LHC Project Note

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LHC Ion Filling Schemes with 75ns basic Bunch Spacing

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Summary

The present nominal LHC ion filling scheme is based on a minimum basic bunch spacing of 100 ns with larger gaps, which are in general non-integer multiples of this basic spacing, for injection kickers and the LHC beam dump kicker. This standard scheme comprises accumulation of up to 13 PS/LEIR batches on a long SPS low energy plateau. Alternative filling schemes with a basic spacing of 75 ns and where all longer gaps are integer multiples of the basic spacing are proposed. The initial motivation was a scheme with a shortened SPS low energy plateau, but almost the same number of bunches in LHC. This allows mitigating the consequences of partial debunching of ion bunches observed during machine experiments carried out in autumn 2007, with only a small reduction of the luminosity. In addition, a scheme with a long SPS front porch accumulating 15 PS/LEIR batches, aiming at increasing the average LHC luminosity, is proposed as well.

1. Introduction

The basic bunch spacing and filling scheme for LHC ion operation has evolved with time and the present nominal 100 ns [1] bunch spacing is the result of several iterations. Initially a basic spacing of 135 ns corresponding to 660 equally spaced potential bunch positions had been envisaged [2,3]. The drawback of this solution was that this 135 ns spacing is not a multiple of the standard 25 ns proton spacing and, thus, not very suitable for experiments interested in observing both proton and ion events. Thus, for the next iteration, following a request from the experiments [4], the LHC ion filling has been revised bringing the minimum spacing has been set to 125 ns [5,6]. Note that the LHC revolution time does not correspond to an integer multiple of this minimum spacing. Thus, larger gaps with a length, which is not an integer multiple of the minimum spacing, had to be introduced.

The discovery that the direct space charge tune shift at SPS injection may be a fundamental limitation led to another revision of the LHC ion filling scheme. The PS to SPS transfer energy had to be increased, leading to an increase of the SPS injection kicker rise time. Reducing the basic bunch spacing to 100 ns to compensate the space lost due the increase of the SPS injection kicker gaps led to the present LHC ion scheme [1]. A very long (more than 43 s) SPS front porch accumulates up to 13 PS/LEIR shots in order to reduce the number of gaps needed for the LHC injection kicker and, in turn, to fill the LHC with a sufficient number of bunches (592 per ring) to obtain the design luminosity. The longer gaps between bunch trains in the LHC are not always integer multiples of the basic 100 ns spacing (e.g. spacing of 225 ns for the SPS injection kicker between adjacent PS transfers), but all gaps are multiples of 25 ns.

The following considerations, based on an analysis of the harmonic number of the LHC, were the initial motivation for proposing a basic bunch spacing of 75 ns and give some insights on special properties:

- The basic harmonic number of the LHC (400 MHz RF system corresponding to 2.5 ns between buckets) decomposes into the following prime factors:

$$h_{LHC} = 35640 = \underbrace{2 \times 2}_{\text{fill in quarters}} \times \underbrace{2 \times 3 \times 5}_{\text{75 ns between bunches}} \times \underbrace{3 \times 3 \times 3 \times 11}_{\text{297 positions per quarter available}}$$

  Any basic bunch spacing is the product of some of the above prime factors times 2.5 ns. For the proposal in this report, the chosen basic bunch spacing is 2x3x5x2.5 ns = 75 ns. The product of the remaining prime factors gives the number of potential bunch positions (in this case 2x2x3x3x3x11 = 1188) equally distributed over the ring with this given bunch spacing.
- If the LHC is filled in quarters (with almost –disregarding the long gap needed for the dump kicker- identical quarters), collisions take place in all three experiments (ALICE, ATLAS and CMS) interested in ion runs. Thus, a factor 4 in the prime number decomposition of the LHC harmonic number is reserved for filling in quarters.
- The product of factors, remaining after determining the basic bunch spacing and taking a factor 4 for filling the LHC in quarters, gives the number 3x3x3x11 = 297 of potential bunch position per LHC quarter.

The generation of the 75 ns basic spacing, which is needed already at the transfer to the SPS, in the PS is hampered in the case of Pb^{54+} by the vicinity of the transition and, thus, is an issue for this proposal. Two schemes, one requiring a new tunable 13 MHz RF system and, another one replacing the initially envisaged bunch splitting at the flat-top by a batch compression by a large factor in one step with an additional lower frequency RF component, are described in section 2.

For a given basic bunch spacing, different filling schemes depending on the number of shots accumulated in the downstream machines and additional gaps can be devised. The two 75 ns schemes presented, although proposed for very different scenarios, both feature a very uniform LHC filling pattern and all larger gaps are integer multiples of the basic spacing:

- There are concerns [7,8] that the beam quality degrades during long low energy plateaus in the SPS due to IBS and/or other effects. The filling scheme described in section 3 aims at providing almost the same number of ion bunches in the LHC as the nominal 100 ns scheme, but with a shorter SPS front porch. The space needed for additional LHC injection kicker gaps is mainly created by the reduction of the basic bunch spacing from 100 ns to 75 ns.
- The scheme described in section 4 may be of interest in case (i) the LHC collimation system can cope with a total ion intensity higher than nominal, because for example the assumptions on the minimum beam life-time were pessimistic, and (ii) accumulation of many PS/LEIR shots during long SPS low energy plateaus works. In this case, the space saved by reducing the basic spacing may be used to inject additional bunches. The increase of the total number of bunches is expected not to increase the peak luminosity, which has to be adjusted by an appropriate choice of the β^* to the direct limitation by magnet quenches due to "bound free pair production" [9]. However, the luminosity life-time can be increased, especially if the burn-off of beam particles is compensated by a dynamic adjustment of β^*.

Ion collisions with a filling structure based on 75 ns are acceptable [10] for the ALICE experiment at least for Pb^{54+} runs.

2. RF Gymnastics in the PS to provide the 75 ns spacing ion beam

The scheme for the generation of the nominal 100 ns bunch spacing in the PS consists of a succession of batch compressions interleaved with a double splitting and, finally, h=169 rebucketing and bunch compression as described in [11,12]. For the generation of the Early LHC ion beam, only one bunch is provided per PS/LEIR cycle, and, thus, no other gymnastics than bunch compression (after rebucketing with the 80 MHz cavities) prior to transfer to the SPS is needed.

The schemes proposed here for the generation of the 75 ns bunch spacing are based on successions of batch compressions and bunch splittings, and h=169 rebucketing and bunch compression, as the scheme for the 100 ns scheme. No scheme featuring at the same time operational simplicity and feasibility with the presently installed RF cavities has been found, and, thus, two schemes are proposed.

A simple scheme with Bunch Splitting from h=14 to h=28

A scheme with relatively simple RF gymnastics allows creating the bunch structure needed at PS extraction, but requires an additional not existing cavity operated at a frequency of about 13 MHz suitable for bunch splitting and part of the acceleration. The main steps in the PS are:

- Injection: Two bunches coming from LEIR (harmonic number $h_{LEIR} = 2$) are injected into adjacent h = 16 buckets of the PS (identical to nominal LHC ion filling).
- After acceleration to an intermediate plateau, the harmonic number is reduced to h = 14 (the distance between bunches is increased). Then, the bunches are split into two yielding 4 bunches in adjacent h = 28 buckets followed by acceleration to top energy. Note that the existing "13.3 MHz" cavities cannot be used for these operations since the tuning range and the maximum possible duty factor are not sufficient.
- The beam arrives at top energy with h = 28 and almost the correct bunch spacing for transfer. Then, the bunches are transferred to the 80 MHz system (slightly compressing the batch) resulting in a harmonic number h = 169 and a bunch spacing compatible with the bandwidth of the SPS RF system.

The implementation of this scheme would require a significant investment to provide a suitable RF system with a frequency around 13 MHz and a sufficient tuning range and duty factor.

Note that the final splitting for Pb ions cannot be carried out at top energy due to the vicinity of the transition [13]. The associated slow motion and large acceptance in longitudinal phase space imply that the splitting lasts only very few synchrotron periods and thus suffers from non-adiabaticities. Moreover, the relative phase of the two RF systems has to be controlled very precisely, since the bunches tend to be short and to fill only a small portion of the bucket.

Direct transfer of the Ion Beam from h=21 to h=28

A scheme based on a direct transfer of the ion beam from harmonic number h=21 to h=28 allows generating the 75 ns bunch spacing with the existing RF systems, but at the price of relatively complicated RF gymnastics. The main steps are:

- Up to arrival at the PS flat top, the same gymnastics as for the nominal 100 ns ion bunch spacing as described in [11,12]:
    - Injection of two bunches from LEIR into adjacent h=16 buckets and acceleration to an intermediate plateau.
    - At an intermediate plateau, first batch expansion in several steps to h=12, followed by splitting to obtain four bunches in adjacent h=24 buckets and further batch expansion up to h=21.
    - Acceleration up to the flat top with harmonic number h=21.
- Batch compression from harmonic number h=21 to h=28 at top energy. Since no cavities suitable for intermediate frequencies are available, this transfer has to be carried out in one step. This is possible only, because the beam covers only a small part (four adjacent buckets) of the PS circumference and by adding an additional lower frequency RF component. The basic idea is shown in Fig. 1 showing wave forms during the transfer process with and without additional h=10 component. Without the additional RF component, the longitudinal focusing experienced by the outer bunches (at phases around $\pm 15^{o}$) becomes insufficient. The temporary addition of a lower harmonic component during the batch compression allows improving the longitudinal focusing.
- Finally, the bunches are transferred to the 80 MHz RF system resulting in h=169 and short bunches with a spacing appropriate for the bandwidth of the SPS 200 MHz RF system.

First preliminary simulations have shown that the batch compression with direct transfer from h=21 to h=28 is feasible. However, the scheme presented here is more complex than the nominal 100 ns scenario and (even more) than the scheme presented above requiring additional, at present not existing, RF cavities.

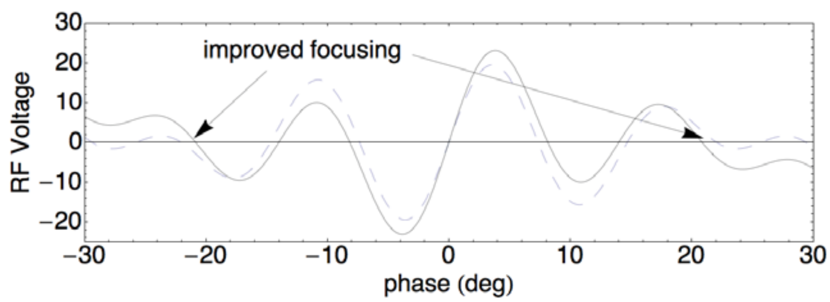

Figure 1: RF wave forms during the transfer from h=21 to h=28 with equal voltages for the two systems. The solid and dashed curves are with and without additional h=10 component.

3. LHC Ion Filling with short SPS low Energy Plateaus

Description of the Scheme

The scheme proposed is depicted in Fig. 2 using a representation similar to one used to describe various LHC proton and ion filling schemes [1]. All SPS cycles are identical and accumulate 4 PS/LEIR ion batches as indicated on the lower part of Fig. 2. Two empty positions are inserted to create the gap needed for the SPS injection kicker. The procedure to fill one LHC ring with ions is outlined on the upper part of Fig. 2:

- Eight or nine SPS batches serve to fill one quarter of the LHC ring. Between consecutive SPS transfers belonging to the same quarter, 11 empty buckets are inserted to create the 900 ns gap needed for the LHC injection kicker [15].
- Only one additional longer gap has to be inserted for the LHC beam dump kicker. This is done by filling one LHC quarter with only eight SPS transfers creating a gap of 3375 ns (44 positions not filled with beam).
- Note that nine SPS transfers and the gaps needed for the LHC injection kicker fill exactly one quarter of the LHC. Thus, there are no additional (to the dump kicker) gaps needed to fill the LHC in quarters.

This scheme allows LHC operation with 560 out of 1188 potential positions filled with bunches. This means that the number of bunches is only very slightly decreased with respect to the nominal 100 ns scheme with 592 bunches.

Implications on LHC filling time

For the evaluation of the increase of the LHC ion filling time with the 75 ns scheme, due to the fact that the SPS has to cycle more often, the following assumptions (based on the cycle used for the SPS ion commissioning in 2007) have been used:

- Length of the accumulation plateau: time interval between the first and the last injection plus 0.5 s (needed by the low level RF system).
- Time from the start of the acceleration (including ramp down) until the first injection of the following cycle: 10.3 s. Note that this value is taken from the magnetic cycle used for the commissioning of the "early" LHC ion beam in the SPS in autumn 2007. However, this magnetic cycle could very likely be shortened by optimizations.

Under these assumptions, the total LHC ion filling (for both ring) time can be estimated in the following way:

- One SPS cycle lasts 3*3.6s + 0.5 s + 10.3 s = 21.6 s
- 70 transfers from the SPS are necessary to fill both LHC rings. The total duration between the first and the last transfer is 69*21.6 s = 24 Min 50 s.

This has to be compared with the LHC ion filling time with the present nominal 100 ns scheme:

- One SPS cycle (it is assumed that for simplicity all SPS magnetic cycles are identical and with a low energy plateau accumulation up to 13 PS/LEIR shots) lasts 12*3.6s + 0.5 s + 10.3 s = 54 s.
- 24 transfers from the SPS are necessary to fill both LHC rings. Thus, the total duration between the first and the last transfer is 23*54 s = 20 Min 42 s.

Thus, the 75 ns LHC ion filling scheme with short SPS low energy plateau implies a small increase of the LHC ion filling time (for both rings) from 20 Min 42 s (for the present nominal scheme) to 24 Min 50s.

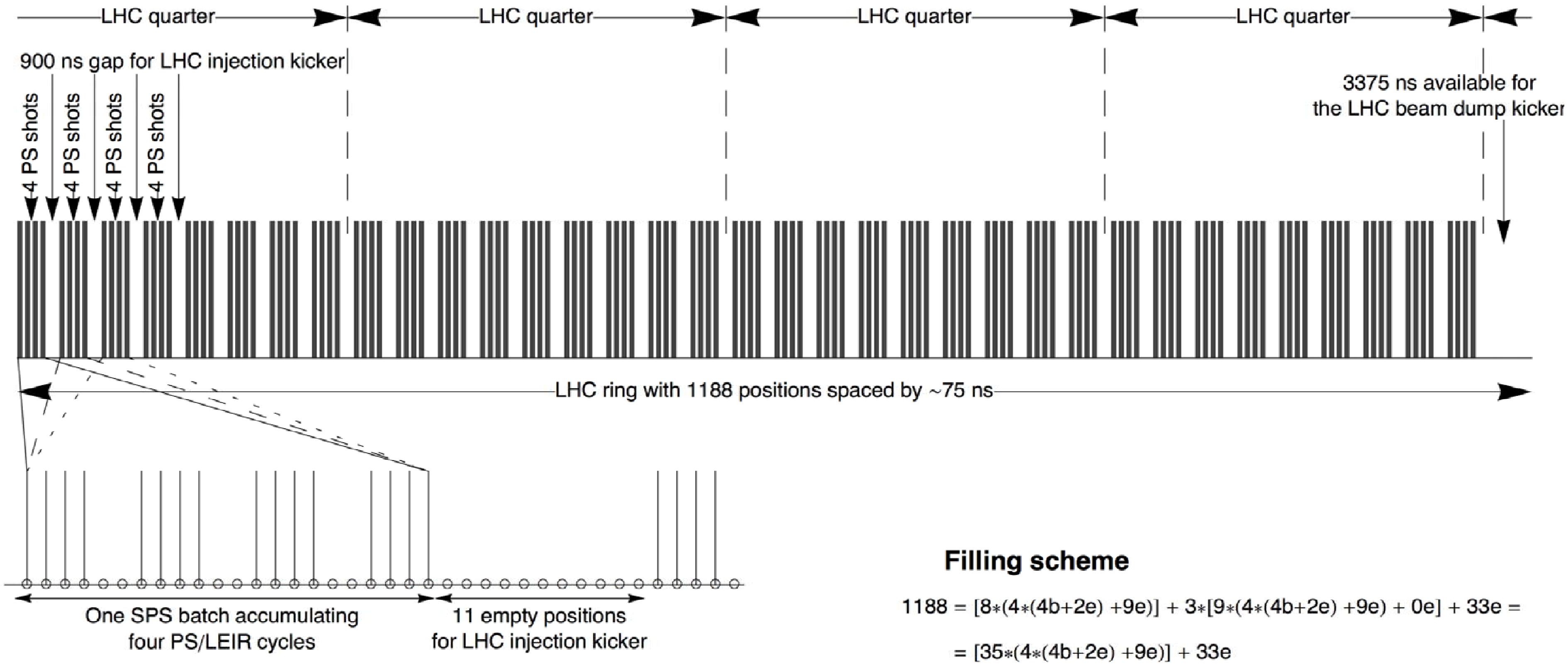

Figure 2: LHC ion bunch pattern and filling with 75 ns (minimum) bunch spacing and a shortened SPS front porch.

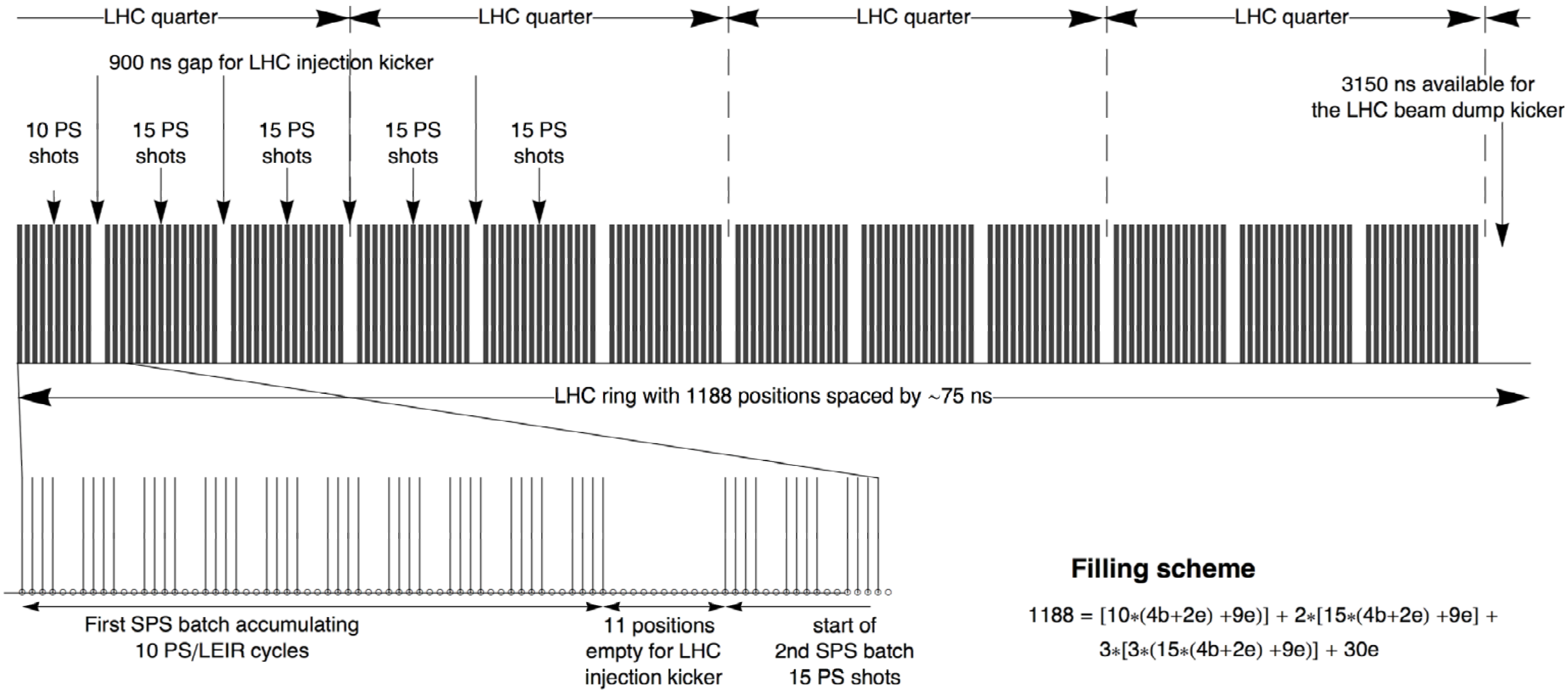

Figure 3: LHC ion bunch pattern and filling with 75 ns (minimum) bunch spacing and a long SPS front porch to increase the number of bunches available in LHC.

4. LHC Ion Filling with very long SPS low Energy Plateaus and an increased Number of Bunches

Description of the Scheme

The LHC ion filling scheme described here aims at using the space saved by reducing the basic spacing for an increase of the total number of bunches available in LHC. This may be of interest in case (i) the accumulation of many PS/LEIR shots on very long SPS low energy plateaus works and (ii), the LHC collimation system can handle a higher intensity than estimated now, e.g. because the assumptions on minimum beam life-times are pessimistic.

This scheme for filling the LHC with an increased number of bunches is depicted in Fig. 3. Most of the LHC circumference of the LHC is filled regularly with SPS ion batches accumulating 15 PS/LEIR shots. Only the first SPS cycle accumulates only ten PS/LEIR shots in order to create the gap for the LHC beam dump kicker. The filling pattern for one LHC ring is outlined on the upper part of Fig. 3:

- A regular LHC quarter is filled with three SPS cycles, each one accumulating 15 PS/LEIR shots. The 225 ns gap for the SPS injection kicker is created by inserting two positions not filled with beam. A 900 ns gap for the LHC injection kicker is again created by 11 positions (between adjacent bunches of two consecutive SPS transfers) not filled with beam.
- No additional larger gaps are needed to establish almost (perturbed only by the LHC beam dump kicker gap) fourfold periodicity of the LHC filling pattern.
- A longer gap needed for the LHC beam dump kicker is created by shortening the first bunch train provided from the SPS. Accumulating only 10 PS/LEIR batches instead of 15 yields a gap of 3150 ns (41 empty positions).

This scheme allows LHC operation with 700 out of 1188 potential positions filled with bunches. This means that the number of bunches is significantly increased with respect to the present nominal scheme with 592 bunches.

Note that the LHC peak luminosity for ion operation is directly limited by “bound free pair production”, i.e. generation of Pb^{81+}, which are lost on a superconducting magnet of the dispersion suppressor and induce a quench [9]. Thus, the additional intensity cannot be used to increase the LHC peak luminosity, but β^* has to be chosen sufficiently large such that the maximum possible luminosity is not exceeded. However, the luminosity life-time is improved directly by the reduction of the burn-off (particle loss due to interactions at the collision points). A further improvement of the luminosity life-time could, in principle, be obtained with a dynamic β squeeze scheme, if it can be implemented in practice. However, up to now, a dynamic β squeeze scheme has not yet been implemented in any hadron collider.

Implications on LHC filling time

Under the assumptions on time intervals needed for the SPS cycle stated already above, the total LHC ion filling (for both ring) time can be estimated in the following way:

- One SPS cycle lasts 14*3.6s + 0.5 s + 10.3 s = 61.2 s
- 24 transfers from the SPS are necessary to fill both LHC rings. The total duration between the first and the last transfer is 23*61.2 s = 23 Min 28 s.

Thus, the 75 ns LHC ion filling scheme with a very long SPS low energy plateau to increase the total number of bunches in the LHC implies a small increase of the LHC ion filling time (for both rings) from 20 Min 42 s (for the present nominal scheme) to 23 Min 28 s.

5. Summary and Conclusions

LHC ion filling schemes with a basic bunch spacing of 75 ns instead of 100 ns have been proposed. Initially, this bunch spacing was the result of an analysis of the LHC harmonic number with the aim for a regular filling pattern with quasi-four fold periodicity (perturbed only by a gap for the LHC beam dump kicker).

The two schemes proposed feature rather “regular” LHC filling patterns, but make different use of the space gained by reducing the basic minimum spacing: the first scheme features short SPS low energy plateaus to mitigate possible limitations due to particles leaving the RF bucket observed recently [8]; the saved space is used for the resulting additional LHC injection kicker gaps. In addition all SPS cycles are identical and the scheme is less sensitive to missed ejections from the PS requiring the repetition of a whole SPS cycle. The second scheme uses the saved space for additional bunches to increase the luminosity life-time.

The generation of the 75 ns spacing in the PS is difficult for Pb^{54+}, since at ejection the beam is close to transition. The schemes presented either require additional hardware or imply an additional complexity of the RF gymnastics. First simulations led to the conclusion that the required structure can be generated in the PS. However further studies are required to validate the RF gymnastics proposed. In particular, machine studies for the fast batch compression could be carried out soon to clarify whether if the scheme not requiring an additional RF system is feasible.

For both schemes presented, the gaps available for the LHC injection kicker are 900 ns, i.e. shorter than the ones for standard proton and ion LHC filling schemes presented in [1]. This gap is just sufficient according to the kicker rise time given in [14], but too short for the one cited in [1]. Recent measurements [15] indicate that the LHC injection kicker rise time is short enough for the filling schemes presented.

The ALICE experiment can, at least for Pb^{82+} operation [10], cope with a basic bunch spacing of 75 ns.

Acknowledgments

This proposal has been triggered by discussions on the consequences, if the SPS front porch has to be shortened, initiated by G. Arduini, who has furthermore continuously encouraged this study and given valuable comments on the scheme and the report. S. Hancock has pointed out that the initially envisaged splitting of ion bunches at high energy in the PS is not feasible. T. Bohl, E. Carlier, M. Chanel, P. Collier, L. Ducimetiere, J. Jowett, S. Maury, D. Manglunki, R. Steerenberg have contributed in discussions and/or given comments on this report.

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