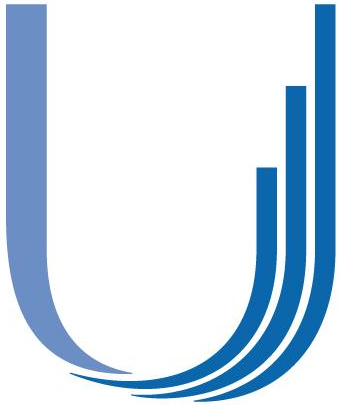

LHC Injectors Upgrade

LHC Injectors Upgrade

PS: the Longitudinal Plane

H. Damerau, S. Hancock

LIU Beam Studies Review Meeting

28 August 2012

Many thanks to H. Bartosik, T. Bohl, A. Findlay, S. Gilardoni, G. Metral, M. Migliorati, B. Mikulec, M. Paoluzzi, D. Perrelet, S. Persichelli, C. Rossi, E. Shaposhnikova, H. Timkó, PSB, PS and SPS Operations Teams, …

CERN

Overview

- Introduction
  - Impedance studies
  - Coupled-bunch and 1-turn delay feedbacks
  - Alternative production schemes of LHC beams
  - Performance reach after LS1
  - Longitudinal transfer PS-SPS
- Summary

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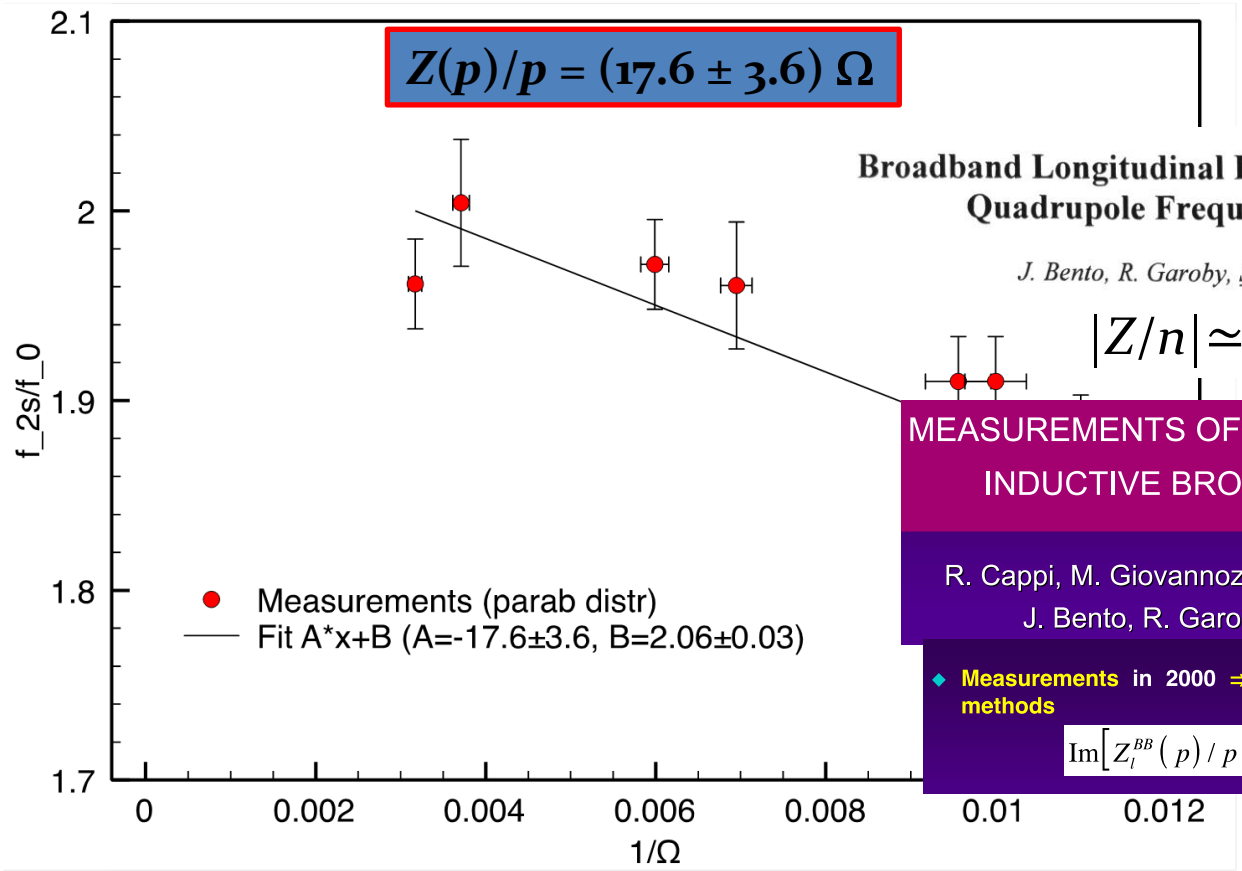
Broadband impedance measurements (1/2)

→ **First MD session on 10/05/12:**

$$\frac{f_{2s}}{f_{s0}} = 2 + \frac{12eN_p}{V_{RF}h\cos\phi_s\omega_0^2\tau_b^3}\frac{Im[Z(p)]}{p}$$



Broadband Longitudinal Impedance from Incoherent Quadrupole Frequency Measurements (2001)

J. Bento, R. Garoby, S. Hancock, J.-L. Vallet

$$|Z/n| \simeq (21.7 \pm 5.1)\ \Omega$$

MEASUREMENTS OF THE PS LOW-FREQUENCY INDUCTIVE BROAD-BAND IMPEDANCE

R. Cappi, M. Giovannozzi, E&G. Metral, R. Steerenberg
J. Bento, R. Garoby, S. Hancock, J.L. Vallet

- **Measurements in 2000 ⇒ Good agreement between the 3 methods**

$$\mathrm{Im}\left[Z_l^{BB}(p)/p\right] \approx 20\ \Omega$$

In agreement with the measurements done in the past

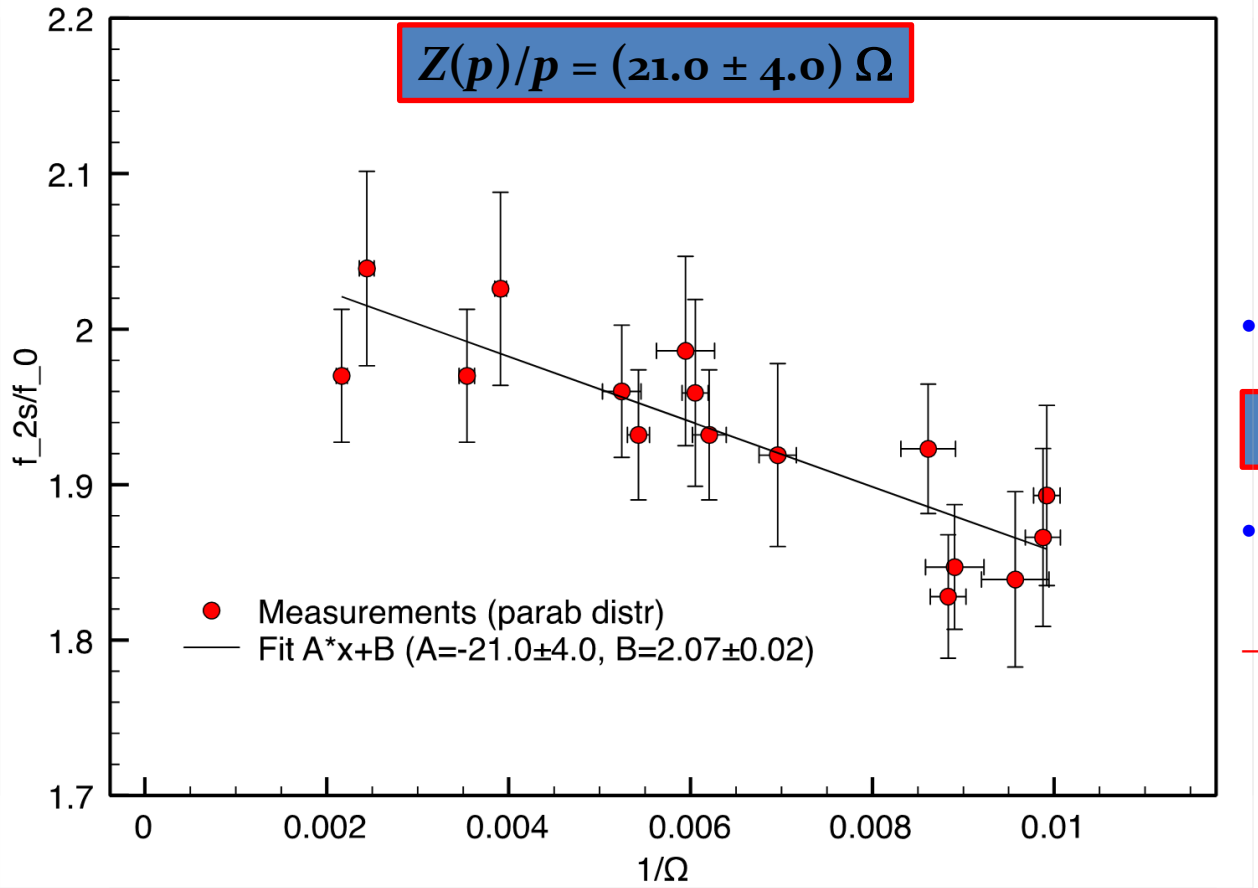
Mauro Migliorati

Broadband impedance measurements (2/2)

Mauro Migliorati

→ **Second MD session on 13/06/12:**

$$\frac{f_{2s}}{f_{s0}} = 2 + \frac{12eN_p}{V_{RF}h\cos\phi_s\omega_0^2\tau_b^3}\frac{Im[Z(p)]}{p}$$



- **Combined result:**

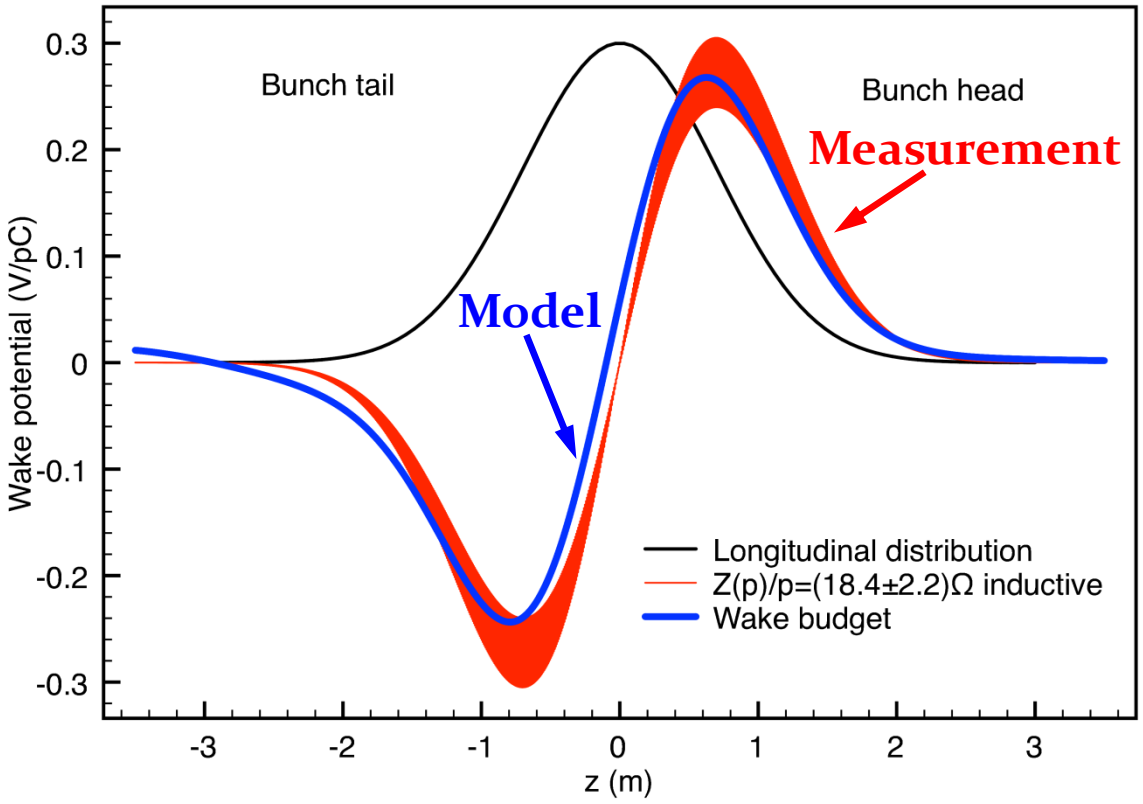
$Z(p)/p = (18.4 \pm 2.2)\ \Omega$

- **Reproducible**

→ **Reference for measurements after LIU installations**

Comparison with theoretical model

- **Theoretical impedance budget including kickers, cavities, pumping ports, step transitions of beampipe, etc.**



→ **Excellent agreement of measured impedance with model**

→ **No further MD time required before LS1**

H. Damerau, S. Hancock, LHC Beam Studies Review 28/08/2012

Broadband impedance studies

#	Subject	
1	Broad-band impedance measurement (quadrupole BTF, using C40-78)	✅
2	Re-measure #1 as independent crosscheck (using C40-77)	✅

→ **Broad-band impedance studies completed**

→ **Reference point for later measurements**

✅ **Completed**

✖ **Ongoing**

✖ **To be done before LS1**

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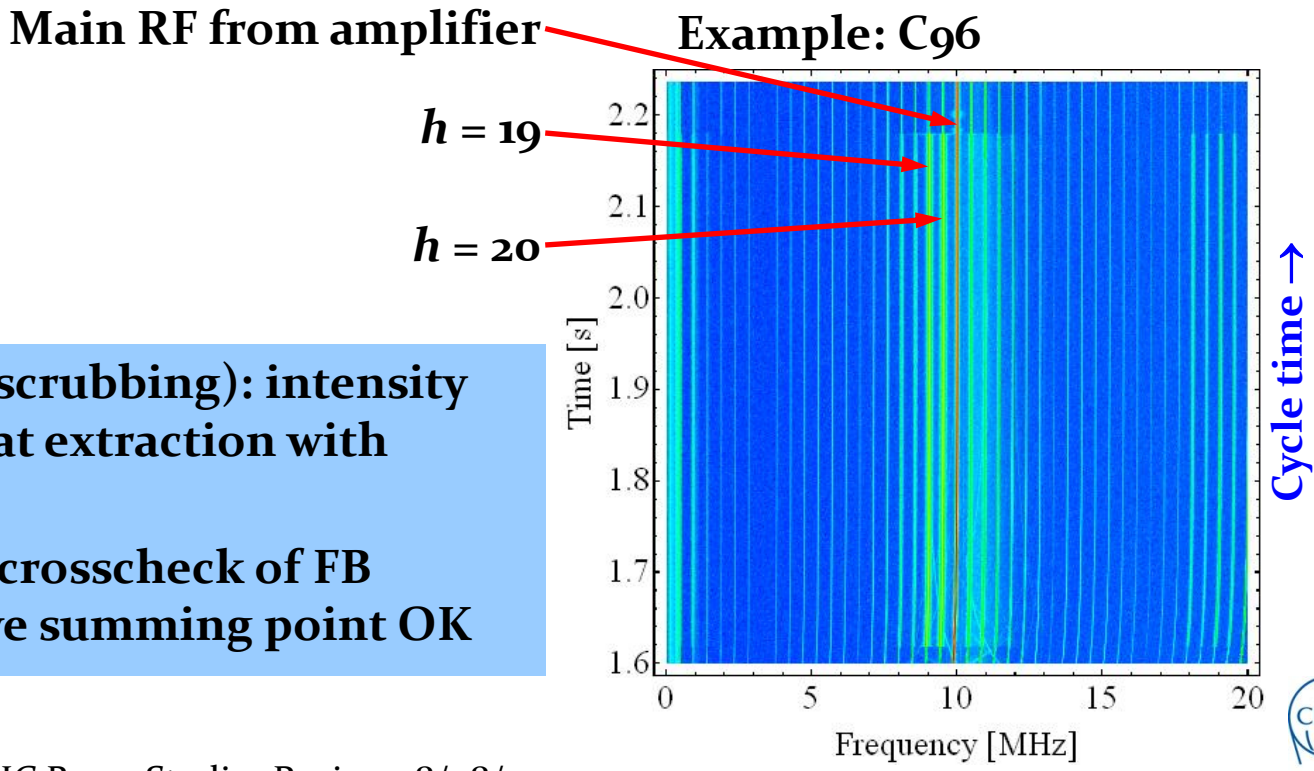
Kick strength of PS coupled-bunch FB

- **Present coupled-bunch feedback acts on 10 MHz cavities C86/96**
- **Generates RF voltage at $(h\text{-}1) \cdot f_{rev}$ and $(h\text{-}2) \cdot f_{rev}$, far away from cavity resonance**

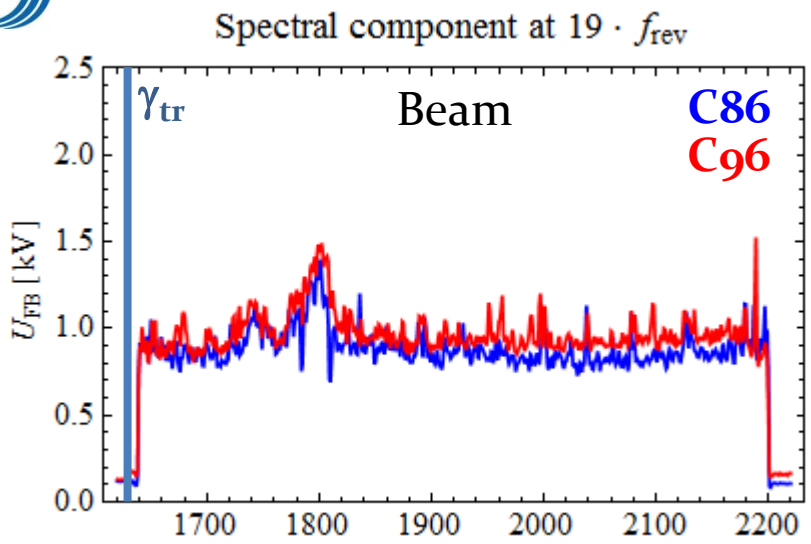
→ **New Finemet-based wide-band kicker cavity installed during LS1**

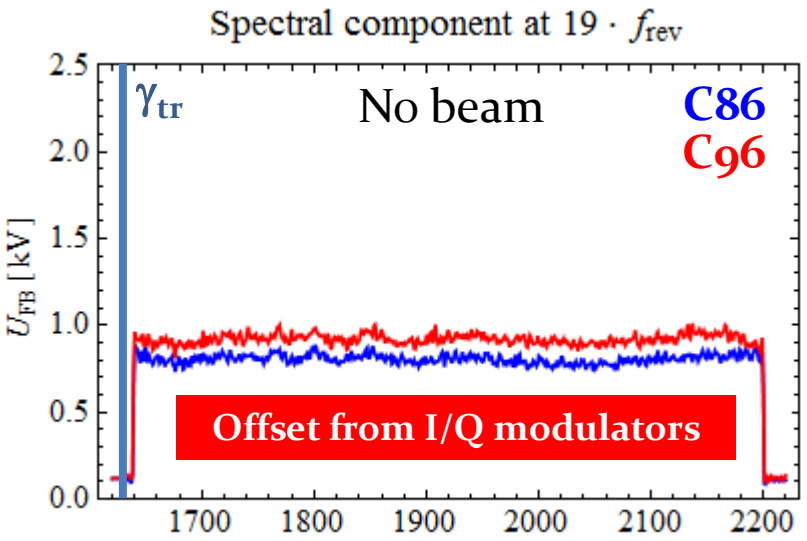


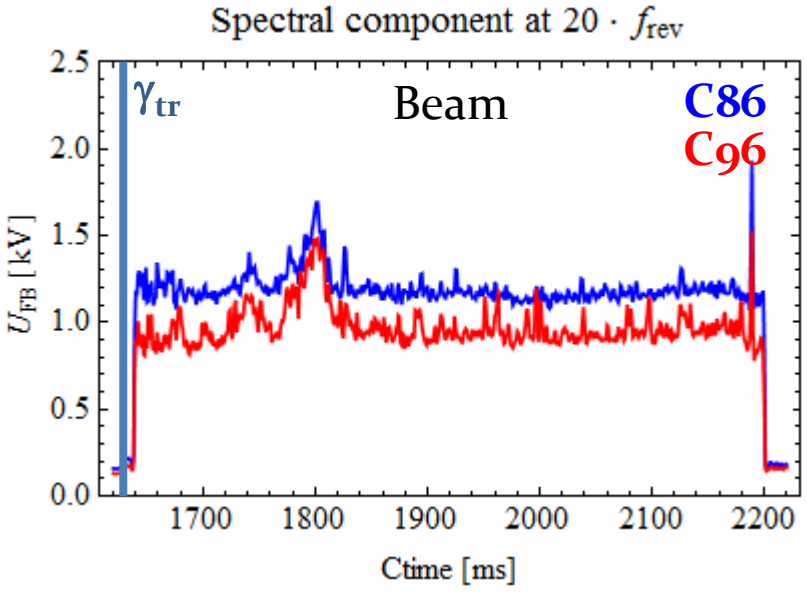
→ **LHC25ns (for scrubbing): intensity $1.75 \cdot 10^{11}$ ppb at extraction with nominal ε_l**

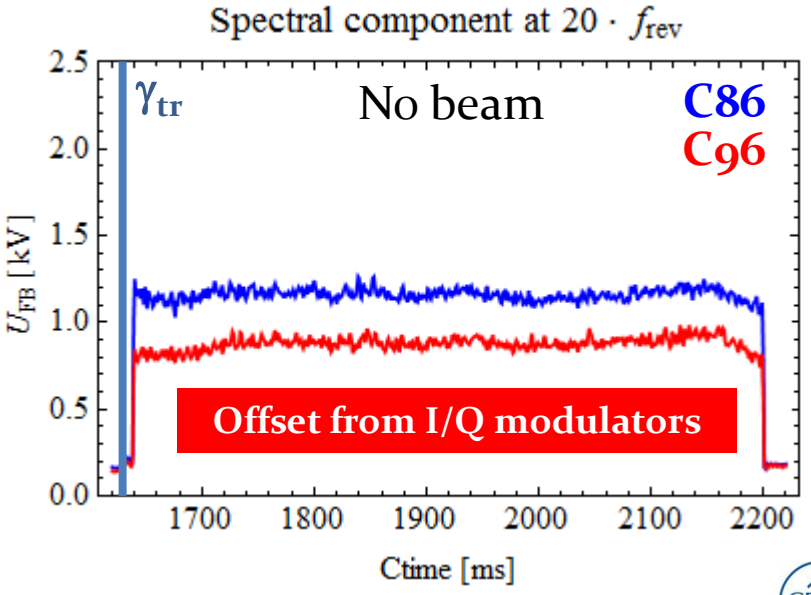
→ **Independent crosscheck of FB signals at drive summing point OK**

Spectral components at h = 19 and 20









Results of preliminary studies

- **Effective kick strength of the order of ~ 0.5 kV per mode for 25 ns beam with an intensity of 1.75 · 10^{11} ppb → to be checked**
- **Unwanted carrier leakage from existing feedback already observed earlier**
  → **Offset problem with up-conversion mixers identified**

→ **Present work hypothesis: Damper cavity dimensioned for 5-6 simultaneous harmonics from 0.4 to 5.5 MHz with an amplitude of ~ 1 kV each**

- **Feed-forward beam compensation studies independent from LS1**
  → **Collaboration with KEK**

Mauro Paoluzzi

Coupled-bunch feedback studies

#	Subject	
1	Adjustment of coupled-bunch (CB) feedback modulator offsets	✓/✗
2	Coupled-bunch measurements with 100 ns beam	✓
3	Measurement of kick voltages of CB feedback	✓/✗
4	Use spare cavity C10-11 as CB feedback kicker, high density acceleration	✗
5	Show damping with detection at h_{FB} = 1 + 2 and kick at h_{FB} = 20 + 19	✗
6	Check stability with C10-11 introducing synchrotron spread	✗

✓ Completed ✗ Ongoing ✗ To be done before LS1

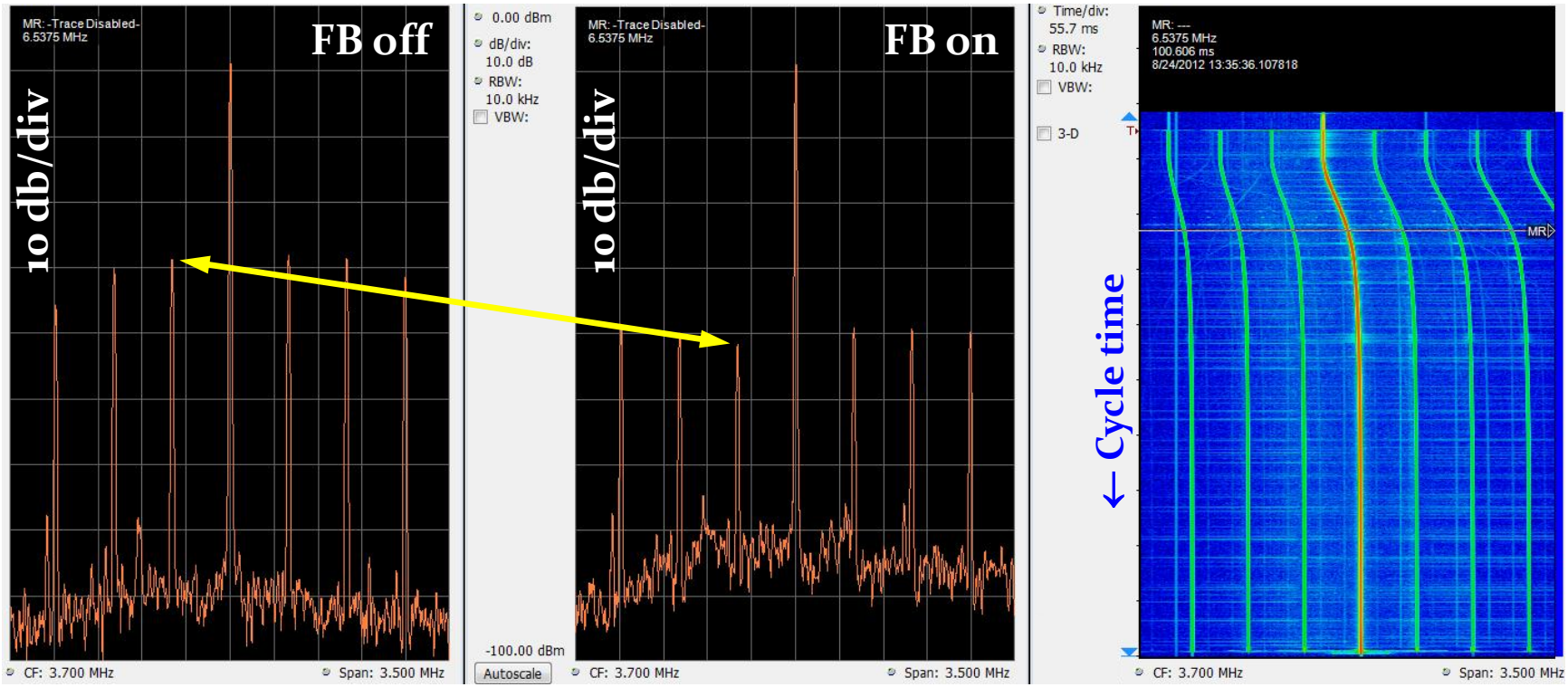
→ **Still important studies to be performed before LS1: #4 - #6**

→ **Beginning of 2013 ideal period for #4 since CB-FB not required for high-intensity LHC beam production anymore**

Impedance and 1-turn feedback studies

- **Fully digital 1-turn feedback prototype, based on LHC 1-turn FB**

Beam induced spectrum on cavity return signal along cycle (TOF)



→ **Excellent result: prototype already better than operational system**

→ **Validate series version board in Q1/2013?**

→ **Full installation on all 10 MHz cavities during LS1**

Damien Perrelet

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New 1-turn feedbacks

#	Subject	
3	Test of new 1-turn feedback on 10 MHz test cavity (no beam)	✅
4	Test of new 1-turn feedback on spare cavity C10-11 (with beam)	✅
5	Full validation of 1-turn feedback prototype with beam	✖
6	Test of I/Q modulator/demodulator for 1-turn feedback 20/40/80 MHz	❌

✅ **Completed** ✖ **Ongoing** ❌ **To be done before LS1**

→ **Full validation of 10 MHz 1-turn feedback prototype ongoing**

→ **Validate pre-series version with beam before LS1**

→ **Modulator/demodulator test depends on availability of prototype hardware**

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Alternative schemes from PSB and PS

- **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

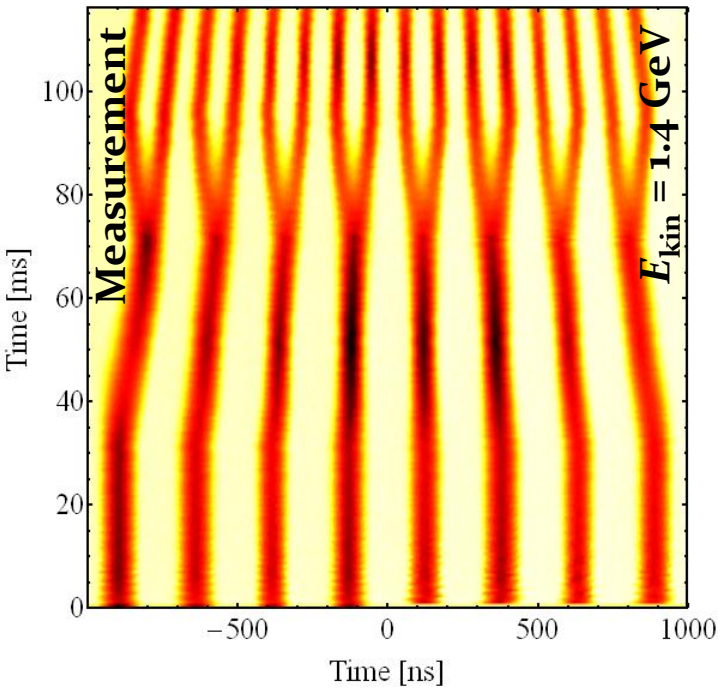
Longer PS batches

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
- ✓ Top energy RF manipulations
- ✓ Delivered to SPS and LHC
- ✓ Positive operational experience from 100 ns CNGS run

→ Fully operational at 1.4 GeV

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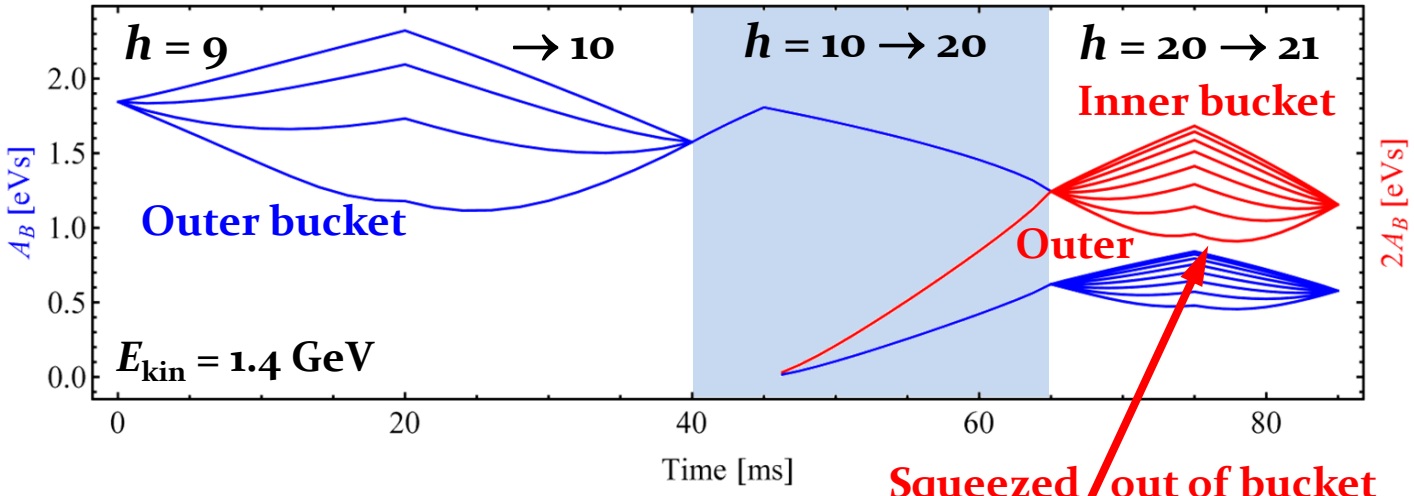
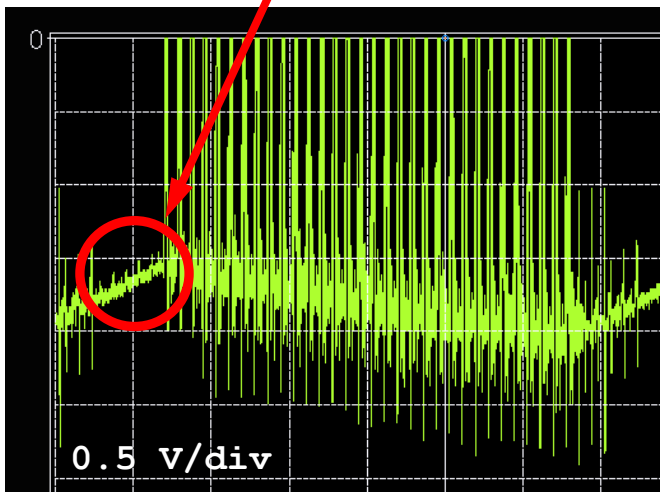
Present limits of $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$

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



- **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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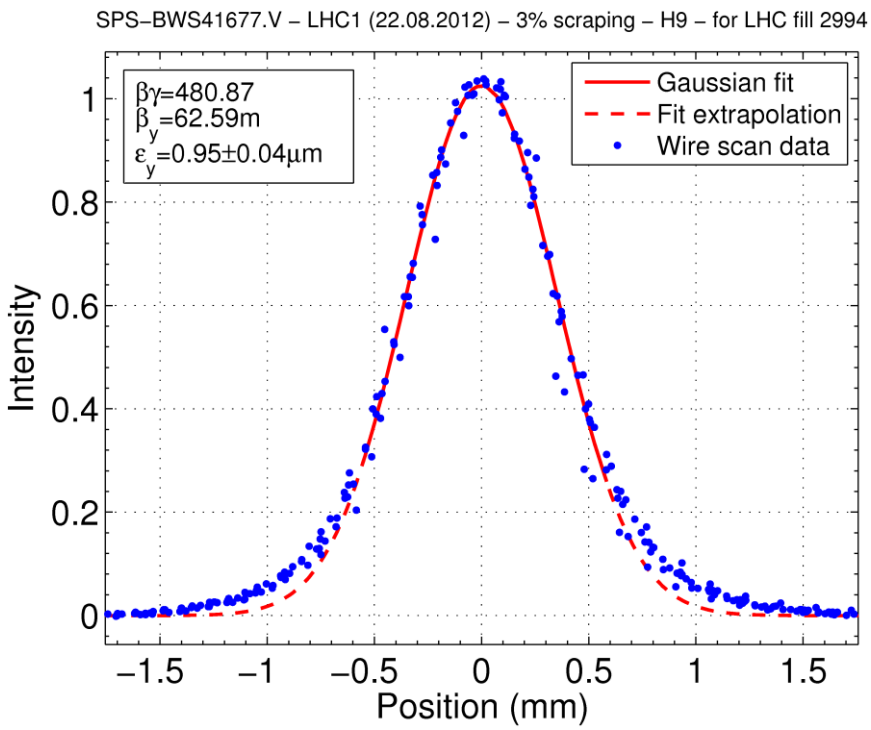
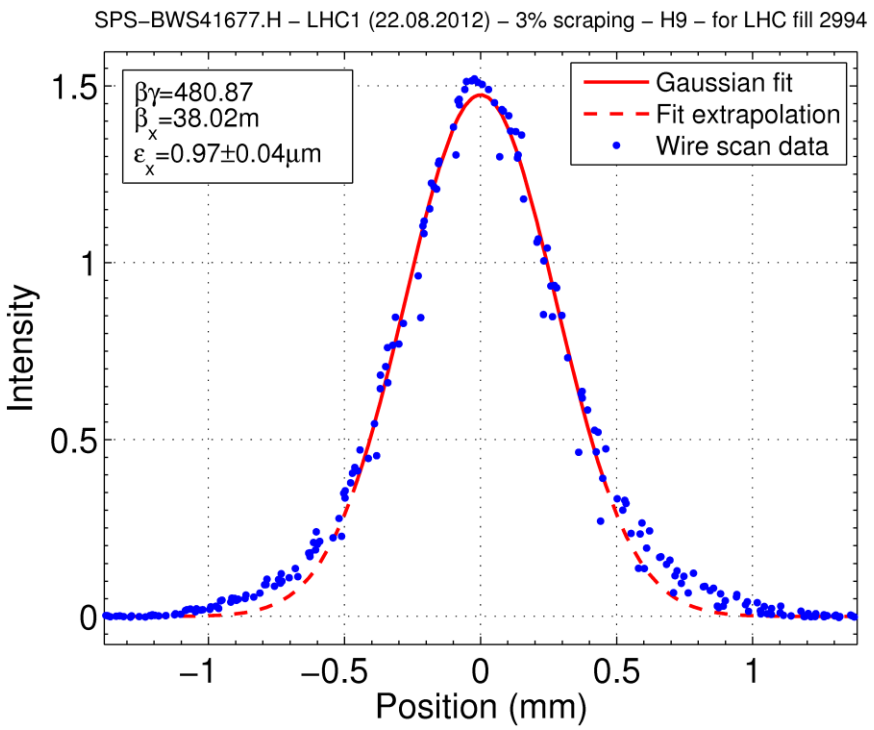
Emittances at SPS flat-top (32 bunches)

Horizontal



Vertical



Hannes Bartosik

→ 32 bunch beam ~ 1.1 · 10^{11} ppb; ε_h, ε_v ~ 1.0 μm at SPS extraction

→ Short fill with 32 bunch beam in LHC on 22/08/2012

→ Results from the LHC → See tomorrow's LMC

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High brightness beam studies

#	Subject	
1	Establish transfer $h_{PSB2+1} \rightarrow h_{PS9}$ + RF manipulation $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$	✓
2	Set-up top energy RF manipulations for 100 ns beam to CNGS	✓
3	Demonstrate double-batch transfer to $h = 9$	✓
4	Establish top energy RF manipulations to produce 50 ns, 32 bunches	✓
5	Validate high brightness 50 ns, 32 bunch beam in SPS and test in LHC	✓
6	Test RF manipulation at $E_{kin} > 1.4$ GeV	✗

✓ **Completed** ✓ **Ongoing** ✗ **To be done before LS1**

- **$h = 9$ injected beams fully operational**

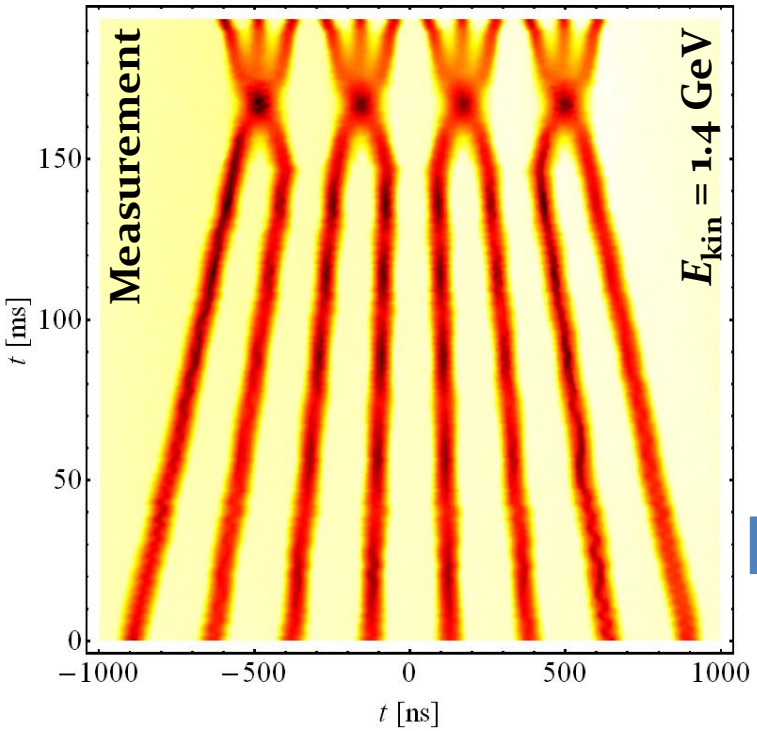
→ **Results from test in LHC will define further strategy**

Batch compression and bunch merging

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

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

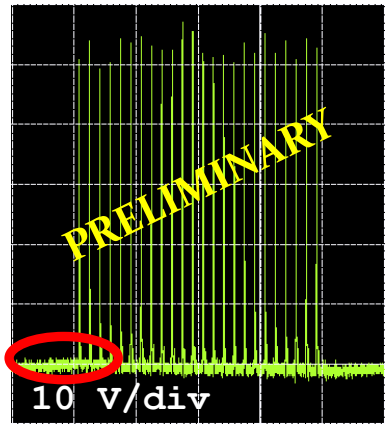
Pure h = 21



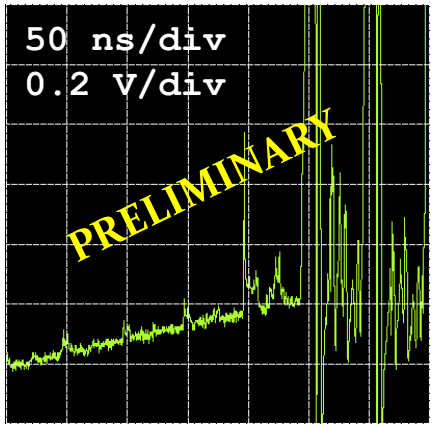
Pure h = 9

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

24 b, 50 ns at PS ej.



Satellites



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High brightness beam studies

#	Subject	
1	Establish RF manipulation $h = 9 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 13 \rightarrow 14 \rightarrow 7 \rightarrow 21$	✓
2	Execute top energy RF manipulations and produce 50 ns, 24 bunches	✓
3	Test high brightness 50 ns, 24 bunch beam with SPS (and LHC?)	✗
4	Test RF manipulation at $E_{kin} > 1.4$ GeV	✗

✓ **Completed** ✗ **Ongoing** ✗ **To be done before LS1**

- **RF hardware ready**
- **Proof-of-principle demonstrated**

→ **Priority now driven by LHC needs**

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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

→Significant commissioning time required after LS1

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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)

→ **Moderate intensity high brightness 25 ns beam after LS1**

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PS-SPS longitudinal transfer studies

#	Subject	
1	Scan rotation times 1 × 40 MHz + 2 × 80 MHz, single injection to SPS	✓
2	Scan rotation times 2 × 40 MHz + 2 × 80 MHz, single injection	✓
3	Scan rotation times 1 × 40 MHz + 3 × 80 MHz , single injection	✓
4	Check dependence on longitudinal emittance and intensity	✓
5	Validate measurements 2 × 40 MHz and 3 × 80 MHz on operational cycle	✓
6	Commission operational implementation of 2 × 40 MHz + 2 × 80 MHz?	✗

✓ **Completed** ✓ **Ongoing** ✗ **To be done before LS1**

Helga Timkó

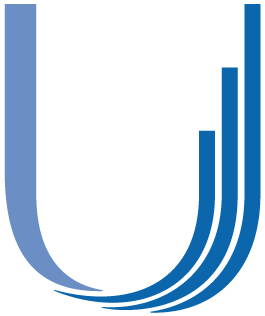
→ **See dedicated presentation**

Summary

1. **Fully completed studies**
   - **Broad-band impedance measurements**

2. **Advanced, but to be completed with high priority to fully specify hardware requirements**
   - **1-turn feedback tests**
   - **Studies of high brightness options**
   - **PS-SPS longitudinal transfer optimization (→ Helga's talk)**

3. **Started, will especially profit from run in Q1/2013**
   - **Stability measurements with coupled-bunch FB**
   - **Repeat extensive studies with C10-11 as feedback kicker**



LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!