DOUBLE BATCH INJECTION INTO LEP

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ABSTRACT

LEP is now routinely filled from two elementary injector cycles, one positron and one electron. During each of these cycles, 8 bunches are accelerated in the PS accelerator, then the SPS and then injected into 4 bunches in LEP. Two SPS bunches being injected into the same LEP bucket. This mode of operation has become possible as a result of synchrotron injection. The time between successive injections into the same LEP bucket is presently 6 LEP turns. This value is optimum for the present synchrotron tune used at injection in LEP. The LEP injectors normally run with a 14.4 second cycle repetition, of which four 1.2 second elementary cycles were traditionally dedicated to LEP filling. However with the new scheme only two elementary cycles (each lasting 1.2 seconds) are needed for LEP. The time saved, amounting to one sixth of the total injector cycle time has become available for other users. During the last year these have included extra physics cycles in the PS and heavy ion and LHC machine development cycles in the SPS. No loss in performance has been observed with the accumulation rates in LEP. The scheme as put into place will be described in detail.

1. INTRODUCTION

During 1994, LEP operated with a pretzel scheme, colliding 8 bunches of positrons with 8 bunches of electrons. The beams being separated in mid-arc by the use of electrostatic separators installed at the ends of each of the 8 straight sections [1]. In this mode the most efficient way to operate the injectors was to provide, within one elementary injector cycle, 8 equidistant SPS bunches, which could be directly transferred into 8 equally spaced buckets in LEP. This scheme had several advantages for the LEP injector chain, shown in figure 1, consisting of the LEP Injector Linac, the electron-positron accumulator, the PS, and SPS. Within one injector supercycle, only 8 bunches of positrons can be produced. If these are taken on one elementary cycle then the other cycles become free for other users. The use of only one electron and one positron cycle also simplifies operation considerably.

In 1995, however, LEP moved to bunch train operation. In this scheme four equidistant trains of up to 4 bunches per beam are accumulated. The bunch spacing within the train was chosen to be 247 μs [2]. With this scheme it is not possible to inject into more than one bunch of each train within the same elementary injector cycle. In order to maintain the 8 bunch mode in the injectors, it was therefore necessary to design a new scheme which would allow to inject two bunches from the injectors into one bucket in LEP. As both injections would be within the same elementary cycle, the time between them would be in the sub-millisecond, rather than the second range. As the transverse damping time in LEP at injection is of the order of 400 ms, the beam from the first injection would have no time to damp out the injection oscillations before the second batch arrived. For betatron injection this would have almost certainly resulted in the loss of the first batch as the second was injected. A means of avoiding this problem was found once LEP moved to the use of synchrotron injection.

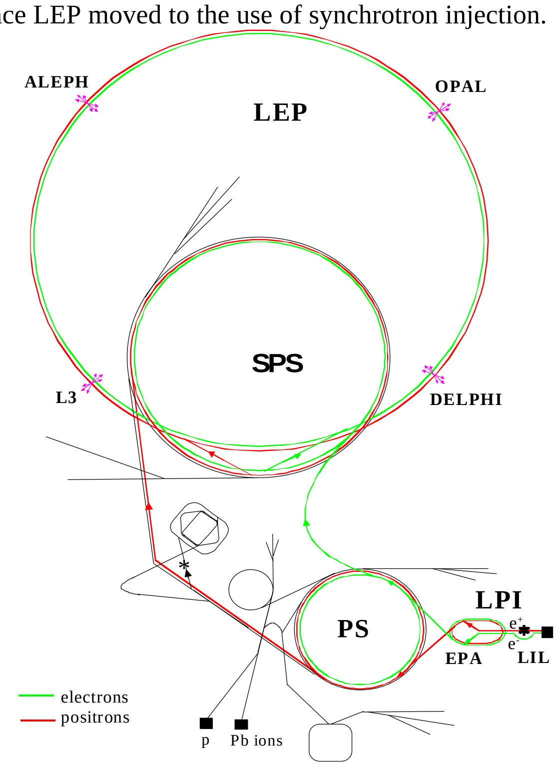

Figure 1 : The LEP Injector Chain of Accelerators

2. MULTI-BATCH SYNCHROTRON INJECTION

Synchrotron injection has been routinely used in LEP now for more than one year [3]. It has several advantages over the more normal betatron injection; including flat trajectories in the straight sections of the machine and a factor of two faster damping of injection oscillations. In addition this method of injecting beam into the machine allows several injections into the same RF bucket over a period of a few turns.

Injection in synchrotron phase space relies on the injection point being in a place where the dispersion (in the plane of the injection) is non-zero. The circulating beam is brought close to the septum with an AC bump and the incoming beam is injected with a negative offset in energy such that the product of the energy offset and the dispersion matches the distance to the circulating beam. The sign of the energy offset is determined by whether the beam is injected on the inside, or the outside of the machine. The injected beam then follows the natural closed orbit that a circulating particle would have with the same energy offset. As the beam is injected off-energy, it will perform synchrotron oscillations at the synchrotron tune (Q_s) and slowly damp into the circulating beam.

The synchrotron tune is always very much lower than the betatron tunes. In LEP the horizontal betatron tune is nominally 90.28, whereas the synchrotron tune is 0.085. The latter corresponds to about 12 LEP turns to complete a single synchrotron oscillation. 6 turns after the injection, the recently injected beam will have an energy offset of opposite sign. It will thus be further away from the septum and will not be perturbed by a second injection. This is illustrated in Figure 2 for the case of the injection of two batches. Using this method up to four batches can be injected, separated in time by ¼ of the synchrotron period in the receiving machine.

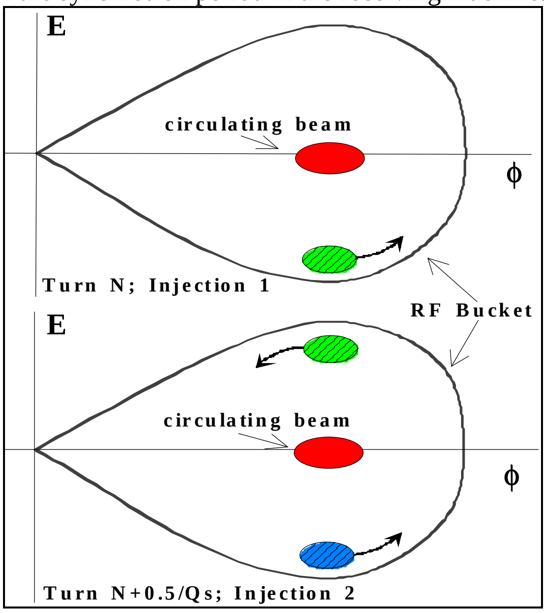

Figure 2: Multiple Injections into the Same RF Bucket.

The situation for the double batch scheme implemented in LEP is shown schematically in figure 2. The second injection has to be timed to take place an odd multiple of ½Q_s after the first. The bunch pattern in the injectors fixes the minimum time between batches at 6 LEP turns (see section 3). Extra time between batches can be added, to cope with changing values of Qs in LEP by inserting multiples of 7 LEP turns (27 SPS turns), given by the circumference ratio between the two machines. The bunch to bucket configuration repeats exactly with this period.

The Q_s in LEP strongly affects the delay between successive batch injections. Figure 3 shows the various batch delays as a function of Q_s in LEP. The vertical scale corresponds to the angular rotation of the first batch in phase space in the time between successive injections. For optimum injection with the double batch scheme, cosine(θ) should be close to -1.

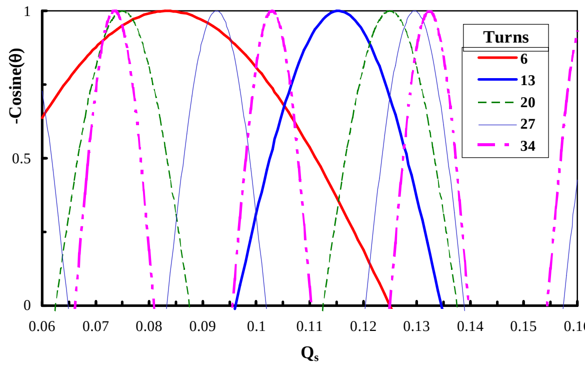

Figure 3 : The Choice of the Second Batch Delay is Determined by the Qs in the Receiving Machine.

For the present configuration in LEP, the six turn delay is used. This gives a maximum for values of Q_s around 0.085. In the future higher values of Q_s will be used to achieve higher accumulated intensities in LEP. For this scheme, larger delays will be necessary. For example, with a Q_s of 0.13, the delay between the first and second batches should be 27 turns.

There is a forbidden region in Q_s for the present scheme. This is for values in the range $0.14 < Q_s < 0.15$. This range corresponds to the region where one synchrotron period is around 7 LEP turns. Generating an odd multiple of ½Q_s is not possible here by adding multiples of 7 turns.

3. MODIFICATIONS TO THE INJECTOR CHAIN

The new injection scheme called for modifications in the RF systems of both the PS and the SPS. Only the SPS will be presented here. The re-phasing used in the PS was presented in the original LEP design report[4]. In the SPS, three RF systems are used for lepton capture and acceleration:

- Long lepton bunches from the PS are captured and accelerated during the first part of the cycle by a 100 MHz system consisting of 4 cavities.
- Bunches are then accelerated by adding a 200 MHz system, consisting of 21 cavities.
- In the middle of the accelerating ramp, four superconducting RF cavities operating at the LEP frequency (352.2 MHz) are used to supply sufficient additional voltage to reach top energy (22 GeV).

We wish to inject 8 SPS bunches into 4 equi-spaced LEP buckets. Keeping the harmonic number of the SPS RF at 352.25 MHz unchanged (h_1 = 8120), and given the ratio of the LEP and SPS radii (R_2/R_1 = 27/7), one can show that only 7 SPS buckets can be used for injection into a given LEP bucket [5]. We thus have 7 families of SPS buckets, each family containing 4 equi-spaced buckets and the families being rotated, one with respect to the other, by a multiple of $1/7^{th}$ of an SPS turn. Any pair of families can be chosen, but a more uniform choice for the second family is the one resulting in a pattern of 8 bunches in the SPS spaced by $3/28^{th}$, $4/28^{th}$, $3/28^{th}$ of an SPS turn, as shown in figure 4.

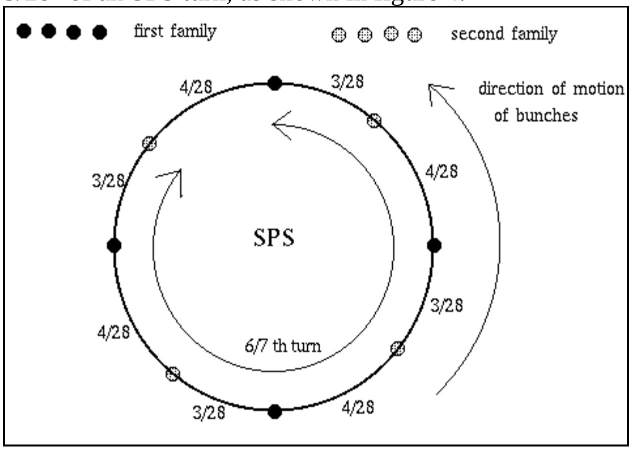

Figure 4 : The Arrangement of the 8 bunches in the SPS.

Capture and acceleration of this bunch pattern implies that the 3 lepton RF systems operate with harmonic numbers that are all divisible by 28. With the frequencies in use for the scheme in use until 1994, this condition was not satisfied by the 100 MHz and the 200 MHz systems (respective harmonic numbers h_1 = 2312 and h_1 = 4616).

The new parameters are given in table 1. The 200 MHz system could easily be operated at the new frequency, by changing the temperature of the water cooling circuits for the cavities. The 100 MHz cavities had to be squeezed by 7 mm to reduce their resonant frequency by 650 kHz.

Figure 5 shows the kicker pulses injecting the 8 SPS bunches into the 4 LEP buckets. The time between successive injections into one LEP bucket is set to 6 turns. As explained in section 2, this corresponds to a rotation of 183.6° (with Qs = 0.085), very close to the ideal value of 180°.

SPS RF (at 352 MHz) Harmonic Number	352.209 MHz h_1 = 8120 (=2^3.5.7.29)
SPS RF (at 200 MHz) Harmonic Number	200.395 MHz h_1 = 4620 (=2^2.3.5.7.11)
SPS RF (at 100 MHz) Harmonic Number	99.590 MHz h_1 = 2296 (=2^3.7.41)

Table 1 : The New SPS RF Parameters.

4. CONCLUSIONS

The double batch injection scheme has been used operationally throughout 1995. It has worked well with no reduction in the accumulation rate of beam in LEP. In fact, with only one injector cycle for each particle type being used, more effort could be put into keeping these cycles optimised. This has resulted in a higher beam transport efficiency to LEP.

The availability of spare time in the injector supercycles has allowed extra machine development time to be allocated in the SPS. During 1995 an estimated 42 days of available beam time were used for machine development purposes using the time liberated by the new LEP injection scheme. This time is set to grow significantly in the coming years.

5. REFERENCES

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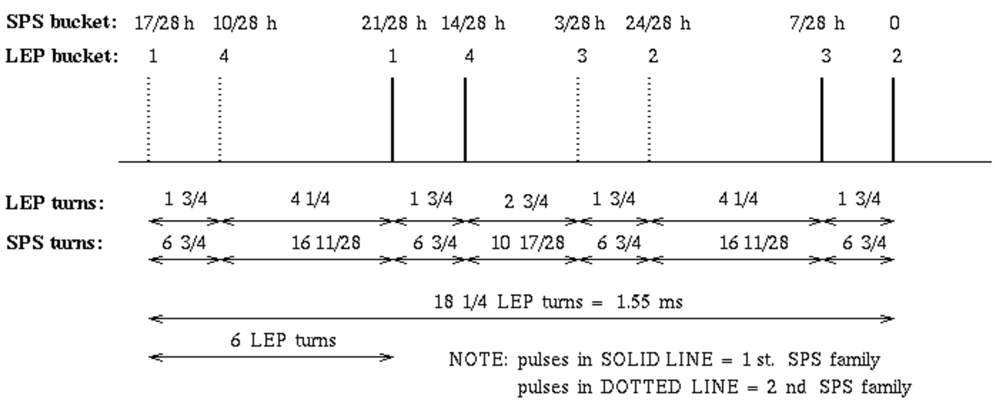

Figure 5 : Kicker Pulses Transferring 8 SPS Bunches into 4 LEP Buckets