RF SCENARIOS AND LONGITUDINAL DYNAMICS IN SPS AND LHC FOR 12.5 AND 75 NS BUNCH SPACINGS

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Abstract

Beams with proton bunches spaced at 12.5 ns and twice shorter than nominal, or spaced at 75 ns and twice longer than nominal, are the key ingredients for two main scenarios considered for an LHC upgrade. These two options are analysed from the point of view of the choice of both RF systems and beam parameters in the SPS and LHC and the corresponding longitudinal beam stability.

CLOSE AND SHORT BUNCHES

The closer bunch scenario for the LHC luminosity upgrade [1] contains in fact three different ingredients which can be treated separately: (1) higher total current in injectors and LHC, (2) smaller bunch spacing in injectors and LHC, and (3) shorter bunches in the LHC. Only the last two items are considered below. Higher then ultimate total current would require upgrades of many systems both in the LHC and its injectors (collimators, beam dump, RF power, beam control, instrumentation and others) and is not analysed here.

Reduced bunch spacing

Increasing the number of bunches in the LHC by reducing the bunch spacing from the present nominal 25 ns is one of the possible ways to increase the LHC luminosity. The modifications required in the injectors and LHC itself for different bunch spacings (12.5 and 10/15 ns) were considered in [2] and are also analysed below.

Several systems would need serious upgrading for closer bunches with any bunch spacing. For example,

- Transverse damper/feedback in the SPS and LHC: additional system covering frequency range (10 - 40) MHz for 12.5 ns spacing. Space in the LHC rings already reserved for 50% upgrade (current or bandwidth) [3].

- Beam control in the SPS and LHC (e.g. sampling rates).

- Beam instrumentation in the SPS and LHC.

The present injector chain is able to produce bunches spaced at 10 or 15 ns with minimum change (nevertheless an extra RF system is required in the PS [4]). However in this case significant upgrades would be needed in the LHC detectors. The 12.5 ns spacing also is not transparent for detectors but is better supported by the LHC experiments [5]. These bunches can be produced in the PS by one more bunch splitting, but then cannot be accelerated in the SPS by the existing RF system (200 MHz). One possibility is to use the fact that only a half of the SPS ring is occupied by four LHC batches in the nominal production scheme and after filling the whole ring by eight batches, move bunches of four batches inside the other four using momentum slip stacking on the flat top (it takes ∼ 700 ms), just before extraction, to produce the 12.5 ns spacing. The 200 MHz RF system of the SPS allows these manipulations to be performed due to its large frequency bandwidth, however this method may not be robust enough for high intensity operation.

RF system at f_{rf} [MHz]				
SPS (1 ring)			LHC (2 rings)	
capture	accel.	flat top	capture	accel.
200	200	200	- (200)	400
160	160	160	160	400
160	160	160	-	400
160	160	160	240	400
160	160	400	-	400
80/160	240	240	-	400
240	240	240	-	400
80/160	240	240	240	400
160	400	400	-	400

Table 1: Possible combinations of RF systems in the SPS and LHC for the 12.5 ns bunch spacing.

A more appropriate solution for producing 12.5 ns spaced bunches is the installation in the SPS of completely new RF system(s). In addition to the already discussed 160 and 240 MHz RF systems [2], a 400 MHz RF system should also be considered. This system can be superconducting (SC) and therefore have relatively small impedance and power consumption. However it obviously implies an additional capture system in the SPS. Different possible combinations of RF systems in the SPS and LHC are summarised in Table 1.

We assumed that an additional capture RF system is required in cases when the bunch-to-bucket transfer between the two rings (PS to SPS or SPS to LHC) becomes tighter in comparison with the present situation (the first line in Table 1) which is already critical for the capture loss.

There are also other considerations which can be important for the choice of the RF systems:

- Beam stability (for the same emittance) increases with harmonic number h approximately $\propto h^2$. Therefore larger emittance (controlled blow-up) would be necessary for lower frequency RF systems (e.g. 160 MHz).

- The 160 MHz system would be difficult to install in the LHC due to the transverse size of cavity and beam separation.

- The possibility of using the existing 800 MHz RF sys-

	V [MV] for ε [eVs]		
f_{rf}	1.0	0.5	0.4
160 MHz	6.3	3.5	
200 MHz	10.6	4.2	
400 MHz	71.0	19.3	13.0

Table 2: Accelerating voltages in the SPS for different RF systems and longitudinal emittances with the momentum filling factor of 0.95 for the nominal 7.5 s ramp.

tem as a Landau system for fixed target beam (each bucket full) at constant phase shift (e.g. bunch shortening mode - BSM).

- Only one capture RF system is required in the SPS in comparison with two in the LHC (one per ring).

Voltages required in the SPS for beam acceleration with different RF systems and bunch emittances are shown in Table 2.

The 400 MHz RF system needs more voltage for acceleration for the same emittance, but emittances can be smaller due to a higher beam stability.

Taking into account all the issues discussed above it looks as if two different RF systems are required to replace the actual (broad-band) 200 MHz RF system. Possible scenarios could be:

(1) SPS: 80 or 160 MHz plus 240 MHz, LHC: 240 MHz (2 rings);

(2) SPS: 160 MHz plus 400 MHz.

Note that in case (1) the use of the 800 MHz RF system, essential for high intensity beams, will not be possible for the FT and CNGS beams.

In the case (2) the transfer to the 400 MHz system can be done either on the SPS flat bottom or on the flat top. On the flat top 16 MV at 160 MHz and 8 MV at 400 MHz would be necessary for adiabatic transfer (less in the case of bunch rotation, but this option is not sufficiently robust). The voltage required in both RF systems on the SPS flat bottom, see Table 3, or during the rise is less than on the SPS flat top. Note, that for the transfer to the 400 MHz on the LHC flat bottom one would need 7 MV at 160 MHz per ring (for emittance 1.75 eVs, necessary for stability in the SPS).

ε eVs	V [MV] @160 MHz at P_s [GeV/c]			
	26	40	50	100
0.35	2.5	3.6	3.3	1.9
0.5	5.2	7.3	6.7	4.0

Table 3: Voltages required at 160 MHz for the transfer to the 400 MHz RF system at different injection momentum and longitudinal emittances.

ε eVs	V_{t1} MV	V_{t2} MV	E_1 TeV	E_2 TeV
1.0	21	15	3.5	3.0
1.25	33	25	3.4	5.0
1.5	47	40	3.3	6.0
1.75	64	57	2.8	6.5

Table 4: The 1.2 GHz voltage needed at 7 TeV to provide for different emittances ε a 0.5 ns bunch length (4σ) with 1.2 GHz alone - V_{t1} or with 16 MV at 400 MHz in addition - V_{t2}. Acceleration with V_{t2} is possible from energy E_1 and transfer from 400 MHz to 1.2 GHz RF system from E_2.

However more 160 MHz voltage is needed for the transfer at 40 or 50 GeV/c (possible with the future PS2 [6]) compared to 26 or 100 GeV/c. Besides this voltage, minimum 13 MV at 400 MHz are required for the acceleration.

Short bunches

Short bunches in the LHC can be a part of the LHC upgrade scenarios both with 12.5 and 25 ns bunch spacings [7]. Previous studies of this option [8], [9] have shown that the use of the 1.2 GHz RF system can provide the required bunch parameters. The 1.2 GHz voltage needed at 7 TeV to obtain for different emittances ε a 0.5 ns bunch length (4σ) with the 1.2 GHz RF system, alone or with 16 MV at 400 MHz in addition, is shown in Table 4. As one can see, with 16 MV at 400 MHz $\sim 10 - 20\%$ reduction in voltage at 1.2 GHz is possible.

The beam stability in a higher harmonic RF system is also better. The transfer from 400 MHz to 1.2 GHz can be done during the acceleration ramp or on the flat top (for emittances above 1.5 eVs), Table 4. During the ramp the 1.2 GHz system with much more modest voltage can be used as a Landau cavity in bunch-shortening mode [10].

The technological difficulties of the 1.2 GHz RF system, discussed in [9], are mainly related to the small transverse size of cavities leaving very limited space for traditional power and HOM couplers. A serious R&D program is needed to address these issues.

Another option to produce short bunches is the 800 MHz RF system, which would have the advantages of larger transverse size and smaller bucket filling factor (in comparison with 1.2 GHz, but the same as for the nominal 400 MHz case). Disadvantages are increased longitudinal dimensions and voltage and power consumption. Indeed 70 MV alone or 60 MV with 16 MV at 400 MHz needed for 0.5 ns bunch length and $\varepsilon = 1.65$ eVs ($\Delta p_{2\sigma}/p = 3.1 \times 10^{-4}$) - to be compared with 64 MV and 57 MV for 1.2 GHz RF system. Beam loading is higher due to the larger beam component at 800 MHz in comparison with 1.2 GHz.

f_{rf} [MHz]	200	200 + 400
V [MV]	8.0	10 + 5
rms τ [ns]	0.48	0.83
rms $\Delta p/p$ [10^{-4}]	1.08	1.0
rms ε [eVs]	1.14	2.0

Table 5: Voltages in a single or double RF systems needed for production of flat bunches with given parameters.

LONG AND FLAT BUNCHES

Long and flat bunches are part of the LHC upgrade scenario dealing with the 75 ns or 50 ns bunch spacing [7]. These bunch spacings can be produced in the present PS (and future PS2). In this case beam loading and coupled bunch instabilities issues are similar to those in the scenario with the ultimate bunch intensity and the 25 ns bunch spacing. The main problem with this option is a very high bunch intensity which can lead to different types of instabilities not only in the LHC itself but in the injectors as well. In the SPS the thresholds of the TMCI and microwave instability should go up with a higher injection energy possible due to a future PS2 [11]. Additional measures to control other instabilities could be

(1) larger longitudinal emittance (1 eVs) already at injection into the SPS leading to more voltage needed in the SPS for acceleration (11 MV at 200 MHz) and in the LHC for capture (200 MHz);

(2) momentum slip stacking on the SPS flat top using again the fact that only a half ring is filled in the nominal scheme. This manipulation will lead to emittance blow-up which should be acceptable in the LHC with probably more voltage at 200 MHz. This RF manipulation can be tested in MDs in the SPS.

Flat bunches

The flatness of long bunches during collisions can give a 40% luminosity increase [7]. These bunches can be obtained

(1) by creating a hollow particle distribution in a single RF system using a second RF system during the RF manipulations;

(2) in bunch-lengthening mode (BLM) in multi-harmonic RF system.

The bunch parameters required for this mode of operation together with voltages in a single and a double RF system are shown in Table 5. While a hollow bunch distribution gives ideally flat projections in both momentum and phase, the double RF system, providing close to flat bunch profiles due to the shape of potential well, can at the same time have a Gaussian (or other) distribution in momentum. What is presented in Table 5 as rms bunch length momentum and emittance corresponds to maximum excursions and area of particle trajectory. The full length of a bunch with the flat profile is $\sqrt{12}$ its rms value.

The hollow bunches have been produced experimentally by redistribution of the phase space (empty bucket in the bunch center) [12], [13]. However the evolution of this distribution during the coast is not obvious due to the influence of the white RF noise and other similar processes. Most probably hollow distribution will tend to the Gaussian during the coast. The introduction of weak continuous band-limited noise could be a possibility to keep the bunch center empty.

Experimental studies of the hollow bunch evolution and stability can be done in the SPS.

The second method to produce flat bunches is by the bunch-lengthening mode in a double RF system. In the LHC 3 MV at 200 MHz used together with 1.5 MV at 400 MHz can provide flat bunches with an emittance of 4.6 eVs (value determined mainly by IBS lifetime requirements, [14]) and a full bunch length of 2.88 ns (for perfectly flat bunch profile this corresponds to the rms bunch length of 0.82 ns). However observations made in the SPS with a double RF system (200 MHz plus 800 MHz), used for stabilisation of the high intensity LHC beam, show [15] that the coupled-bunch instability threshold in the BLM is lower than in the BSM and even than in the single RF system (the 800 MHz off). Lower beam stability was also seen in ESME simulations.

No instability was observed at low intensity, but rather a change of the equilibrium distribution with the creation of shoulders [15]. This phenomenon was also observed in particle simulations [16].

Other (new) scenarios suggested before the workshop [7] can be considered as intermediate options for those discussed above. They are

(1) short bunches with nominal 25 ns bunch spacing and twice ultimate bunch intensity;

(2) long and flat bunches with 50 ns bunch spacing.

For these options some very difficult requirements (single bunch intensity, heat load, pile-up) can be relaxed.

SUMMARY

- For closer bunches option the choice between 12.5 ns and 10/15 ns bunch spacing should be based on a detailed cost comparison (machines plus experiments)
- A few combinations for RF systems in the SPS and LHC are possible for 12.5 ns bunch spacing. The most promising seems to be a 400 MHz RF system installed in the SPS together with a capture system at 160 MHz.
- Shorter bunch option in the LHC needs 1.2 GHz or 800 MHz RF system, in both cases a lot of RF voltage and power (and physical space). The reduced version of this system can be used as a Landau cavity to increase beam stability.
- Long and flat bunch option needs to address a problem with very high single bunch intensity in the SPS and stability of a flat distribution in the LHC.

- Intermediate options (short bunches at 25 ns and long at 50 ns) are certainly a better compromise to satisfy different requirements mentioned above.
- Possible MDs in the SPS:

  - Momentum stacking for 12.5 ns and 50/75 ns bunch spacings;

  - Beam lifetime in a single and a double RF system;

  - Stability and evolution of the hollow bunch during the coast.

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