PERFORMANCE REACH OF THE INJECTORS IN 2011

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Abstract

The characteristics of the various LHC beams have been defined long before the LHC became operational. After a year of successful LHC running with the different types of LHC beams much experience has been gained in the LHC, but also in the injectors. This paper will summarise the defined and presently obtained beam characteristics of the LHC beams in the injector chain together with a brief overview of their production schemes and difficulties. Finally an outlook for 2011 will be presented, indicating the possible characteristics for the different LHC beams in the injector chain.

DOCUMENTED BEAM CHARACTERISTICS

The LHC beam characteristics for the 25 ns bunch spacing were defined at the beginning of this century. Once the 25 ns bunch spacing beam was available and tested in the different LHC injectors it became clear that beams with other bunch spacings, 50 ns and 75 ns, would be required. In 2004 the operational beam characteristics of all the LHC beam flavours were defined and summarized [1]. Table 1 gives an overview of these characteristics per accelerator in the LHC injector chain.

Although the 150 ns bunch spacing, indicated in italic at the bottom of table 1, was not yet specified in 2004, it has been added for completeness. The development of this additional flavour was requested late spring 2010 for use by the LHC in September 2010. The main parameters, besides the bunch spacing, that are important for the LHC, are the bunch intensity and transverse emittance at extraction of the SPS, which are identical for all multi-bunch beams. It should also be noted that the defined intensities for each machine do not take into account any beam losses in the injector chain. Therefore the upstream injector will have to provide slightly higher intensities making up for the losses. The PS typically delivers 1.3x10^{11} p/b for 1.15x10^{11} p/b extracted from the SPS. Another important observation is that the multi-bunch beams are all produced using double batch injection from the PS Booster into the PS; 4 bunches from the PS Booster during the 1st batch and 2 bunches during the 2nd batch, giving in total 6 bunches from the PSB that are then longitudinally split in the PS to the required number of bunches to be extracted towards the SPS.

MULTI-BUNCH BEAM PRODUCTION SCHEMES

The protons coming from LINAC2 are injected into the PS Booster using a classic multi-turn injection scheme. This means that the consecutive injected turns are accumulated in the horizontal phase space, resulting, in combination with coupling in the transverse plane, in approximately equal transverse emittances for both planes that increase proportionally with the number of turns and thus number of protons injected. This dependence is clearly visible from the measurements given in Fig. 1.

The total number of protons, required from the PS Booster to produce the different flavours of the multi-bunch LHC beams in the PS and SPS, varies proportionally with the number of bunches required at PS extraction.

Table 1: Documented LHC beam characteristics for the injectors [1]

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb batch**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**$\varepsilon_{long.}$ bunch [eVs]**	**nb bunch**
PROBE	0.05 – 0.2	≤ 1	1	1	0.05 – 0.2	≤ 1	1	0.05 – 0.2	≤ 1	≤ 0.3	1
PILOT	0.05	≤ 2.5	1	1	0.05	≤ 3	1	0.05	≤ 3.5	≤ 0.8	1
INDIV	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
25 ns	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
50 ns	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
75 ns	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
150 ns	*0.8 – 4.6*	*≤ 2.5*	*1*	*3 x 2*	*0.2 – 1.15*	*≤ 3*	*12*	*0.2 – 1.15*	*≤ 3.5*	*≤ 0.8*	*1 – 4 x 12*

Therefore the transverse emittance of the different multi-bunch beams with different bunch spacing will decrease as the bunch spacing at the PS extraction increases.

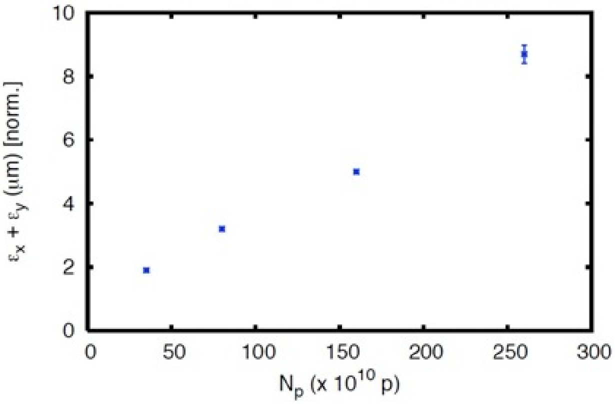

Figure 1: The sum of transverse horizontal and vertical emittance versus accelerated intensity in the PS Booster.

25 ns beam

The LHC multi-bunch beam with a bunch spacing of 25 ns is produced in the PS [2][3], using a double batch injection from the PS Booster, with 4 bunches injected during the first injection and 2 bunches 1.2 seconds later during the second injection. This gives a total of 6 bunches in the PS with an RF harmonic of h=7, leaving 1 bucket empty. Figure 2 illustrates the PS cycle with the long flat bottom, clearly indicating the two batches injected form the PS Booster.

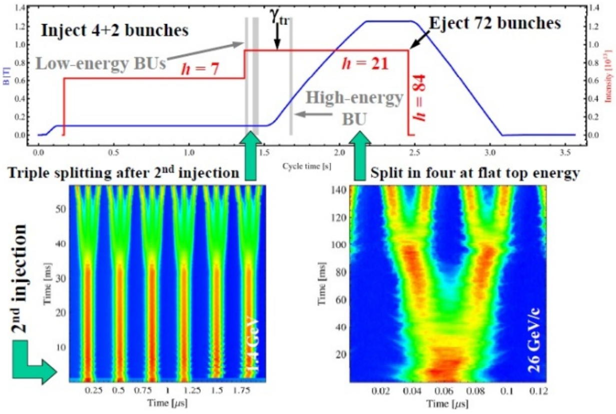

Figure 2: LHC 25 ns beam PS production scheme.

Once all 6 bunches are in the PS each bunch is split in 3 by changing the RF harmonic from h=7 through h=14 to H21, giving 18 bunches and leaving 3 buckets empty as is shown in the water fall plot in the left hand bottom of Fig. 2. Before and after this splitting process a controlled longitudinal blow-up is applied to obtain the desired longitudinal emittance before accelerating the beam through transition, indicated in Fig. 2 by the vertical gray bars. After acceleration to 26 GeV/c the beam is twice split in 2, increasing the number of bunches from 18 to 72, leaving 12 buckets empty to accommodate the rising edge of the extraction kicker. Just before extraction the bunches are rotated in longitudinal phase space using a non-adiabatic bunch rotation scheme for which the voltage of the 40 MHz and 80 MHz cavities is increased rapidly.

The initial longitudinal emittance received from the PS Booster is divided by a factor 12 as a result of the multiple longitudinal splittings. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 3.23. Therefore the final longitudinal emittance can be calculated using Eq. 1.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{3.23}{12} \qquad (1)$$

The final longitudinal characteristics taking into account the high energy blow up after transition crossing are a bunch length < 4 ns and a longitudinal emittance of 0.35 eVs. The transverse emittance provided by the PS Booster is well preserved during acceleration and results in a round beam at PS extraction with transverse normalised emittances in both planes of 2.5 μm at 1σ and a bunch intensity of $1.3\text{x}10^{11}$ p/b.

During acceleration in the PS a dipolar longitudinal coupled bunch instability is damped using a feedback on 2 of the 10 MHz cavities as longitudinal kickers.

In 2001, e^--cloud like instabilities have been observed at high energy in the PS. In order to avoid these instabilities the processes of adiabatic bunch shortening and bunch rotation have been optimised to keep short bunches as little time as possible at 40 MHz.

The SPS suffers from, e^--cloud instabilities and therefore requires scrubbing in order to decrease the secondary electron emission yield of the vacuum chamber. When this scrubbing has been done the beam at extraction in the SPS has the characteristics as given in Table 1.

This beam also suffers from longitudinal coupled-bunch instabilities in the SPS, which are cured by using a 4th harmonic RF system and controlled longitudinal emittance blow-up [5].

50 ns beam

Initially the LHC multi-bunch beam with 50 ns bunch spacing was foreseen to be produced using double batch injection in the PS [2][3]. At extraction of the PS this beam provides 36 bunches spaced by 50 ns. The intensity per bunch remains the same as for the 25 ns beam. Therefore the PS Booster injects fewer protons per ring, resulting in much smaller transverse emittances than specified in Table 1. In 2009 it was decided to produce this beam using a single batch injection, reducing the time the beam has to wait on the PS flat bottom for the second batch injection, while remaining within the specified beam characteristics of Table 1.

Presently the 50 ns beam in the PS Booster is produced with 2 bunches from 3 PS Booster rings, requiring longitudinal bunch splitting and bunch phasing in order to be compatible with the PS injection at RF harmonic h=7. Figure 3 shows a tomogram of the two bunches beam at extraction of the PS Booster, clearly illustrating the h=1 and h=2 buckets, required for the correct phasing of the bunches.

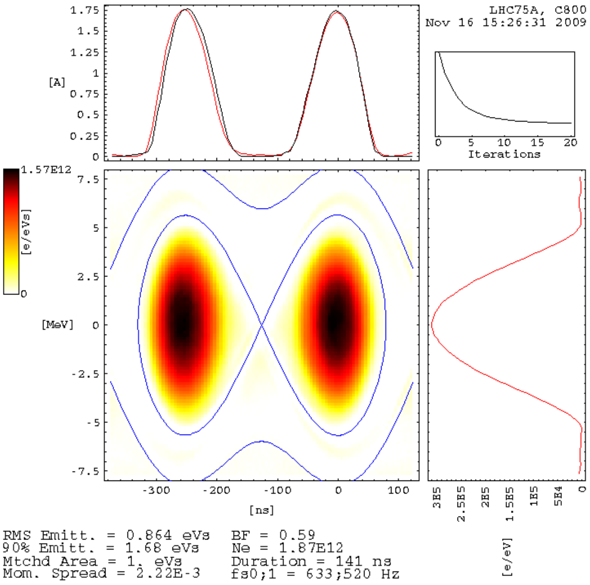

Figure 3: The longitudinal tomogram of the 2 bunches per ring at extraction in the PS Booster.

Figure 4 illustrates the PS cycle for the production of the 50 ns beam, clearly indicating the single batch injection from the PS Booster.

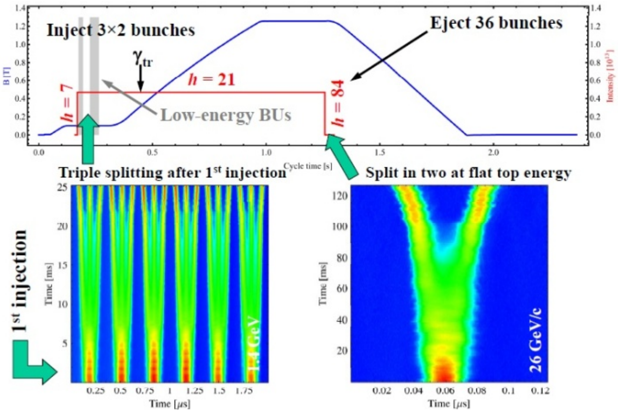

Figure 4: LHC 50 ns beam PS production scheme.

Once the 6 bunches are in the PS each bunch is split in 3 in exactly the same way as is done for the 25 ns beam. The difference with respect to the 25 ns beam lies mainly in the longitudinal bunch splitting at 26 GeV/c.

The 18 bunches are each split in 2, resulting in 36 bunches on RF harmonic h=84 with 1 out of 2 buckets filled and 12+1 buckets empty to accommodate the extraction kicker rising edge. The final non-adiabatic bunch rotation results in the same longitudinal bunch characteristics as for the 25 ns beam.

The initial longitudinal emittance received from the PS Booster is divided by a factor 6 as a result of the multiple longitudinal splitting. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 2.33. Therefore the final longitudinal emittance can be calculated using Eq. 2.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{2.33}{6} \qquad (2)$$

The final longitudinal characteristics are a bunch length < 4 ns and a longitudinal emittance of 0.35 eVs. The transverse emittance provided by the PS Booster is well preserved during acceleration and results in a round beam at PS extraction with transverse normalised emittances in both planes < 2.5 μm at 1σ and a bunch intensity of 1.3×10^{11} p/b.

During acceleration in the PS a dipolar longitudinal coupled bunch instability is damped using a feedback on 2 of the 10 MHz cavities.

No e^--cloud like instabilities have been observed neither in the PS nor in the SPS and the beam at the exit of the SPS is well within the characteristics given in Table 1. In case the longitudinal emittance from the PS is smaller than 0.35 eVs a controlled longitudinal blow up is applied in the SPS [5].

75 ns beam

Initially the LHC multi-bunch beam with 75 ns bunch spacing was also foreseen to be produced using double batch injection in the PS [2][3]. At extraction of the PS this beam provides 24 bunches spaced by 75 ns. However, the intensity per bunch remains the same as for the 25 ns and 50 ns beams. Therefore the PS Booster will inject fewer protons per ring, resulting in much smaller transverse emittances than specified in Table 1. In 2009 it was decided to produce this beam using single batch injection while remaining within the specified beam characteristics of Table 1.

Presently the 75 ns beam in the PS Booster is produced in the same way as for the 50 ns single batch injection beam with two bunches from three PS Booster rings.

Figure 5 illustrates the PS cycle for the production of the 75 ns beam, which is magnetically identical to the 50 ns single batch cycle.

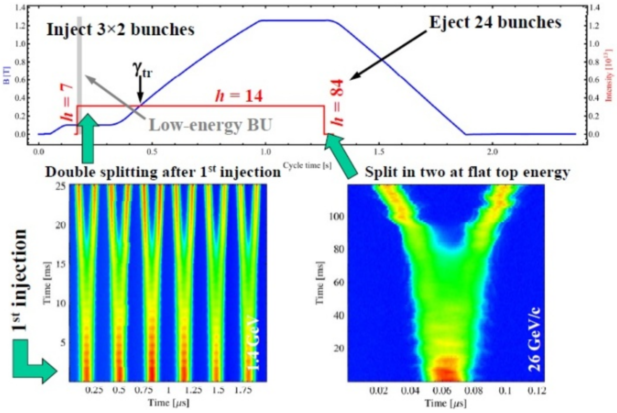

Figure 5: LHC 75 ns beam PS production scheme.

. Once the 6 bunches are in the PS each bunch is split in 2 and not in 3 as is done for the 25 ns and 50 ns beams. The 12 bunches are then accelerated using RF harmonic h=14 up to 26 GeV/c. On the flat top the beam is longitudinally split in 2, again followed by a non-adiabatic bunch rotation prior to extraction

The initial longitudinal emittance received from the PS Booster is divided by a factor 4 as a result of the multiple longitudinal splitting. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 1.56. Therefore the final longitudinal emittance can be calculated using Eq. 3.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{1.56}{4} \tag{3}$$

The final longitudinal characteristics are a bunch length < 4 ns and a longitudinal emittance of 0.35 eVs. The transverse emittance provided by the PS Booster is well preserved during acceleration and results in a round beam at PS extraction with transverse normalised emittances in both planes of < 2.5 μm at 1σ and a bunch intensity of $1.3\text{x}10^{11}$ p/b.

The longitudinal coupled bunch instability in the PS that is observed on the 25 ns and 50 ns beams during the ramp after transition crossing does not develop on the 75 ns beam. However, there is a longitudinal coupled bunch instability on the 26 GeV/c flat top that is a potential source of longitudinal emittance blow up and can therefore produce satellite bunches in the SPS. The longitudinal feedback based on 2 of the 10 MHz cavities cannot damp this instability as it requires frequencies that are beyond the bandwidth of the cavities. Means to reduce the longitudinal impedance sources for this instability, like adding more gap relays and putting the inactive cavities on a parking frequency, are being explored. The effectiveness of these measures will be evaluated during the 2011 run.

The SPS has no e^--could issues with this beam and at extraction from the SPS the beam is within the required characteristics as given in Table 1.

150 ns beam

The 150 ns beam is the youngest among the multi-bunch beams for the LHC. The request for this beam came late spring 2010 for use by the LHC in September, leaving a very short period for setting up such a beam and optimizing it for nominal performance, as specified in Table 1. At the extraction of the PS this beam provides 12 bunches at nominal intensity spaced by 150 ns. Therefore the PS Booster will inject even fewer protons per ring than for example with the 75 ns beam, resulting in much smaller transverse emittances than specified in Table 1.

The beam production in the PS Booster is based on the 75 ns beam, which normally provides a longitudinal emittance of 0.9 eVs at extraction, but which was brought down to 0.5 eVs. The 2 bunches produced in each of the 3 rings used are injected in the PS at RF harmonic h=7.

Figure 5 illustrates the PS cycle for the production of the 150 ns beam, clearly indicating the single batch injection from the PS Booster.

After injection the only controlled longitudinal blow up in the cycle is applied to increase the incoming bunches from 0.5 eVs to 0.6 eVs in order to achieve a good symmetric splitting in 2 of each bunch, resulting already at this stage in the 12 bunches on RF harmonic h=14 with a longitudinal emittance close to 0.35 eVs, as required at extraction, leaving very little margin for any non-controlled longitudinal blow up. After acceleration, but just before extraction the bunches are rotated non-adiabatically using the 40 and 80 MHz cavities in order to obtain the required longitudinal characteristics; bunch length < 4 ns and a longitudinal emittance of 0.35 eVs.

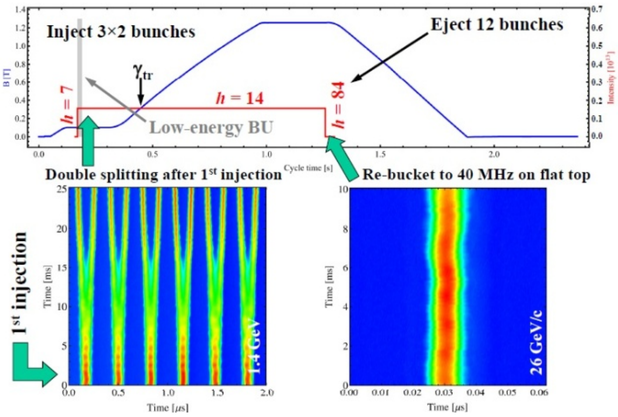

Figure 5: LHC 150 ns beam PS production scheme.

The initial longitudinal emittance received from the PS Booster is divided by a factor 2 as a result of the double splitting. The controlled and uncontrolled longitudinal blow up along the PS cycle amounts to a factor of 1.17. Therefore the final longitudinal emittance can be calculated using Eq. 4.

$$\varepsilon_{long\ final} = \varepsilon_{long\ initial} \times \frac{1.17}{2} \tag{4}$$

During acceleration, after transition crossing, the beam with an intensity of > $0.8\text{x}10^{11}$ p/b develops a quadrupolar coupled bunch instability, driven by the 40 and 80 MHz cavities and compromising the already very tight longitudinal emittance budget in the PS. A measurement of the quadrupolar bunch shape during the instability is given in Figure 6.

The beam with nominal intensity per bunch was nevertheless taken by the SPS and LHC up to a maximum of 8 instead of 12 bunches per PS extraction. The consequences of the quadrupolar longitudinal coupled bunch instability, satellite bunches due to too large longitudinal emittance, will most probably be more important for 12 bunches than observed when only 8 bunches were taken.

The transverse emittance provided by the PS Booster are well preserved during acceleration and result in a round beam at PS extraction with transverse normalised emittances in both planes < 2.5 μm at 1σ and a bunch intensity of 1.3x10^{11} p/b.

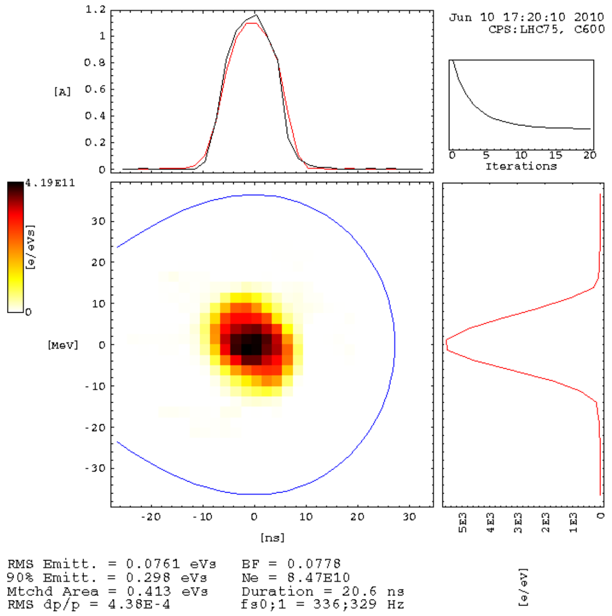

Figure 6: Tomogram of a LHC 150 ns bunch in the PS during the quadrupolar coupled bunch instability. The bunch is not matched, but slightly stretched.

2010 OBTAINED BEAM CHARACTERISTICS

The multi-bunch beams as described in the previous section have been used in the LHC injector chain, mainly for machine development purposes. Some of the beams were pushed to higher intensities with the aim to explore limitations in the different injectors.

Table 2 gives an overview of the peak performances for the different LHC multi-bunch beams, achieved in 2010. These peak performances can by no means be considered as stable operational performances for the near future.

More details on the machine development studies that led to these performances can be found in [5].

The 25 ns beam as indicated in the first row of Table 2 has been produced close to, but within the specifications as given in Table 1. The transverse emittance at extraction of the SPS can perhaps be slightly reduced as will be proposed in the next section

In May and June 2010 the 25 ns beam intensity was pushed well beyond nominal, indicated in Table 2 as “25 ns HI”. A respectable 1.5x10^{11} p/b was produced at high energy in the SPS, but the transverse emittances were nearly a factor 3 higher than nominal. In addition the longitudinal beam quality was compromised due to transient beam loading in the PS cavities that caused degradation in the bunch-to-bunch reproducibility. The beam was also unstable in the SPS.

The 50 ns single batch beam with nominal intensity per bunch was produced and resulted in transverse emittances at high energy in the SPS that are much smaller, 2.5 μm, than nominal, 3.5 μm, showing excellent transverse emittance preservation from the PS Booster until the SPS extraction. During a machine development session the intensity on this beam was increased for which the beam characteristics are given in Table 2 in the row indicated by “50 ns SB HI” The maximum intensity obtained was 1.52x10^{11} ppb. The transverse emittance of 3.5 μm was measured at low energy in the SPS and is thus no guarantee for transverse emittances at extraction, which will have to be measured. In addition the bunch-to-bunch reproducibility, mainly in terms of bunch intensity along the batch, was compromised. Nevertheless this beam provides a large prospective for the LHC in terms of luminosity and deserves therefore further consideration.

The 75 ns beam was produced with nominal bunch intensity with much smaller transverse emittances, 2 μm, at extraction than specified in Table 1. However, presently the intensity is limited by the longitudinal coupled bunch instabilities observed on the 26 GeV/c flat top in the PS for which no longitudinal feedback is available.

Table 2: Obtained LHC beam characteristics for the injectors in 2010 (peak performances)

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb batch**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**$\varepsilon_{long.}$ bunch [eVs]**	**nb bunch**
25 ns	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.6	≤ 0.8	1 - 4x 72
25 ns HI	25	3.6/4.6	2	4 + 2	1.7 (1.9)	5	72	1.5	~ 10	≤ 0.8	1 - 3 x 72
50 ns SB	16	2.5	1	3 x 2	1.3	2.5	36	1.15	2.5	≤ 0.8	1 - 4 x 36
50 ns SB HI	24	3.5	1	3 x 2	1.8	3.5	36	1.5	(3.5)	≤ 0.8	1 - 4 x 36
75 ns SB	11	1.5	1	3 x 2	1.3	1.8	24	1.2	2	≤ 0.8	1 – 4 x 24
150 ns SB	5	< 1.5	1	3 x 2	1.3	< 2	12	1.2	≤ 2.5 (1.6)	≤ 0.8	1 – 4 x 12

Further studies in 2011 will have to confirm if the proposed measures, like extra gap relays for the 10 MHz cavities and putting the inactive high frequency cavities on a parking frequency, will cure or at least reduce the instability, allowing for a potential increase of intensity.

Finally the 150 ns beam was used extensively and successfully by the LHC during the last period of the proton run. The transverse emittance was blown up in a controlled way in the PS to meet the requirements of the LHC, which was ~2.5 µm. The beam, without controlled transverse blow up, has a transverse emittance of ~ 1.6 µm at extraction of the SPS, which was taken once by the LHC for a test. In case this beam will be required for a longer period of time by the LHC its performance, especially in terms of longitudinal stability for intensities beyond 0.8×10^{11}, needs to be improved, requiring studies, machine developments and possibly hardware modifications on the RF equipments.

POSSIBILITIES AND ISSUES FOR 2011

Possible improvements

Two improvements that potentially can be implemented in a short period of time and that will be of benefit for the brightness of the multi-bunch LHC beams out of the injectors are:

- The increase of the beam current at the exit of LINAC2 from presently ~ 160 mA to 180 mA as specified in [4]. The main advantage is an intensity increase at injection in the PS Booster for constant transverse emittance.
- Returning to double batch injections for the 50 ns and 75 ns variants of the multi-bunch beams. The main advantage will be the reduced transverse emittance of the beams coming from the PS Booster because fewer turns have to be accumulated in the horizontal phase space for the production of a single bunch per ring.

Issues

The increase of the LINAC2 current from the presently 160 mA to 180 mA, as specified [4], requires, in addition to a very good conditioned source, an increase of the amplifier tubes’ anode voltage, a parameter that will then be applied for all LINAC pulses and not just the ones producing the high brightness LHC beams. This increase of anode voltage reduces significantly the life time of these tubes.

Last year the RFQ started sparking after increasing the intensity, in particular when many high intensity beams like ISOLDE and CNGS were present in the PS Booster super cycle. Therefore the increase will have to be tested thoroughly and should be justified.

Returning to double batch injections for the PS will surely result in smaller transverse emittances and provide potential to increase the intensity per bunch. However, it is presently not clear how large this potential is. This will have to be explored during machine development sessions in 2011.

It will also require more beams to be setup, in particular in the PS Booster as each “user” in the PS will require 2 “users” in the PS Booster. The maximum number of “users” available is limited to 24 and cannot be extended due to hardware limitations in the control system. Presently all 24 “users” in the PS Booster are assigned to different beams, required for LHC, non-LHC physics and machine developments. Therefore it will require a new way of working with the available number of “users”, relying heavily on a 100% unfailing archiving system to restore archived settings in the machine hardware, depending on the needs of the LHC. As a consequence the switching times between the different multi-bunch beams might be longer and some limitations on machine developments may arise. This way of working will therefore impose careful planning of the required beams in order to leave time for validation after restoring an archive.

Double batch injection in the PS also requires very good magnetic field stability, with identical conditions for both injections, 1.2 seconds apart. Presently the PS suffers from fluctuations of ~ 0.5% on the magnetic field at injection, but this goes unnoticed for the single batch injected beams. The consequences, in terms of transverse emittance growth, will have to be evaluated during setting up or machine development sessions in 2011 and all efforts will have to be applied to reduce the injection field fluctuations.

Another consequence of double batch injection is the lengthening of the PS cycles from 2.4 seconds to 3.6 seconds, resulting in a longer flat bottom in the SPS and this a longer filling time for the LHC.

An advantage of returning to double batch injection is the increased resolution of the number of bunches that can be selected by switching on or off PS Booster rings. For the 75 ns beam this will go from 8 bunches per PS Booster ring for single batch injection to 4 bunches per PSB ring for double batch injection. For the 50 ns beam this will go from 12 to 6 bunches per PSB ring. This increased resolution might be useful for the injection scheme as used in the LHC, where after the injection of the Probe beam the first multi-bunch injection will take place with a reduced number of bunches with respect to the remainder of the filling with bunch trains. However, the switch of the number of bunches between the first and second injection of the multi-bunch beam in the LHC has also consequences in the PS. In order to keep the bunch splitting symmetric a few cavity phase related parameters in the PS need to be adjusted manually. Approaches to making these changes more automatic and less prone to human error are being explored.

Other issues not necessarily related to returning to double batch injection are:

- Controlled transverse blow up; following the small transverse emittances of the LHC beams, but in particular for the 150 ns beam, the LHC required a controlled transverse emittance blow up. A few years ago a strategy, to preserve the transverse emittances as long as possible in the injector chain, was decided and it was defined that the controlled blow up to tailor the final required transverse emittance would be done in the SPS. Due to limitations on the SPS transverse damper settings, for the different multi-bunch beams, this blow up is presently done ad-hoc in either the PS Booster or the PS, with the risk of losing track of where different blow ups are performed. It is therefore requested that the settings of the SPS transverse damper can be different for the different users (ppm-mode)

- Controlled longitudinal blow up; the same request as for the controlled transverse blow up was made for the controlled longitudinal blow up in the SPS, which was implemented during the 2010 – 2011 technical stop and will be operational for the 2011 run.
- When ions are produced in parallel in the PS, 2 of the 80 MHz cavities are tuned for protons and 1 for ions, leaving no hot spare in case one of the cavities breaks and a manual intervention will have to take place in order to retune a cavity excluding the nominal production of either ions or protons.
- Satellite bunches can be a result of too long bunches or too large longitudinal emittances extracted from the PS and injected in the SPS. Using a 3rd 80 MHz cavity at extraction in the PS can result in shorter bunches for larger longitudinal emittances. The effectiveness of this will have to be confirmed during machine development sessions in 2011. This proposal is not compatible with ion operation in the PS, unless an additional cavity or pulse-to-pulse tuning can be installed.
- The injectors will require more logging in order to make post mortem analysis on issues that happen during the filling of the LHC possible. As an example it would be very useful to have the wall current monitor signals in the injectors digitised and logged during the last turn of each cycle going to the LHC. These extensions to the logging capabilities in the injectors will require investments in terms of money and support from the equipment groups.

Possible 2011 beam characteristics

For the single bunch beams no changes are foreseen as there is little or nothing to gain. However, the emphasis should be on the 50 ns and 75 ns beams, with the 150 ns as fall back solution. Returning to the double batch injection for the 50 ns and 75 ns beams together with further development of these beams could not alone lead to smaller emittances, but also to higher than nominal bunch intensities.

However kicker out gassing and e-cloud issues in the SPS will have to be evaluated and dealt with for the enhanced performance of the different beams.

Table 3 provides a list of realistic beam characteristics that can be obtained in 2011 for operational use to fill the LHC.

The 25 ns beam with double batch injection is produced within the nominal characteristics and leaves little margin for improvement. The only possibility to enhance the performance of this beam within the present production scheme can be obtained by increasing the LINAC2 source current to 180 mA, which will lead to smaller emittances and potentially allows for injecting more protons and return to the nominal emittances.

The performance of the 50 ns and 75 ns single batch injection beams is known from last years' experience. Nevertheless they were produced during machine development sessions and some time will be needed to make them operationally available in a stable way.

The 50 ns and 75 ns double batch beams were not used since a long time. Therefore the 50 ns beam characteristics given in Table 3 remain to be confirmed and can perhaps be enhanced further during machine development sessions.

Table 3: Possible 2011 LHC multi-bunch beam characteristics for the injectors

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb batch**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**nb bunch**	**Ip/bunch [x10^{11}]**	**$\varepsilon_{h/v}$ [μm] 1σ norm.**	**$\varepsilon_{long.}$ bunch [eVs]**	**nb bunch**
25 ns DB	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.6	0.7	1 - 4 x 72
50 ns SB	24	3.5	1	3 x 2	1.75	3.5	36	1.45	~ 3.5	≤ 0.8	1 - 4 x 36
50 ns DB	8	1.2	2	4 + 2	1.3	1.3	36	1.15 (?)	1.5 (?)	≤ 0.8	1 - 4 x 36
75 ns SB	11	1.5	1	3 x 2	1.3	1.8	24	1.2	2	≤ 0.8	1 - 4 x 24
75 ns DB	5.5	0.9	2	4 + 2	1.3	0.9	24	1.2 (?)	1 (?)	≤ 0.8	1 – 4 x 24
150 ns SB	5	< 1.5	1	3 x 2	1.2	< 2	12	1.1	≤ 2.5 (1.6)	≤ 0.8	1 – 4 x 12

The characteristics for the 75 ns double batch beams are a ‘tentative guess” and were never obtained. This beam will therefore require still some time to be set up correctly before confirming, let alone enhancing its performance.

The 150 ns beam seems to be usable by the LHC with 8 out of 12 bunches at nominal intensity, but substantial work is needed to stabilise this beam. However, is the 150 ns beam still required and if so, how much work and financial resources for equipment modifications should be devoted to its optimisation?

CONCLUDING REMARKS

The experience gained in 2010, mainly during machine development sessions, on the different multi-bunch beams in combination with the better knowledge of the LHC machine capabilities have led to a realistic set of enhanced beam characteristics for the multi-bunch LHC beams. The explanation of the production schemes of each of the multi bunch beams also outlined the major difficulties and limitations for each of these beams.

A substantial amount of machine development time, in addition to the time needed for the LIU activities, is required to obtain enhanced performance on these beams and to make them operationally available.

In order to be able to prepare and provide good quality beams from the injectors, clear requirements sufficiently ahead of time need to be established and communicated. It is also important to provide understanding of the beam parameters that are critical for the LHC, but also those that are less critical.

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