Beam Control for Protons and Ions

P. Baudrenghien
CERN, Geneva, Switzerland

Abstract

The SPS will inject proton and ion beams into the LHC. Proton beams consist of 3 batches of 81 bunches spaced by 25 ns injected into the SPS by 3 successive transfers on a 26 GeV/c flat bottom. They are accelerated to 450 GeV/c and transferred into the LHC. Ion beams consist of 13 batches of four bunches each spaced by 125 ns. They are injected into the SPS by 13 transfers at 5.1 GeV/c/u and accelerated to 160 GeV/c/u. The RF beam control used for protons is presented in detail: synchronization of the injection from the CPS, capture of the bunches, acceleration and transfer into the LHC. Low intensity LHC beams have already been accelerated successfully by this system. The method proposed for ion beams will also be outlined.

1 PROTON BEAMS

1.1 Bunch disposition

During one SPS supercycle, three batches of 81 bunches are injected from the CPS at 26 GeV/c. The bunches are spaced by 25 ns. The intensity per bunch ranges from 0.03×10^{11} (pilot) up to 1.05×10^{11} (nominal). These three batches are accelerated to 450 GeV/c and transferred into the LHC. Normal filling will call for 12 such SPS supercycles [1].

1.2 CPS-SPS-LHC synchronization

The transfer between the CPS and the SPS is of the bunch into bucket type. Two signals are sent to the CPS: the SPS revolution frequency train f_{rev}^{SPS} tells where to inject the beam. The CPS locks its RF onto the SPS radio frequency train f_{RF}^{SPS} in order to inject on stable phase zero in the SPS bucket (figure 1). By changing the SPS bucket number shown on the figure, we can delay the revolution frequency train by a multiple of the SPS RF period and thereby choose the position of the beam injected in the SPS. The LHC will similarly be the master for the SPS-LHC transfer. The SPS receives a train of pulses at the SPS-LHC common frequency ($f_c = \frac{f_{rev}^{SPS}}{27} = \frac{f_{rev}^{LHC}}{7}$). With its bucket selector the LHC can select the position for transfer from the SPS. Notice that the SPS-LHC common frequency is also used to resynchronize the reference sent to the CPS so that the beam falls in the right SPS buckets for future transfer to the LHC.

1.3 Capture

At injection the bunch length equals 4 ns, and the longitudinal emittance is in the range 0.35 eVs to 0.5 eVs [2]. The beam is captured by the 200 MHz TW system consisting of

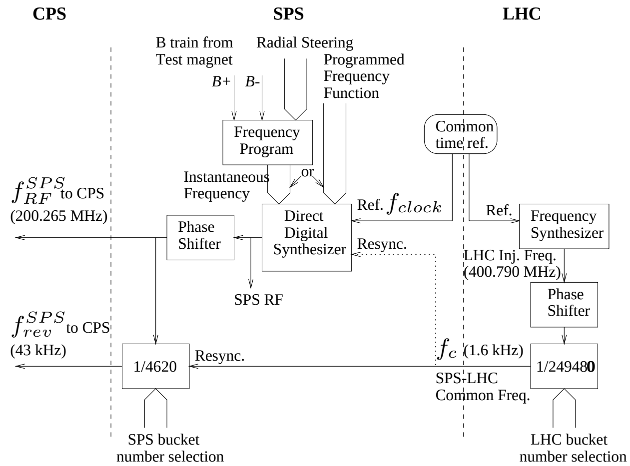

Figure 1: CPS-SPS-LHC synchronization.

four cavities [3]. Injection frequency is 200.264520 MHz. Matched voltage is 0.65 MV for the smaller emittance and 1.3 MV for the larger.

A DC coupled phase loop makes the RF jump onto the bunch at injection, thereby avoiding the blow-up of the emittance that would result from dipole oscillations (leftmost loop on figure 2). This loop remains operational during acceleration to keep stability and to reduce the effect of RF noise on the emittance: it keeps the beam-cavity phase ($\phi_b^{200} - \phi_c^{200}$) equal to the programmed stable phase (ϕ_s). Its time constant is about 2 turns (44μs).

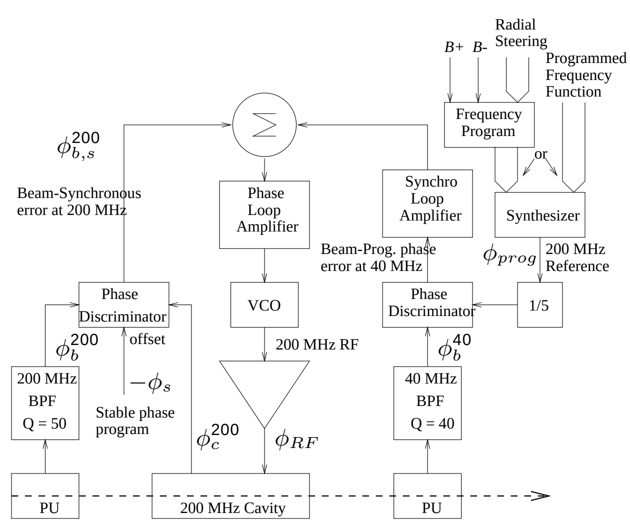

Figure 2: Low Level RF.

Figure 3 shows the capture of one bunch. Each trace shows the bunch line density as it crosses the pick-up. Traces are stacked vertically and are displayed at each turn, with the first turn at the bottom.

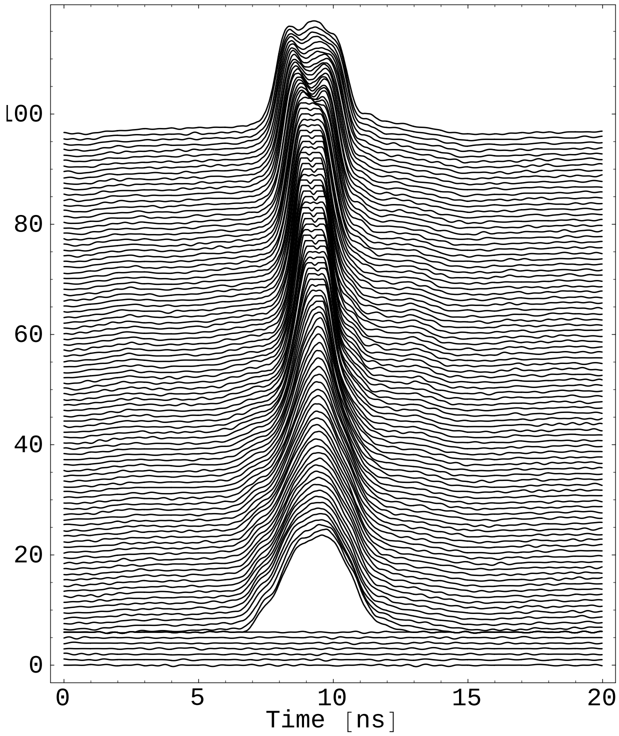

Figure 3: Capture of a bunch of reduced intensity (0.4×10^{11} per bunch). The mountain range displays one trace per turn. Quadrupole oscillations are due to a RF voltage too high (2 MV) but it could not be reduced for technical reasons. The synchrotron frequency is around 250 Hz.

1.4 Acceleration

On each of the twelve successive transfers, the SPS beam must be injected in a different location in the LHC ring. The LHC will pilot the filling by delaying the common frequency train f_c sent to the SPS by an additional $\frac{1}{12}$ revolution period (see figure 1). Before transfer, the SPS beam must be positioned precisely with respect to this reference. Rephasing on the flat top must be avoided: As explained in [4] this procedure would take about 330 ms on the flat top for a rephasing orbit decentered by 5 mm. Beside lengthening the cycle, the beam may deteriorate if instabilities develop during this long manipulation. The beam control is thus designed to minimize rephasing.

As mentioned above, the CPS-SPS transfer was synchronized onto the SPS-LHC common frequency (figure 1). During the acceleration, the RF frequency rises from 200.265 MHz at 26 GeV/c to 200.394 MHz at 450 GeV/c as the magnetic field rises from the 0.1211 T to 2.0284 T. The RF frequency is derived from a measurement of the magnetic field B according to the frequency program formula:

$$f_{RF} = \frac{hc}{2\pi R} \frac{B}{\sqrt{B^2 + (\frac{E_0}{c\rho})^2}} \tag{1}$$

where B is in Tesla, h is the harmonic number (4620), E_0 the proton rest energy in eV (938.26 MeV), and ρ the bending radius (741.3 m). The fluctuations of the magnetic field measurement (jitter between successive supercycles) is about $\pm 10^{-5}$ T at low field and $\pm 3 \times 10^{-5}$ T at top energy. This will result in an uncertainty in the longitudinal position of the beam that can be estimated to $\pm\frac{1}{240}$ SPS turn. The resulting rephasing time would be 30 ms [4]. To avoid this, we propose a procedure in two steps to fill the LHC:

Setting up. We let the B field drive the frequency program and we acquire statistics on the resulting frequency function (equation 1).

Filling. We drive the frequency program with the average frequency function derived from the setting up. We ignore the actual B field.

This renders the beam longitudinal position on the flat top independent of the noise in the magnetic field. The penalty is a fluctuation of the orbit since the RF frequency does not adapt to the magnetic field: at injection this displacement is ± 0.32 mm maximum. It is negligible ($\pm 10^{-4}$ mm) at transfer into the LHC [4].

During the acceleration, the beam must be locked in phase onto the frequency function. This is the purpose of the synchronization loop (rightmost loop on figure 2). We compare the beam phase at 40 MHz (ϕ_b^{40}) with the output of the synthesizer divided by 5. The frequency 40 MHz matches the beam structure well (25 ns bunch spacing) and reduces the needed dynamic range for the phase discriminators . The synchronization loop is slow, with a response time of the order of a synchrotron period.

Figure 4 shows the voltage and stable phase program during the cycle [1] for an emittance of 0.6 eVs and a bunch filling 95% of the bucket height. The corresponding evolution of the bunch length and synchrotron frequency are shown on figures 5 and 6. The drop of the voltage at the end of the cycle and the corresponding increase in bunch length come from the required fixed bucket size but, in practise, the voltage will be raised on the flat top to reduce bunch length down to the desired 1.7 ns. Note that the synchrotron frequency does not vary much during the acceleration thereby making the design of a stable synchronization loop easy [5].

1.5 Rephasing and transfer to LHC

The bunches must be compressed to 1.7 ns for a clean transfer into the 400 MHz LHC buckets [3]. For an emittance of 0.6 eVs this is achieved with 6 MV RF voltage. However,

[1] We use the same magnetic cycle as in ppbar.

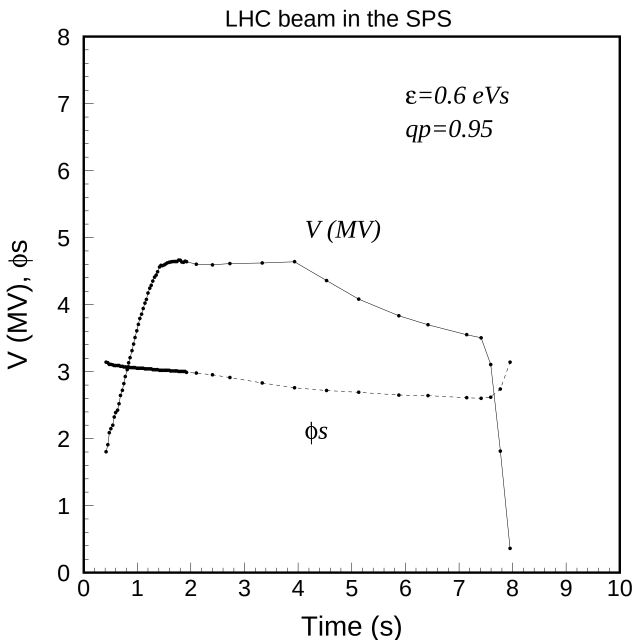

Figure 4: Voltage and stable phase program during the cycle for 0.6 eVs. (Reproduced from [6]).

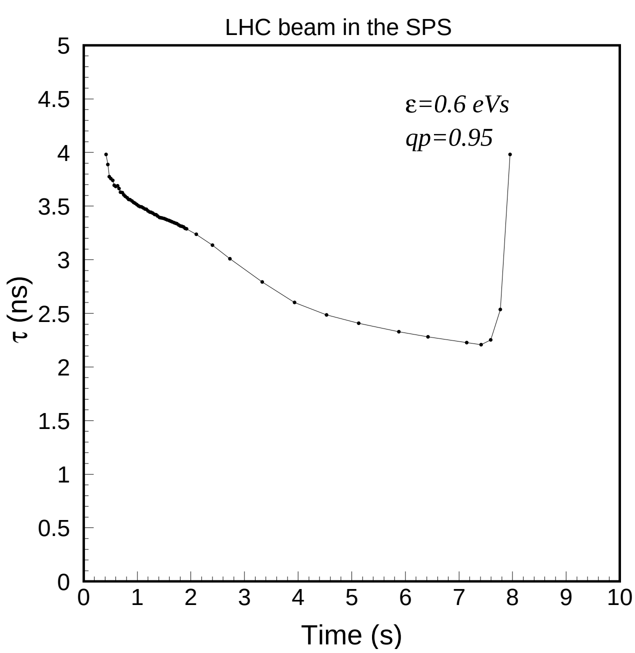

Figure 5: Evolution of bunch length during the cycle. (Reproduced from [6]).

adding a 200 MHz system in the LHC is under consideration. With this, 2 ns long bunches are acceptable [7].

Rephasing on the flat top will be needed but the angle is small: the magnetic field and the programmed frequency function shown on figures 1 and 2 are driven by the master timing while the CPS-SPS injection and SPS-LHC transfer are synchronized on the SPS-LHC common frequency.

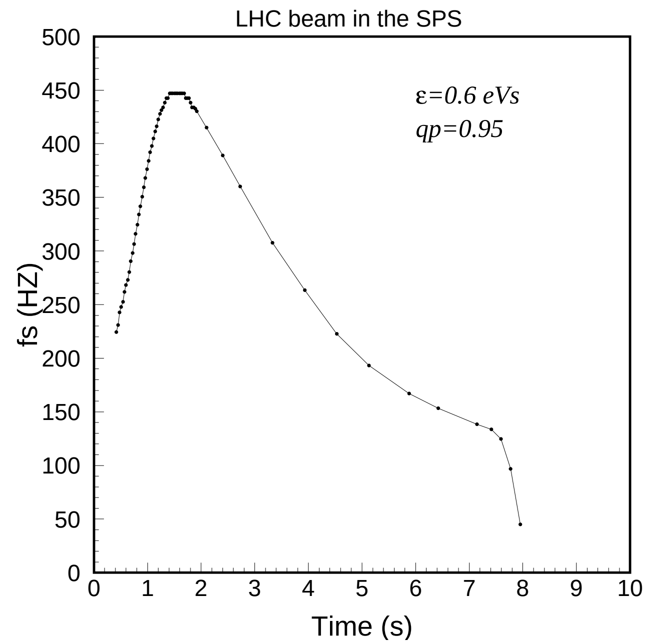

Figure 6: Synchrotron frequency during the cycle. (Reproduced from [6]).

Without precaution, the resulting phase error at 200 MHz will be

$$|\Delta\phi| = 2\pi \times T \times (f_{max} - f_{min}) \tag{2}$$

where f_{max} equals 200.395 MHz (450 GeV/c), f_{min} equals 200.265 MHz (26 GeV/c) and the maximum value of T is one common frequency period (600μs) as shown on figure 7. In case (a) the RF phase will accumulate at the flat bottom frequency f_{min} during the time T while in case (b) it will accumulate at the flat top frequency f_{max}. The maximum resulting phase error is thus 78 RF periods at 200 MHz. We propose to measure the phase of the f_c train with respect to the master timing before the first CPS-SPS transfer, and to adjust the SPS bucket number selector (figure 1) accordingly. We aim at a final rephasing of less than ± 1 bucket at 200 MHz.

2 ION BEAMS

2.1 Bunch disposition

On the flat bottom the CPS injects 13 batches of four bunches each. Bunch spacing is 125 ns. The batches are stored in succession so that the beam ends up filling slightly more than one quarter of the ring. Twelve SPS cycles are needed to fill the LHC [1] [2].

2.2 CPS-SPS synchronization and capture

The transfer is of the bunch into bucket type. The CPS bunches the beam on his harmonic 17 prior to transfer at 5.11 GeV/c/u. This corresponds to a CPS RF at 7.977 MHz [2]. To avoid emittance blow-up at injection, the SPS RF

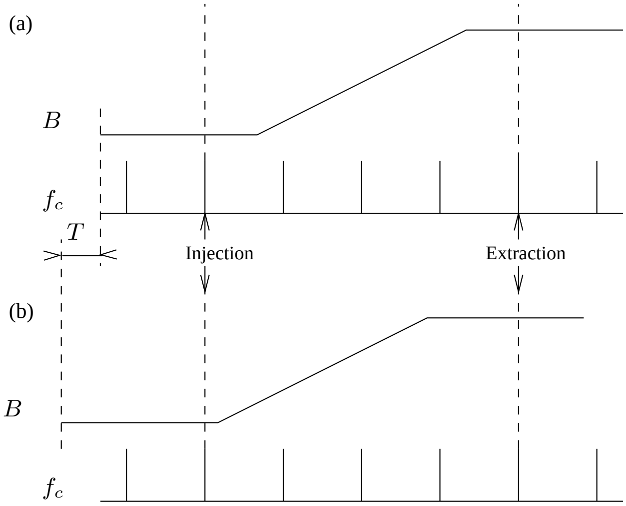

Figure 7: Asynchronism between the magnetic field B and the SPS-LHC common frequency f_c. (a) shows B and f_c. (Not drawn to scale. $f_c = 1.6$ kHz). On figure (b) the magnetic field has been shifted by T.

period must be a sub-multiple of the bunch spacing. This gives

$$h_{SPS} = 17 \times 11 \times n \tag{3}$$

where the factor 11 is the SPS/CPS ratio of radii. With the choice $n = 25$ we get $h_{SPS} = 4675$ and the resulting RF frequency (199.418 MHz) falls in the range of the TW cavities (zero voltage seen by the beam at 198.5 MHz and 202 MHz). At top energy however, $h_{SPS} = 4675$ gives a RF frequency outside the range of the cavities (202.8 MHz). Fixed frequency acceleration [8] [9] must thus be used with a cavity RF equal to $4675 \times f_{rev}$ at injection and a frequency program on harmonic 4620 (197.072 MHz at injection). We propose to synchronize the transfer by sending to the CPS the usual two signals: the SPS revolution frequency and the SPS RF on harmonic 4675.

2.3 Acceleration

After the injection of the last CPS batch, the cavity RF will be raised adiabatically to 200.222 MHz where the highest accelerating voltage is available from the cavities [10]. Fixed frequency acceleration will then proceed untill the RF on harmonic 4620 equals 200.222 MHz. We will then switch to fixed harmonic number acceleration on $h = 4620$ (i.e. the method presently used for fixed target beams).

2.4 Rephasing and transfer into the LHC

Once on the SPS flat top, the bunches on $h = 4620$ are correctly spaced for transfer into the LHC buckets since the LHC RF frequency is exactly twice the SPS RF frequency. At present it is not clear whether the amplitude of rephasing can be reduced in a manner similar to the one proposed for proton beams.

3 CONCLUSION

The beam control presented here for protons has successfully accelerated a beam consisting of a single batch of 81 low intensity bunches (0.3×10^{11} per bunch) made available by the CPS during a machine development session (31/8/98 - 1/9/98). It was again used to capture the beam on a flat bottom at 26 GeV/c (81 bunches, 0.4×10^{11} per bunch) in November 98 but the magnetic field was not allowed to rise (no acceleration). The method proposed for ion beams is still in the design stage.

The work presented here has involved many people in the SL/HRF section. Particular credit is due to T. Bohl, D. Boussard,T. Linnecar and E. Shaposhnikova whose contributions shaped the final design.

4 REFERENCES

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