SINGLE-BATCH FILLING OF THE CERN PS FOR LHC-TYPE BEAMS

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Abstract

Since the CERN PS Booster cannot simultaneously provide the beam brightness and intensity required, the nominal (25ns bunch spacing) proton beam for the LHC involves double-batch filling of the PS machine. Linac 4, which is under construction, will eventually remove this restriction. In the meantime, the request for 50 and 75ns bunch spacings to mitigate electron cloud effects has lowered the intensity demand such that the Booster can meet this in a single batch without compromising beam brightness. Single-batch transfer means providing two bunches from each of three Booster rings and, in turn, that the bunch spacing is modified by the addition of an h=1 rf component to the h=2 in the Booster in order to fit the h=7 rf buckets waiting in the PS (whilst leaving one bucket empty for kicker purposes). Following the first experiments performed in 2008, the rf manipulations in the Booster have been refined and those in the PS have been modified to cope with single-batch beams. This latest work is presented for both the 50 and 75ns variants.

INTRODUCTION

Presently all multi-bunch LHC-type cycles in the PS start with rf harmonic h=7 at injection. The size ratio of the PS and its Booster is such that the four rings of the latter fill the circumference of the former. Consequently, the transfer of 2 bunches from each of 3 Booster rings into 6 out of 7 PS buckets requires the addition of an h=1 component to modify the spacing of each bunch pair [1]. This separates the bunches by more than 360° of rf phase, but at a cost in acceptance (which is already reduced by going to a principal harmonic of h=2). The extraction kicker of each ring must fire in the shortened gap between bunches (see Fig. 1 top) so that the extended spacing is transferred to the PS (see Fig. 1 bottom). The risetime of these kickers determines the upper limit of the longitudinal emittance that can be delivered.

BOOSTER MACHINE

75ns Case

The transverse emittances are dictated at injection to the Booster by the injection angle and position, injection kicker slow timing, the tune and the number of turns of the multi-turn injection process. To improve shot-to-shot intensity stability, slightly more intensity than required is injected and the final 1.1×10^{12} protons per ring achieved by vertical shaving. Although this does not give the most efficient injection, it does yield normalized rms emittances in accordance with the specification of less than 2.5 μm in both planes, which were not attained when this beam was first demonstrated [1].

The bunch spacing for single-batch transfer requires the control of which bunch is extracted first, so the rf synchronisation is performed using the first harmonic of the revolution frequency.

50ns Case

This variant is very similar to the 75ns case except that the number of turns injected is increased to deliver the required 1.6×10^{12} protons per ring and this makes it more delicate to keep the transverse emittances below 2.5 μm.

PS MACHINE

The separation of the bunches arriving in the PS is readily measured by analysing the injection oscillations that occur in the absence of any phase loop gain. Fig. 2 shows (coloured lines) the deviation of this separation from the ideal as seen at injection into rigidly stationary buckets in the PS.

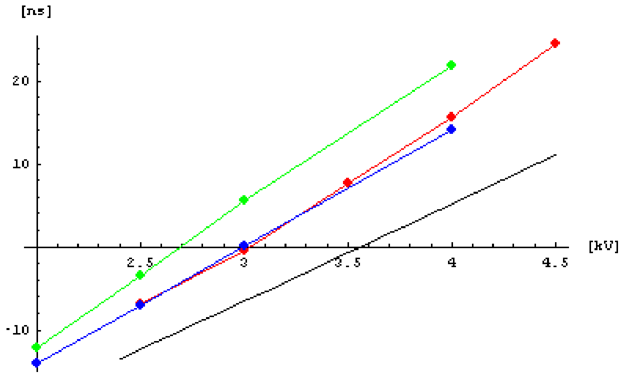
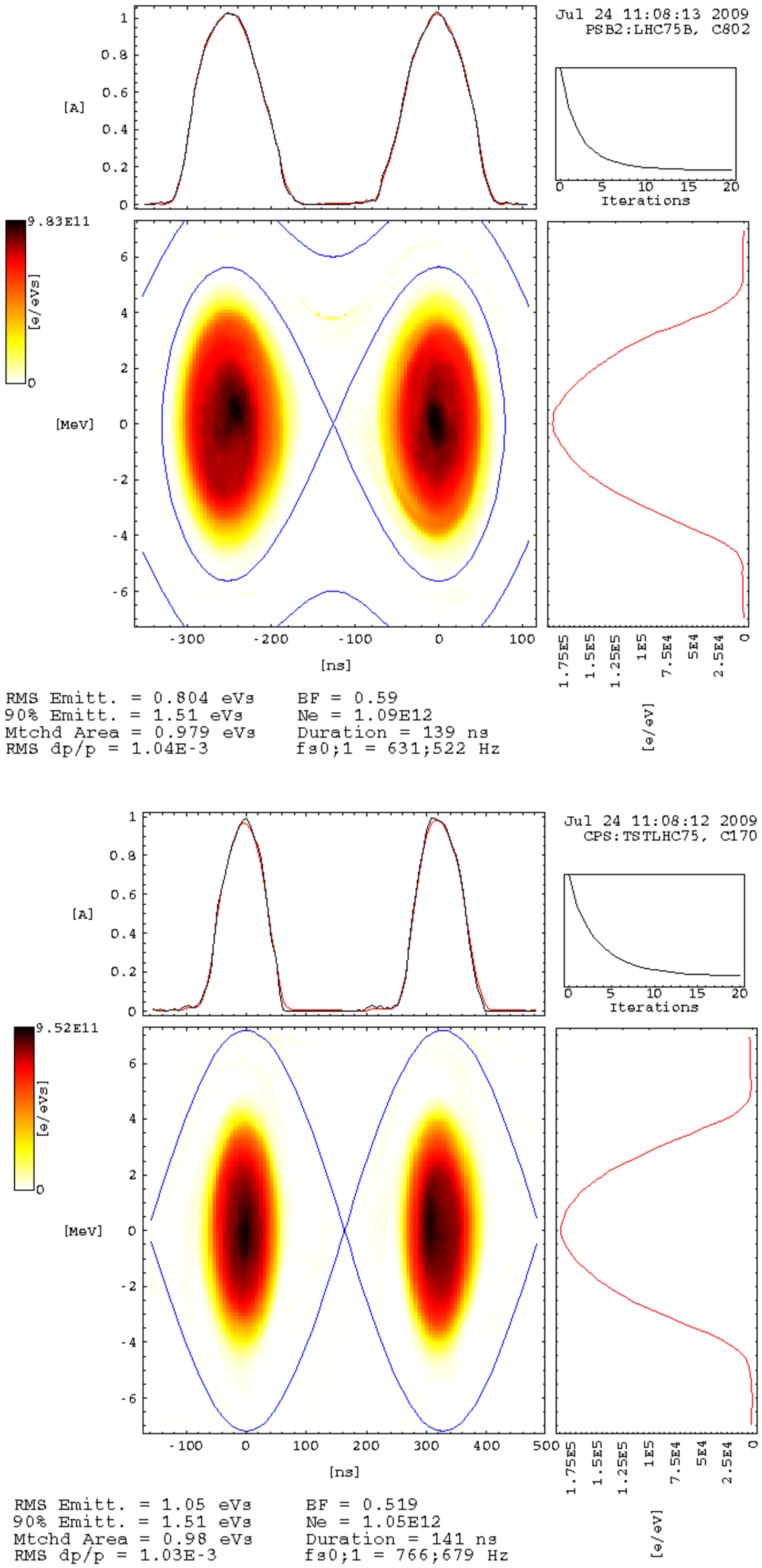


Figure 2: Bunch pair separation with respect to PS bucket separation measured at PS injection as a function of programmed h=1 rf voltage for rings 2, 3, 4 (blue, red, green) of the Booster. Cf., the calculated separation from Booster bucket centre to bucket centre (black).

The measurements differ from each other due to calibration errors in the h=1 and h=2 Booster voltage components. (The latter was maintained at its nominal maximum of 8 kV.) Possible errors in the relative phasing of the two components should have comparatively minor effect. They differ from the theoretical curve (black) because the measurements are based on the first moment of the bunches and this is displaced from the centre of the Booster buckets by an amount that depends on the distribution of particles. Nevertheless it is clear that programmed voltages of ~3kV of h=1 and 8kV of h=2 provide a voltage ratio that puts the measured first moment of each bunch of a pair at the centre of its respective PS bucket. These values have been adopted and are those applicable in Fig. 1.



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Jul 24 11:08:13 2009
  PSB2:LHC75B, C802

RMS Emitt. = 0.804 eVs      BF = 0.59
90% Emitt. = 1.51 eVs       Ne = 1.09E12
Mtchd Area = 0.979 eVs      Duration = 139 ns
RMS dp/p = 1.04E-3          fs0;1 = 631;522 Hz
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Jul 24 11:08:12 2009
  CPS:TSTLHC75, C170

RMS Emitt. = 1.05 eVs       BF = 0.519
90% Emitt. = 1.51 eVs       Ne = 1.05E12
Mtchd Area = 0.98 eVs       Duration = 141 ns
RMS dp/p = 1.03E-3          fs0;1 = 766;679 Hz
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Figure 1: Screenshots of online tomographic measurements [2] prior to extraction from one ring of the Booster (top) and at injection for the same bunch pair in the PS (bottom). The differing bunch spacings and rf periods between the two machines affect the rms emittance and bunching factor ("BF") calculations. In particular, the former is corrupted as it is made on the basis of the entire particle distribution. Similarly, the 90% emittance figure should be divided by two.

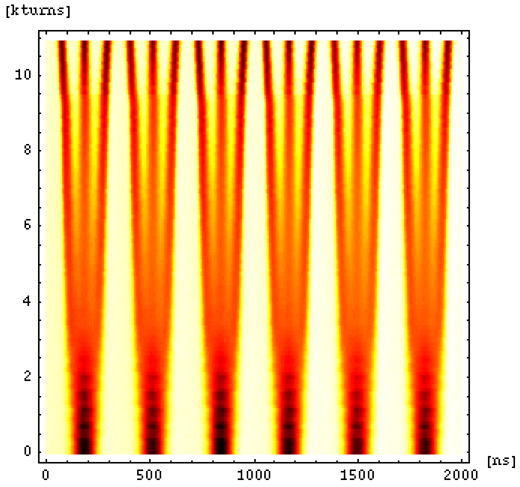
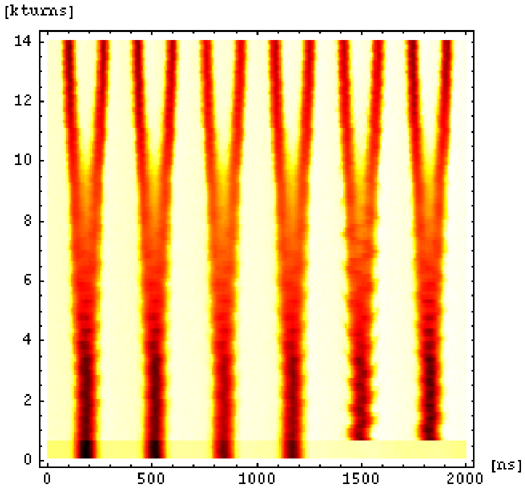


Figure 3: Triple splitting following single-batch injection and controlled longitudinal blow-up.



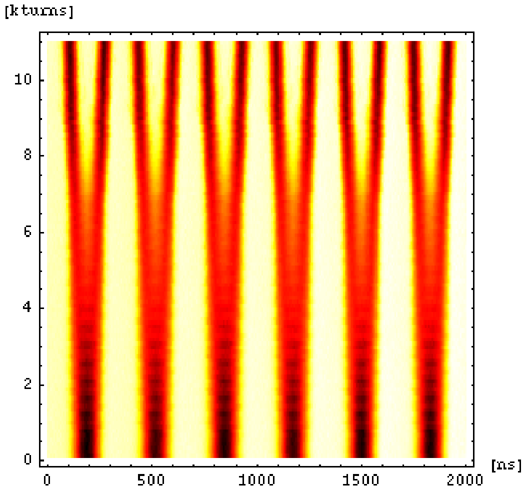


Figure 4: Comparison of bunch splitting in the case of double-batch injection (top, which is followed by a longitudinal blow-up step) and single-batch injection (bottom, which has blow-up before splitting).

Such a voltage ratio provides a theoretical acceptance of 1.6 eVs in the Booster. In practice, the ~100ns risetime of the Booster extraction kickers imposes an upper limit on the emittance that can be transferred which has been experimentally confirmed as 1.0 eVs. Whereas this is sufficient for the double splitting that occurs on the PS injection plateau in the 75ns case, it is necessary to blow up the emittance to 1.3 eVs prior to the triple splitting that is required for the 50ns variant [3, 4] (see Fig. 3). Consequently, the injection plateau of all single-batch cycles has been lengthened to permit controlled longitudinal blow-up to tailor the emittance both before and after the first splitting step. Larger bunches are more easily split because the constraint on the relative phase between rf components is relaxed and the extra flexibility has been exploited to increase the emittance beyond 1.0 eVs prior to splitting in the 75ns case as well (see Fig. 4).

Longitudinal blow-up is performed using 200 MHz cavities in the PS. At injection energy, a frequency loop is required to maintain the revolution frequency of the beam at a sub-harmonic of the narrowband frequency of these cavities. The hardware of this loop has been modified so that it can be closed more than once on the injection plateau.

Thereafter, from the start of acceleration onwards, each single-batch cycle proceeds exactly as its double-batch counterpart.

CONCLUSIONS AND OUTLOOK

Single-batch transfer has been demonstrated at nominal intensity for both the 50 and 75ns variants of LHC-type beams. For the time being this renders the double-batch versions of these cycles redundant and will shorten the filling time of the LHC at these bunch spacings.

In order to provide more kicker margin at Booster extraction, the longitudinal emittance at transfer has more recently been reduced to 0.9 eVs by fine tuning the settings of the second-harmonic rf system.

The mainstay of future work will be to investigate how far the intensity can be pushed before the transverse emittance budget for LHC-type beams is consumed. Rather than exceed the nominal intensity for the 50 and 75ns variants, the aim will be to approach as closely as possible the nominal intensity (3.2×10^{12} protons per ring) required in the 25ns case.

REFERENCES

[1] A. Blas et al., "Studies of single-batch transfer of LHC-type beams between the CERN PS Booster and the PS", in Proc. Particle Accelerator Conf., Vancouver, 2009.
[2] http://cern.ch/tomography/
[3] R. Garoby, S. Hancock, J.L. Vallet, "Demonstration of bunch triple splitting in the CERN PS", in Proc. European Particle Accelerator Conf., Vienna, 2000.
[4] R. Garoby, "Multiple splitting in the PS: results and plans", CERN-PS-2001-004-RF (2001).