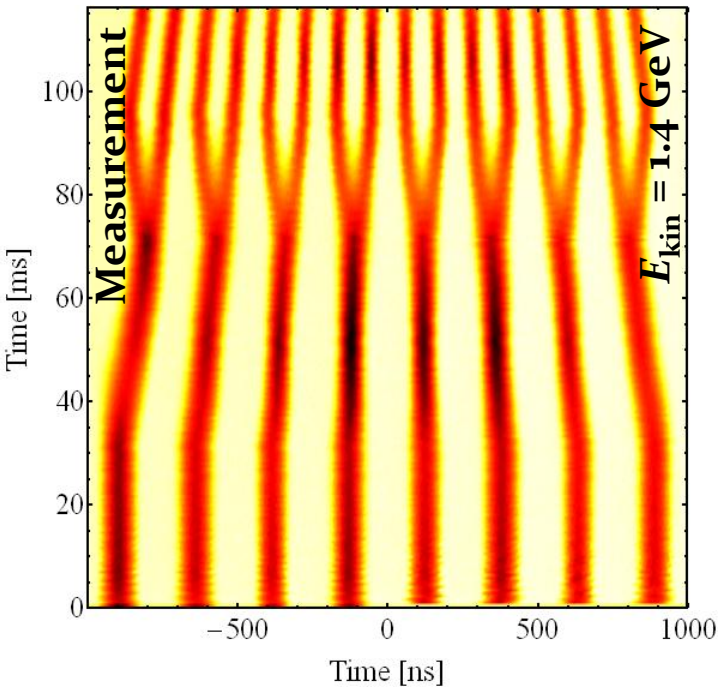
Longer PS batches

Batch comp. + split: $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$

- **Suggested in Chamonix 2011 as option to produce higher intensity or higher brightness per bunch for LHC, first beam tests in PS in 2011**

16 bunches at start of acc.
→ 32 bunches, 50 ns @ extraction

Pure $h = 21$



Pure $h = 9$

4+4 bunches injected into $h = 9$

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

- ✓ New hardware commissioned
- ✓ Double-batch injection
- ✓ High energy RF manipulations
- ✓ Delivered to SPS and LHC
- ✓ Positive operational experience from 100 ns CNGS run

→ Fully operational

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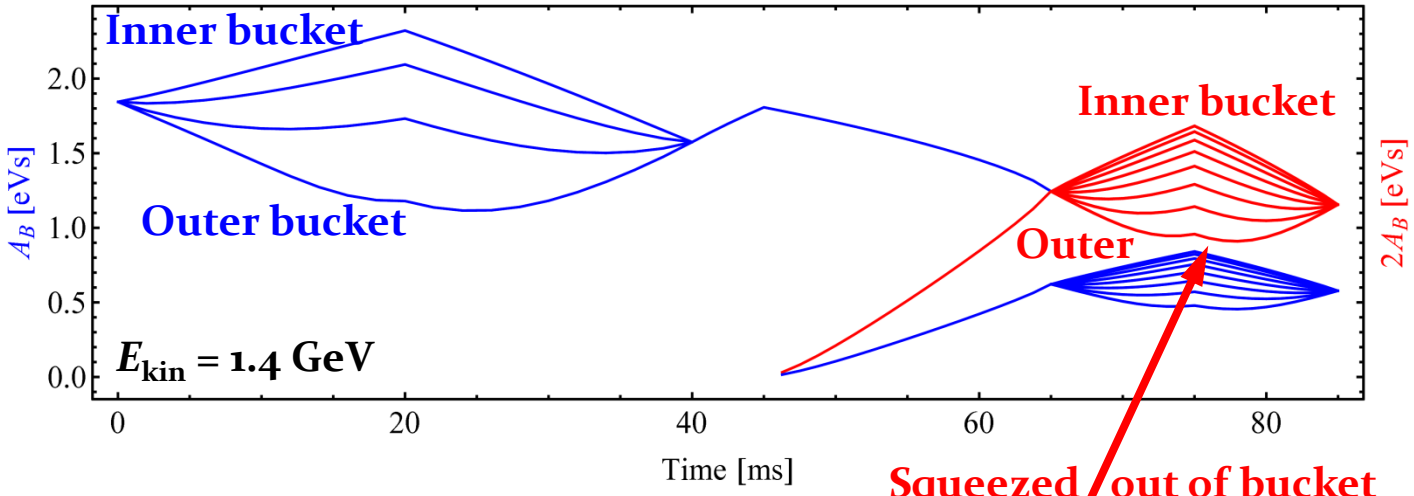
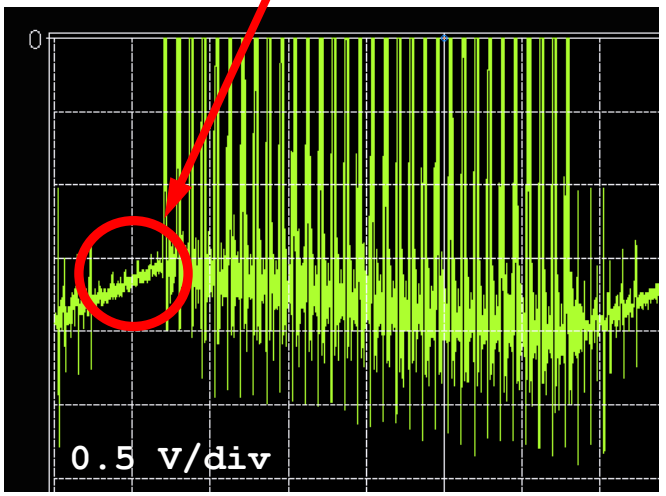
Present limits of $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$

- **Bucket area limitation (0.91 eVs) during $h = 20 \rightarrow 21$ puts stringent longitudinal requirements to bunches from PSB at 1.4 GeV**



Squeezed out of bucket



- **Intensity presently limited to what PSB can deliver within**
  $\varepsilon_h, \varepsilon_v \sim 1.0/0.9\ \mu m, \varepsilon_l \sim 0.7 - 0.8$ eVs

→ **Will profit from intermediate flat-top above 1.4 GeV (before LS1?) and optimized tuning groups (after LS1)**

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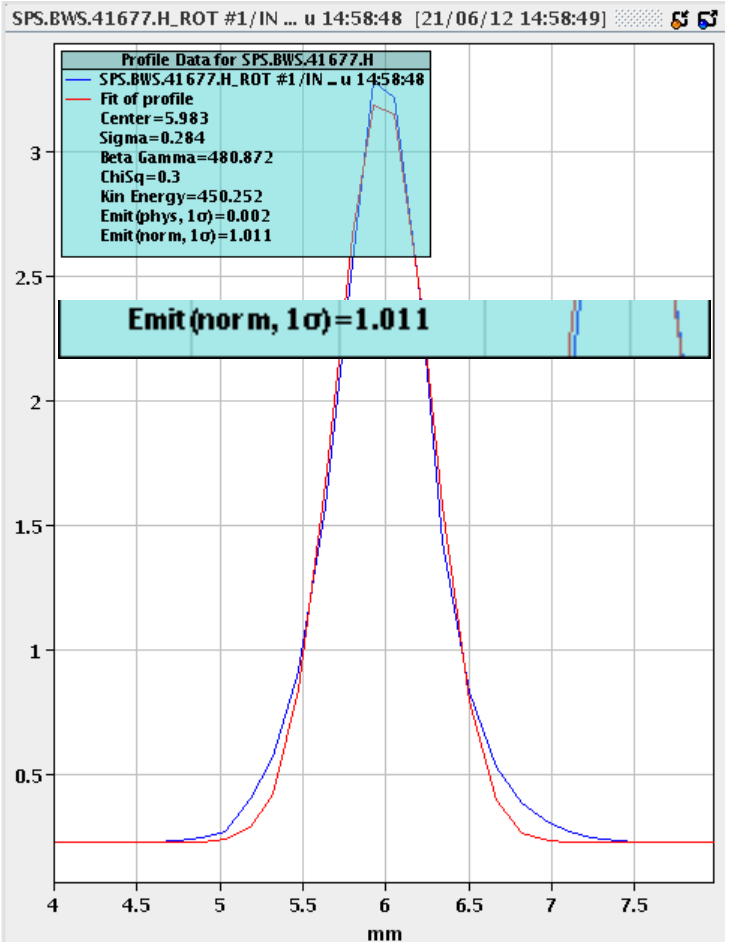
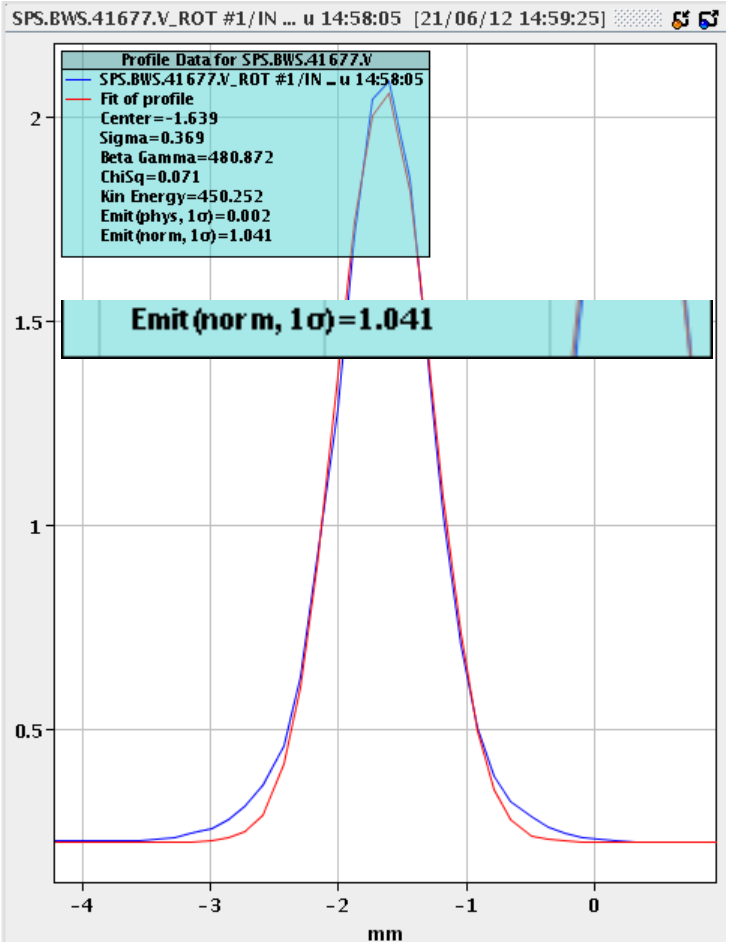
Emittances at SPS flat-top (32 bunches)

Horizontal



Vertical



→ 32 bunch beam ~ 1.1 · 10^{11} ppb; ε_h, ε_v ~ 1.1 μm at SPS extraction

→ 30% smaller $\varepsilon_{h/v}$ than normal 36 bunch at comparable intensity

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Batch compression and bunch merging

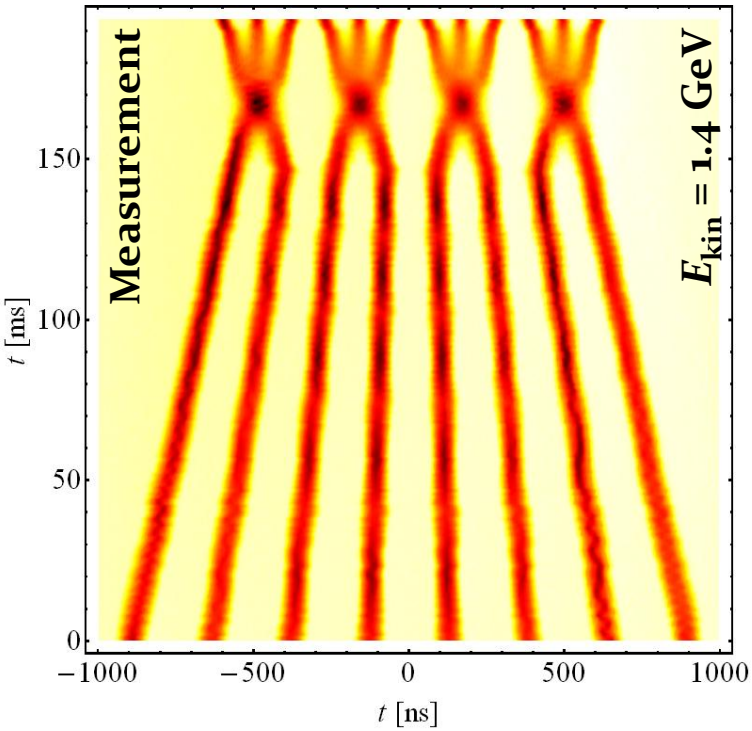
- More evolved RF manipulations schemes from $h = 9$ to 21 (Chamonix 2012)

→ Most 'simple' scheme: $h = 9 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 13 \rightarrow 14 \rightarrow 7 \rightarrow 21$

	25 ns	50 ns
Splitting ratio PS ejection/injection	6	3
Batch length from PS	48	24

- 30 % higher intensity from PS compared to $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$
- Shorter batch at PS extraction: 24 instead of 32 bunches

Pure $h = 21$



Pure $h = 9$

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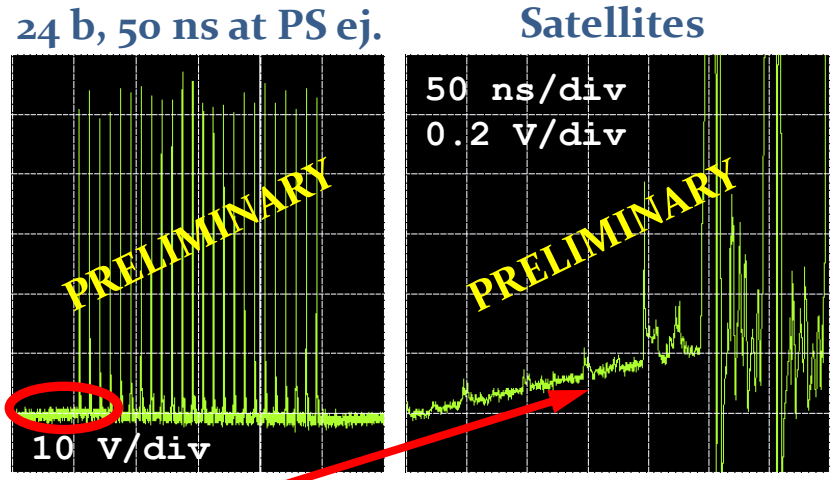
Batch compression: reach in 2012

Proof-of-principle at 1.4 GeV:

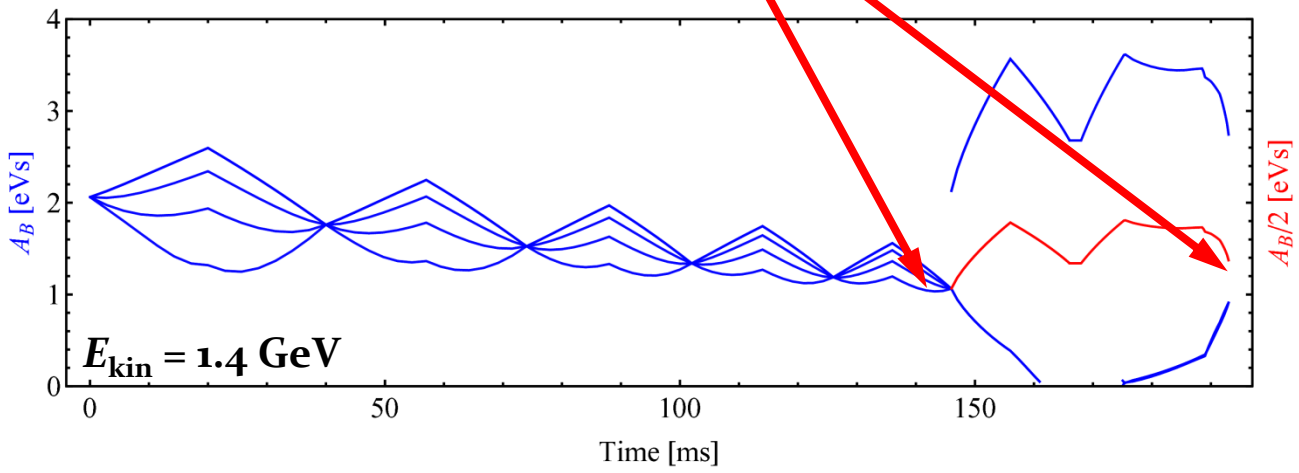
- ✓ Double batch injection
- ✓ RF manipulations on flat-bottom
- ✓ RF manipulations on flat-top

→ 24 bunches, $1.6 \cdot 10^{11}$ ppb extracted from PS



→ Bucket area limitation: 1.0 eVs

→ Emittance limit during triple splitting



At limit of today's RF control (restart timings)

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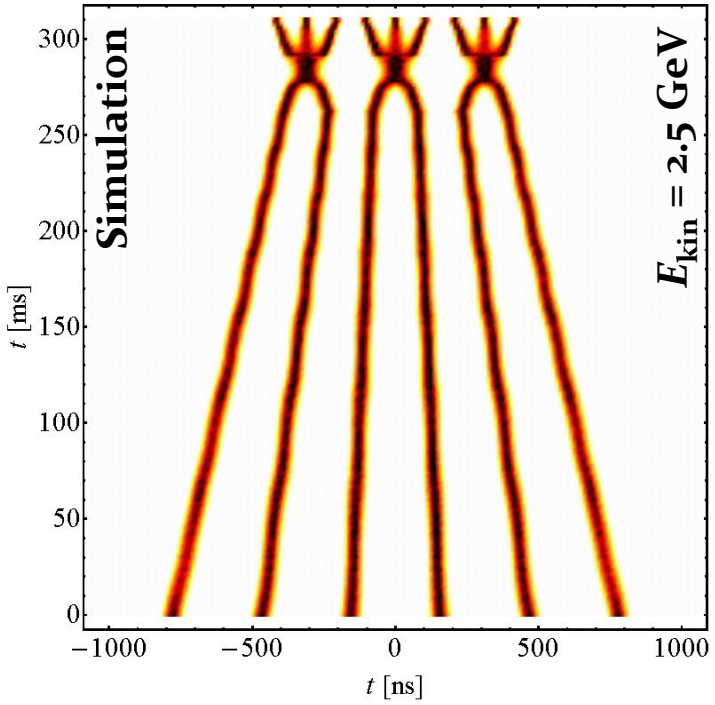
Alternative schemes

Batch compression, merging + triple split starting from $h = 7$

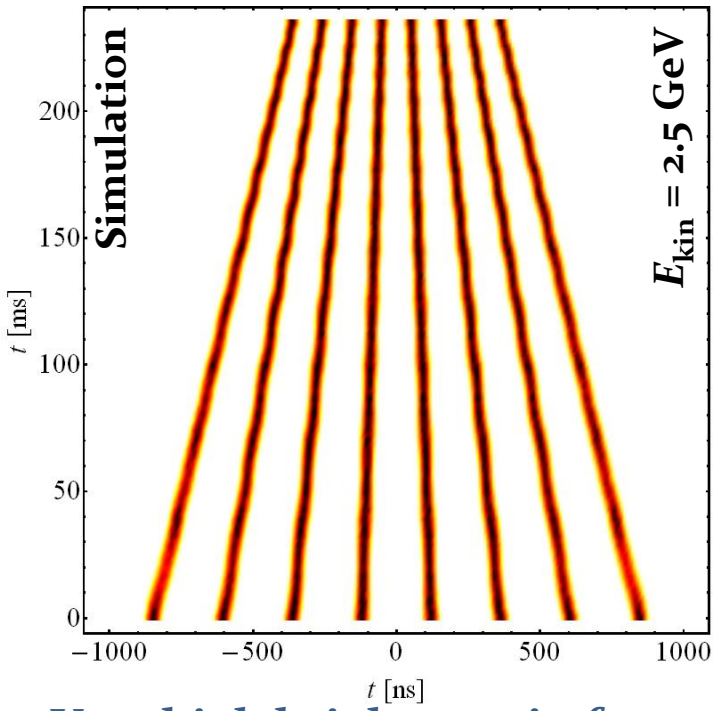
$h = 7 \rightarrow 8 \rightarrow \ldots \rightarrow 14 \rightarrow 7 \rightarrow 21$



- Favorable for space charge at inj.
- Uses brightness from 4+2 PSB rings only (36 bunches, 25 ns)

Pure batch compression

$h = 9 \rightarrow 10 \rightarrow \ldots \rightarrow 20 \rightarrow 21$



- Very high brightness in few bunches (32 bunches, 25 ns)
- Explore limit of SPS

→ Both schemes should become technically feasible after LS1

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Injector performance before LS1

Possible tests with SPS/LHC in 2012		50 ns 32 bunches	50 ns 24 bunches	25 ns 48 bunches
PS injection	Bunch intensity	**0.5·10¹² ppb**	**0.5·10¹² ppb**	**0.5·10¹² ppb**
	Emittance, $\beta\gamma\varepsilon$	**~ 1.0 μm**	*~ 1.0 μm*	*~ 1.0 μm*
	Vert. tune spread, ΔQ_y	-0.26	-0.26	-0.26
PS ejection	Bunch intensity	**1.2·10¹¹ ppb**	1.6·10¹¹ ppb	*0.8·10¹¹ ppb*
	Emittance, $\beta\gamma\varepsilon$	**~ 1.0 μm**	*~ 1.0 μm*	*~ 1.0 μm*
	Bunches per batch	**32**	**24**	*48*
SPS ejection	Bunch intensity	**1.1·10¹¹ ppb**	*1.5·10¹¹ ppb*	*0.75·10¹¹ ppb*
	Emittance, $\beta\gamma\varepsilon$	**1.1 μm**	*1.1 μm*	*1.1 μm*
Relative intensity/luminosity in LHC		*0.62/0.76*	*0.81/1.4*	*0.81/0.68*

$\varepsilon_l = 0.7$ eVs

Low $\varepsilon_{h/v}$ exploration **Luminosity production?**

(**measured**/*expected* performance;
operational 50 ns LHC beam has relative intensity/luminosity of about 1.0/1.0

→ **50 ns, 32 bunches to be tested in the LHC soon**

→ **Can LHC profit from high brightness of these low emittance beams?**

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Potential improvements after LS1

- **RF manipulations on intermediate flat-top**
  - → Reduces space charge
  - → Bucket areas twice larger at E_{kin} = 2.5 GeV

MDs before LS1

- **New tuning group structure 10 MHz cavities**
  - → 22 % larger bucket area during RF manipulations
- **Upgraded RF controls**
  - → More complicated programming of voltage programs, etc.
- **Upgraded/new longitudinal feedbacks**
  - → New 1-turn delay feedback on main cavities
  - → Coupled-bunch feedback 2014/2015

Estimated performance after LS1

Full implementation after LS1		50 ns 32 bunches	50 ns 24 bunches	25 ns 48 bunches
PS injection	Bunch intensity	$0.8 \cdot 10^{12}$ ppb	$0.6 \cdot 10^{12}$ ppb	$0.8 \cdot 10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	~ 1.3 μm	~ 1.0 μm	~ 1.1 μm
	Vert. tune spread, ΔQ_y	-0.26	-0.21	-0.26
PS ejection	Bunch intensity	$1.9 \cdot 10^{11}$ ppb	$1.9 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	~ 1.3 μm	~ 1.1 μm	~ 1.3 μm
	Bunches per batch	32	24	48
Brightness limit PSB			X	
Space charge limit PS		X		X
Coupled-bunch limit PS		X	X	
SPS ejection	Bunch intensity	$1.71 \cdot 10^{11}$ ppb	$1.71 \cdot 10^{11}$ ppb	$1.15 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.5 μm	1.2 μm	1.4 μm
Relative intensity/luminosity in LHC		0.96/1.3	0.92/1.6	**1.2/1.2**

Chamonix 2012, including reduced bunch number in LHC

(expected performance, conservative PS space charge limit)

→ **High intensity 50 ns or moderate intensity high brightness 25 ns beam**

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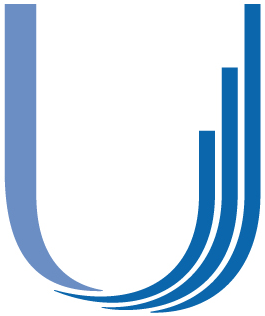
Conclusions

- **Higher brightness beams from the LHC injector complex are feasible**
  - → **Low longitudinal and transverse emittance beam from PSB**
  - → **RF manipulations demonstrated in the PS**
  - → **Small transverse emittances can be conserved to SPS extraction**
- **Expected improvements and upgrades after LS1**
  - → **More flexibility in the PS for complex RF schemes**
  - → **Upgrade of feedback systems**

→ **Possibility to exceed nominal luminosity with 25 ns bunch spacing after LS1**

→ **Can LHC profit from small emittance beams?**



LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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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(Preliminary) LHC filling patterns

- **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

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