Analysis of performance progress in the injectors in 2011

Giovanni Rumolo

in *HL-LHC / LIU Joint Workshop*, 30 March 2012

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LHC Injectors Upgrade

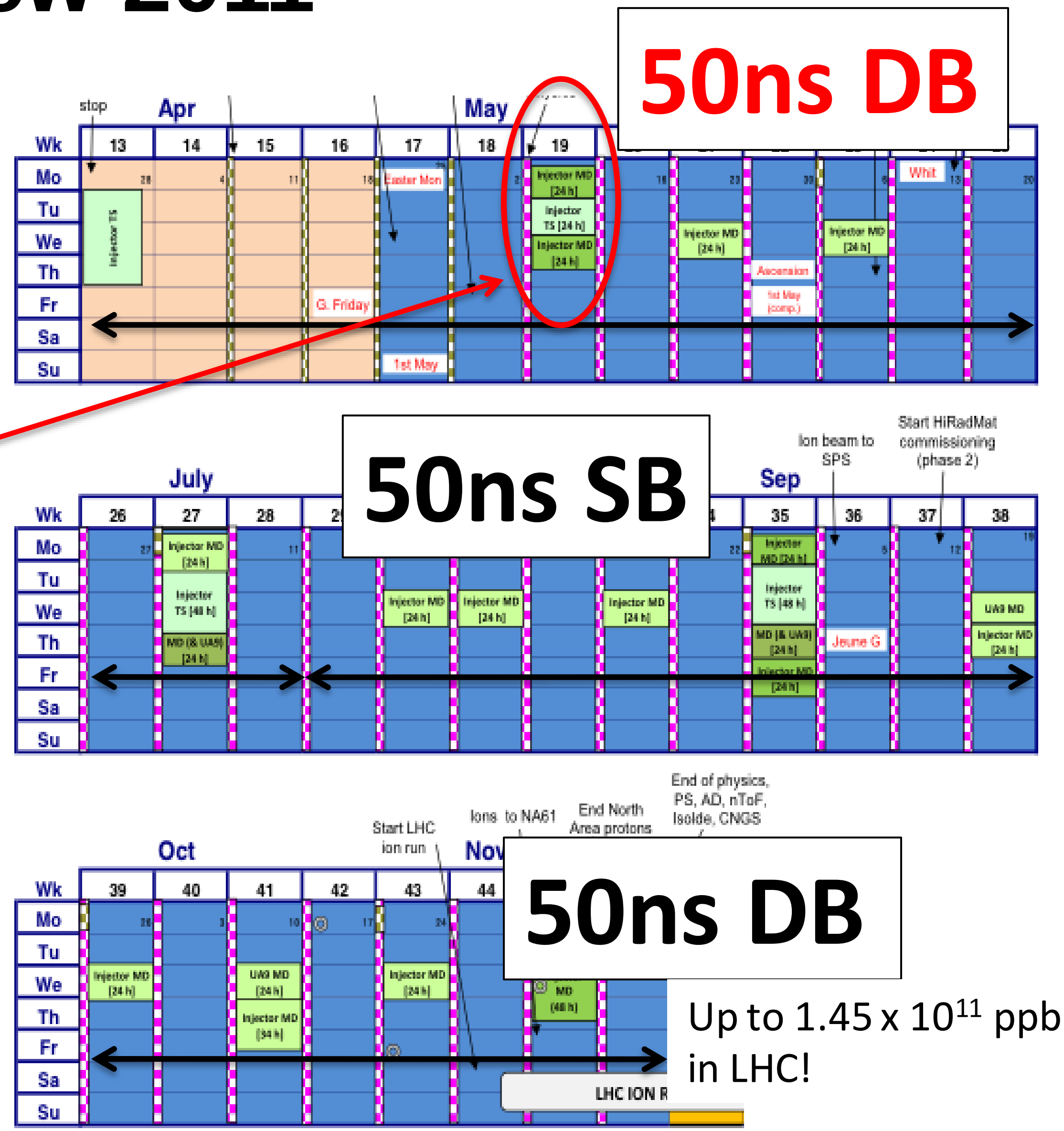
Focus of the talk → Review the progress made in 2011 with both operational and MD LHC-type beams (protons)

- ☑ Double PSB batch in the PS
- ☑ SPS improvement because of scrubbing?
- ☑ Special beams explored in MDs
- ☑ Instrumentation-related issues

Overview 2011

LHC Injectors Upgrade

- First 50ns beams production was with with single batch PSB/PS transfer (operational until mid July 2011)
- Double batch 50ns beams were already set up during the first long MD block
- Double batch 50ns beams became operational after mid July 2011 and the intensity was gradually ramped up
- 25ns beams are only double batch and were used in MDs (PS, SPS, LHC)



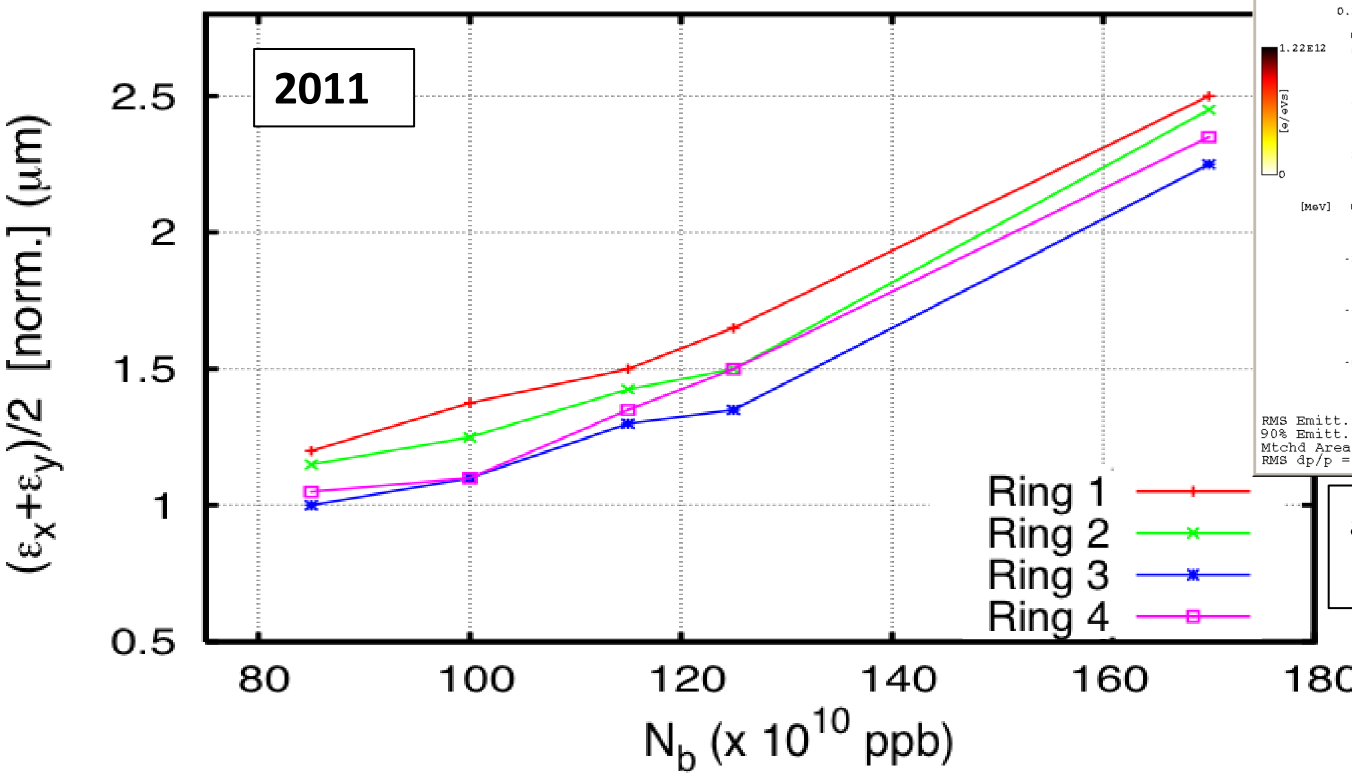
Up to 1.45 x 10^{11} ppb in LHC!

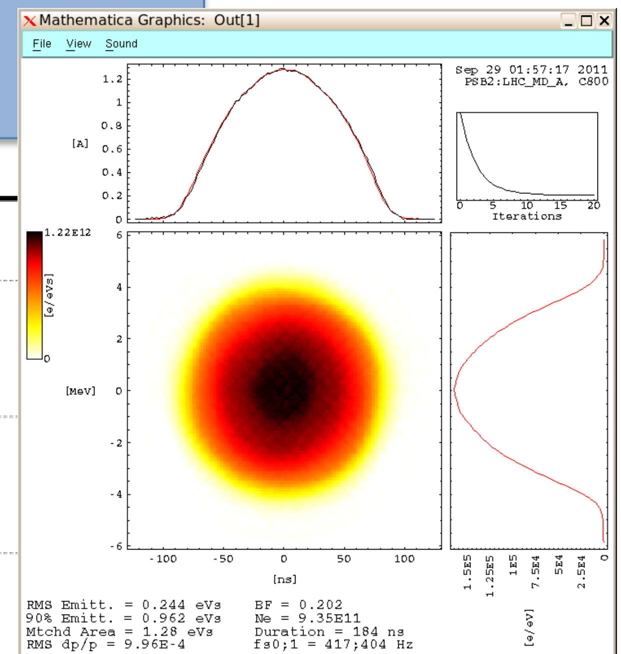
LHC multi-bunch beams in the PSB

LHC Injectors Upgrade

– **Emittance vs. intensity curves**

1. Transverse emittances determined by the multi-turn injection process (number of injected turns), space charge (?)
2. Losses due to injection, capture, space charge, etc.



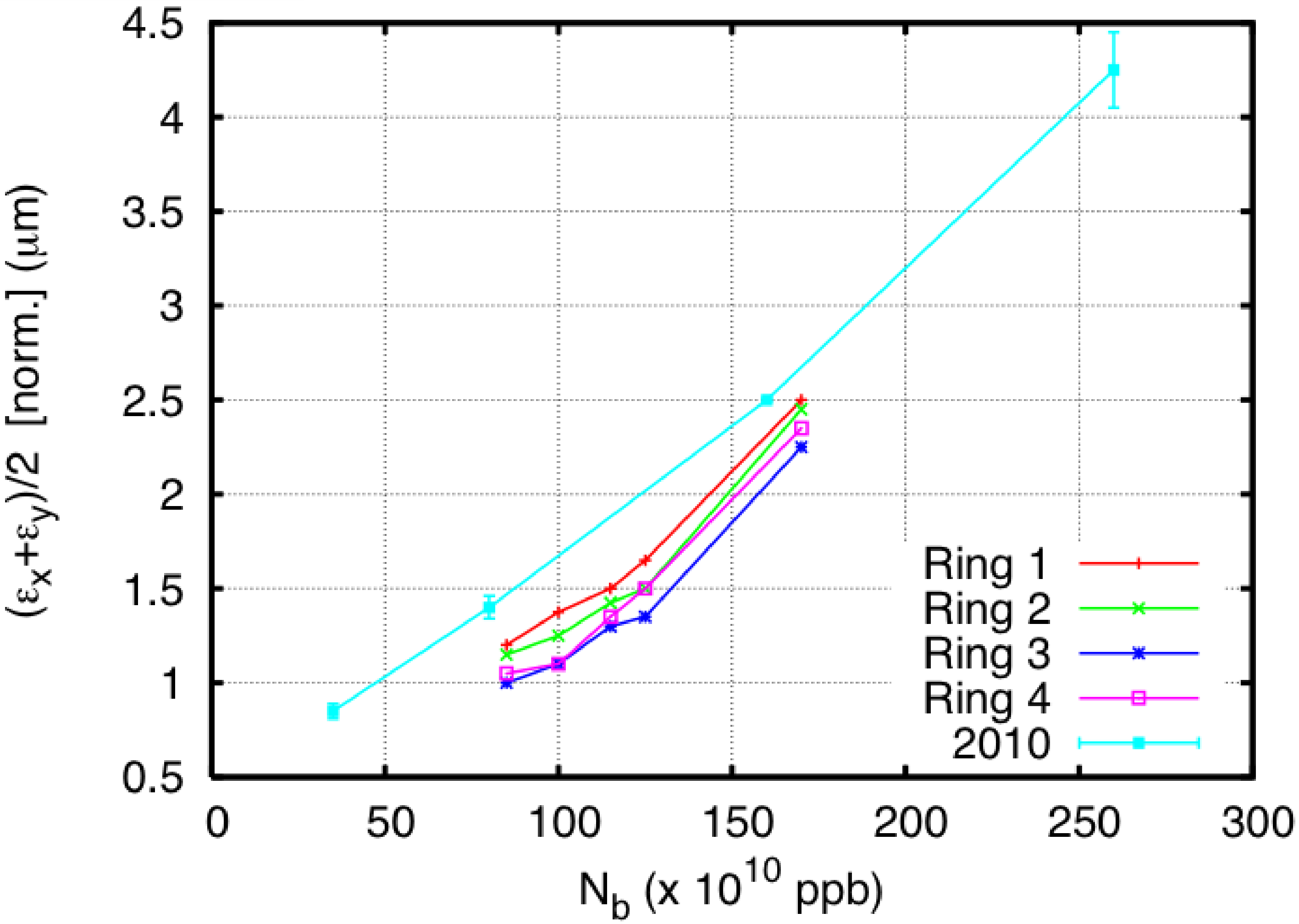


ε_z=1.3 eVs

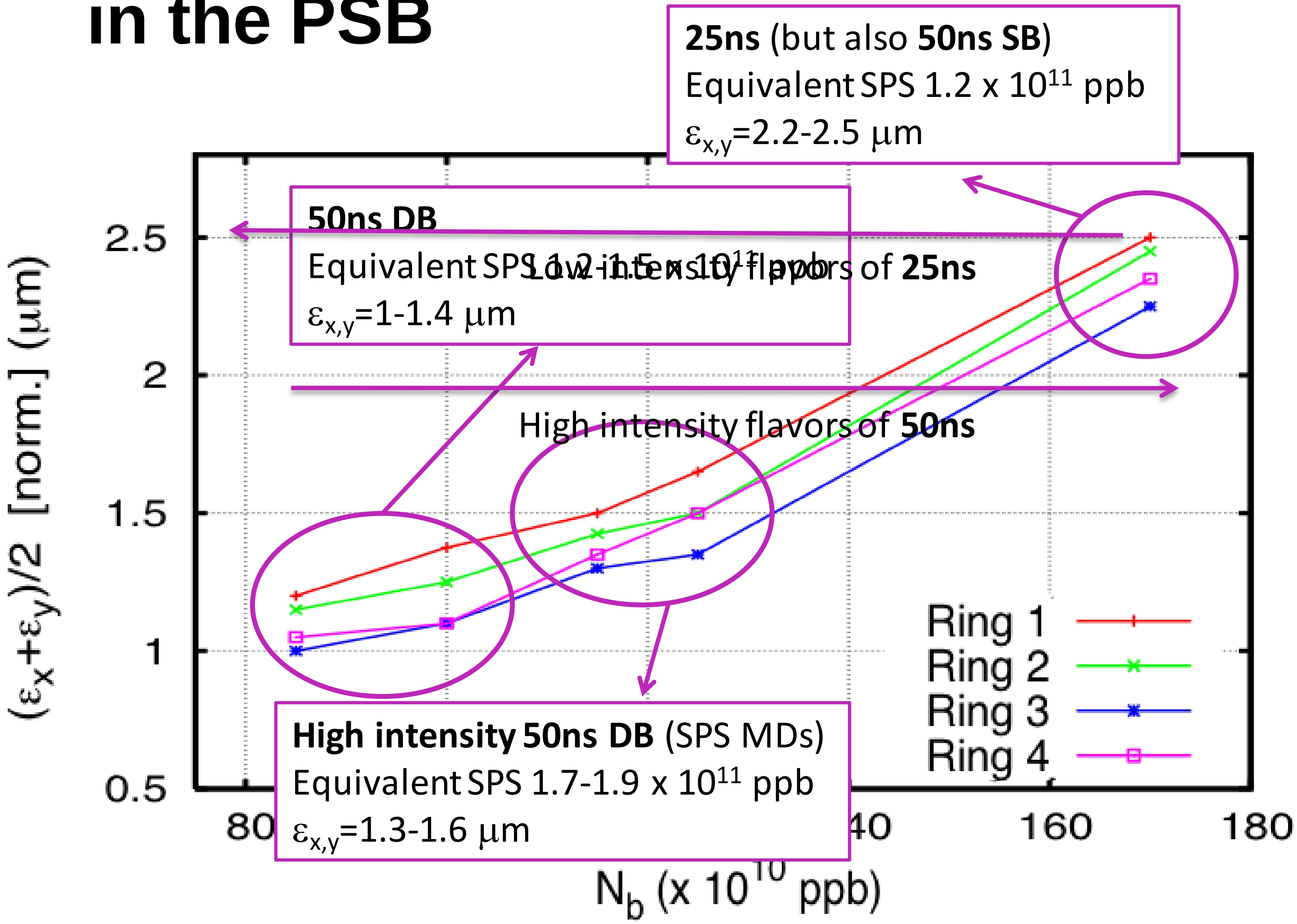
B_l=180 ns

LHC multi-bunch beams in the PSB

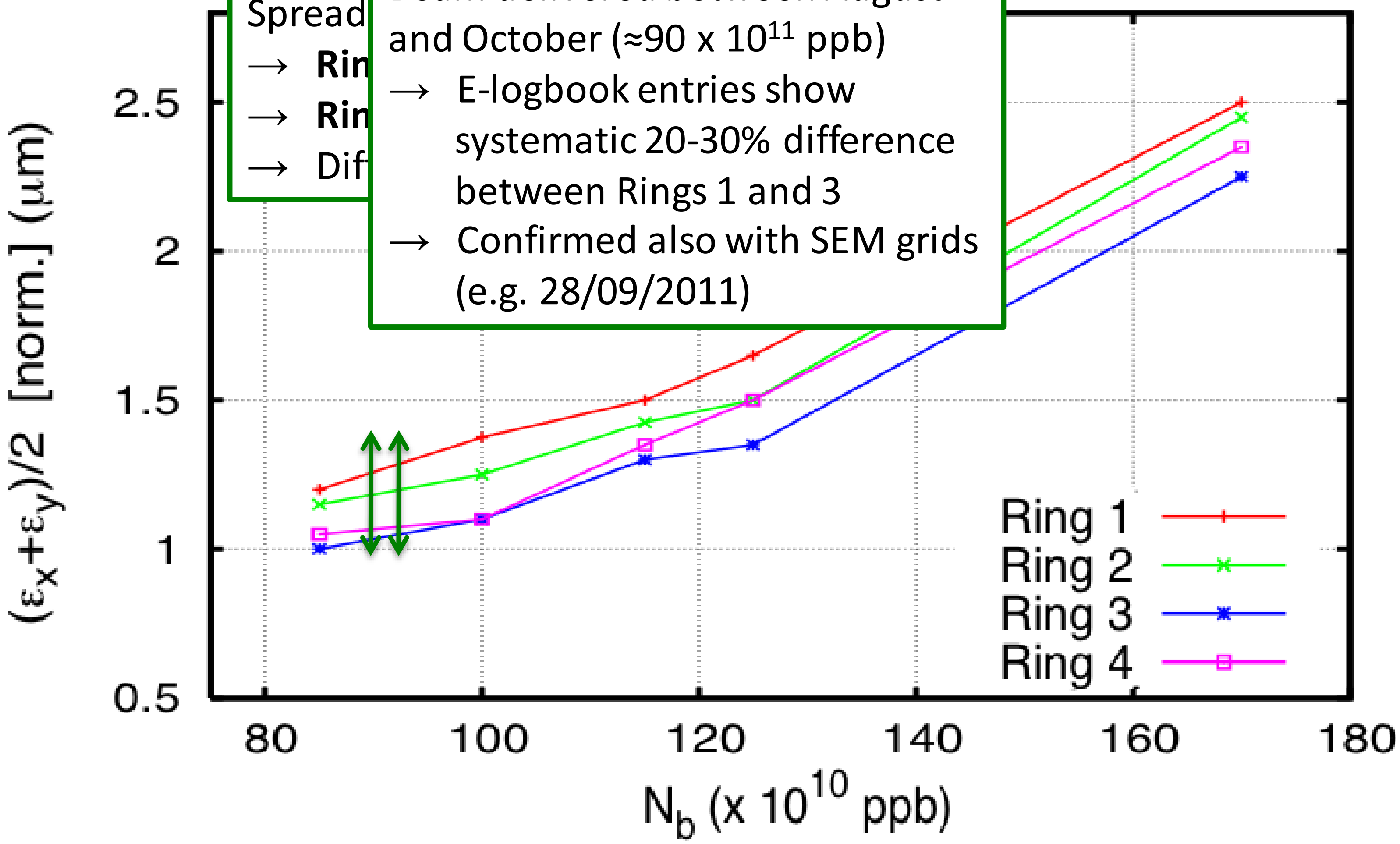
– **2011 vs 2010**



LHC multi-bunch beams in the PSB



LHC multi-bunch beams in the PSB



Spread
→ **Rin**
→ **Rin**
→ Dif

Beam delivered between August and October (≈90 x 10^{11} ppb)

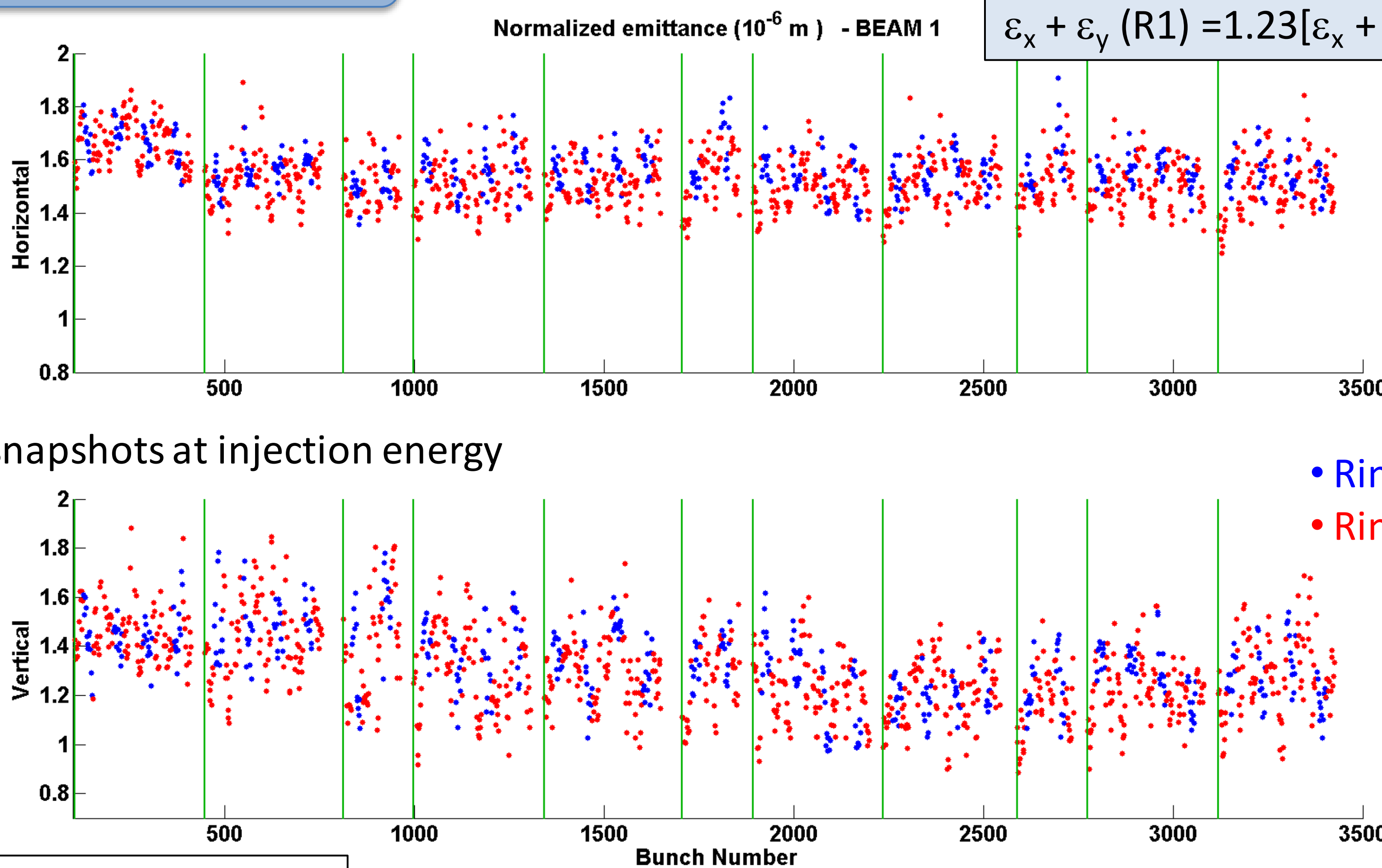
→ E-logbook entries show systematic 20-30% difference between Rings 1 and 3

→ Confirmed also with SEM grids (e.g. 28/09/2011)

LHC multi-bunch beams in the PSB

– In the LHC….

Fill 2040
PSB measurements:
$\varepsilon_x + \varepsilon_y$ (R1) =1.23[$\varepsilon_x + \varepsilon_y$ (R3)]

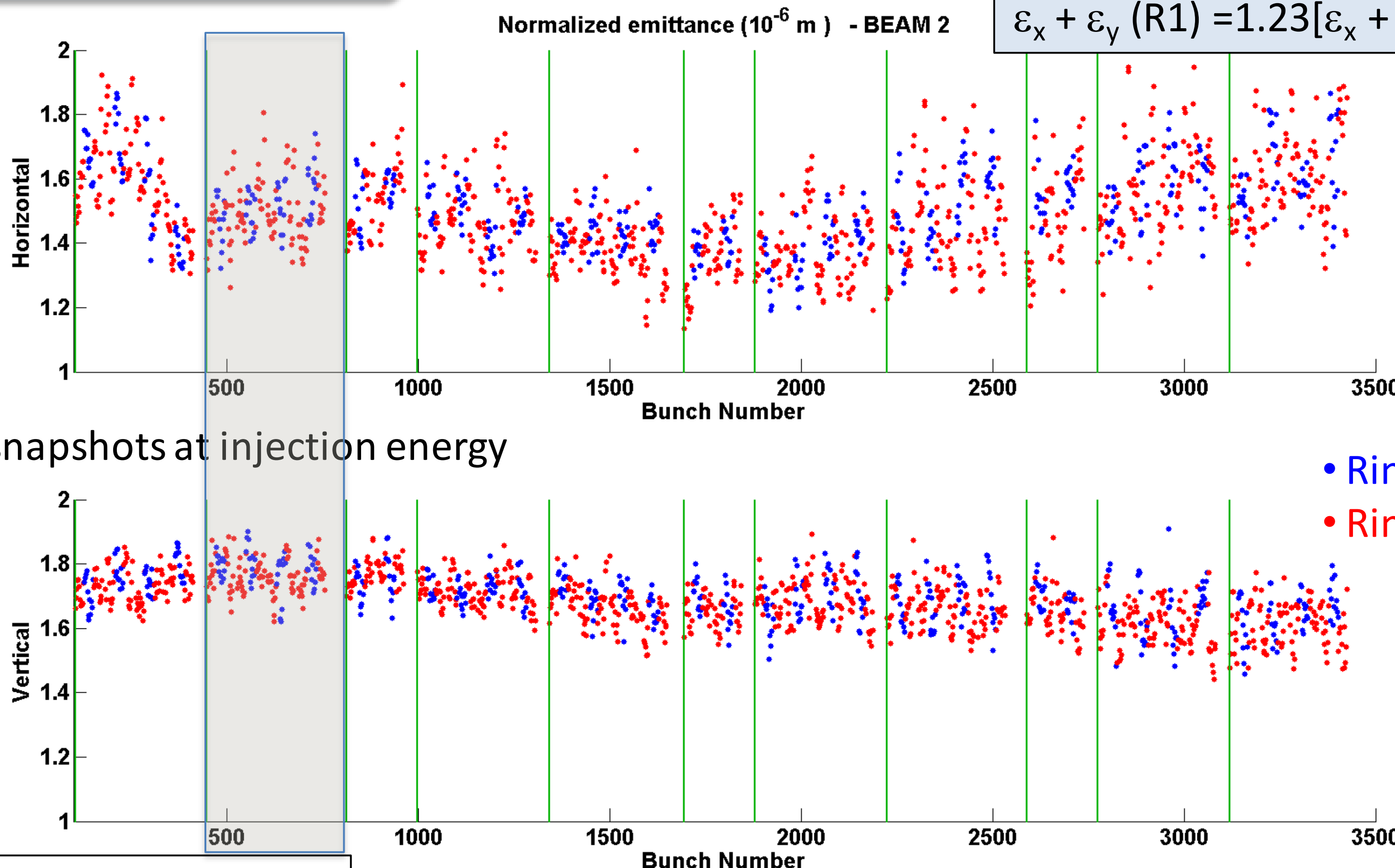


Courtesy G. Trad, F. Roncarolo

LHC multi-bunch beams in the PSB

– **In the LHC….**

Fill 2040
PSB measurements:
$\varepsilon_x + \varepsilon_y$ (R1) $=1.23[\varepsilon_x + \varepsilon_y$ (R3)$]$

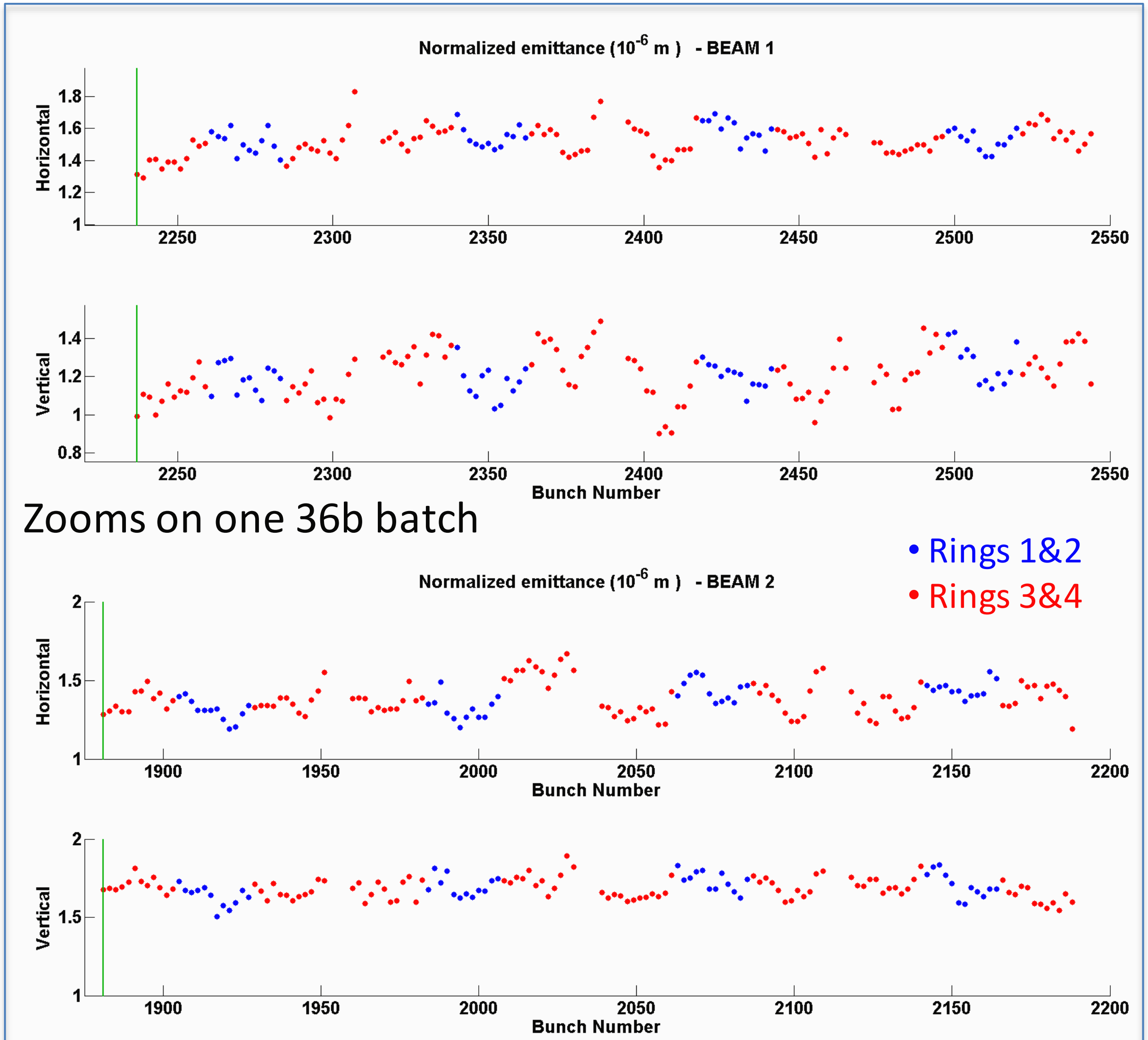


BSRT snapshots at injection energy

• Rings 1&2
• Rings 3&4

Courtesy G. Trad, F. Roncarolo

LHC multi-bunch beams in the PSB



Courtesy G. Trad, F. Roncarolo

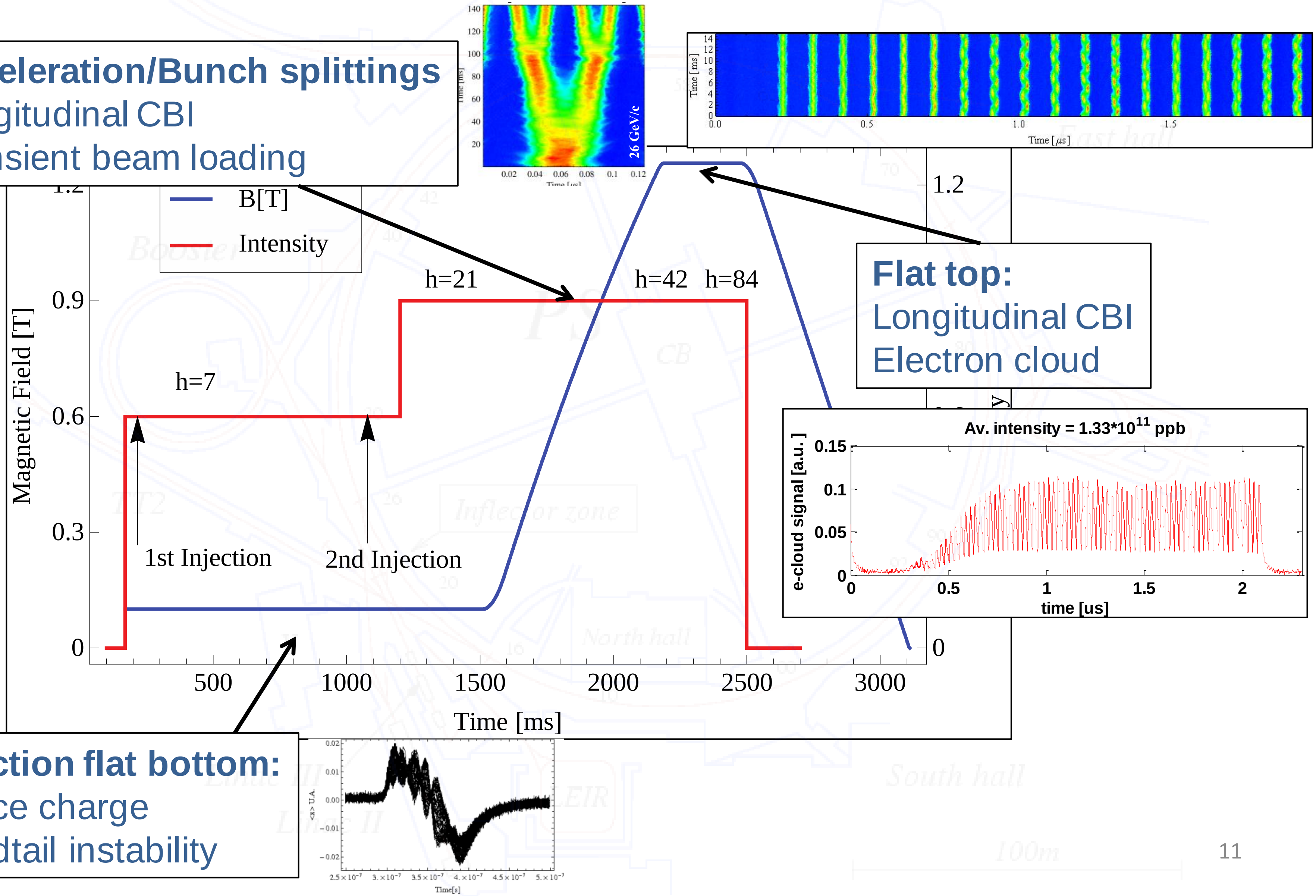
- No obvious pattern from the the PSB
- Maybe the transverse emittances are blown up further down the chain and, as a result, the differences between bunches are equalized?
- Poorer performance of Ring 1 disappeared in 2012

PS intensity limitations

Acceleration/Bunch splittings
Longitudinal CBI
Transient beam loading

Flat top:
Longitudinal CBI
Electron cloud

Injection flat bottom:
Space charge
Headtail instability



CERN

PS: space charge@injection

LHC Injectors Upgrade

$$\Delta Q_y = \frac{r_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z}\frac{1}{\sqrt{\epsilon_y}}\oint \frac{\sqrt{\beta_y(s)}}{\sqrt{\beta_y(s)\epsilon_y}+\sqrt{\beta_x(s)\epsilon_x+\sigma_\delta^2 D_x^2(s)}}ds$$

	N_b (x 10^{10} p)	$\varepsilon_{x,y}$ (μm)	$4\sigma_t$ (ns)	ΔQ_y
LHC50nom (DB)	80	1.1	180	**-0.26**
LHC50ult (DB)	120	1.5	180	**-0.28**
LHC25 (DB)	160	2.5	180	**-0.26**
LHC25ult (DB)	210	3.5	180	**-0.24**
LHC50nom (SB)	160	2.5	130	**-0.18**

Double batch LHC beams, 1.2sec @FB (applies to the four DB rows)

⇒ With a good working point, tune spreads in the **0.25-0.3 range** are found not to produce significant beam quality degradation on the 1.2 sec flat bottom

PS: space charge@injection

LHC Injectors Upgrade

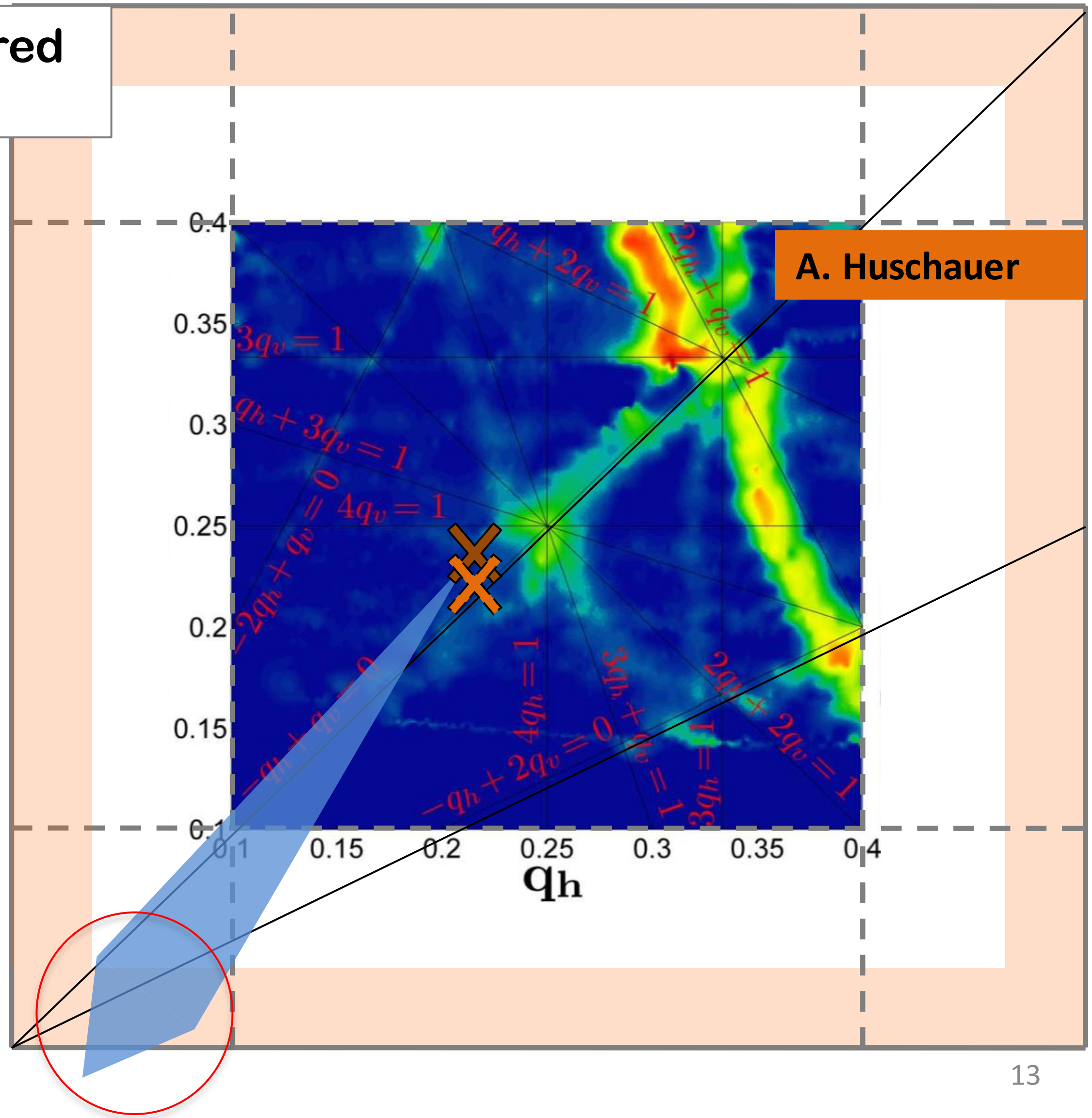
LHC beams in the measured tune diagram @ 1.4 GeV

Working point

⇒ Nominal (0.21,0.24)

⇒ Coherent tune shift about (-0.003,-0.01), as measured by S. Aumon

⇒ Incoherent tune spread (-0.2,-0.26)



Into integer stop-bands, maybe

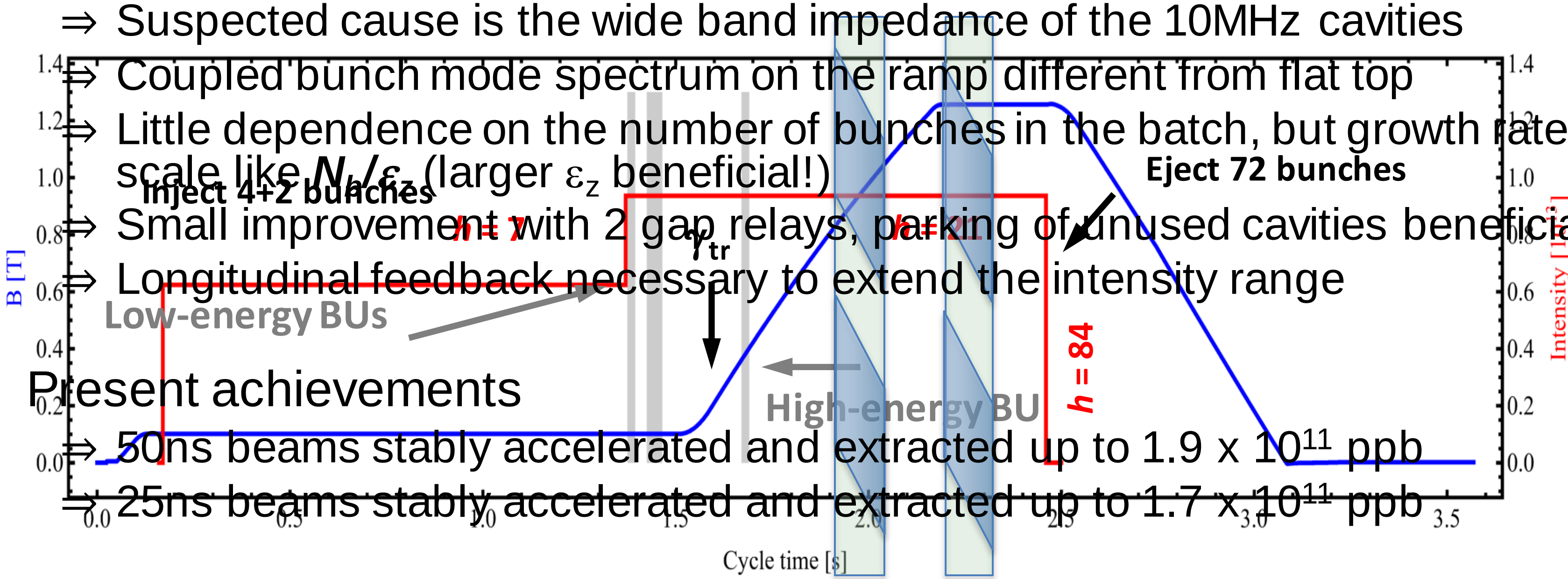
1) Formula overestimates tune spread?

2) Effect of hitting stop-band is overestimated?

PS: Coupled Bunch Instability

- **Longitudinal coupled bunch instabilities** with both 25ns and 50ns beams observed (previously also with 75ns and 150ns beams)
  - ✓ During the ramp
  - ✓ At flat top when ramping down h=21 during bunch splitting

- What we know about it
  - ⇒ Suspected cause is the wide band impedance of the 10MHz cavities
  - ⇒ Coupled bunch mode spectrum on the ramp different from flat top
  - ⇒ Little dependence on the number of bunches in the batch, but growth rates scale like N_b/ε_z (larger ε_z beneficial!)
  - ⇒ Small improvement with 2 gap relays, parking of unused cavities beneficial
  - ⇒ Longitudinal feedback necessary to extend the intensity range



- Present achievements
  - ⇒ 50ns beams stably accelerated and extracted up to 1.9 x 10^{11} ppb
  - ⇒ 25ns beams stably accelerated and extracted up to 1.7 x 10^{11} ppb

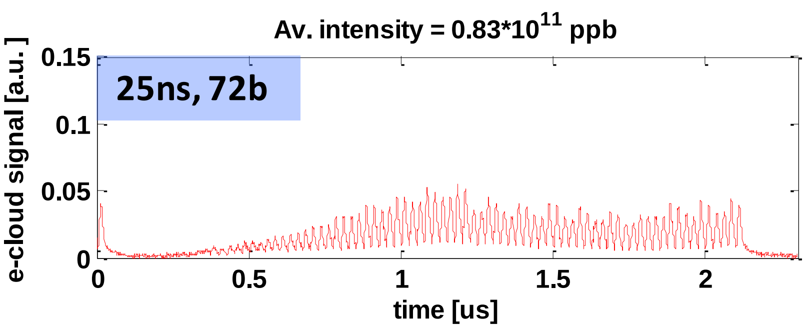
PS: Electron Cloud

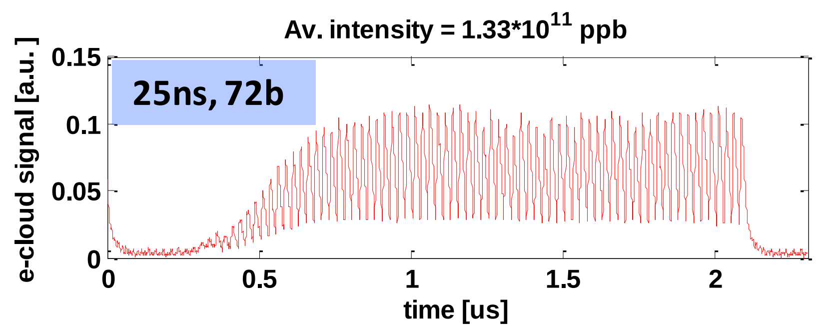
LHC Injectors Upgrade

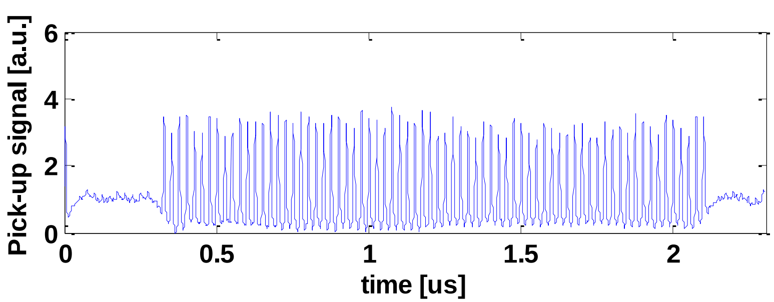
Electron cloud builds up at flat top for intensities

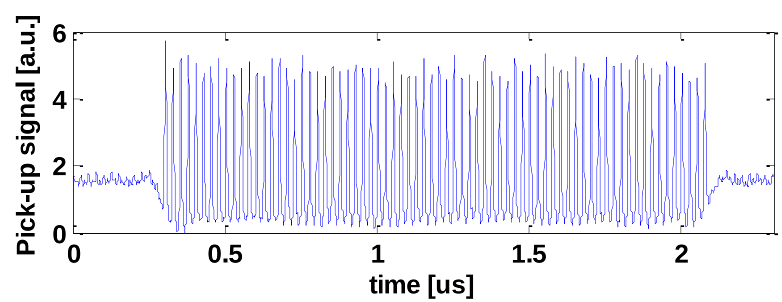
⇒ above 0.8 x 10^{11} for 25ns beams

G. Iadarola, C. Yin-Vallgren









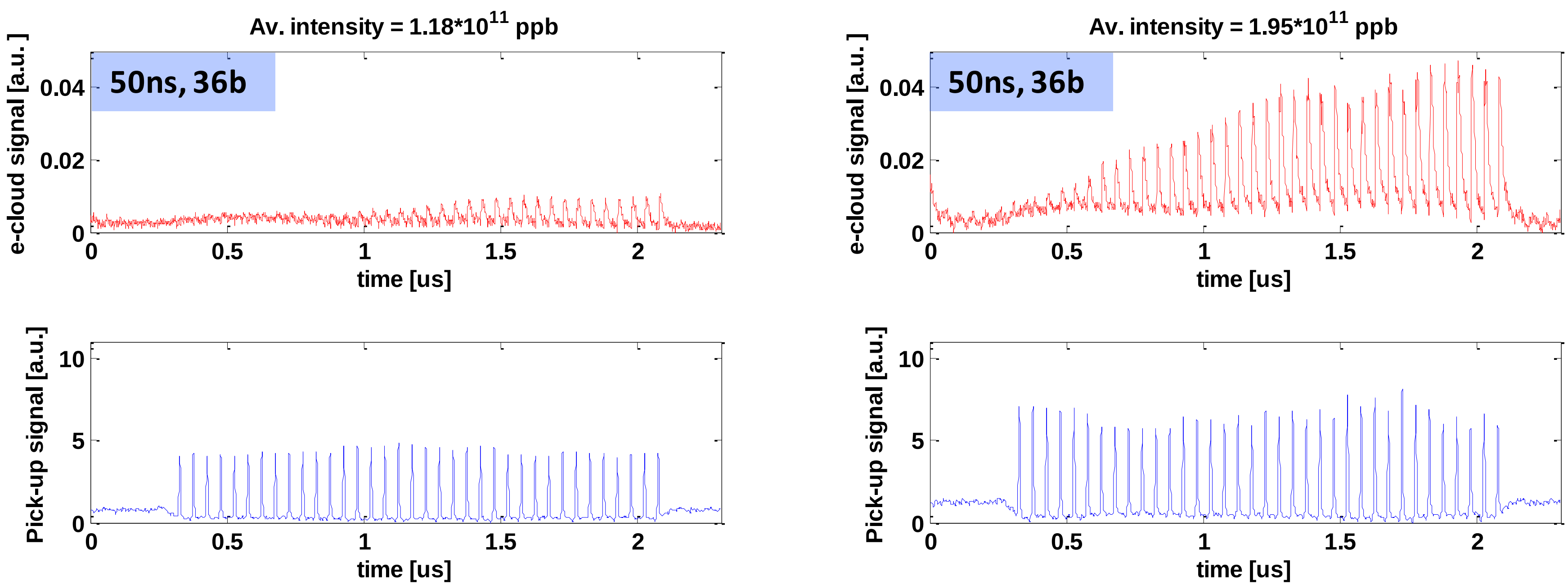
PS: Electron Cloud

Electron cloud builds up at flat top for intensities

⇒ above 0.8 x 10^{11} for 25ns beams

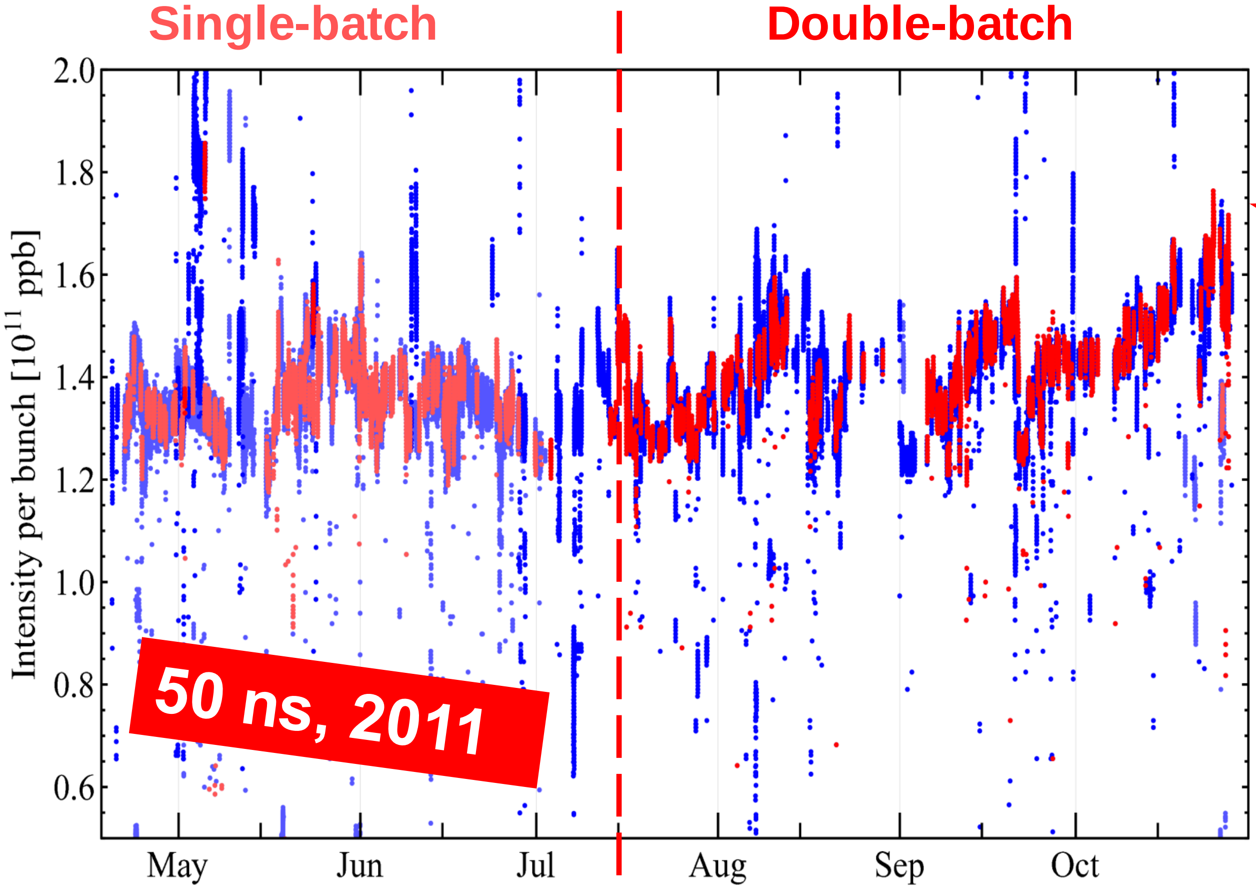
⇒ above 1.1 x 10^{11} ppb for 50ns beams

G. Iadarola, C. Yin-Vallgren



⇒ <u>No evident sign of deterioration due to electron cloud (i.e. beam transversely stable within the explored parameters)</u>

PS performance in 2011



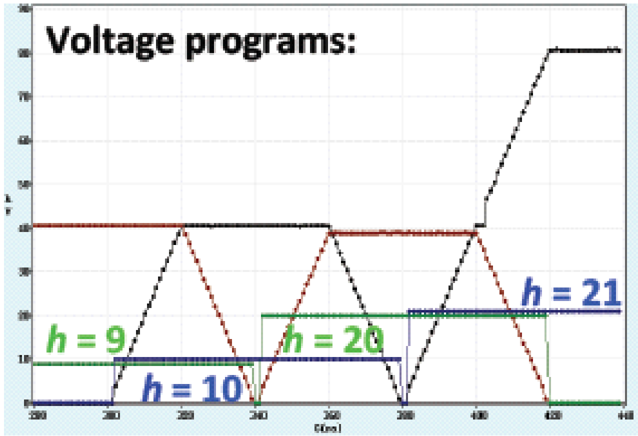
Last LHC fills took ~ 1.7 · 10^{11} ppb

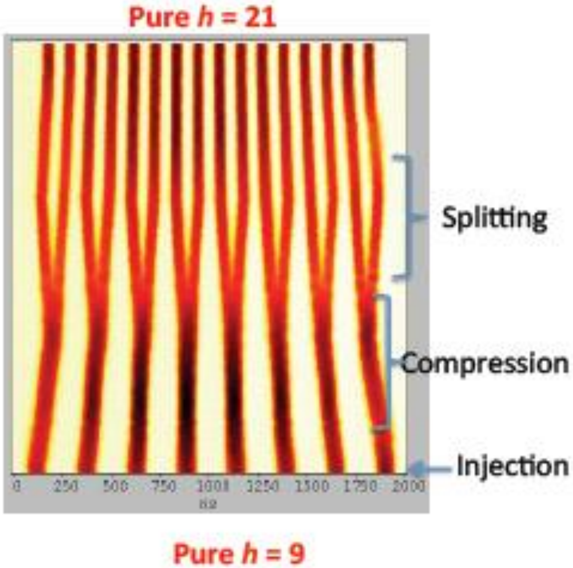
(R. Steerenberg's talk)

- → 50ns: up to 1.7 · 10^{11} ppb delivered for collisions in LHC
- → 50ns: up to 1.9 · 10^{11} ppb delivered to SPS for MDs
- → Nominal 25ns beam (up to 1.3 · 10^{11} ppb)

Exotic beams in the PSB/PS MDs

- Very bright beams for **space charge** studies
  - ✓ Obtained by re-bucketing SB-type beams in the PSB
  - ✓ Improved by using bunch shortening at the PS flat bottom
  - ✓ Used for scans of working point
- Intense LHC-type single bunches with high brightness (4 x 10^{11} ppb, ez=0.3eVs)
- Trains from batch compression schemes
  - ⇒ Scheme h=9 → 10 → 20 → 21 (based on single batch injection 4 x 2 bunches from PSB) successfully tested
  - ⇒ No acceleration + splitting (therefore no transfer to SPS)
  - ⇒ Can produce shorter 25ns trains of brighter bunches





SPS in 2011

LHC Injectors Upgrade

- **MD block 9-11 May 2011 (e-cloud, high intensity)**
  - → Nominal 25ns (four batches, about 1.15 x 10^{11} ppb)
  - → 50ns DB (four batches, 1.4 – 1.6 x 10^{11} ppb)
  - → 50ns SB (four batches, 1.2 – 1.45 x 10^{11} ppb)

- **Beams for LHC**
  - → Operational (April – mid July): 50ns SB (four batches, about 1.2 x 10^{11} ppb)
  - → Operational (mid July – November): 50ns DB (four batches, 1.2 – 1.45 x 10^{11} ppb)
  - → LHC MDs: Nominal 25ns (four batches, about 1.15 x 10^{11} ppb)

- **MD block 9-10 November 2011 (Q20, high intensity)**
  - → Nominal 25ns on Q20 (four batches, about 1.15 x 10^{11} ppb)
  - → 50ns DB on Q20/Q26 (four batches, up to 1.7 x 10^{11} ppb)

* Quoted intensities are at flat top

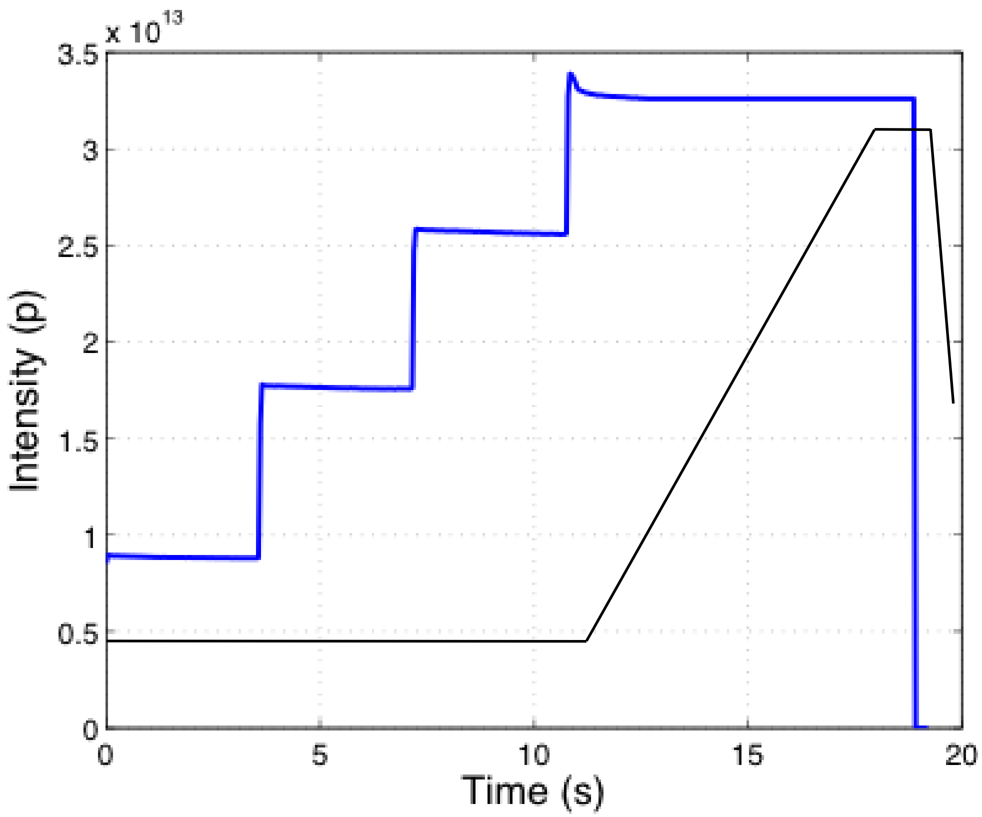
SPS in 2011

– **MD block 9-11 May 2011**

→ **Nominal 25ns (four batches, about 1.15 x 10^{11} ppb)**

→ 50ns DB (four batches, 1.4 – 1.6 x 10^{11} ppb)

→ 50ns SB (four batches, 1.2 – 1.45 x 10^{11} ppb)



	Measurements
Max int @ flat top	1.1 x 10^{11} ppb
$\varepsilon_{x,y}$ @ flat top	2.4/2.7 μm

Losses hard to quantify for lack of data from the PS

☑ 25ns beams seem to be in better shape

- SPS benefits from scrubbing over previous years?
- Any improvement in emittance diagnostics? (consistent cross-checks between machines)

SPS in 2011

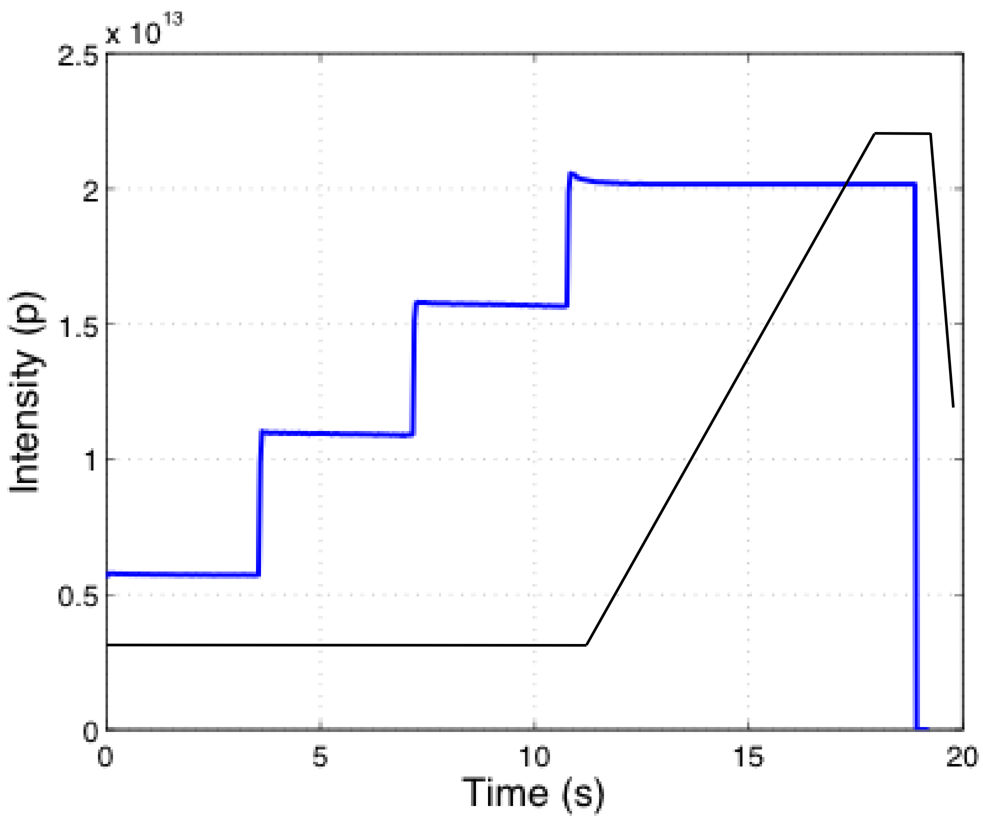
LHC Injectors Upgrade

– **MD block 9-11 May 2011**

→ Nominal 25ns (four batches, about 1.15 x 10^{11} ppb)

→ **50ns DB (four batches, 1.4 – 1.6 x 10^{11} ppb)**

→ 50ns SB (four batches, 1.2 – 1.45 x 10^{11} ppb)



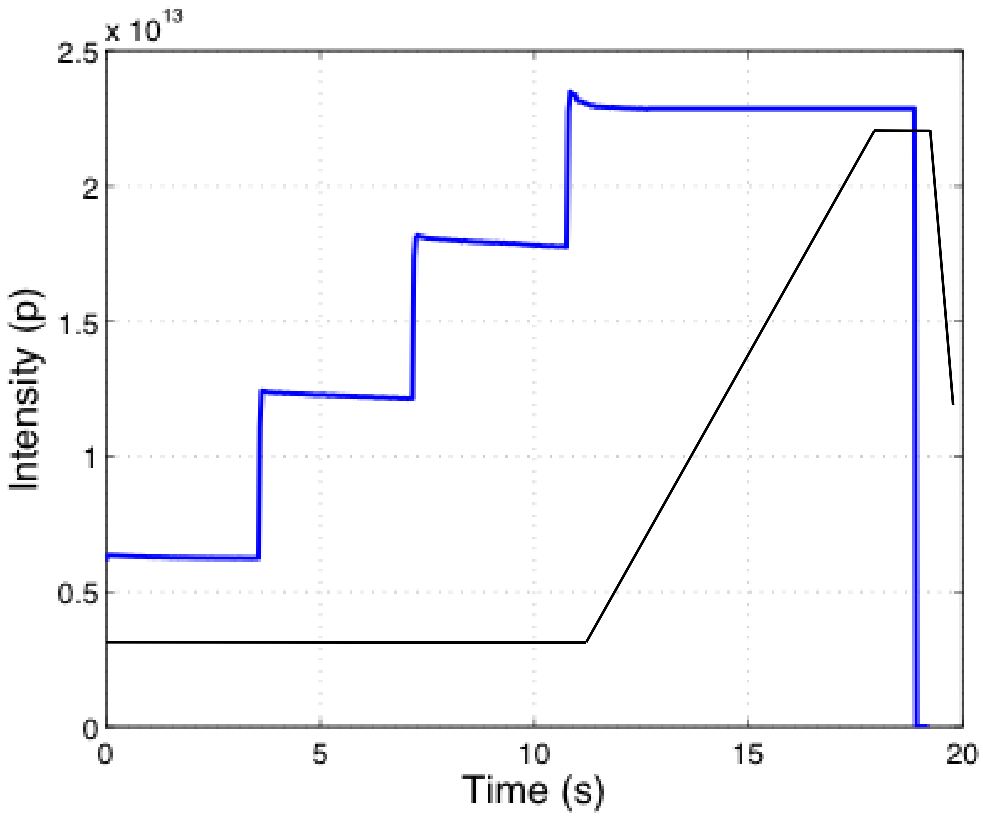
	Measurements
Max int @ flat top	1.4 x 10^{11} ppb
$\varepsilon_{x,y}$ @ flat top	1.7/1.7 μm

SPS in 2011

LHC Injectors Upgrade

– **MD block 9-11 May 2011**

→ Nominal 25ns (four batches, about 1.15 x 10^{11} ppb)
→ **50ns DB (four batches,** 1.4 – **1.6 x 10^{11} ppb)**
→ 50ns SB (four batches, 1.2 – 1.45 x 10^{11} ppb)



	Measurements
Max int @ flat top	1.6 x 10^{11} ppb
$\varepsilon_{x,y}$ @ flat top	2.0/1.9 μm

☑ Intensity limited by longitudinal instabilities along the ramp and flat top

☑ Longitudinal blow up with band-limited noise needs to be optimized for these intensities

SPS in 2011

LHC Injectors Upgrade

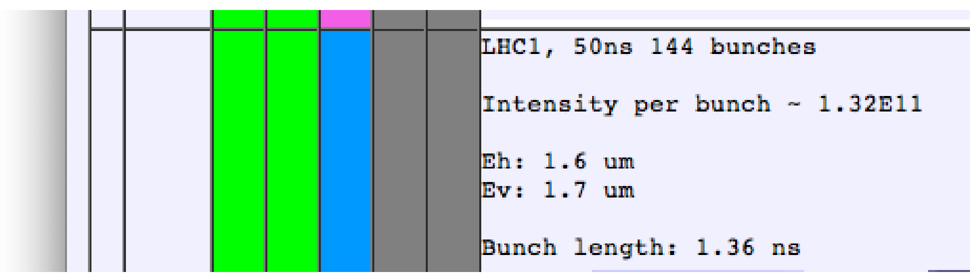
– **Beams for LHC**

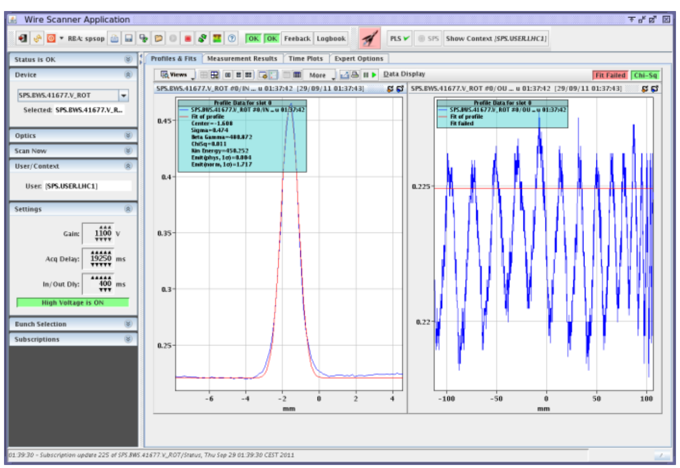
→ Operational (April – mid July): 50ns SB (four batches, about 1.2 x 10^{11} ppb)

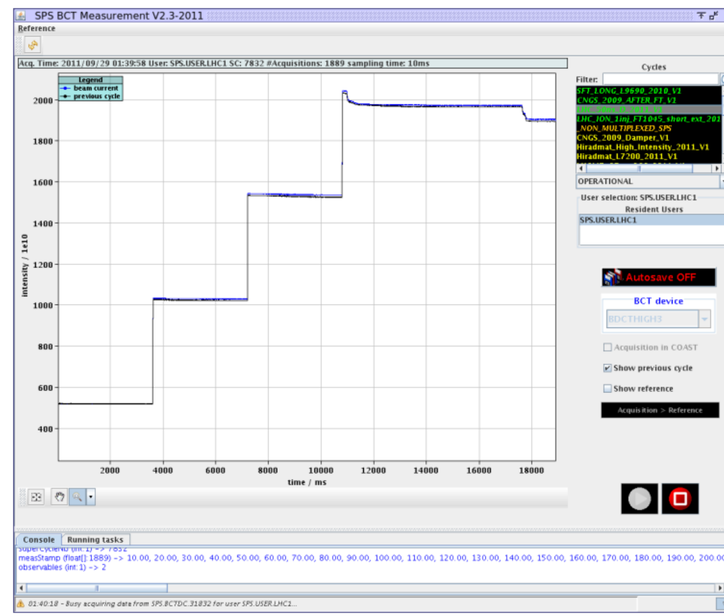
→ **Operational (mid July – November): 50ns DB (four batches, 1.2 – 1.45 x 10^{11} ppb)**

→ LHC MDs: Nominal 25ns (four batches, about 1.15 x 10^{11} ppb)

Typical logbook entry







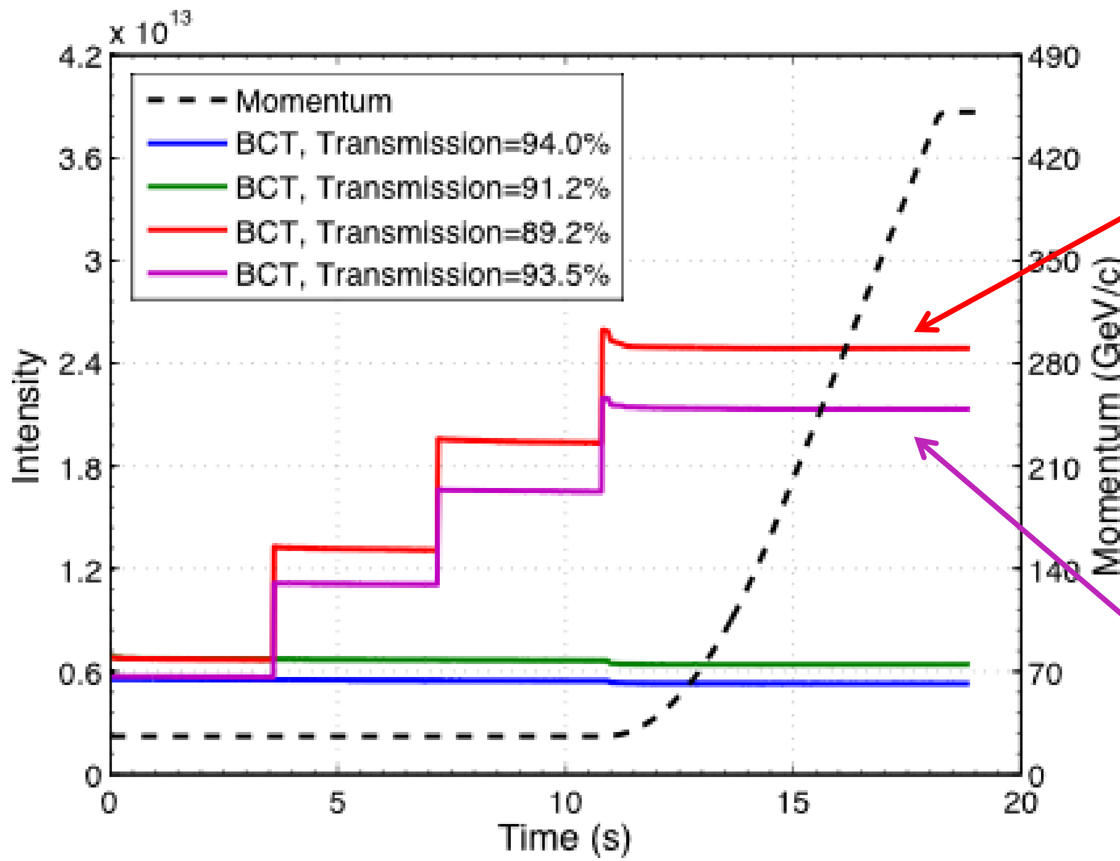
SPS in 2011

LHC Injectors Upgrade

– **MD block 9-10 November 2011 (Q20, high intensity)**

→ Nominal 25ns on Q20 (four batches, about 1.15 x 10^{11} ppb)

→ **50ns DB on Q20**/Q26 **(four batches, up to 1.7 x 10^{11} ppb)**



1.9 x 10^{11} ppb injected
1.7 x 10^{11} ppb at flat top

Q20 – low γ_t optics

1.6 x 10^{11} ppb injected
1.5 x 10^{11} ppb at flat top

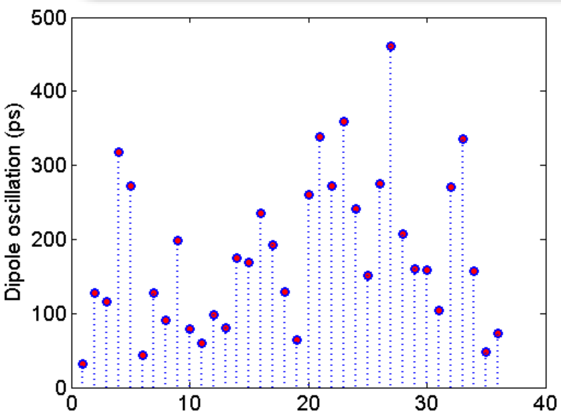
SPS in 2011

LHC Injectors Upgrade

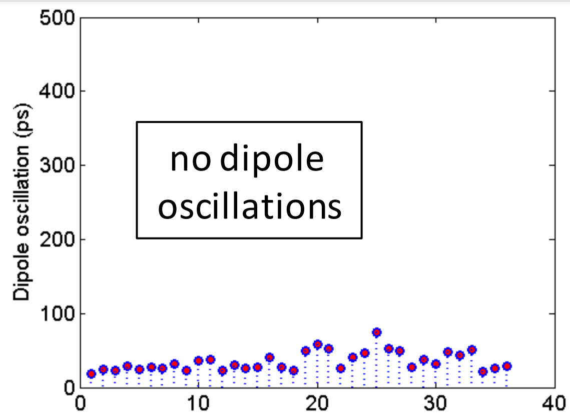
– **MD block 9-10 November 2011 (Q20, high intensity)**

→ Nominal 25ns on Q20 (four batches, about 1.15 x 10^{11} ppb)

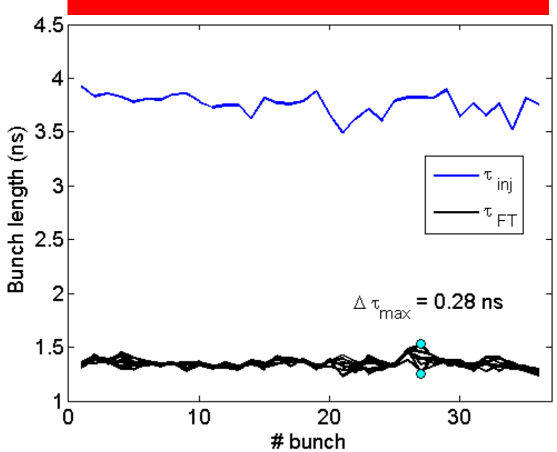
→ **50ns DB on Q20/Q26 (four batches, up to 1.7 x 10^{11} ppb)**

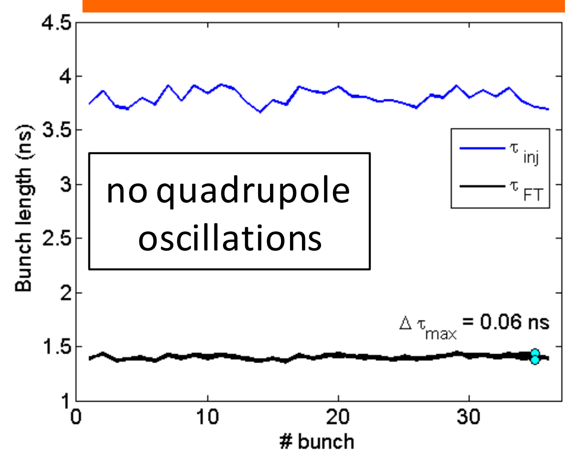


Q26



Q20





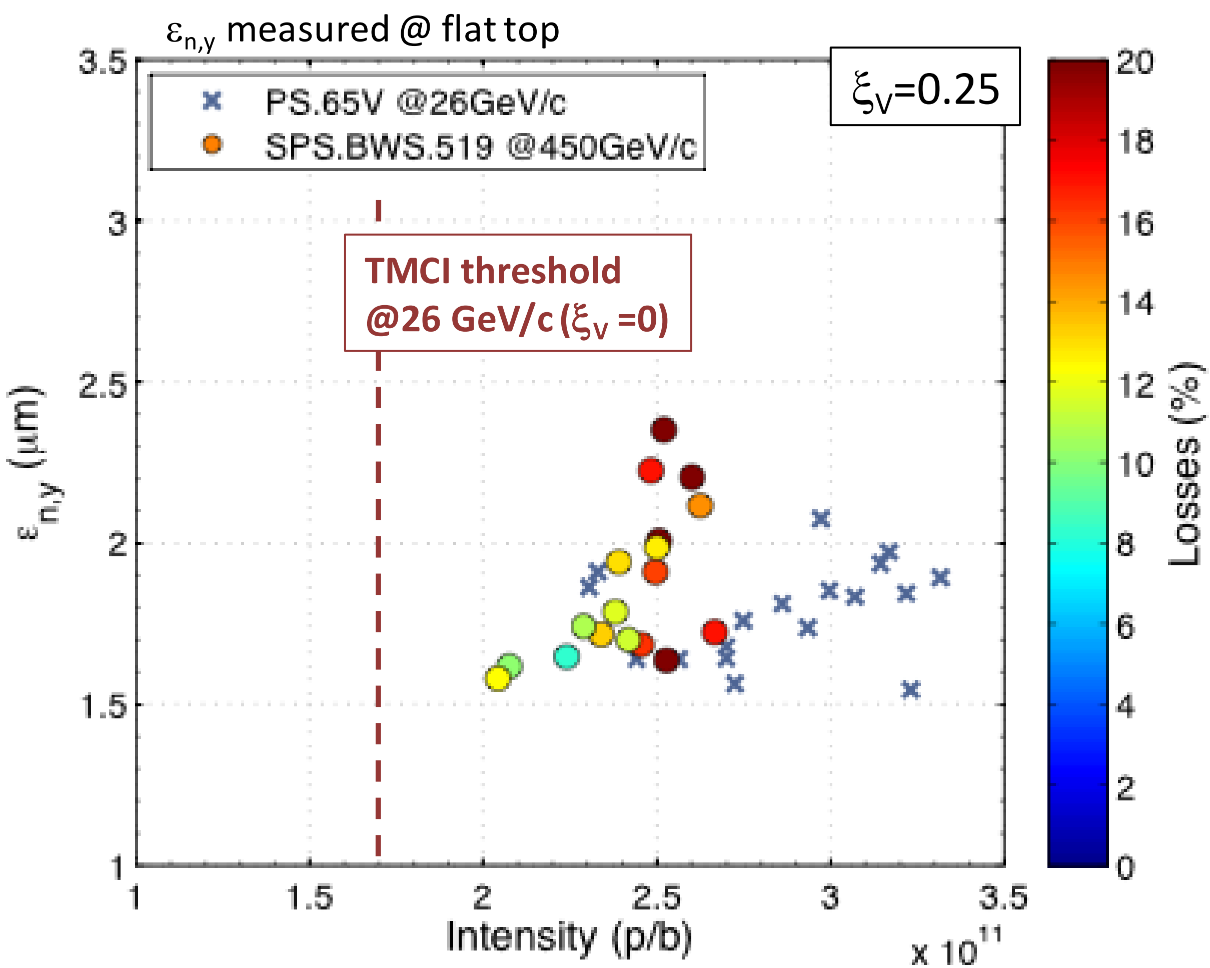
50ns beam at flat top with Q20 (1 batch, 1.5x10^{11}ppb)

- Longitudinally more stable, even without controlled emittance blow-up
- 800MHz cavity (V_{800}=0.15V_{200})

Courtesy T. Argyropoulos

SPS in 2011

– **Single bunch limits (TMCI, space charge, emittance blow up)**



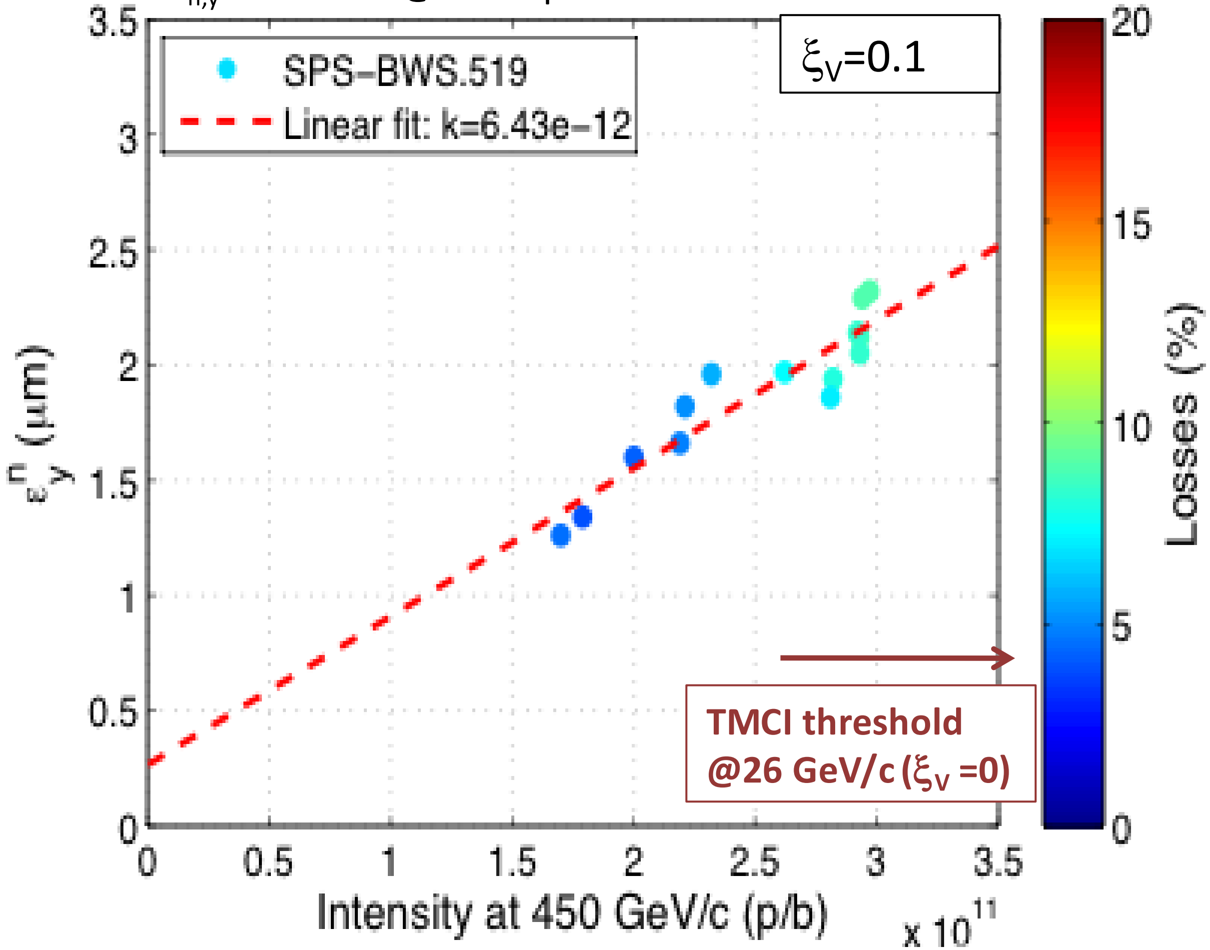
Q26 – nominal optics

- 2–2.5 x 10^{11} ppb injected
  - → Losses around 10%
  - → No emittance growth wrt PS extraction
- Above 2.5 x 10^{11} ppb injected, large losses (20%) and emittance blow up

SPS in 2011

– **Single bunch limits (TMCI, space charge, emittance blow up)**

$\varepsilon_{n,y}$ measured @ flat top



Q20 – low γ_t optics

- Q20 allows for injection of higher intensity bunches (up to 3 x 10^{11} ppb)
  - → Low chroma
  - → Losses below 10% even above 2.5 x 10^{11} ppb
- Trend from injectors or blow up in the SPS (flat bottom + ramp)?

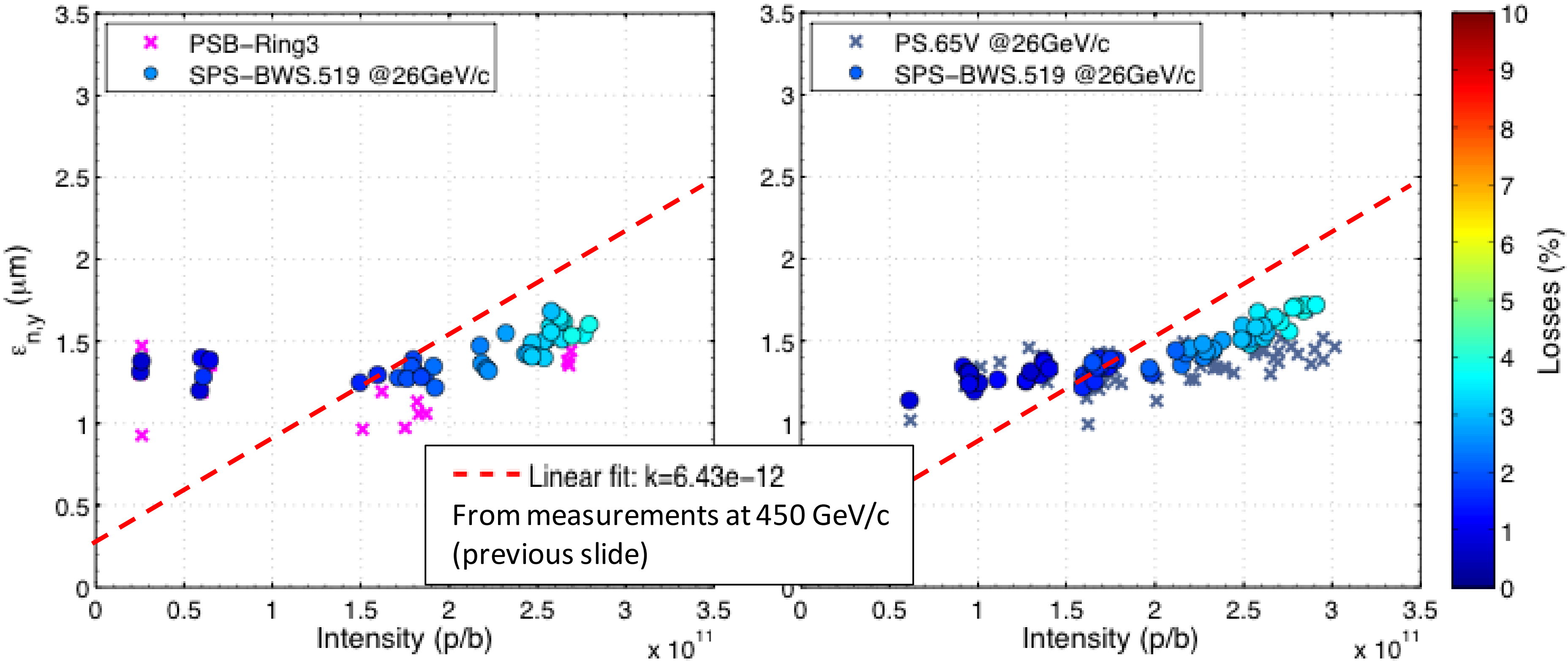
SPS in 2011

LHC Injectors Upgrade

– **Single bunch limits (TMCI, space charge, emittance blow up)**

Q20 – low γ_t optics

$\varepsilon_{n,y}$ measured @ end of 3s flat bottom



Blow up above 1.7 x 10^{11} ppb, during flat bottom (3 to 10 sec) or during ramp?
Working point optimization needed?

Conclusions

*Best performance table (2011)		50ns		25ns		Single bunch	
		N_b (10^{11} ppb)	$\frac{(\varepsilon_x + \varepsilon_y)}{2}$	N_b	$\frac{(\varepsilon_x + \varepsilon_y)}{2}$	N_b	$\frac{(\varepsilon_x + \varepsilon_y)}{2}$
PSB		Curves emittance vs. intensity @ flat top				4.0	2.2
PS		1.9	1.9	1.4	3.0	4.0	2.4
SPS	nominal	1.6	1.9	1.15	2.6	2.5	2.5
	Q20	1.7	?	1.2	2.7	3.0	2.2

- Potential improvements of the **PSB** beam (waiting for Linac4)
  - ✓ Production: Day by day optimization of injection + capture
  - ✓ Use: Alternative PS schemes (batch compression)
- **PS** performance limited by
  - ✓ Longitudinal CBI (need feedback)
  - ✓ In future → space charge @ injection, electron cloud, transverse instabilities
- **SPS** limitations
  - ✓ Injection + capture losses, longitudinal stability, TMCI, emittance growth
  - ✓ Electron cloud seems presently mitigated by years of scrubbing, but what will happen after LS1 (loss of conditioning) and with new stretched parameters?

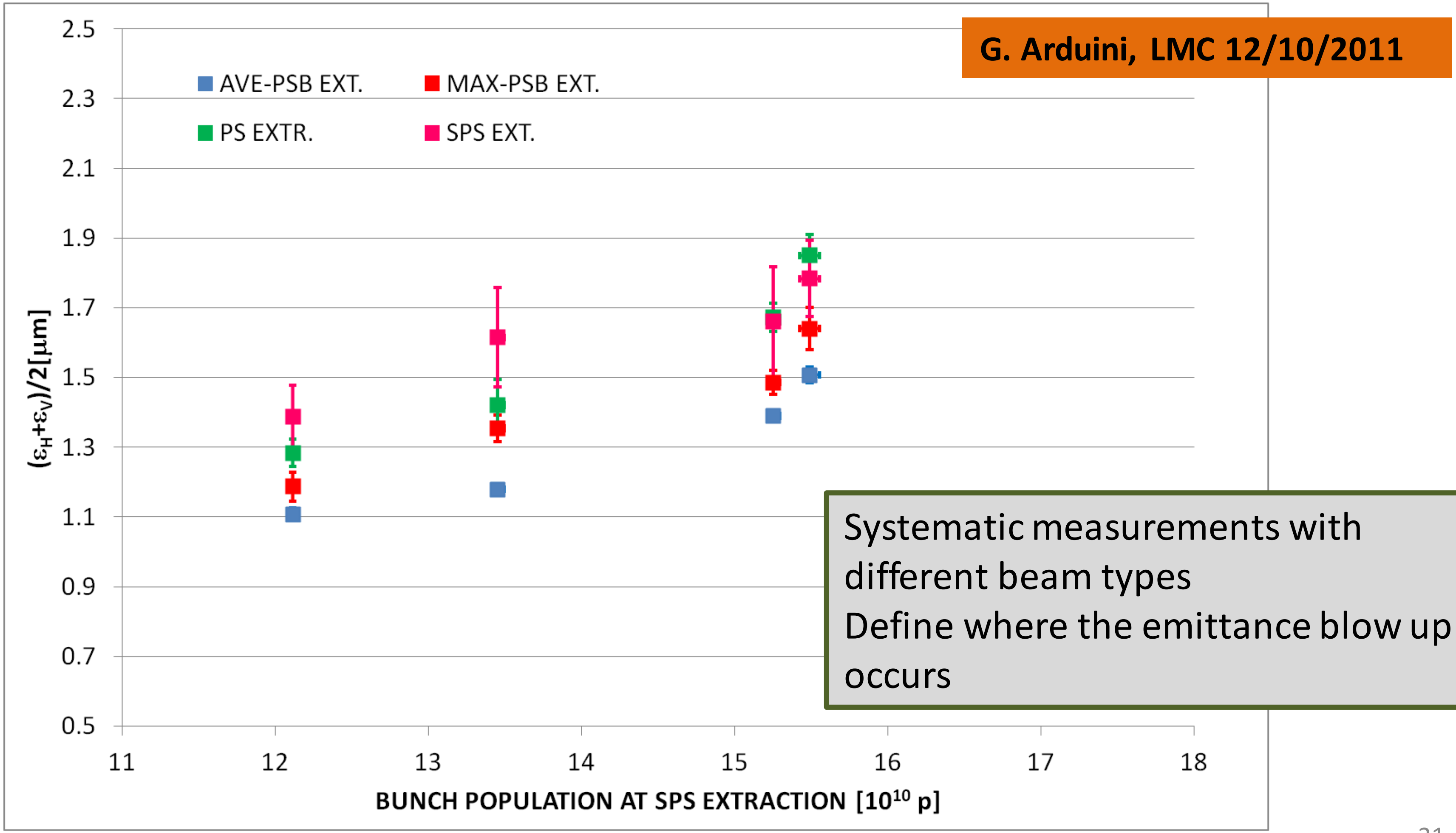
LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN

All the machines

– **Emittance preservation across the injector chain**



Systematic measurements with different beam types
Define where the emittance blow up occurs