Batch Compression Makes Sense

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Motivation

Luminosity scales as

Total charge — Beam brightness in collision

$$L \sim M\,N_b\,\frac{N_b}{\varepsilon}$$

Assuming a fixed percentage of losses downstream, the intensity per Booster ring is

$$N_{PSB} \propto S_{CPS}\,N_b$$

where S_{CPS} is the bunch splitting factor in the PS. Hence, crudely assuming any transverse blow-up in the accelerator chain to be likewise independent of the production scheme,

Booster brightness = constant

$$L \sim \frac{M\,N_b}{S_{CPS}}\,\frac{N_{PSB}}{\varepsilon_{PSB}}$$

So, for given intensity per colliding bunch and assuming no penalty in the final number of bunches accumulated in the LHC, lower splitting factor means lower emittance means higher luminosity.

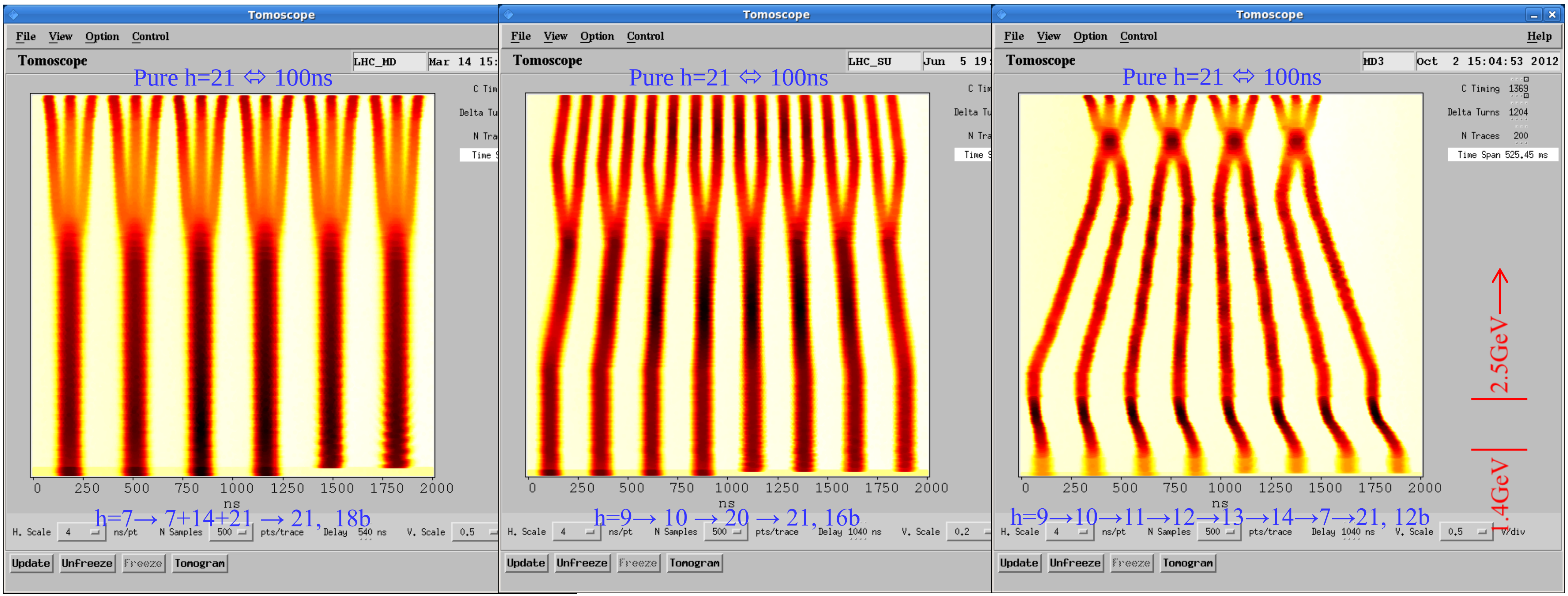
Or, more generally,

$$L \sim M(S_{CPS})\,\frac{N_{PSB}}{S_{CPS}^2}$$

This clearly underlines the importance of the first injectors, but it ignores the downstream ceiling on N_b (due, for example, to beam stability and rf power in the SPS and to electron cloud effects and beam-induced heating in the LHC).

Batch Compression versus Splitting

The desired final harmonic in the PS is achieved by additive steps (batch compression) and not just by multiplicative ones (splitting). Double-batch injection into h=9 makes maximum use of Booster rings. The trick of bunch merging reduces the effective splitting factor by two, so that the BCMS 25ns beam has the same splitting factor as the nominal 50ns one. In principle, this permits switching to 25ns at the same total beam current without compromising luminosity – provided the brightness of such a "half-intensity, half-emittance" beam can be sufficiently well conserved all the way to collision in the LHC.



"Nominal" $S_{CPS}^{(25ns)} = 12$ "h=9" $S_{CPS}^{(25ns)} = 8$ "BCMS" $S_{CPS}^{(25ns)} = 6$

Brief Chronology (2012)

Following the h=9 proposal to generate 100ns protons for p-Pb and, effectively, a two-week test of the associated new hardware in May (to debunk OPERA's superluminal neutrinos!), double-batch injection into this new harmonic became fully operational in the PS and an "h=9" 50ns (32-bunch) beam was subsequently sent to the SPS and later to the LHC. Further hardware modifications to permit multiple LO and phase loop switching enabled a "BCMS" 50ns (24-bunch) beam to be prepared, first with a proof of principal of the gymnastics at 1.4GeV and soon afterwards at 2.5GeV to avoid longitudinal acceptance and, to a lesser extent, space charge issues. After a couple of false starts due to the later PS extraction timing, this beam also made it to collision. At the request of the experiments themselves, the 25ns variant was used for physics in a series of fills during the very last weekend before the end of the proton run. The main milestones were…

21/06 First h=9 trial in the SPS.

04/07 Results presented at LMC 140.

22/08 Fill 2994.

29/08 Results presented at LMC 146.

03/11 First BCMS 50ns beam in the SPS.

07/11 Results presented at LMC 156.

04/12 Fill 3372.

05/12 Results presented at LMC 158.

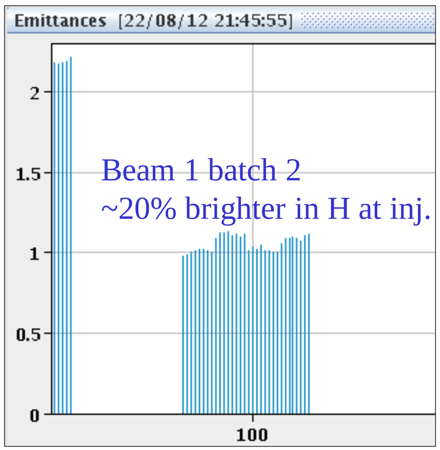
07/12 First BCMS 25ns beam in the SPS.

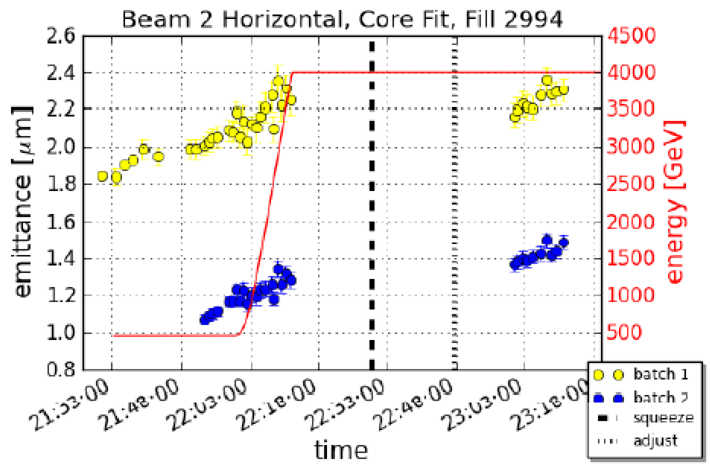
15/12 Fills 3441 and 3442.

16/12 Fill 3453.

Fill 2994, h=9 50ns

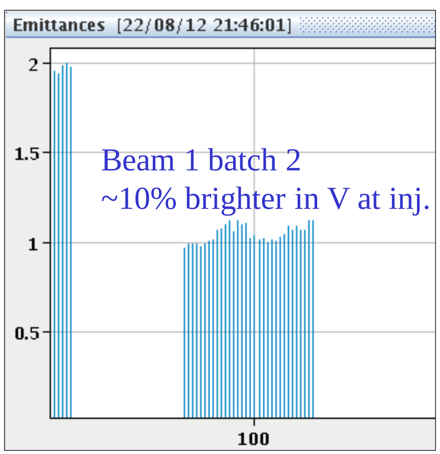
A single 32-bunch batch of 1.1E11 ppb (after scraping in the SPS) plus 6 non-colliding nominal bunches of 1.65E11 ppb were injected in each direction in the LHC. ~40% blow-up (cf., ~50% blow-up for the convoluted emittance derived from luminosity) was observed in the horizontal plane, roughly half of it on the flat-bottom. This is large but not dissimilar to the ~30% blow-up for a standard fill.

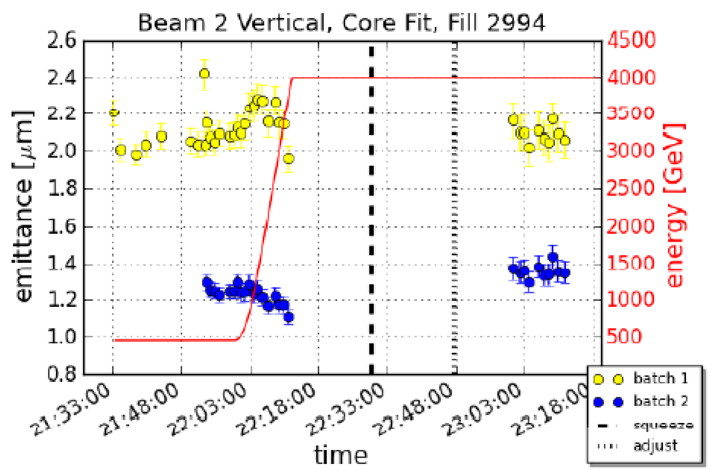




Beam [plane]	Injection emittance [μm]	
	Nom bunches	h=9 bunches
B1 [H]	1.772 ± 0.135	**1.005 ± 0.075**
B2 [H]	1.848 ± 0.006	**1.07 ± 0.026**
	Collision emittance [μm]	
B1 [H]	2.159 ± 0.113	**1.43 ± 0.072**
B2 [H]	2.286 ± 0.185	**1.454 ± 0.166**

Courtesy M.Kuhn

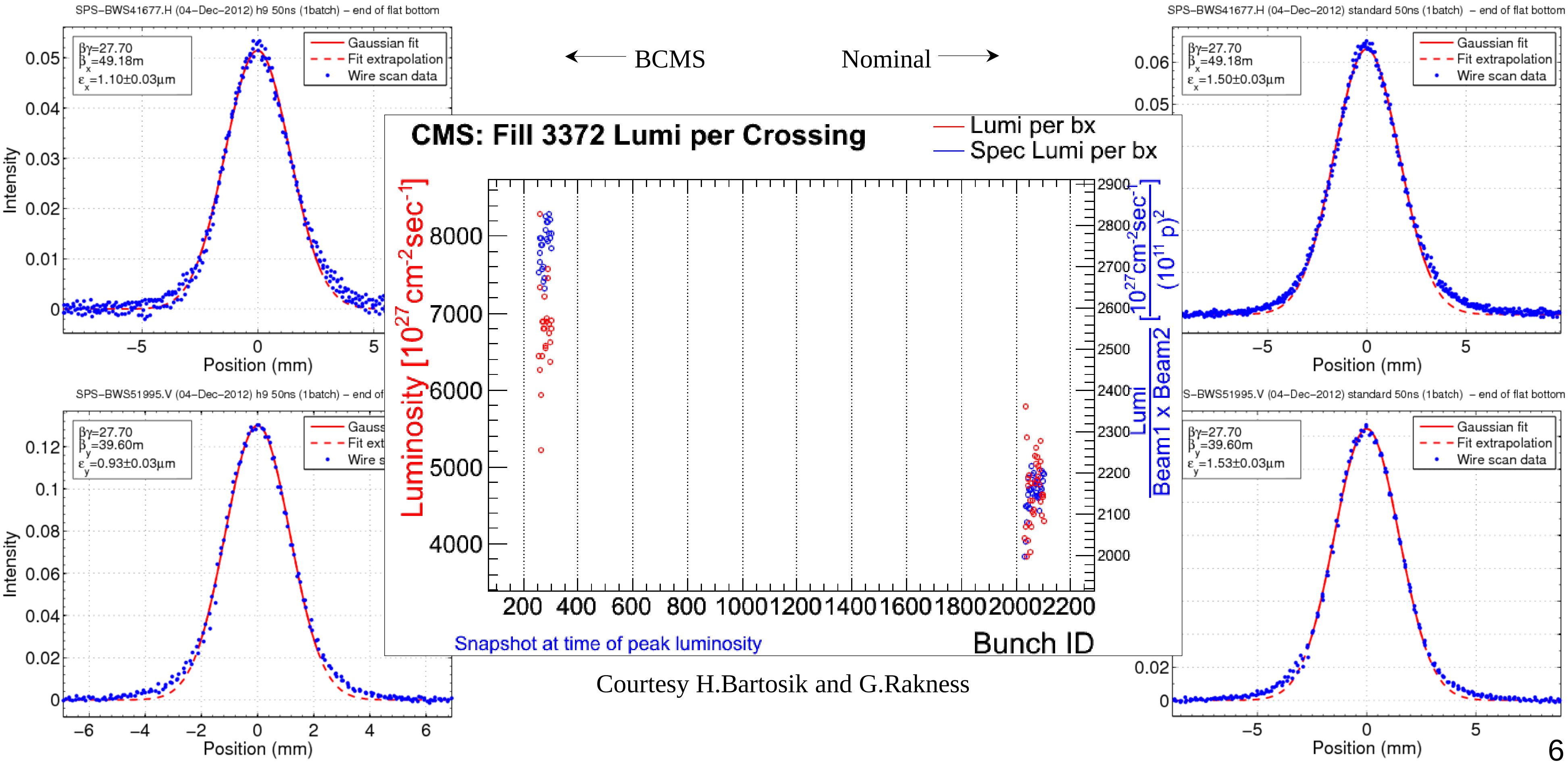




Beam [plane]	Injection emittance [μm]	
	Nom bunches	h=9 bunches
B1 [V]	1.891 ± 0.078	1.169 ± 0.05
B2 [V]	1.986 ± 0.056	1.252 ± 0.039
	Collision emittance [μm]	
B1 [V]	1.83 ± 0.095	1.274 ± 0.087
B2 [V]	2.148 ± 0.119	1.398 ± 0.086

Fill 3372, BCMS 50ns

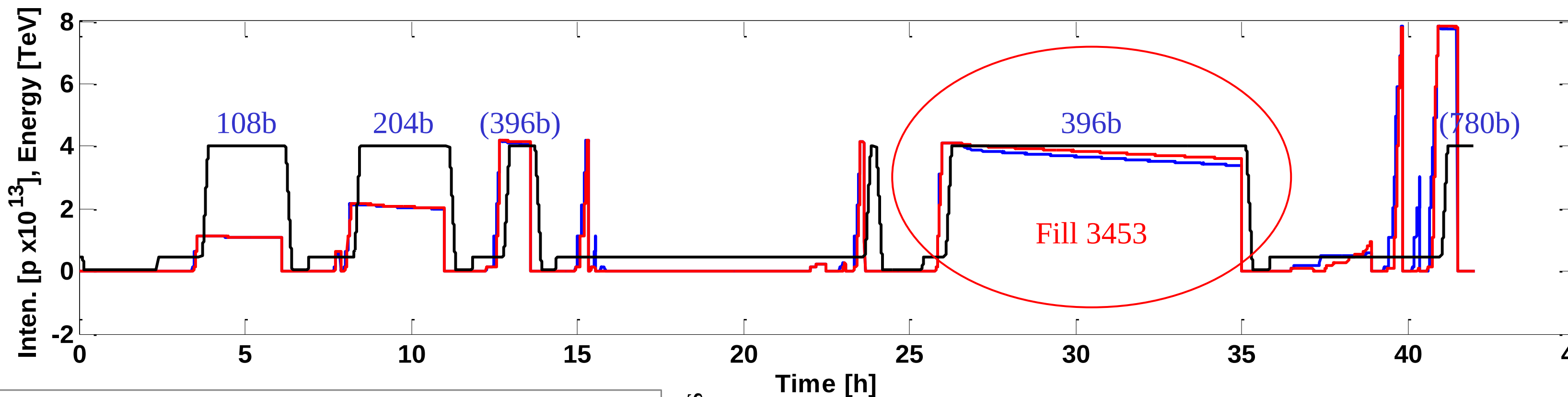
A single 24-bunch batch of 1.6E11 ppb (after a requested reduction!) plus a 36-bunch nominal batch of 1.5E11 ppb and 2×6 nominal bunches were injected in each direction in the LHC. The BCMS beam showed a 50% gain in terms of emittance (cf., 100% for the same intensity) summing over both planes at the end of the SPS flat-bottom, but yielded only ~30% more specific luminosity per crossing.



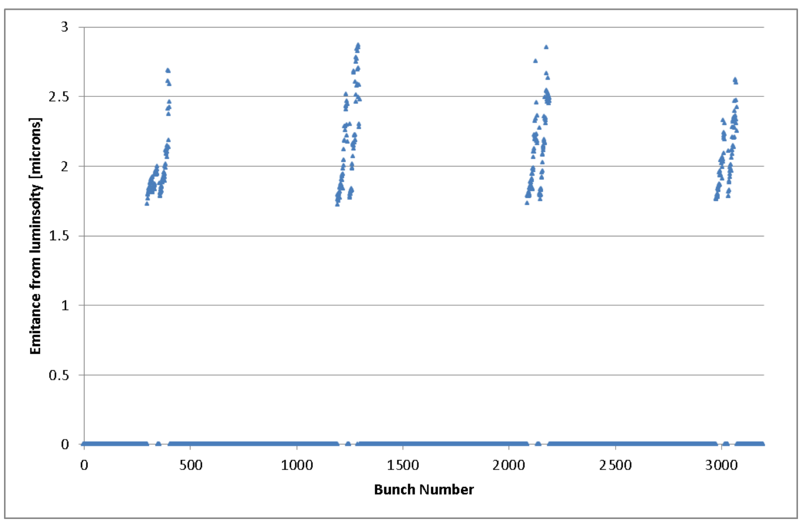
Courtesy H.Bartosik and G.Rakness

Fill 3453, BCMS 25ns

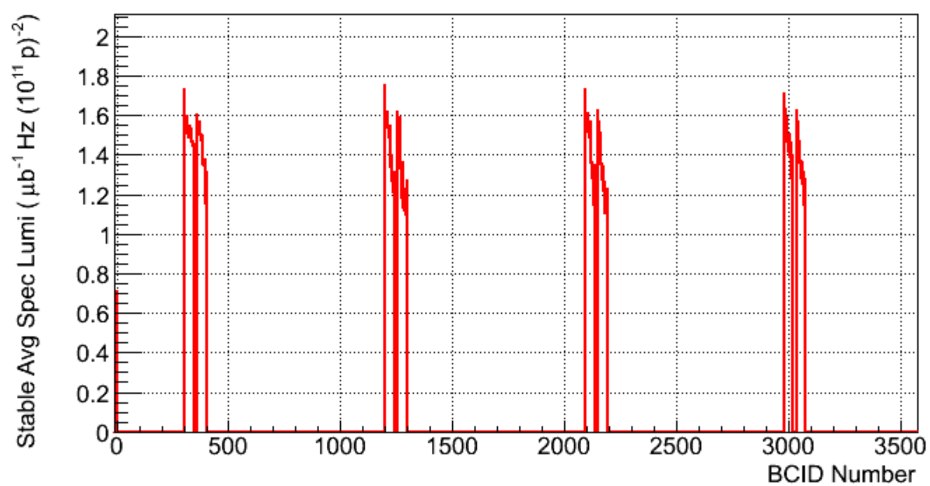
Following a 3.5 day scrubbing run with nominal 25ns beams at 450GeV, a pilot physics run took place with BCMS 25ns beams. Multiple 48-bunch batches of 1.1E11 ppb and ~1.3µm (from wirescans of the first couple of batches) were injected. Three fills made it to stable beams, with typically 1.0E11 ppb and ~1.8µm (from luminosity). The last of these showed clear indications of electron cloud.



Courtesy G.Iadarola



Courtesy M.Lamont p.p. Atlas



Courtesy G.Arduini p.p. Atlas

Summary

Measurements (end 2012)		Nominal 50ns	BCMS 50ns	Nominal 25ns[2)]	BCMS 25ns
1.4GeV	N_{PSB} [10^{12}/Ring]	1.2	0.6	1.6	0.8
450GeV[1)]	N_b [10^{11}]	1.7	1.6[3)]	1.1	1.1
	$\beta\gamma\varepsilon_{<H+V>}$ [µm]	1.7	1.1	2.6	1.3
	Brightness [10^{11}/µm]	1.0	1.5	0.42	0.85
	Rel. Brightness (Potential)	1.5[4)] (2.0)		2.0 (2.0)	
	Equivalent *L*/*M* [arb. units]	1.7	2.3	0.47	0.93

1) Measurements were made early on the LHC injection plateau. It was not always possible to make wirescans at SPS extraction, but agreement between the two machines at transfer is known to be good.

2) Operational experience with nominal 25ns beams was scant. These results are derived from fills 3425 and 3429; the latter saw 804 bunches at 4TeV.

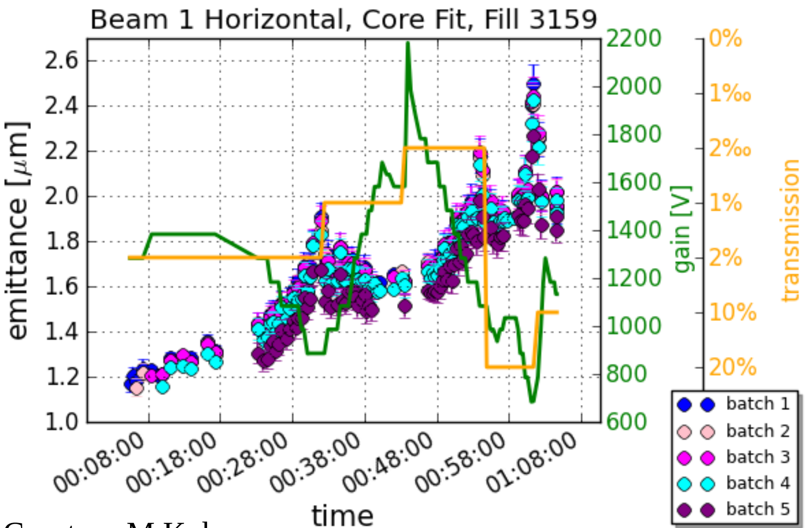
3) 1.9×10^{11} ppb could have been delivered but this was considered inexpedient.

4) The minimum emittance from the Booster is set at ~1.0µm by Linac2. For the BCMS 50ns beam to reach its full potential, it would first have to be shaved down to well below this value.

Some Comments

Since batch compression results in shorter PS batches, new filling schemes must be devised that employ more PS shots per SPS batch in order to minimize the extent of kicker gaps in the LHC.

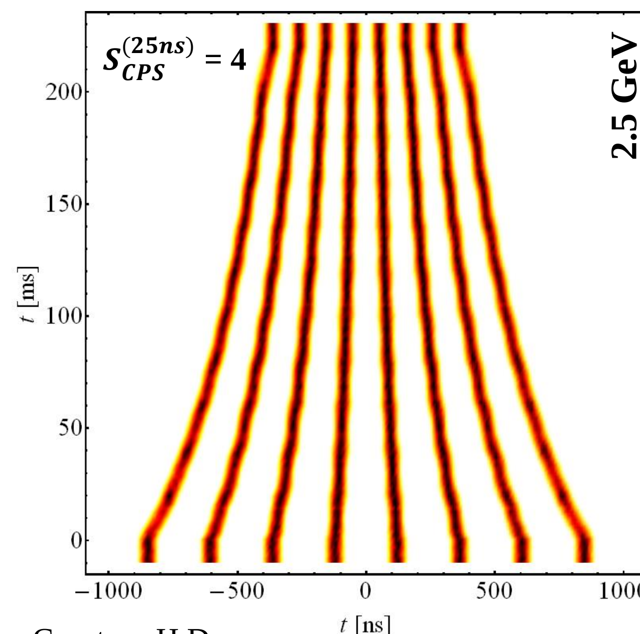
Capture in the intensity regime below 10^{12}/Ring should be better understood in the Booster.



Courtesy M.Kuhn

Instrumentation still struggles to provide the 0.1μm precision required on emittance. The LHC wirescanners are used to calibrate the other transverse measurements, but there are severe limits on the beams through which a wire can be flown. The 10-15% disparity between the wirescanners and convoluted emittance is not understood.

The production of the BCMS beams is a remarkable achievement not only because they exploit to the fullest data structures conceived 20 years ago, but also because the editor of those same structures has remained broken since the introduction of InCA by CO. (Homemade Mathematica and Excel applications were used instead!) This should be fixed and the old structures superseded during LS1, which will allow even more exotic schemes to be contemplated.



Courtesy H.Damerau