PERFORMANCE REACH OF THE INJECTORS IN 2011

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Thanks to the valuable input of:
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Contents

- The Documented Beam Characteristics
- Multi-Bunch Beam Production Schemes
- Obtained Beam Characteristics 2010
- Issues and Possibilities for 2011
- Concluding Remarks

Documented Beam Characteristics

Defined Characteristics 2004 (Source: LHC-OP-ES-0002 rev 1.0, EDMS: 487892)

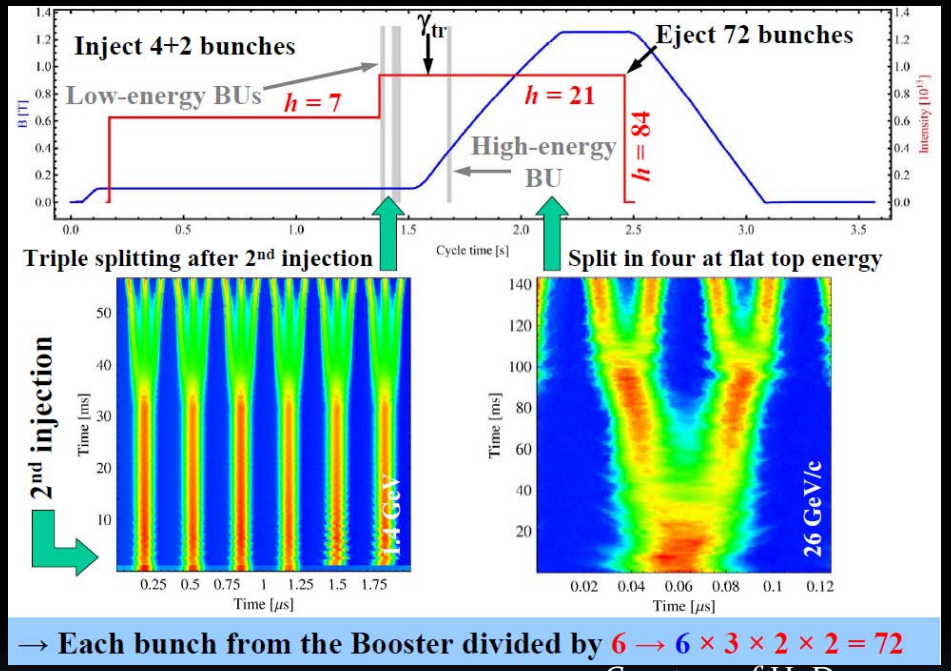
	PSB extraction				PS extraction			SPS extraction			
	Ip / ring [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb bunches	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches
LHCPROBE	0.05 - 0.2	≤ 1	1	1	0.05 - 0.2	≤ 1	1	0.05 - 0.2	≤ 1	≤ 0.3	1
LHCPILOT	0.05	≤ 2.5	1	1	0.05	≤ 3	1	0.05	≤ 3.5	≤ 0.8	1
LHCINDIV	0.2 - 1.15	≤ 2.5	1	1 to 4	0.2 -1.15	≤ 3	1 to 4	0.2 -1.15	≤ 3.5	≤ 0.8	1, 4 or 16
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
LHC75	0.8 - 4.6	≤ 2.5	2	4 + 2	0.2 -1.15	≤ 3	24	0.2 -1.15	≤ 3.5	≤ 0.8	1 - 4 x 24
LHC150	*0.8- 4.6*	*≤ 2.5*	*1*	*6*	*0.2 -1.15*	*≤ 3*	*12*	*0.2 -1.15*	*≤ 3.5*	*≤ 0.8*	*1 - 4 x 12*

- LHC150 was not considered before 2010
- Values in table assume 100% transmission along injectors
- $\varepsilon_{h/v}$ for all multi bunch beams from SPS ≤ 3.5 mm mrad at 1σ normalised
- LHC25, LHC50 and LHC75 initially all foreseen in double batch from PSB (4+2 bunches)
- LHC50 and LHC75 were converted to single batch injection into the PS with all characteristics well within specifications.

LHC25 Production Scheme & Issues

- Double batch injection from PSB (4 + 2 bunches)
- Triple splitting in PS
- Acceleration
- 2 x double splitting in PS
- Bunch rotation in PS
- ε_{Long} divided by a factor 12 and blown up by factor 3.23

  $\varepsilon_{Long\ final} = \varepsilon_{Long\ init} \times 3.23/12$
- $\varepsilon_{h/v} \approx$ nominal for nominal intensity of 1.15×10^{11} p/b

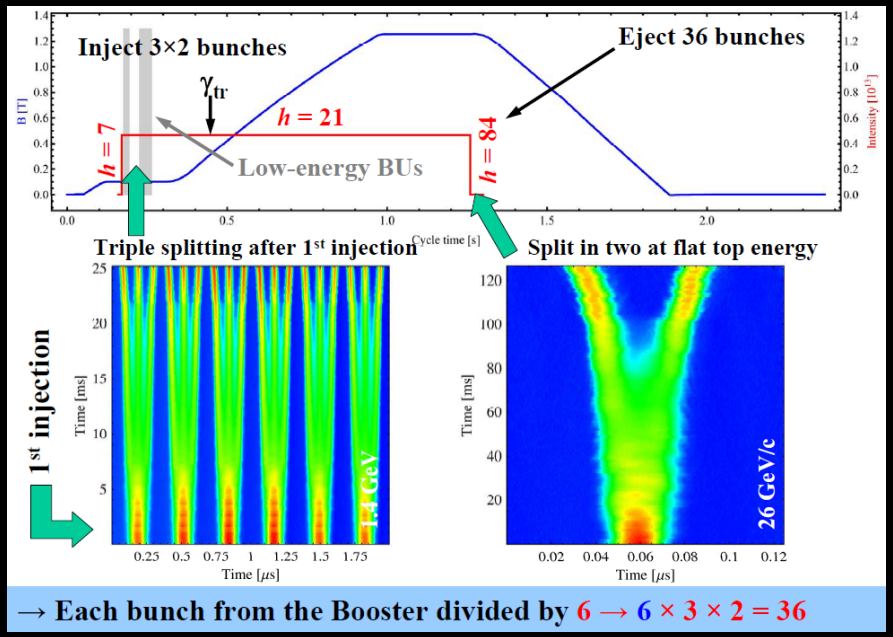


Courtesy of H. Damerau

- Dipolar longitudinal coupled bunch instabilities damped by feedback, using the 10 MHz cavities
- e^--cloud like instabilities have been observed in the PS when bunches before rotation are too short for too long time
- e^--cloud in SPS → scrubbing

LHC50 Production Scheme & Issues

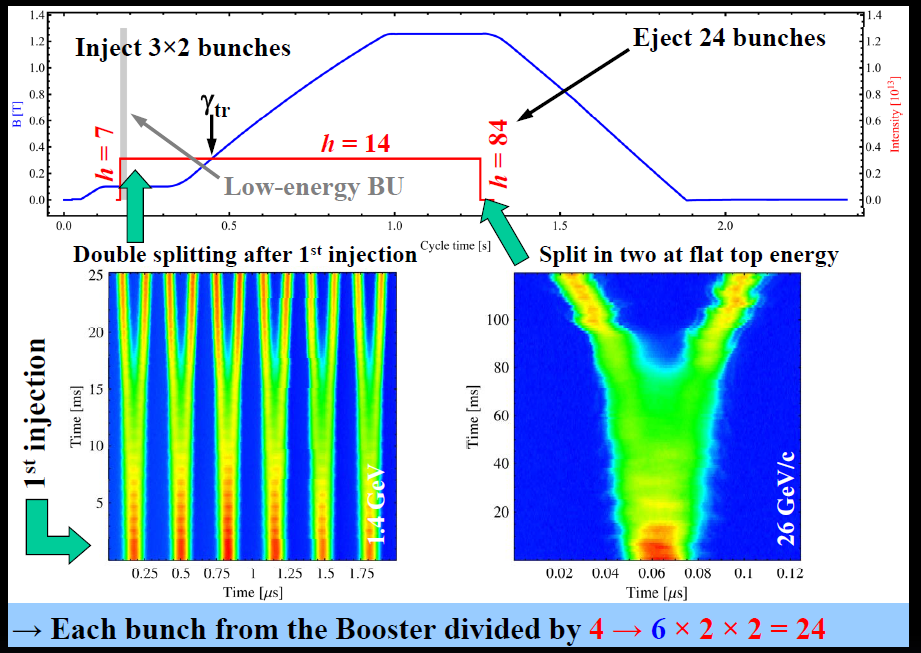
- Single batch injection from PSB (3 x 2 bunches)
- RF gymnastics in PSB
- Triple splitting in PS
- Acceleration
- Double splitting in PS
- Bunch rotation in PS
- One splitting less puts more constraints on ε_{Long}
- $\varepsilon_{Long\ final} = \varepsilon_{Long\ init} \times 2.33/6$
- $\varepsilon_{h/v} < \varepsilon_{nom}$ and well preserved along the chain
- Double batch injection: $\varepsilon_{h/v}$ even lower, providing potential for higher than nominal intensity
- Dipolar longitudinal coupled bunch instabilities damped by feedback, using 10 MHz cavities
- No limits observed in SPS with intensities reached until now



Courtesy of H. Damerau

LHC75 Production Scheme & Issues

- Single batch injection from PSB (3 x 2 bunches)
- RF gymnastics in PSB
- Double splitting in PS
- Acceleration
- Double splitting in PS
- Bunch rotation in PS
- Two splittings less puts more constraints on ε_{Long}
- $\varepsilon_{Long} = \varepsilon_{Long\ init}$ x 1.56/4
- $\varepsilon_{h/v} < \varepsilon_{nom}$ and well preserved along the chain
- Double batch injection : $\varepsilon_{h/v}$ even lower
- Longitudinal CBI not observed during the ramp with 1.3x10^{11} p/b
- Longitudinal CBI on PS FT → increase in ε_{Long} → risk of satellites in SPS
  - Extra gap relay and cavity in $f_{parking}$ give little improvement
  - No longitudinal damper to damp the right modes as they are not covered by the bandwidth of the 10 MHz cavities, used as feedback

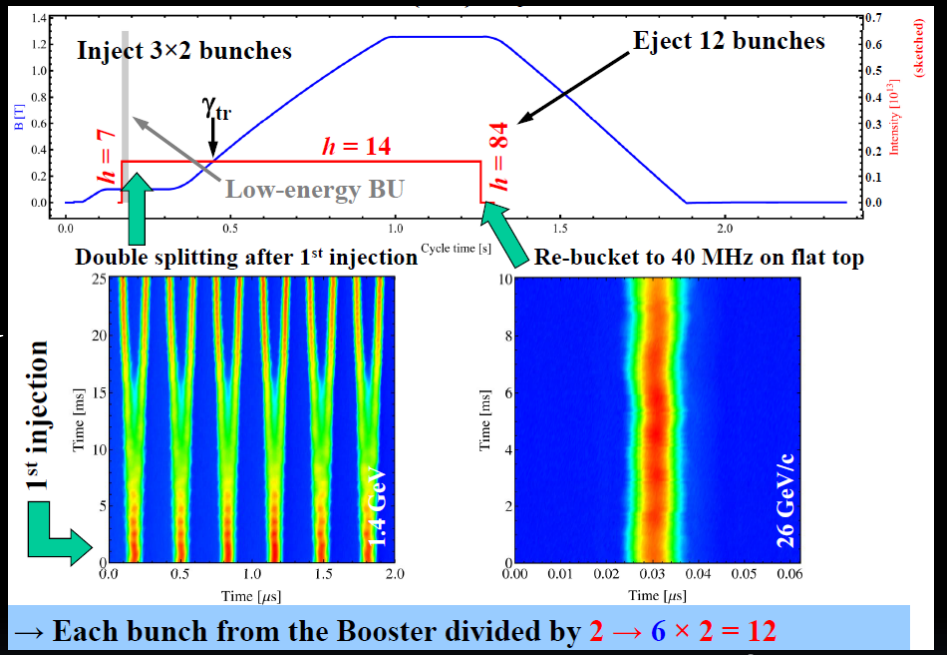


Courtesy of H. Damerau

LHC150 Production scheme

Newest beam
Least experience

- Single batch injection from PSB (3 x 2 bunches)
- RF gymnastics in PSB
- Double splitting in PS
- Acceleration
- Bunch rotation in PS
- Single splitting at low energy makes preservation of ε_{Long} major preoccupation
- $\varepsilon_{Long} = \varepsilon_{Long\ init}$ x 1.17/2
- $\varepsilon_{h/v} << \varepsilon_{nom}$ and well preserved along the chain
- Beam stable up to ~ 0.8x10^{11} p/b then quadrupolar bunch instabilities appears after crossing γ_t that compromise ε_{Long}
- Beam nevertheless delivered to LHC at nominal intensity of 1.1x10^{11} p/b at the exit of the SPS (up to 8 bunches from PS)



Courtesy of H. Damerau

LHC150 issues

- This beam was first considered and requested in 2010.
  - It was setup with very short notice
  - Little experience
- Small ε_{Long} from the start causes a quadrupolar bunch instability after transition crossing at already 2/3rd of the nominal intensity (~0.8x10^{11})
  - Quadrupolar instability causes longitudinal blow-up and might result in increased number of satellites at injection in SPS
  - Work is ongoing to improve the situation, but is in a very preliminary state
  - LHC only used less than 12 bunches out of the PS (4 or 8) → CBI will be worse for 12 bunches which was not used yet
- **Is it worth continuing spending time and money in improving this beam? How long do we still need this beam ?**

Obtained Beam characteristics 2010

Peak Performances !!!

Obtained Characteristics 2010

	PSB extraction				PS extraction			SPS extraction			
	Ip / ring [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	Nb bunches	Ip / bunch [x10^{11}]	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	3.6	≤ 0.8	1 - 4 x 72
LHC25 High int.	25	3.6/4.6	2	4 + 2	1.7 (1.9)	5	72	1.5	~ 10	~ 0.8	1 – 4 x 72
LHC50 (SB)	16	2.5	1	6	1.3	2.5	36	1.15	2.5	≤ 0.8	1 - 4 x 36
LHC50 High int. (SB)	24	3.5	1	6	1.8	3.5	36	1.5	3.5	≤ 0.8	1 - 4 x 36
LHC75 (SB)	11	1.5	1	6	1.3	1.8	24	1.2	2	≤ 0.8	1 - 4 x 24
LHC150	5	< 1.5	1	6	1.2	< 2	12	1.1	< 2.5 (1.6)	≤ 0.8	1 - 4 x 12

- LHC25 high intensity test May/June 2010:
  - $\varepsilon_{h/v}$ at 1σ in PS = ~ 5 mm mrad (>> 3 mm mrad)
  - $\varepsilon_{h/v}$ at 1σ in SPS increased along the ramp from ~ 5 mm mrad to ~ 10 mm mrad
  - Compromised longitudinal beam quality due to transient beam loading in the PS cavities. (compromised bunch to bunch reproducibility)

    ε_{Long} = ~ 0.4 eVs instead of 0.35 eVs
  - For 1.9x10^{11} the 4σ bunch length was 4.3 ns instead of < 4 ns
  - Beam was unstable in SPS
- The maximum bunch length and longitudinal emittance at PS-SPS transfer will have to be revisited in MD's in 2011
- LHC50 was pushed and offers 45% more intensity within otherwise nominal beam characteristics, but bunch to bunch reproducibility was compromised

See also presentation of E. Shaposhnikova for details on issues with these beams

Possible improvements for 2011

- Higher current from LINAC2 (180mA instead of 160mA):
  - Advantage: Increase of intensity while keeping transverse emittance constant (LHC DR, Vol. III page 15)
  - Issue: Presently not done because of lack of spare amplifier tubes
- Double batch injection LHC50/75:
  - Will surely result in smaller transverse emittances
  - Could potentially allow for higher intensities, but **how far can we go with LHC50/75 double batch ?** (MD time needed)

Issues (1/2)

- Returning to double batch for LHC50 and LHC75:
  - Lack of users, mainly in the PSB → They can share LHC25 with LHC50, but this will impose limitations on MD's and setting up
  - LHC75 has presently only 1 user in PSB
  - Very reliable archive system could alleviate the situation, but this will give longer switching periods (InCA should come immediately with 100% reliable archiving system)
  - Identical injection conditions for 2 batches injected in PS, otherwise emittance growth → PS B-field fluctuation issue not yet solved (impact remains to be evaluated)
  - Longer flat bottom on SPS cycles will result in longer filling time for the LHC
  - Advantage: Besides higher luminosity it will increase the resolution on the number of bunches that can be selected
    - LHC75 from 8 to 4 bunches per PSB ring
    - LHC 50 from 12 to 6 bunches per PSB ring

Issues (2/2)

- Voluntary transverse blow-up was requested by the LHC in 2010:
  - Presently done ad-hoc in any of the injectors
  - Strategy was decided to keep $\varepsilon_{h/v}$ as small as possible as long as possible and provide controlled blow–up in SPS
  - Presently SPS transverse damper is non-ppm.
  - The same is valid for the longitudinal blow-up
- e^--cloud:
  - SPS has issues with e^--cloud, especially for 25 ns beam, causing instabilities, kicker heating, etc. (scrubbing)
  - PS has observed e^--could with nominal 25 ns beam in the past. This was mitigated by keeping the beam as little time as possible at 40 MHz with not too short bunches
    - **However, what will happen when the beam characteristics are pushed well beyond nominal?**

Issues (2/3)

- No hot spare 80 MHz cavity available when ions in injectors
- Ghost bunches in SPS could perhaps be reduced by using three 80 MHz cavities
  - To be confirmed in an MD
  - Not compatible with ion operation
- Coupled bunch Instabilities for 150 ns (and 50 and 75 ns)
  - Limited feedback means available
  - Present feedback uses 10 MHz cavities and is limited in bandwidth
- Changing intensity or number of bunches on PS cycle means adjusting cavity phases for correct splitting
  - Reduced number of bunches is required for 1st (over)injection
- Injectors require more logging and analysis tools for LHC filling (intensity, last turn on bunch shape measurement, etc.)
  - We should be able to do a post mortem analysis of every cycle filling the LHC through the whole accelerator chain
  - Is possible, but needs support form CO and equipment groups

Possible Beam Characteristics 2011

- Single bunch beams no changes foreseen (nothing to gain)
- Concentrate on LHC75 and LHC50 with LHC150 as fall back
- Going to double batch for LHC75 and LHC50:
  - Lower emittances for identical intensities
  - Characteristics never really pushed with double batch
  - PS longitudinal CBI and transient beam loading consequences to be evaluated
  - Potential risk of SPS kicker out gassing
- Continue pushing LHC25 performance in injectors, but little margin, as beam characteristics are already (close to) nominal

Possible Beam Characteristics 2011

	Possible Characteristics 2011										
	PSB extraction				PS extraction			SPS extraction			
	Ip / ring [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb batches	nb bunches	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	nb bunches	Ip / bunch [x10^{11}]	ε_h and ε_v [mm · mrad] 1σ, norm.	ε_{longit} [eVs]	nb bunches
LHC25 (DB)	16	2.5	2	4 + 2	1.3	2.5	72	1.1 5	3.6	0.7	1 - 4 x 72
LHC50 (SB)	24	3.5	1	3 x 2	1.75	3.5	36	1.45	3.5	≤ 0.8	1 - 4 x 36
LHC50 (DB)	8	1.2	2	4 + 2	1.3	1.3	36	**1.15 (?)**	**1.5 (?)**	≤ 0.8	1 - 4 x 36
LHC75 (SB)	11	1.5	1	3 x 2	1.3	1.8	24	1.2	2	≤ 0.8	1 - 4 x 24
LHC75 (DB)	5.5	0.9	2	4 + 2	1.3	0.9	24	**1.2 (?)**	**1 (?)**	≤ 0.8	1 – 4 x 24
LHC150 (SB)	5	< 1.5	1	3x 2	1.2	< 2	12	1.1	< 2.5 (1.6)	≤ 0.8	1 - 4 x 12

- The LHC25 high intensity that was tested is not usable for the LHC
- The LHC50 and LHC75 single batch beams are known and verified, nevertheless they were produced during MD's. Some time will be needed to make them operationally available in a stable way

Stable Operational Performance ≠ Peak Performance

- The LHC50 and LHC75 double batch beams were not used in 2010.
  - LHC50DB characteristics remain to be confirmed and can perhaps be pushed
  - LHC75DB characteristics at extraction of SPS were never obtained, "tentative gues"
- The LHC150 not fully stable at nominal intensity, but seems to be usable for LHC

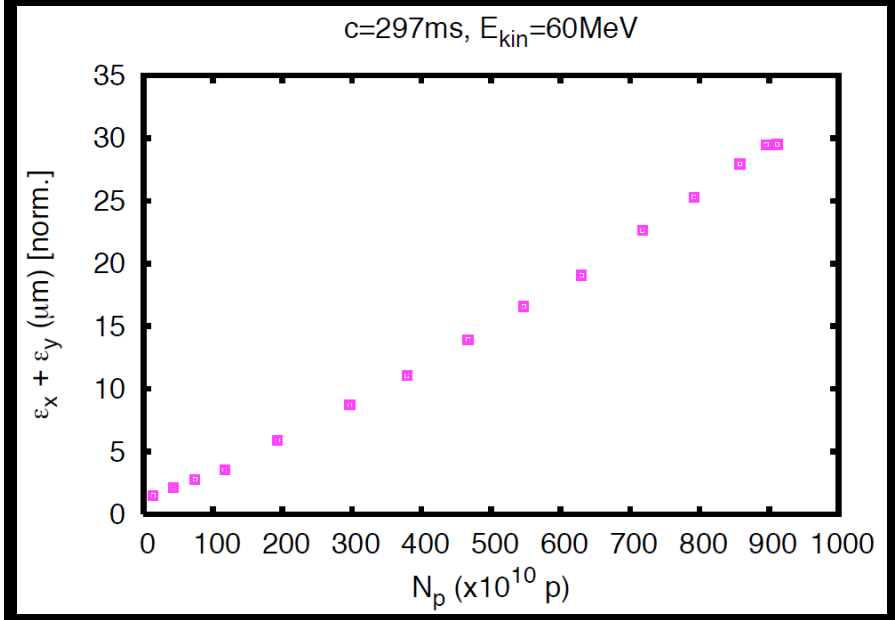
Concluding remarks

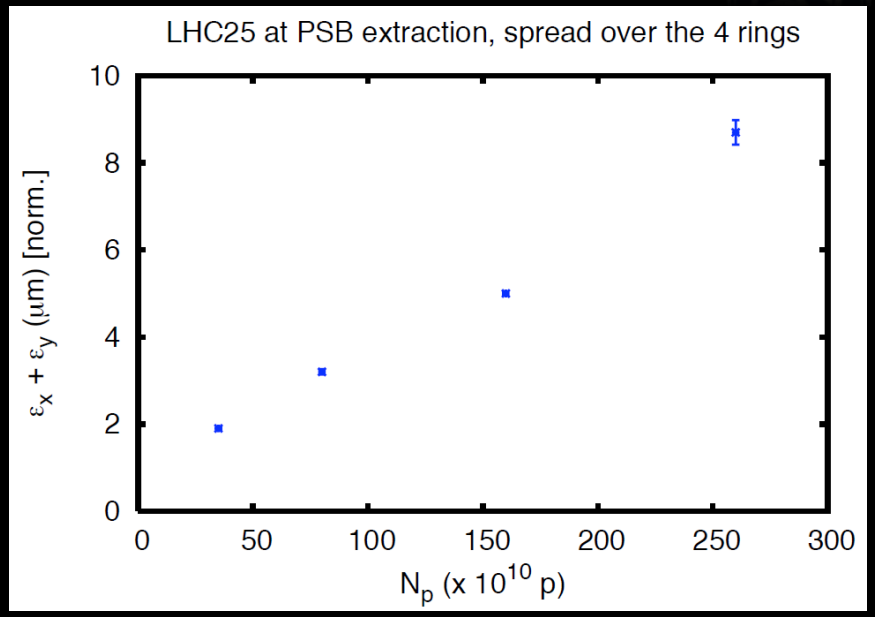
- The experience of 2010 led to a set of possible enhanced beam characteristics for the multi-bunch beams
- The major difficulties and limitations for of each of the multi-bunch beams have been listed
- MD's are needed to explore further improvements:
  - LHC75 (perhaps also LHC150) intensity increase
  - Setup double batch beams and confirm performances
  - Minimize impact of PS B-field fluctuations for double batch beams
  - …….many others….. (enough MD time needed)
- Returning to double batch beams will require a new way of working with the available number of users and will have an impact on MD's
- Controlled transverse and longitudinal emittance blow-up in SPS is requested to be ppm
- How long is the LHC150 still required and how many effort should we still put in it ?

- **The injectors need clear requirements sufficiently ahead of time to allow preparation of quality beams**
  - Provide understanding of the beam parameters that are critical for the LHC

Spare slides....

PSB transv. Emmittance vs intensity





From PSB team.....

PS transv. Emittance vs space charge

The tune shift generated by this bunch is: ΔQh =-0.34, ΔQv = -0.56

The horizontal emittance grows from 2.32 to 3.76, which is an increase of 62% during 1 second, while the vertical emittance grows from 1.61 to 2.03, which is only 22%. The sum of the horizontal and vertical emittance grows therefore by 43%