Injector Performance During 2012 / 2013

Rende Steerenberg

Thanks to:

Gianluigi Arduini, Hannes Bartosik, Karel Cornelis, Heiko Damerau, Roland Garoby, Simone Gilardoni, Massimo Giovannozzi, Steve Hancock, Klaus Hanke, John Jowett, Detlef Kuchler, Django Manglunki, Gabriel Metral, Bettina Mikulec, Yannis Papaphilippou, Richard Scrivens, Didier Voulot.

C-MAC, 14 March 2013

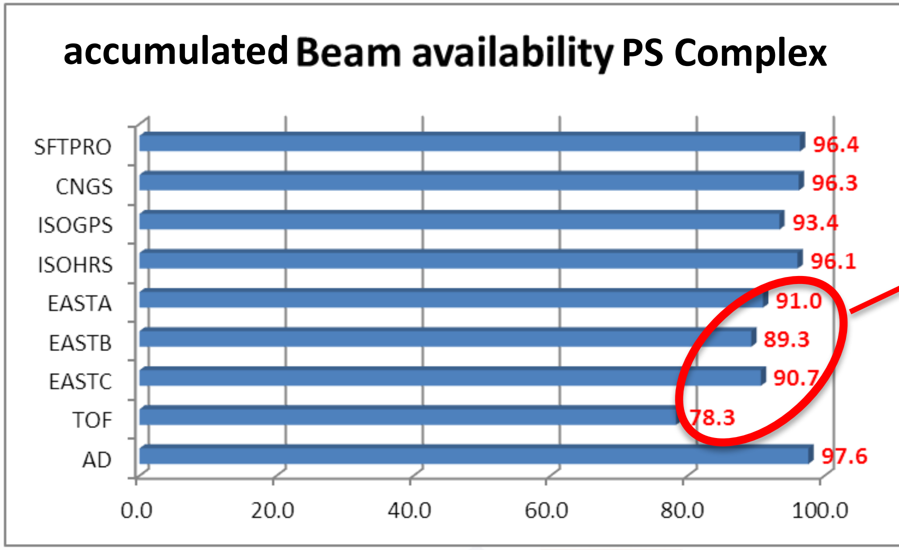
Contents

- Some general machine performance figures
- Injectors for some of the fixed target physics
- LHC protons beam performance
- LHC ions beam performance
- Summary & concluding remarks

- Some general machine performance figures
- Injectors for some of the fixed target physics
- LHC protons beam performance
- LHC ions beam performance
- Summary & concluding remarks

Injector Complex Availability

- LINAC2 and LINAC3 have **close to 100%** beam availability.



EAST and TOF statistics are time of physics (as they have no request or they put it ON all the time) - in reality they are above 90%

On average well above 90%

- SPS accumulated beam availability for
  - CNGS (2012): 80%
  - Protons FT (2012): 79%
  - Ions FT (2013): 93%

On average well above 85%

- LHC uses the beam only for a little fraction of time from injectors.
  - Protons out of SPS 2012: 93%
  - Protons / ions out of SPS 2013: 92% / 87%

Protons distribution at CERN

- To put some things in perspective…

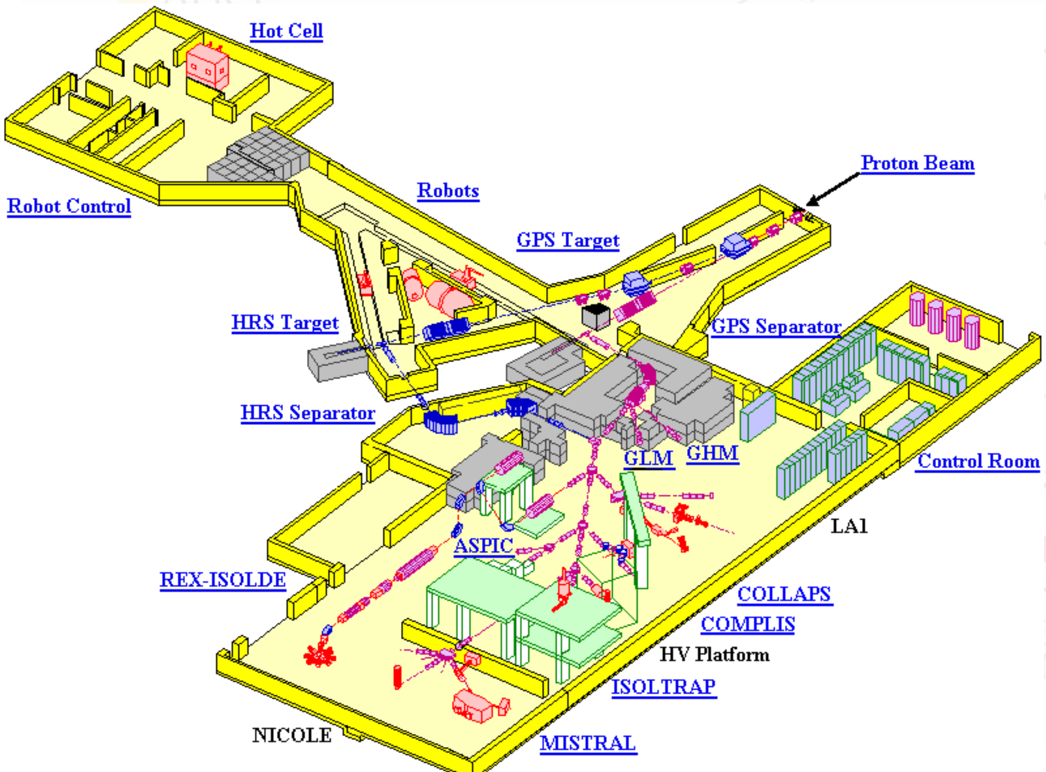
Facility	Protons Delivered	% of Total
Isolde	$1.17 \times 10^{+20}$	63.8%
CNGS	$3.9 \times 10^{+19}$	21.6%
n-TOF	$1.9 \times 10^{+19}$	10.2%
The rest	$8.13 \times 10^{+18}$	4.5%
LHC	$3.25 \times 10^{+16}$	0.018%
Total	$1.83 \times 10^{+20}$	

- The number of protons taken by LHC is less than the number of protons lost in the injectors for CNGS.

- Some general machine performance figures
- **Injectors for some of the fixed target physics**
- LHC protons beam performance
- LHC ions beam performance
- Summary & concluding remarks

ISOLDE

- Shift balance **1009 open shifts** for IS experiments, 53 shifts for LOIs
  - Shift requests 2012: **833 shifts** for **71 IS exp**; 40 shift for 14 LOIs
  - REX requests: **377.5 shifts** (IS + LOIs)
- The 2012 run for ISOLDE was **extended by 2 weeks**, but some **downtime on GPS** was accumulated due to a problem with the target front-end.



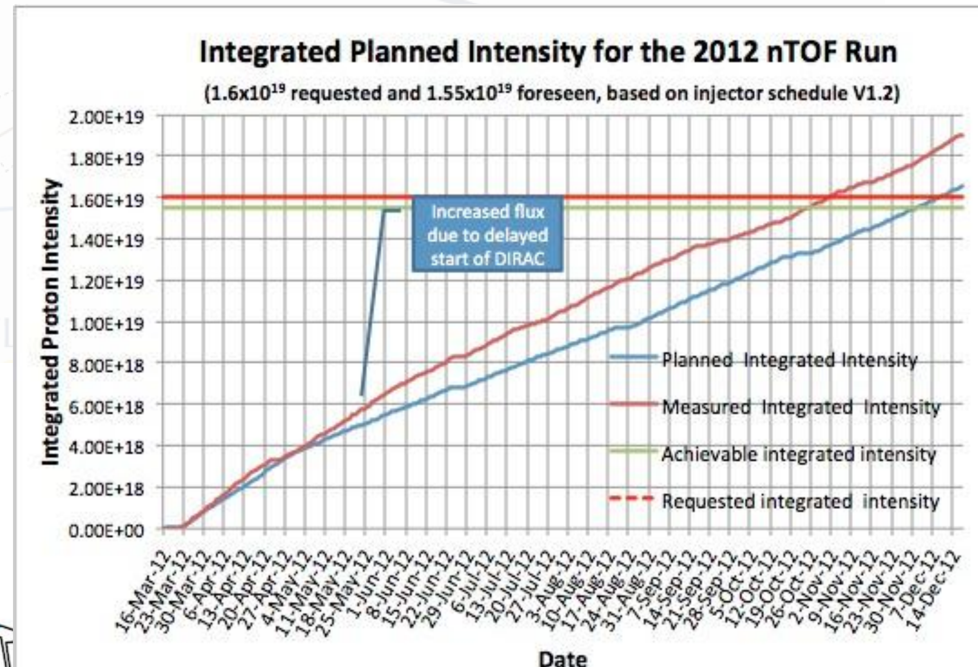
1.17×10^{20} protons on targets

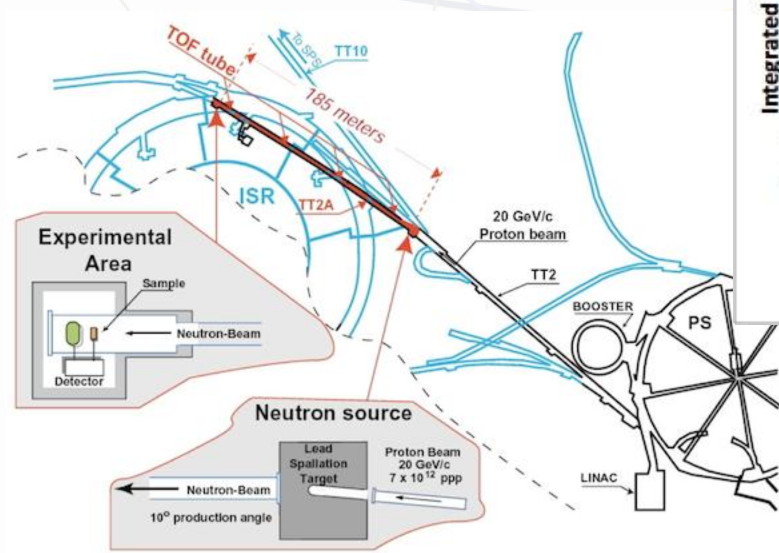
Scheduled	2012	2011
All shifts (IS+LOI+MD)	565	491.5
Shifts for IS exp	539	440
Average shifts/day	2.08	2.31

from INTC meeting

N-TOF beam from the PS

- The scheduled number of protons on target for 2012, **1.55x10^{19}**, was reached already on the 1st on November.
- Earlier thanks to:
  - Delayed start of DIRAC
  - Better machine availability
  - Continuous optimization of the PS super cycle



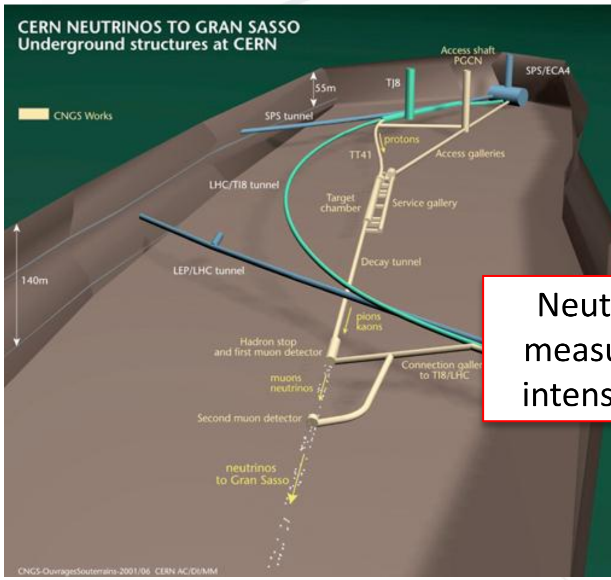


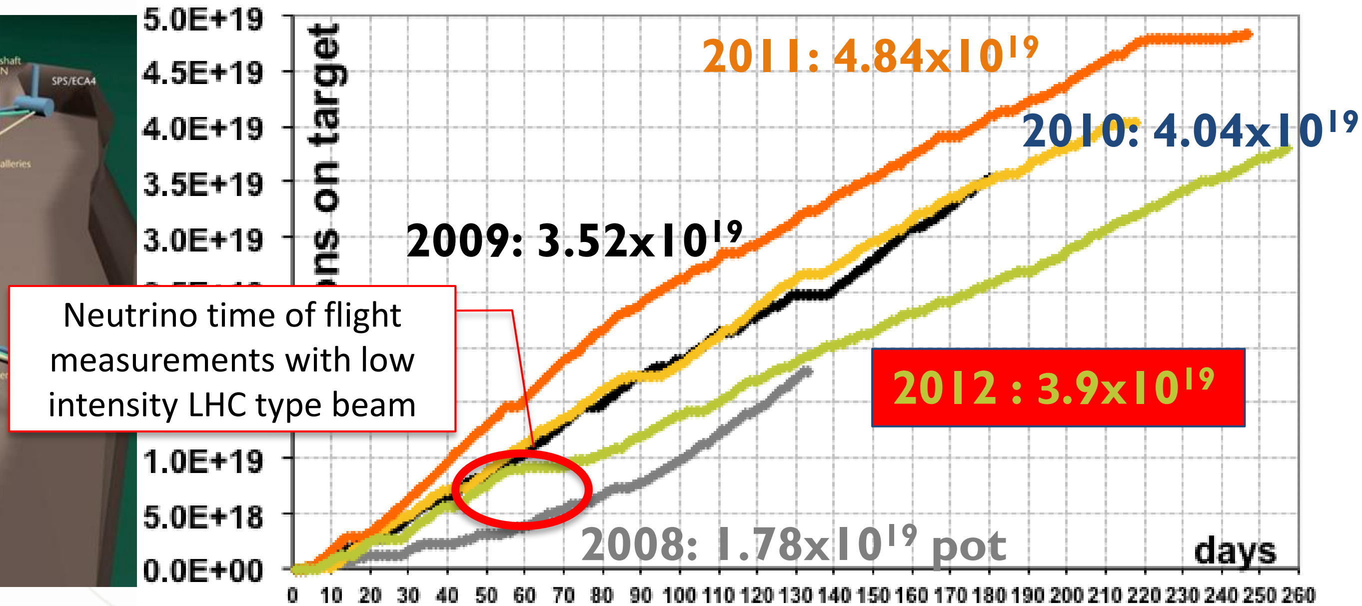
End of the extended 2012 run

1.92x10^{19} p.o.t.

CNGS beam from the SPS

- 3.9x10^{19} p.o.t. instead of 4.5x10^{19} forecasted in 2012.
- 81% of approved number of p.o.t. reached in 5 years.

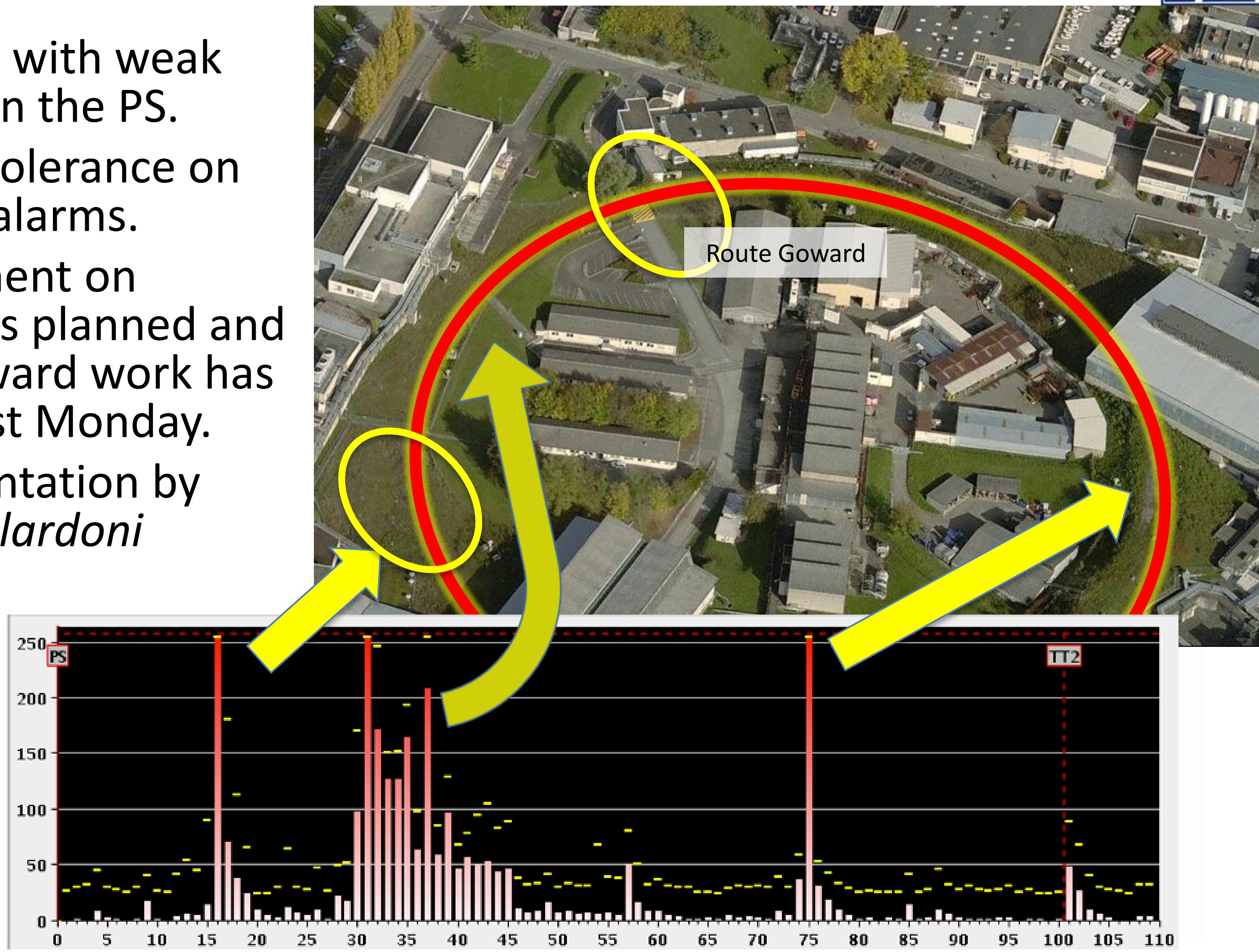




- Limitations:
  - Flux limitation from PS related to CT extraction losses.
    - Strict application of rules related to PS surface radiation alarms.
  - Many machine development cycles and cycles to setup in SPS.

PS proton flux limitation

- Two areas with weak shielding in the PS.
- Reduced tolerance on radiation alarms.
- Improvement on shielding is planned and route Goward work has started last Monday.
- See presentation by *Simone Gilardoni*



- Some general machine performance figures
- Injectors for some of the fixed target physics
- **LHC protons beam performance**
- LHC ions beam performance
- Summary & concluding remarks

Classical 25ns & 50ns Beams

- Initial specification

	Defined Characteristics 2004 (Source: LHC-OP-ES-0002 rev 1.0, EDMS: 487892)										
	PSB extraction				PS extraction			SPS extraction			
	Ip / ring [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches
LHC25	2.4 - 13.8	≤ 2.5	2	4 + 2	0.2 -1.15	≤ 3	72	0.2 -1.15	≤ 3.5	≤ 0.8	1 - 4 x 72
LHC50	1.2 - 6.9	≤ 2.5	2	4 + 2	0.2 -1.15	≤ 3	36	0.2 -1.15	≤ 3.5	≤ 0.8	1 - 4 x 36

- Expected performance for 2012 (Chamonix 2012)

	Tentative Operational Characteristics 2012										
	PSB extraction				PS extraction			SPS extraction			
	Ip / ring [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches
LHC25	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.5	0.7	1 - 4 x 72
LHC50	11	1.6	2	4 + 2	1.8	1.9	36	**1.6**	**2**	≤ 0.8	1 - 4 x 36

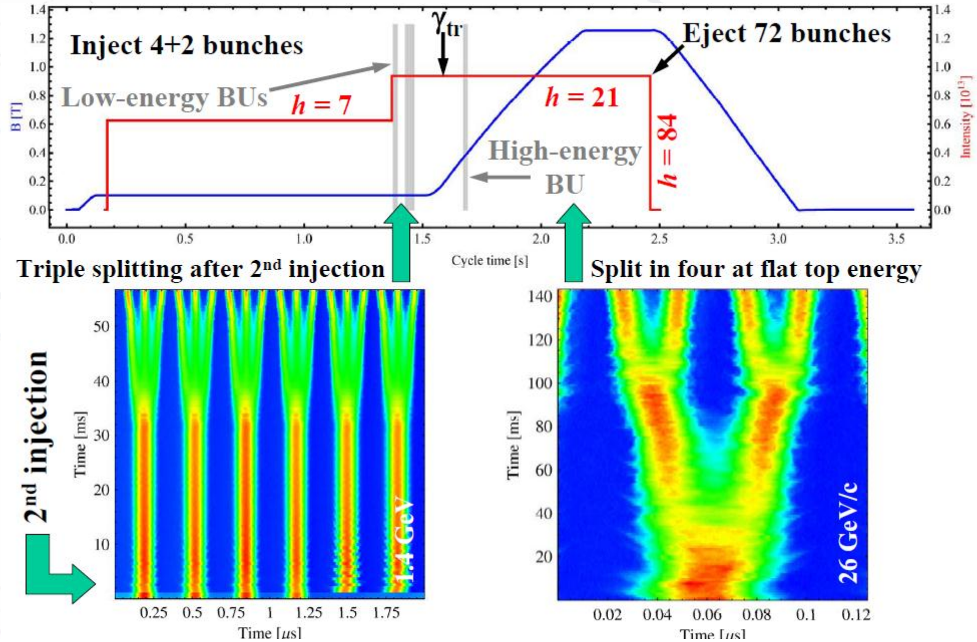
- Achieved performance 2012

	Achieved Operational Characteristics 2012										
	PSB extraction				PS extraction			SPS extraction			
	Ip / ring [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches
LHC25	16	2.3	2	4 + 2	1.3	2.4	72	1.35	~ 3	0.7	1 - 4 x 72
LHC50	12	1.35	2	4 + 2	1.9	1.5	36	**1.65**	**1.65**	≤ 0.8	1 - 4 x 36

Reminder: Beam production scheme

- The 25 ns:
  - Double batch injection from PSB (4 + 2 bunches).
  - Triple splitting at LE in PS.
  - Acceleration.
  - 2 x splitting at HE in PS.
  - Bunch rotation in PS.
  - Up to 4 batches to SPS.
  - 288 bunches out of SPS.

- The 50 ns:
  - Similar to 25 ns at LE.
  - 1 x splitting at HE in PS.
  - Bunch rotation in PS.
  - Up to 4 batches to SPS.
  - 144 bunches out of SPS.

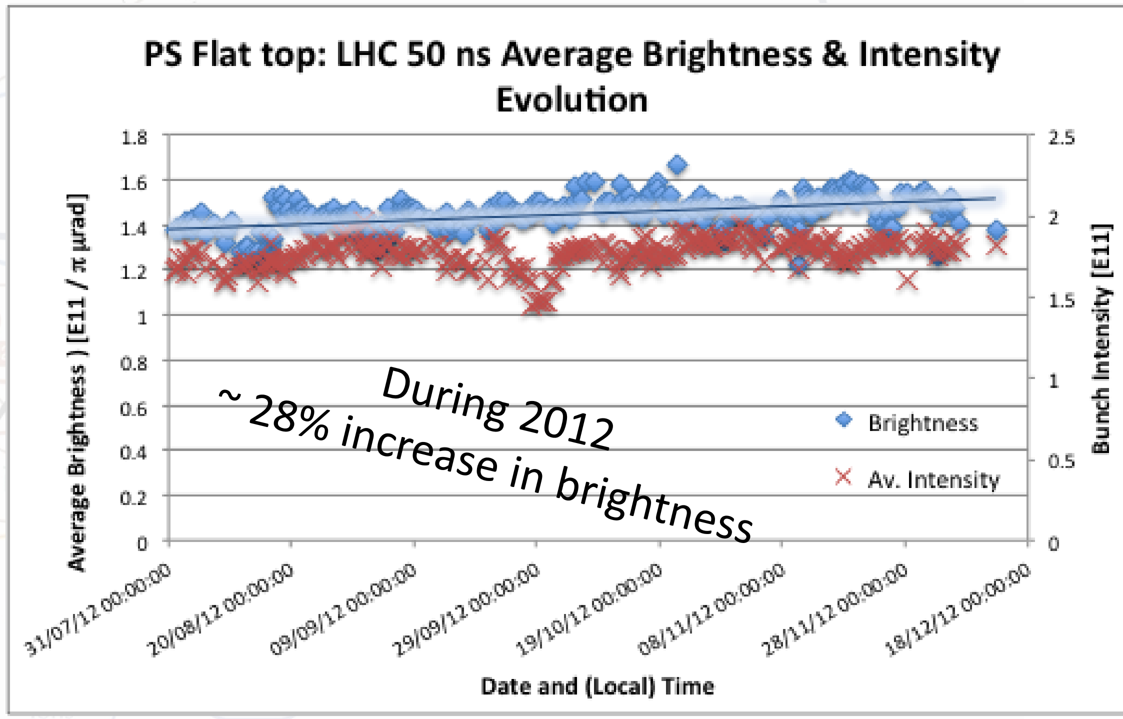


25 ns: Each bunch from the PS Booster is divided by 12 → 6 x 3 x 2 x 2 = 72
50 ns: Each bunch from the PS Booster is divided by 6 → 6 x 3 x 2 = 36

LHC Beam Brightness Evolution

- Continuous optimisation resulted in brighter beams.
- Systematic logging in PSB, PS and SPS started after the summer with at least 1 measurement per shift.

- SPS April/May:
  - $I_p = 1.4 \times 10^{11}$ ppb
  - $\varepsilon_{h/v} = 1.8$ µm rad
- SPS November:
  - $I_p = 1.65 \times 10^{11}$ ppb
  - $\varepsilon_{h/v} = 1.65$ µm rad
- Intensity increase ~ 18%
- Emittance decrease ~ 10%



Injectors contribution to luminosity

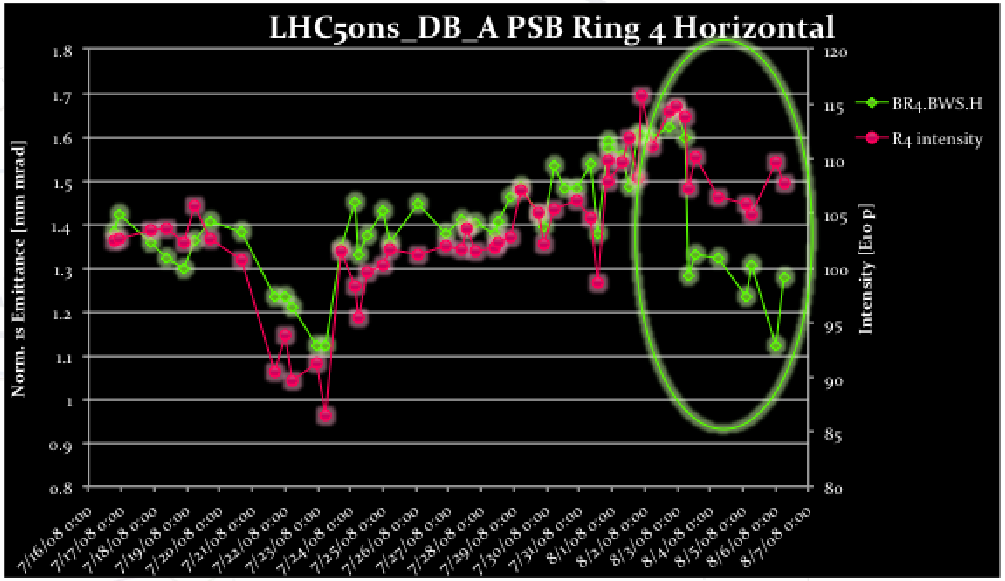
$$L \propto \frac{N_b^2}{\varepsilon}$$

- N_b = number of protons per bunch
- ε = average transverse emittance

- PS Booster transverse **emittance increases linearly with intensity.**
  - Multi turn injection process in horizontal phase space.
  - Horizontal and vertical transverse emittances equalised due to coupling in PSB and PS.
- Important effort made in **increasing intensity**, as well as identifying and **reducing blow up sources** along the whole LHC injector chain.

LINAC2 – PSB matching improvement

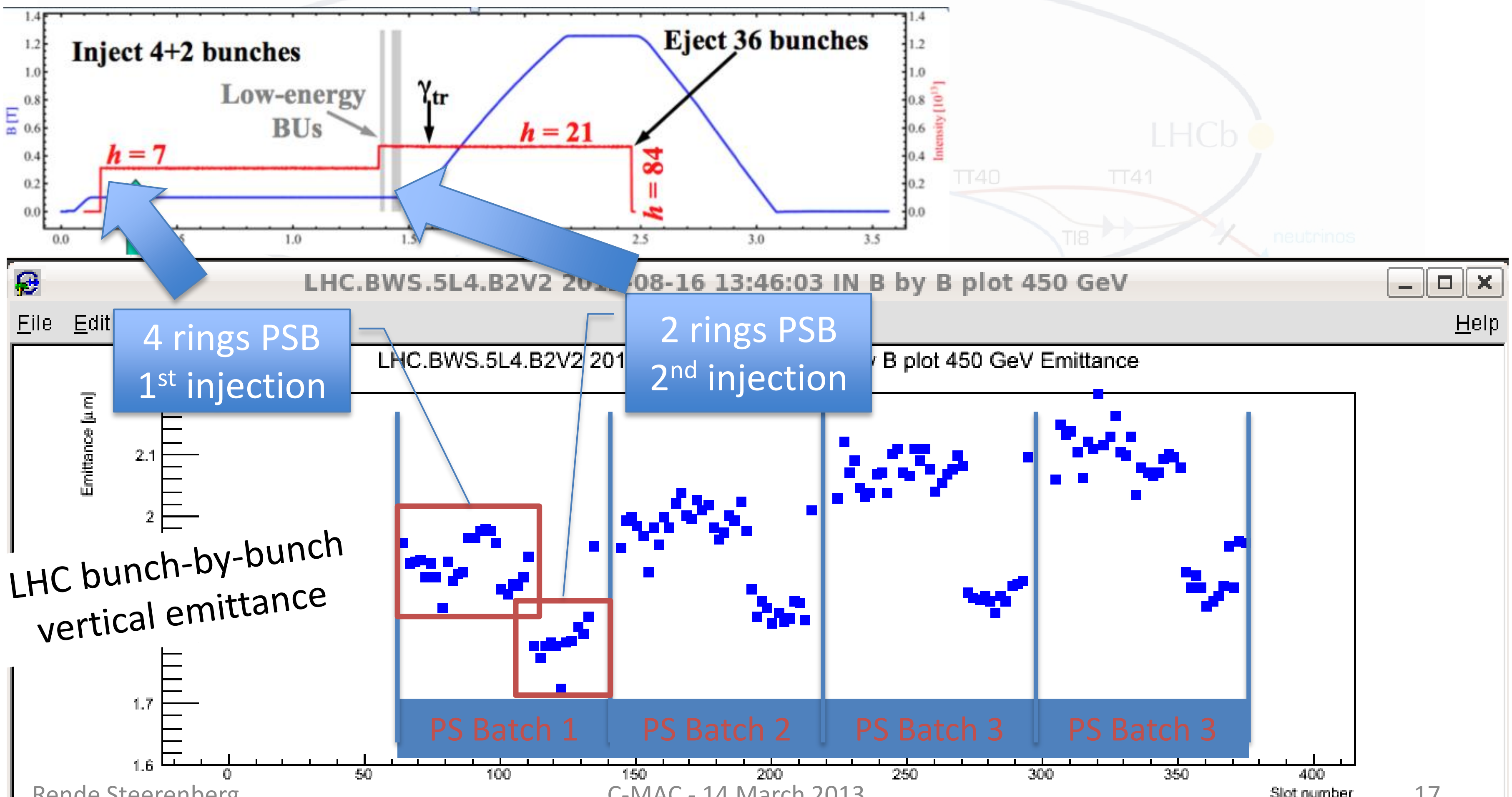
- Early August a **transverse matching improvement** was found and introduced.
  - Two quadrupoles settings in common part of the PSB injection transfer line were modified.
  - The working points of ring 2 and 3 were improved.



- Resulted in an average **brightness increase** for the same intensity per ring of about **5%.**

PS transverse emittance blow up

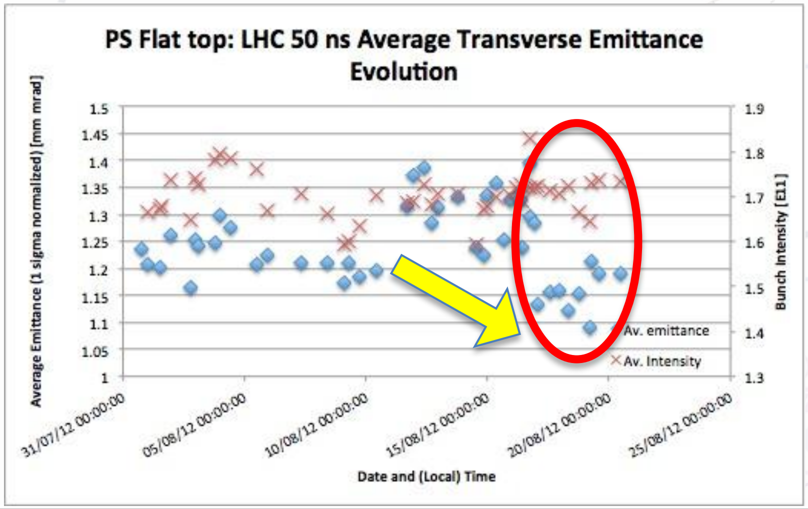
- Since PSB brightness increased PS suffered from mainly vertical emittance blow up between 1st and 2nd injection.

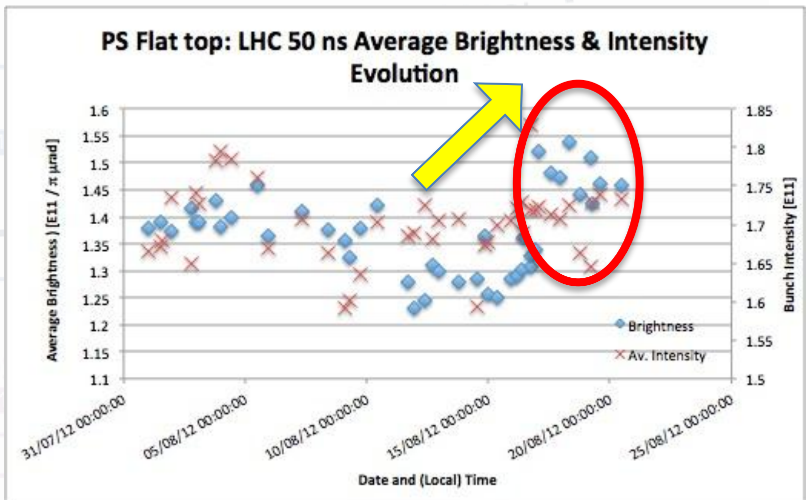


PS low energy working point

- Improvement of the PSB beam brightness increased and shifted the space charge tune foot print, touching integer resonance, causing blow up.
- Low energy tunes were modified:

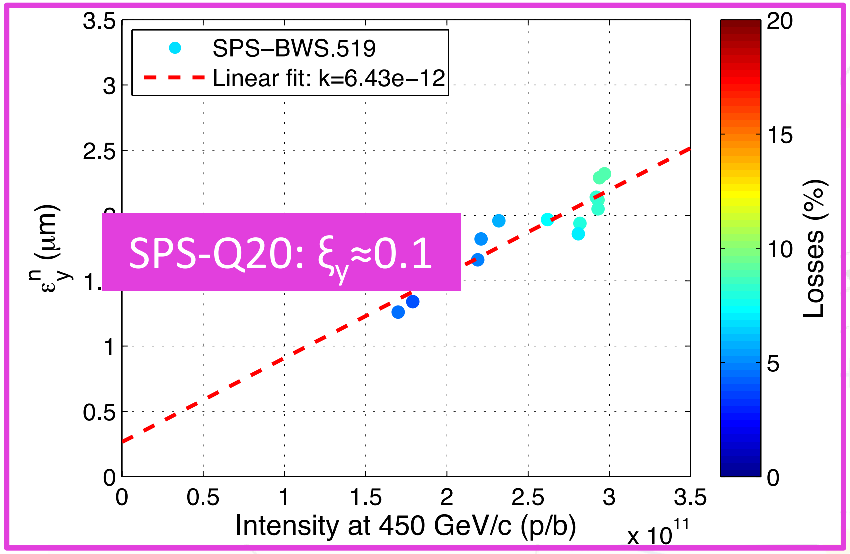
	BEFORE	AFTER
Horizontal tune	6.2104	6.2356
Vertical tune	6.2297	6.2440

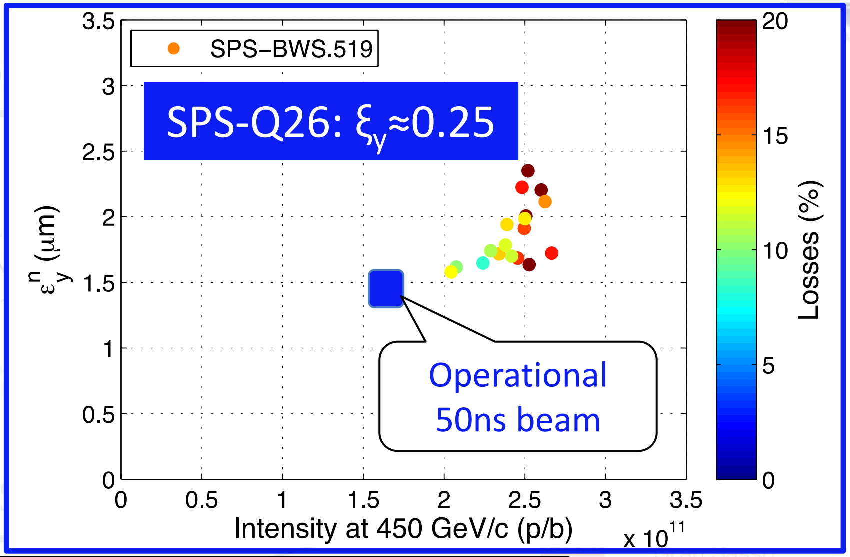




Fill	Fill Times			Energy [Gev]	Intensity		Bunches		Bunch Collision Scheme [IPI&5/2/8]	Peak Luminosity [Hz/ub] = $[10^{30}\ cm^{-2}s^{-1}]$				Delivered Luminosity $[nb^{-1}] = [10^{33}\ cm^{-2}]$			
	Fill Start	SB Start [hh:mm]	SB Duration [hh:mm]		B1 $[10^{12}]$	B2 $[10^{12}]$	Number	Norm Emitt [um]		ATLAS	ALICE	CMS	LHCb	ATLAS	ALICE	CMS	LHCb
2987	11:56 19/08/2012	13:23	0:36	4000	209.43	209.82	1374	2.17	1368/0/1262	7198	0.53	7021	410	14605	1.05	14138	741
2984	07:42 18/08/2012	10:04	19:10	4000	213.52	209.07	1374	2.43	1368/0/1262	7422	0.63	7239	414	223644	16.6	224315	25618
2983	10:06 17/08/2012	15:41	15:54	4000	215.14	207	1374	2.59	1368/0/1262	7049	0.59	6821	421	201135	15.19	198377	22570
2981	03:14 17/08/2012	06:00	0:59	4000	211.79	209.34	1374	2.27	1368/0/1262	7215	0	7159	405	23010	0	22846	1236
2980	21:00 16/08/2012	00:22	2:45	4000	212.62	208.95	1374	2.51	1368/0/1262	6685	0.58	6509	533	55798	0.1	54672	3820
2978	10:30 16/08/2012	15:06	1:16	4000	209.95	205.55	1374	2.52	1368/0/1262	6684	0.64	6608	411	27674	2.62	28070	1720
2977	07:17 16/08/2012	10:12	0:00	4000	207.53	203.28	1374	0	0/0/0	2131	0	6336	157	130	0	213	5

Lower γ-transition optics for the SPS



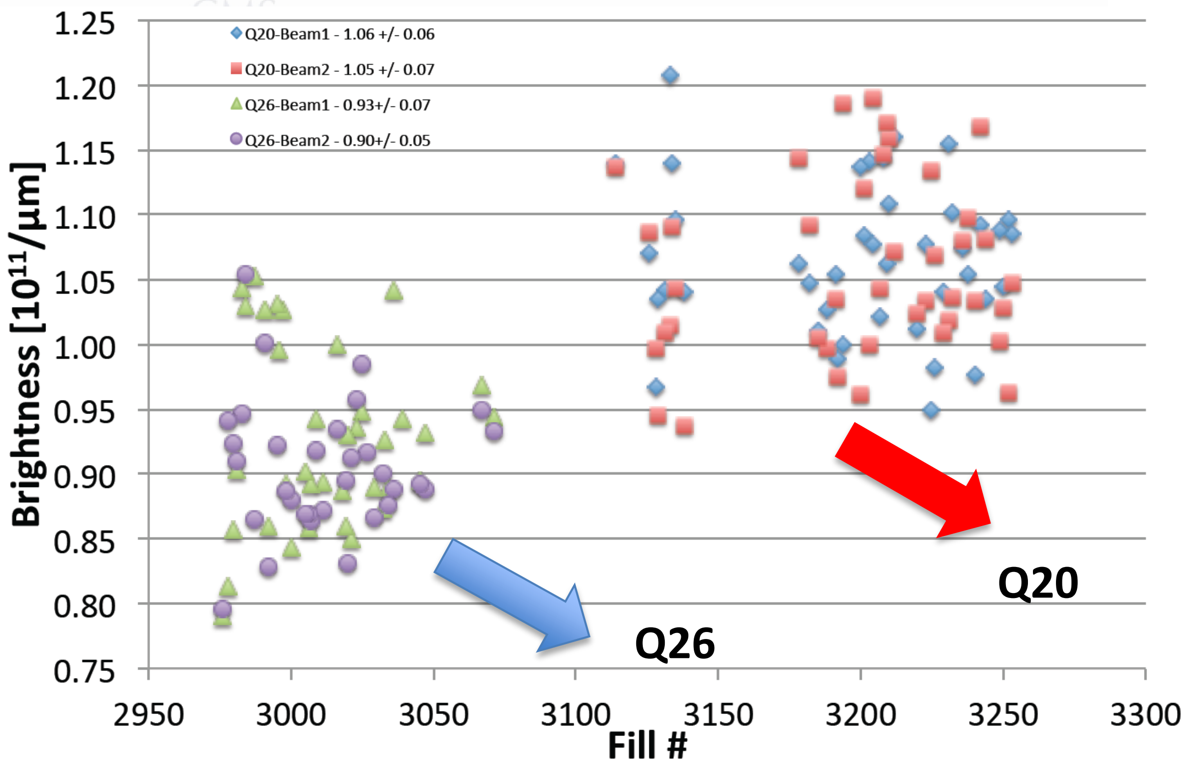


"Low gamma transition optics for the SPS:
simulation and experimental results for high brightness beams", HB2012

- Proposed **new SPS optics** for **lowering transition energy** (integer tune of 20 vs. 26).
  - **Remove or ease intensity limitations in the SPS** which represented the bottleneck in the injector complex (conclusions of Chamonix 2010).
  - With **minimal cost**, no major hardware change.
- Large amount of (single bunch) measurements and simulations during 2010-2012 for transverse and longitudinal instabilities, space-charge, ions (IBS), RF setting up, beam transfer to LHC.
  - Within LIU-SPS beam studies team (see http://paf-spsu.web.cern.ch/paf-spsu/).
- All instabilities that scale with the slippage factor benefit from reducing transition energy

Q20 optics operational performance

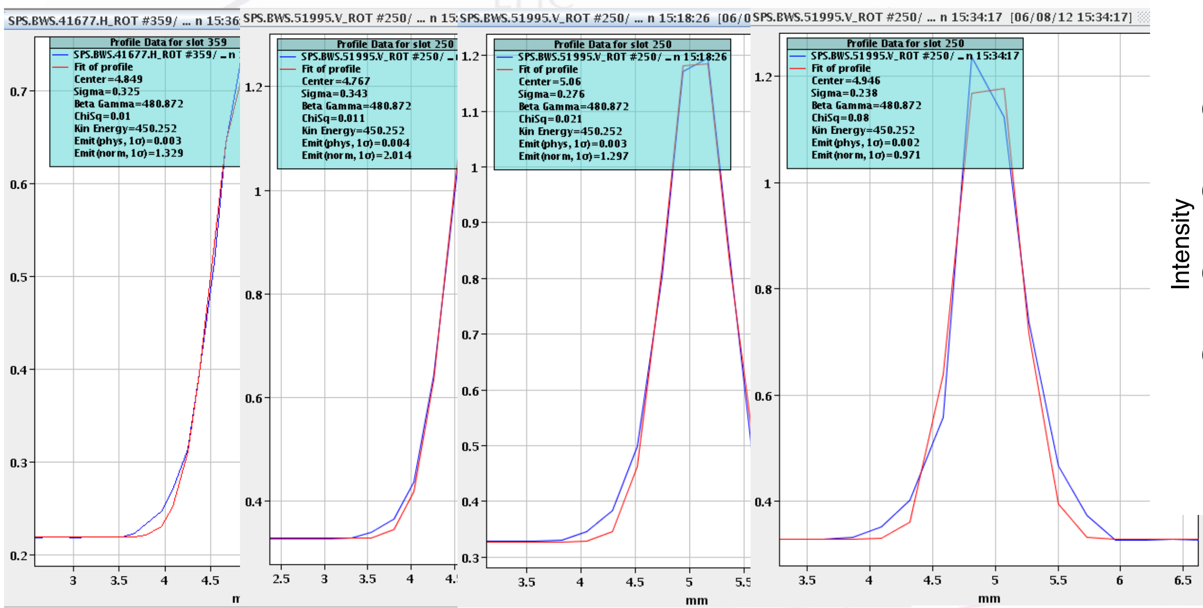
- After **LMC decision** (08/2012), Q20 optics became **operational** 09/2012.
- Very smooth switch, allowing **~20% brighter beams** delivered to LHC flat bottom.
- Opened way for **ultra-high brightness beams** to be delivered in HL-LHC era
- **Individual bunches of 3.5×10^{11}** protons injected in LHC during MDs.

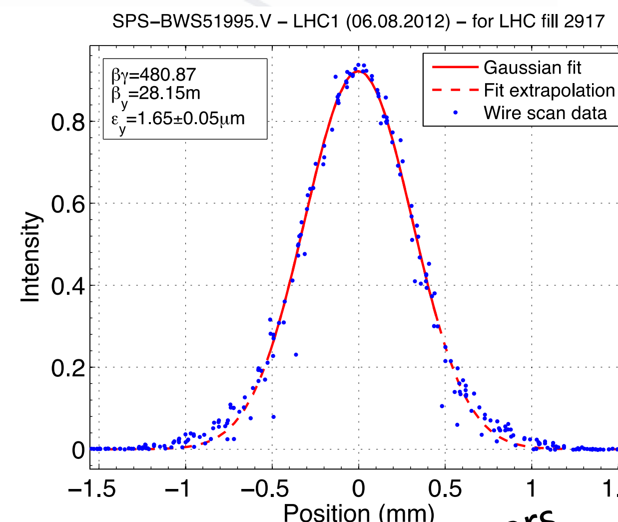


- Prepared **25ns beams** with Q20 (10/2012) for **scrubbing run** (12/2012).
- Used Q20 coupled to **new batch compression scheme of the PS** for tests in the LHC.
- Set-up and delivered LHC ion beam with Q20 optics during the **p-Pb run** (01-02/2013).

Measuring transverse emittances

- Very **small transverse beam sizes** and **few measurement points** with the wire scanners make it difficult to measure precisely the transverse emittances.

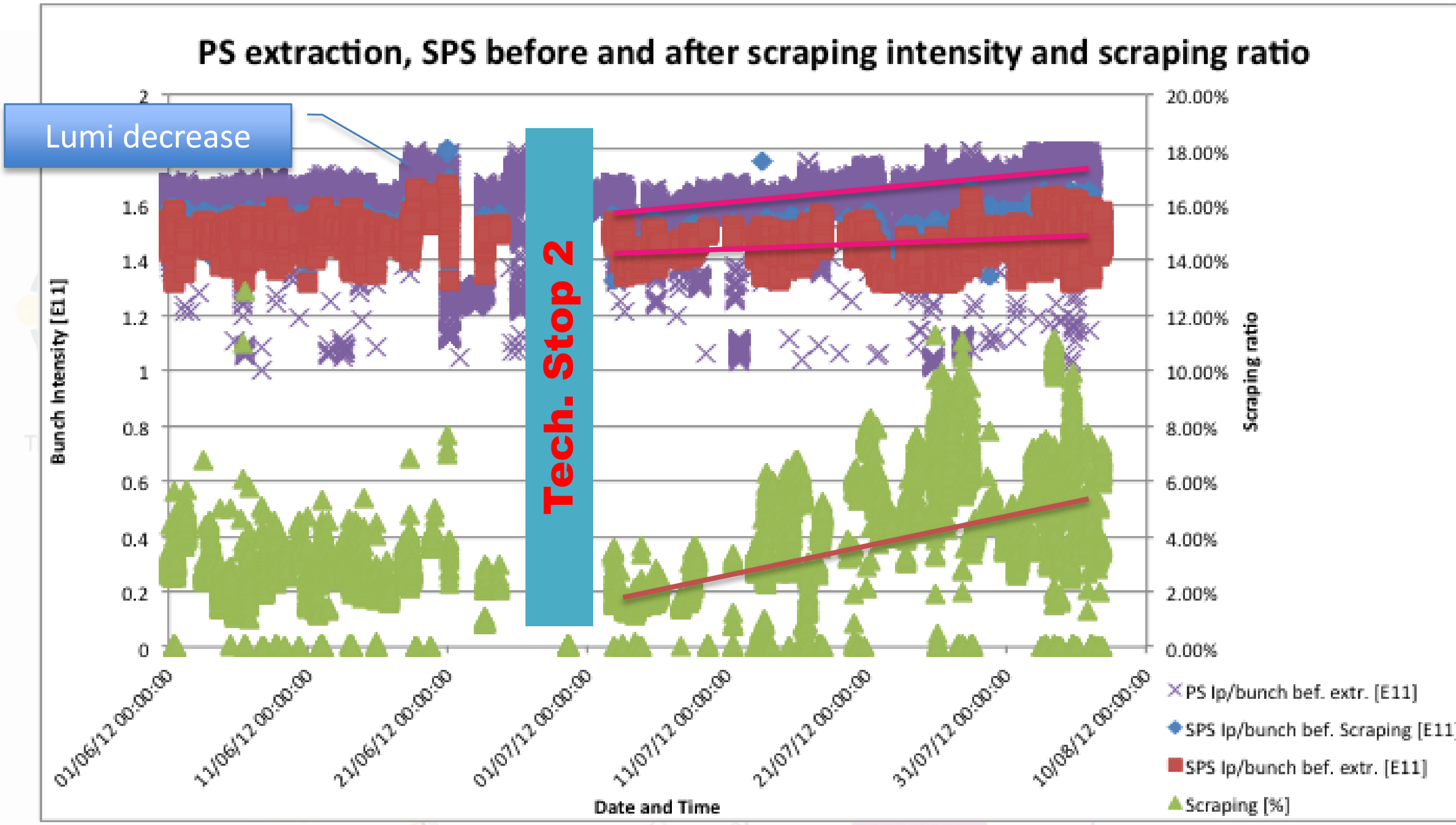




SPS wire scanners

- **Accumulating measurements** over several cycles **increases information** on tails etc., but **averages differences** between batches.
- LHC beam on SPS flat top is **beyond breakage limit of the wire**.

Pushing performance ?



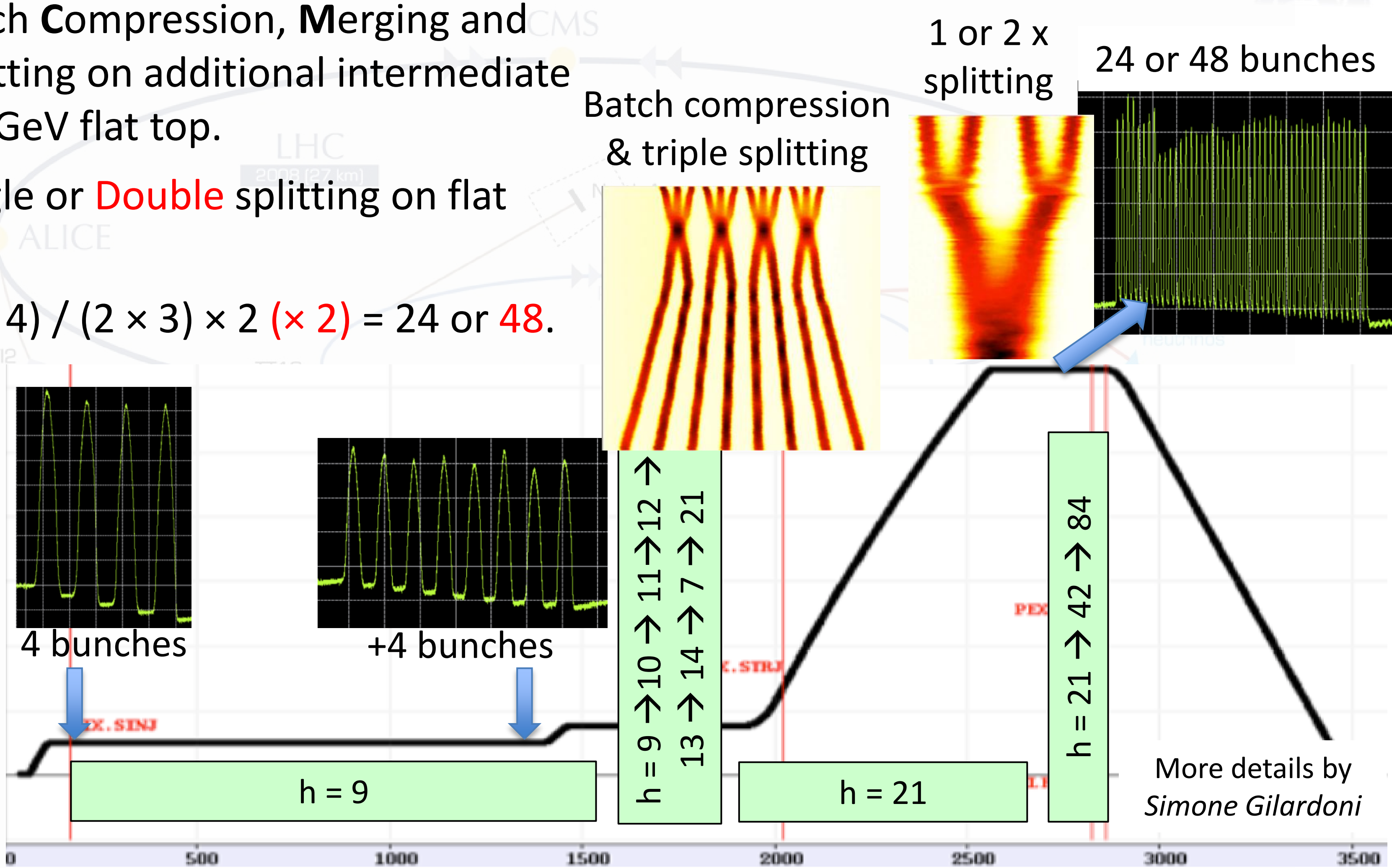
- Sometimes **intensity increase** is requested, but scraping is also increased to avoid tails. Net result **less luminosity.**
- Every increase of intensity should be **carefully adjusted along the whole injector chain**.

Some general performance remarks

- The adjustment of the recombination at extraction of the PS Booster is very important in order to keep transverse emittances in the PS small.
  - PS transverse damper was tested successfully in 2012.
- The PS magnetic field at injection is not 100% the same depending on the super cycle configuration, leading to differences between consecutive batches.
  - An “empty” LHC cycle was put before the filling cycles in the PS super cycle.
- Increasing intensity in the PS causes coupled bunch instabilities and increased bunch length spread in SPS.
  - Limited coupled bunch feedback available, using 2 of the 10 MHz cavities.
- No electron cloud issues in the SPS with the 50 ns beams as a result of “years” of scrubbing.
- Minimise time with LHC beam in the SPS for setting up and measurements, in view of kicker heating.

LHC 25ns and 50ns BCMS (LIU)

- **B**atch **C**ompression, **M**erging and **S**plitting on additional intermediate 2.5 GeV flat top.
- Single or Double splitting on flat top.
- (4 + 4) / (2 × 3) × 2 (× 2) = 24 or 48.



LHC BCMS 2012 test results

- Performance achieved for **classical and BCMS** beams in **2012**:

	Achieved Characteristics 2012											
	PSB extraction				PS extraction			SPS extraction				
	Ip / ring [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb bunches	Ip / bunch [x10¹¹]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches
Classical beams:											
LHC25	16	2.3	2	4 + 2	1.3	2.5	72	**1.35**	**~ 3**	0.7	1 - 4 x 72
LHC50	12	1.35	2	4 + 2	1.9	1.5	36	**1.65**	**1.65**	≤ 0.8	1 - 4 x 36
LHC25 BCMS	7.5	1	2	4 + 4	1.2	1.2	48	**1.15**	**1.4**	0.7	1 - 4 x 48
LHC50 BCMS	6	0.9	2	4 + 4	1.9	1.1	24	**1.6**	**1.2**	≤ 0.8	1 - 4 x 24

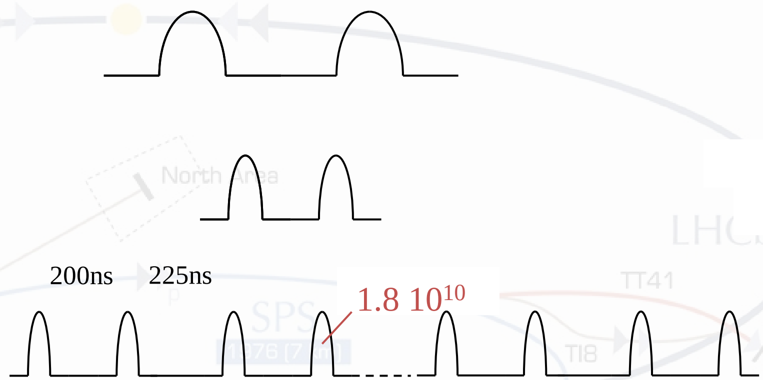
- The **BCMS (high brightness) beams are new** and were only really commissioned autumn 2012:
  - Although there were 3 partial LHC physics fills, these beams were **mainly used in an MD context** and **no operational experience** is available.
  - **More complex and delicate** production process in PSB and PS.
  - SPS working point fine with present brightness, beyond this adaptation is required.

- Some general machine performance figures
- Injectors for some of the fixed target physics
- LHC protons beam performance
- LHC ions beam performance
- Summary & concluding remarks

P-Pb alternating 200/225ns scheme in 2013

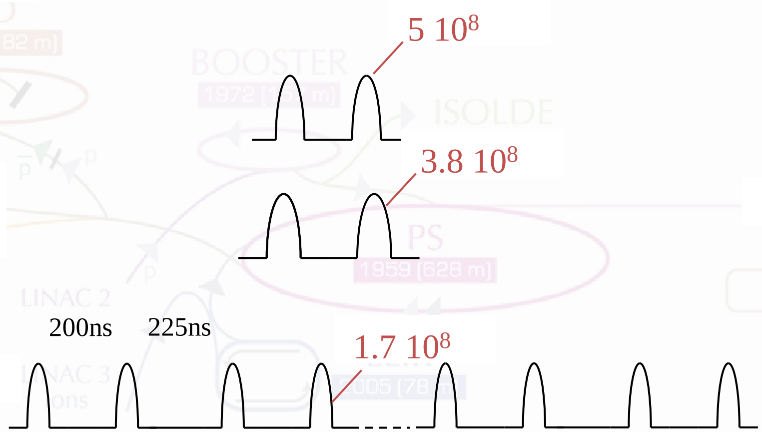
Protons

	No. of bunches		Harmonic number / Frequency
PSB (3.6 10^{10} protons)	2		2+1
PS batch ***compression*** bunch spacing = 200 ns	2		9-10-20 20-21 -84
SPS at extraction, after 12 transfers from PS, **Batch spacing = 225 ns**	24		200 MHz



Pb ions

	No. of bunches		Harmonic number / Frequency
LEIR (10^9 Pb ions / 3.6 s)	2		2
PS batch ***expansion*** bunch spacing = 200 ns	2		16–14-12-24 24-21 -169
SPS at extraction, after 12 transfers from PS, **Batch spacing = 225 ns**	24		200 MHz



Ions improvement and modification in 2013

- LINAC3
  - New mode for filling source, more stability
  - Changed longitudinal parameters (phase between tanks)

- LEIR
  - Continuous machine developments; better understanding of machine
  - Delayed run and preparation for fixed target allowed a longer preparation time

- PS
  - Shorter magnetic cycle, less prone to heating issues

- SPS
  - Operating with Q20 optics: less IBS and space charge on flat bottom
  - Improved RF noise on flat bottom

- OVERALL
  - Excellent performance (average bunch intensity in LHC ~2.5 x nominal)

- Some general machine performance figures
- Injectors for some of the fixed target physics
- LHC protons beam performance
- LHC ions beam performance
- Summary & concluding remarks

Summary & Concluding Remarks

- Very good overall machine availability and performance.
- Much progress was made in the injectors and performance for LHC beams was pushed.
  - Classical 50 ns beam became ~ 28% brighter in 2012.
  - Many machine developments were made for and by the LIU project.
- Continuous and careful adjustments are required to maintain high performance.
- Precise transverse emittance measurements with small transverse beam sizes becomes more and more difficult.

- Optimization in the injectors provides more and more bright beams, searching for every percent.
  - There is still a potential gain in the LHC, as there is about 30% transverse emittance blow up.