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BUNCH MERGING AND SPLITTING TECHNIQUES IN THE INJECTORS FOR HIGH ENERGY HADRON COLLIDERS

R. Garoby

Abstract

One problem in the design of TeV hadron colliders arises from the choice of the radio frequency. To produce economically the short bunches needed during collision, a high frequency (400 MHz or more) is essential. On the other hand, in the injector chain at lower energies, lower frequencies are generally preferred to alleviate space charge and instability problems and, partially also, for historical reasons. The classical solution is to transform the bunch structure by passing via a debunched beam state, during which the whole machine circumference becomes filled with particles and the beam is subjected to induced parasitic fields and is often prone to microwave instabilities. Bunch merging and bunch splitting have therefore been developed as alternative methods that allow the number of bunches to be changed without passing via that state. Bunch merging has been used in the CERN-PS since 1989 for the anti-proton production beam. The reverse process of bunch splitting was first proposed in the frame of the CERN injector complex for LHC, as a means of quasi-adiabatically changing the time structure of the beam, increasing the number of bunches from four at low energy in the PS Booster to 16 at high energy in the PS. When the CERN accelerator complex re-started in March 1998, this technique became a routine operation. New plans are now being considered to replace the debunching-rebunching process that is still needed at 26 GeV/c in the PS to generate the train of 84 bunches required by the SPS and LHC. The experience gained in the application of bunch merging and splitting techniques is reviewed in this paper together with the extensions now envisaged and the analysis of the expected advantages with respect to the more classical process of debunching-rebunching.

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One problem in the design of TeV hadron colliders arises from the choice of the radio frequency. To produce economically the short bunches needed during collision, a high frequency (400 MHz or more) is essential. On the other hand, in the injector chain at lower energies, lower frequencies are generally preferred to alleviate space charge and instability problems and, partially also, for historical reasons. The classical solution is to transform the bunch structure by passing via a debunched beam state, during which the whole machine circumference becomes filled with particles and the beam is subjected to induced parasitic fields and is often prone to microwave instabilities. Bunch merging and bunch splitting have therefore been developed as alternative methods that allow the number of bunches to be changed without passing via that state. Bunch merging has been used in the CERN-PS since 1989 for the anti-proton production beam. The reverse process of bunch splitting was first proposed in the frame of the CERN injector complex for LHC, as a means of quasi-adiabatically changing the time structure of the beam, increasing the number of bunches from four at low energy in the PS Booster to 16 at high energy in the PS. When the CERN accelerator complex re-started in March 1998, this technique became a routine operation. New plans are now being considered to replace the debunching-rebunching process that is still needed at 26 GeV/c in the PS to generate the train of 84 bunches required by the SPS and LHC. The experience gained in the application of bunch merging and splitting techniques is reviewed in this paper together with the extensions now envisaged and the analysis of the expected advantages with respect to the more classical process of debunching-rebunching.

1 INTRODUCTION

The longitudinal beam parameters in high energy hadron colliders are selected to attain the highest possible luminosity that can be handled by physics experiments. The task of the injection chain is then to satisfy these requirements in terms of longitudinal emittance, number of particles per bunch and distance between bunches.

A low harmonic number (low RF frequency) and a bunch frequency equal to the RF frequency are well adapted to and often used in low energy synchrotrons, because (i) acceleration of a high intensity beam is easier (reduced effect of longitudinal space-charge, less modes of coupled bunch instabilities and simpler lossless beam transfer) and (ii) the technology for such RF cavities is well mastered. On the contrary, in the high energy colliders a high RF frequency is preferred, often in association with a low bunch frequency, to obtain the high voltage needed for acceleration and the short bunches required by luminosity. Consequently, the beam delivered by the injectors is generally not adequate, especially since present projects re-use existing low and medium energy accelerators. Beam gymnastics are then required with the added constraint to minimise the amount and cost of equipment to be built.

2 OPERATIONAL BEAM GYMNASTICS

2.1 Debunching / rebunching

The conventional method for changing the longitudinal structure of the beam is to debunch by cancelling the voltage at the initial frequency, to drift without longitudinal focusing, and to rebunch with another RF frequency. To minimise emittance blow-up, voltage variations have to be iso-adiabatic over a large dynamic range. Although widely used, this technique presents a number of drawbacks:

- RF voltages must be controlled down to small amplitudes in the presence of beam-loading,
- while drifting, the beam is left uncontrolled,
- the full circumference is filled with particles,
- the continuous beam has a very small $\Delta p/p$ which makes it prone to microwave instability.

2.2 Merging pairs of bunches

Merging pairs of bunches is a convenient alternative when their number must be divided by 2 (or a power of 2). Starting with $2m$ bunches held with an RF system on harmonic $2h$, RF voltage on harmonic h is slowly turned on while it is reduced on harmonic $2h$. With the correct phasing between both systems and sufficiently slow voltage changes, the $2m$ bunches merge into m, and the longitudinal emittance is preserved. Being quasi-adiabatic this process is reversible and Figure 1, which shows splitting in the CERN PS, also illustrates merging.

Since the beam is never debunched and RF voltages are always applied, the difficulties mentioned previously are largely overcome:

- feedback loops using the RF can be active and help stabilise the beam,

- particles stay in the same fraction of the circumference.

Initially proposed in 1983 [1], bunch merging has been successfully applied for the generation of the anti-proton production beam in the CERN PS [2]. The nominal scheme for filling RHIC [3] uses it extensively to concentrate all the ions of one Booster pulse into a single bunch at the output of the AGS.

2.3 Splitting bunches in two

Splitting bunches in two was originally proposed for processing beams in the PS complex after the modifications for LHC [4]. Both in the PSB and PS, bunch splitting has been demonstrated in routine operation since March 1998 to be viable up to the highest intensities (see Figure 1).

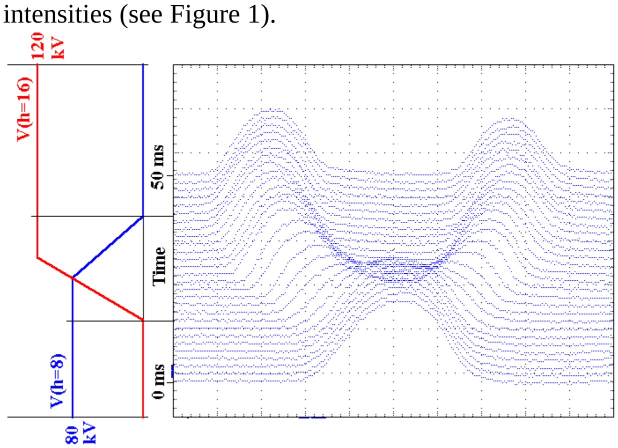

Figure 1: Splitting of a 3 10^{12} protons bunch in the PS at 3.57 GeV/c (25 ns/div)

The beam phase loop on *h*=16 is turned on when this component of the beam signal has attained its final phase and has sufficient amplitude. For a couple of milliseconds, it operates simultaneously with the loop on *h*=8 which is kept active until the *h*=8 component of the beam vanishes. Beam loading tends to make the process asymmetric. To keep split bunches equal, the phase relation between the two harmonics is changed as a function of intensity.

Disturbances in the RF or beam phase are very detrimental. Transients at loop switching have to be carefully minimised and a damping system has been installed for modes *n*=6 and 7 in the PS to suppress coupled bunch oscillations.

3 NEW PLAN FOR LHC

3.1 Status of the LHC beam in the PS Complex

After the standard beams for the on-going physics programme had been re-established following the RF upgrades for LHC [5], tests have been made to generate the nominal proton beam for LHC [6]. Using debunching on *h*=16(7.6 MHz) and rebunching on *h*=84 (40 MHz) at 26 GeV/c, beam characteristics approaching the specifications have already been obtained (Table 1). However the debunched beam requires a too high emittance for stability, and there is no gap for the kicker rise-time in the train of bunches [6]. Work is now going on to find and reduce the disturbing impedances, which will help achieve smaller emittances.

Table 1: PS beam for LHC (10^{11} p/bunch - 26 GeV/c)

Performance level	**Bunch emittance (eVs)**	**Bunch length (ns)**	**Number of bunches**
Achieved (1998)	0.5	5	84
Nominal [6]	0.35	4	84
Ideal [6]	0.35	4	< 81

3.2 Generalisation of splitting

Based on the successful experience gained with bunch splitting and to provide a gap in the bunch train, the following scenario is now envisaged which replaces debunching-rebunching by splitting:

- 7 bunches are injected in the PS on *h*=7 in 2 successive batches from the PSB (4 + 3)
- each of these 7 bunches is split in 3, giving 21 bunches in *h*=21 RF buckets. One bunch is eliminated by fast ejection at low energy. The 20 remaining bunches are accelerated on *h*=21.
- at 26 GeV/c, bunches are split in two twice, giving 80 adjacent bunches held on *h*=84.

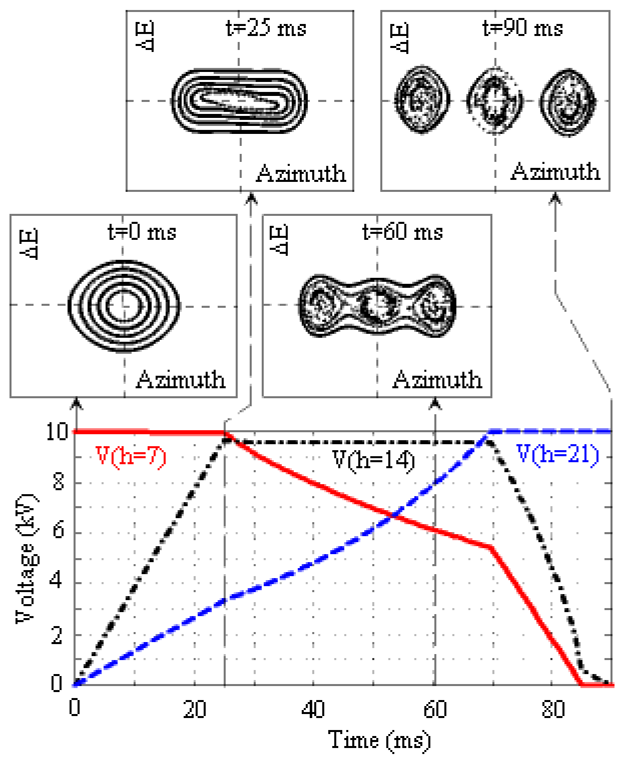

Figure 2: Voltage programmes and longitudinal phase space during triple splitting in the PS (*pc*=3.57 GeV)

Splitting in 3 at 3.57 GeV/c makes simultaneous use of 3 RF harmonics (*h*=7, 14, 21) which are within the capabilities of the present PS ferrite cavities. The voltage programmes (bottom of Figure 2) are derived numerically to obtain an equal distribution of the particles between the 3 bunches. Particles initially encircling areas of 1.5, 1, 0.65, 0.36 and 0.16 eVs evolve in the longitudinal phase plane as shown in the upper part of the Figure 2. Figure 3 is a mountain range display of the line density of charges during the process computed with the tracking code ESME [7, 8]. Computation of the amplitude of the beam signal at harmonics 7, 14 and 21 indicates that phase loops can be successively activated at these harmonics and overlap in time.

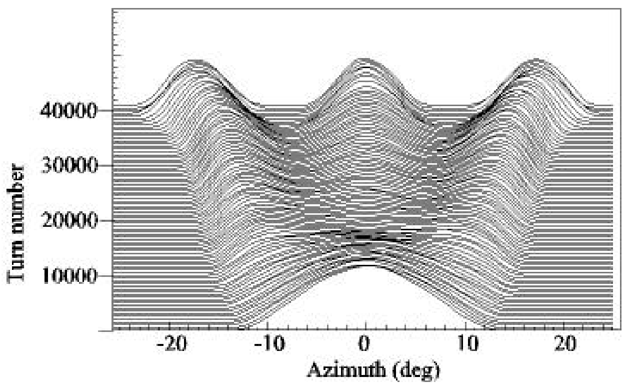

Figure 3: Simulation [7, 8] of triple splitting in the PS (*pc*=3.57 GeV)

Figure 4 is a mountain range display of the splitting in 4 at 26 GeV/c, computed with the same code. Voltage programmes are sketched on the left of the figure. Three RF harmonics are used, and a new 20 MHz (*h*=42) system is required in the PS, whose draft characteristics are given in Table 2.

Table 2: Characteristics of the *h*=42 RF system for splitting in 4 at 26 GeV/c

Freq. (MHz)	**V** (kV)	**Pulse length** (ms)	**Impedance** (Ω)
20.025	20	130	<400 when active ~ 0 when inactive

The microwave instability is expected to be a lesser problem thanks to the higher $\Delta p/p$ of the beam during splitting. The longitudinal emittance of the final bunches will then be smaller than with debunching-rebunching and more easily meet the specifications (Table 1). Moreover, the continuous presence of beam phase loops should help stabilise performance.

A prototype 20 MHz system is being prepared for installation during the shut-down 1999-2000, so that the full process can be tested during the year 2000.

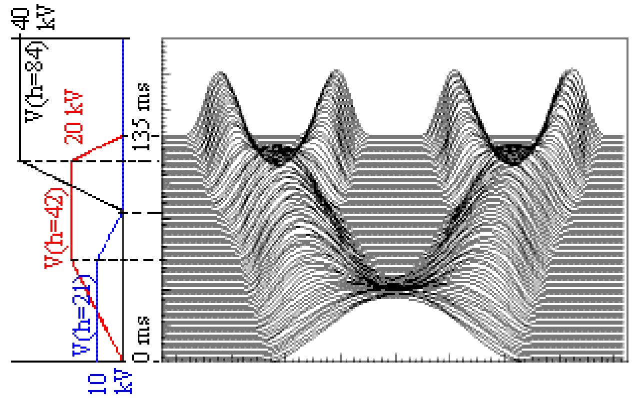

Figure 4: Simulation [7, 8] of quadruple splitting in the PS (*pc*=26 GeV)

4 CONCLUSION

Both merging and splitting pairs of bunches have been successfully used in high intensity synchrotrons. These techniques, which can preserve longitudinal emittance, present specific interests compared to debunching-rebunching. Splitting (and merging) bunches in 3 is now proposed as part of an improvement for the generation of the proton beam for LHC in the PS which should help reliably provide bunches of nominal emittance and a gap in the train of bunches.

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