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SPS Beams for LHC: RF Beam Control to Minimize Rephasing in the SPS

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Abstract

After acceleration to 450 GeV/c in the CERN SPS, the proton beams for the LHC must be rephased in order to be injected into the correct place in the collider. If the position before rephasing is random, the beam must be rotated by up to 1/14 SPS turn. This procedure will take about 330 ms on the flat top. Besides lengthening the cycle, the beam may deteriorate if instabilities develop during this long process. We present a beam control system that reduces the rotation angle needed.and which has been successfully tested in the SPS.

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Abstract

After acceleration to 450 GeV/c in the SPS, the proton beams for the LHC must be rephased in order to be injected into the correct place in the collider. If the position before rephasing is random, the beam must be rotated by up to $\frac{1}{14}$ SPS turn. This procedure will take about 330 ms on the flat top. Besides lengthening the cycle, the beam may deteriorate if instabilities develop during this long process. We present a beam control system that reduces the rotation angle needed and which has been successfully tested in the SPS.

1 INTRODUCTION

After acceleration to 450 GeV/c, the SPS beam must be rephased with respect to the LHC, in order to be injected in the correct place [1]. Rephasing is done by letting the particles run for a short moment Δt at an average radius different by ΔR from the central orbit ($R = 1100$ m). If we assume a random position before rephasing, we may have to rotate the SPS beam by $\frac{1}{14}$ th SPS turn: 27 SPS turns correspond to 7 LHC turns, so that after each LHC turn the SPS beam has moved by 4 SPS turns minus $\frac{1}{7}$. We can choose the optimum LHC turn for transfer and by rotating the beam in both directions, we reduce the rotation angle to $\frac{1}{14}$ th SPS turn. Accepting to decenter the orbit by 5 mm:

$$\frac{\Delta R}{R} \approx 5 \times 10^{-6} \tag{1}$$

the frequency offset at 450 GeV/c ($\gamma = 481$) is

$$\frac{\Delta f}{f} = -\frac{\gamma^2 - \gamma_{tr}^2}{\gamma^2}\frac{\Delta R}{R} \approx -5 \times 10^{-6} \tag{2}$$

where $\gamma_{tr} = 23.23$. That is 1 kHz at 200 MHz, small compared to the bandwidth of the RF system. The time spent on the rephasing orbit is given by

$$\Delta t = \frac{\Delta\theta}{2\pi}\frac{T_{rev}}{\frac{\Delta f}{f}} \tag{3}$$

where $\Delta\theta$ is the rephasing angle and T_{rev} is the revolution period ($23\mu s$). To rephase $\frac{1}{14}$ th turn, we get $\Delta\theta = \frac{2\pi}{14}$ and

$$\Delta t \approx 330\,\mathrm{ms}. \tag{4}$$

Beside lengthening the flat top proportionally, this long manipulation may deteriorate the beam. High intensity bunches will be at the limit of stability [1].

2 CPS-SPS-LHC SYNCHRONIZATION

We can *anticipate* the position on the SPS flat top: We inject the CPS beam in the right SPS buckets so that, after acceleration, it is in the correct position for transfer to LHC. The transfer between CPS and SPS is of the *bunch into bucket* type [2]. By providing its revolution frequency train f_{rev}^{SPS} the SPS tells the CPS where to inject the beam (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 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 LHC. Synchronization of the transfer proceeds as follows:

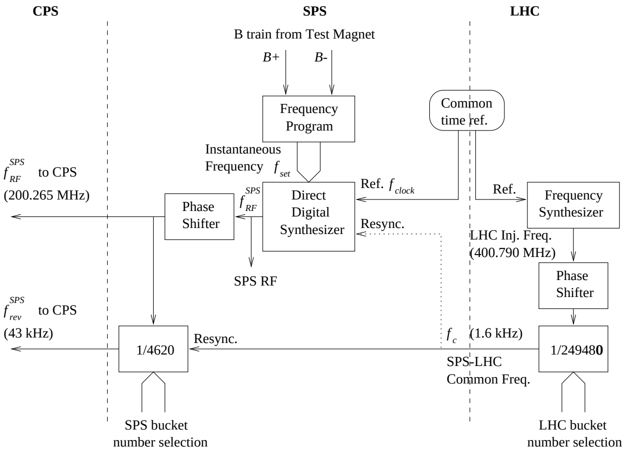

Figure 1: CPS-SPS-LHC synchronization.

Flat bottom. No beam. The synthesizer is set to the SPS injection frequency.

Flat bottom. CPS-SPS transfer. Three CPS cycles are used to inject into the SPS. Each transfer is synchonized on the SPS revolution frequency train so that the bunches arrive in the right buckets.

Ramping. After the last injection the magnetic field starts rising. The SPS synthesizer now follows either the B driven frequency program (section 3) as shown on figure 1 or a programmed frequency function (section 4).

3 FREQUENCY PROGRAM DERIVED FROM THE MAGNETIC FIELD

The LHC injection frequency synthesizer is locked on the *same time reference* (a 10 MHz quartz for example) as the SPS synthesizer (figure 1). The frequency program is derived from a *measurement* of the main dipole field according to the relation

$$f_{set} = \frac{hc}{2\pi R} \frac{B}{\sqrt{B^2 + (\frac{E_0}{c\rho})^2}} \tag{5}$$

where B is the magnetic field 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 source of longitudinal position error is then the fluctuation of the magnetic field ΔB. The resulting phase error at 200 MHz will be

$$\Delta\phi = 2\pi \int_{StartRamp}^{Transfer} \frac{\partial f_{set}}{\partial B} \Delta B dt \tag{6}$$

where the partial derivative is taken at constant R. Using the well known differential relation (at constant R):

$$\frac{\Delta f}{f} = \frac{1}{\gamma^2} \frac{\Delta B}{B} \tag{7}$$

and considering the revolution frequency f_{rev} constant, we get the bound

$$|\Delta\theta| \leq 2\pi f_{rev} |\Delta B| \int_{StartRamp}^{Transfer} \frac{1}{\gamma^2} \frac{1}{B} dt \tag{8}$$

where $\Delta\theta = \frac{\Delta\phi}{h}$. (A value of 2π corresponds to an entire SPS turn). The *short term* reproducibility of the magnetic field (jitter between successive supercycles) is about $\pm 10^{-5}$ T at low field and $\pm 3 \times 10^{-5}$ T at top energy. After integrating over the magnetic ramp we get:

$$|\Delta\theta| \leq 2\pi \times 4.1 \times 10^{-3} \approx 2\pi \frac{1}{240}. \tag{9}$$

The rephasing angle is thus reduced by a factor of almost 20. A precise derivation of the resulting duration of the rephasing must include the time needed to move the beam to the off-centred orbit and back: With 8 MV available from the 200 MHz Travelling Wave Cavities, a maximum stable phase angle of 30 degrees will keep the desired bucket area of 1 eVs at 450 GeV. This will change the beam frequency at the rate of 140 kHz/s. Figure 2 shows the modulation applied to the RF. The total duration is 26.2 ms.

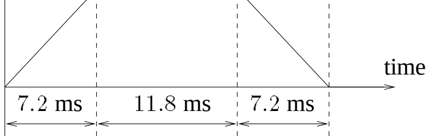

Figure 2: Modulation of the SPS RF in order to rephase the beam by $\frac{1}{240}$ turn at 450 GeV.

4 PROGRAMMED FREQUENCY FUNCTION

Driving the frequency program from a measurement of the magnetic field (equation 5) is commonly used in proton synchrotrons. Alternatively we can drive the synthesizer from a function driven by the timing: At all times during the acceleration ramp the frequency will be matched to the *theoretical* value of the magnetic field at that instant. The longitudinal position at transfer becomes perfectly predictable, but the magnetic fluctuations now transform into radial excursions:

$$\frac{\Delta R}{R} = \frac{1}{\gamma^2 - \gamma_{tr}^2} \frac{\Delta B}{B}. \tag{10}$$

At injection ($B = 0.1211$ T, $\gamma = 28.73$, $\Delta B = \pm 10^{-5}$ T) the orbit will thus be displaced by ± 0.32 mm. At transfer into the LHC the displacement is negligible: $\pm 10^{-4}$ mm. On the long term the field varies much more. We propose a procedure in two steps:

Setting up the SPS for filling the LHC. We let the B field drive the frequency program and we acquire statistics on the resulting frequency function (equation 5).

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

5 RF BEAM CONTROL

Figure 3 shows the proposed low level system. It consists of two loops. The leftmost loop is a classic DC coupled *beam phase loop*: It gives fine control of the phase seen by the beam when crossing the 200 MHz cavities. An ideal phase loop keeps the beam-cavity phase ($\phi_b^{200} - \phi_c^{200}$) equal to the programmed stable phase (ϕ_s) in the presence of RF noise and damps longitudinal dipole oscillations. In our design its time constant is about 2 turns (40μs). A second loop is needed to control the orbit during acceleration. Beam and synthesizer must be compared in phase in order to keep phase coherence. This phase-locked loop is called a *synchronization loop* [3] (rightmost loop on figure 3). 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 . We will now analyse the synchro loop in detail.

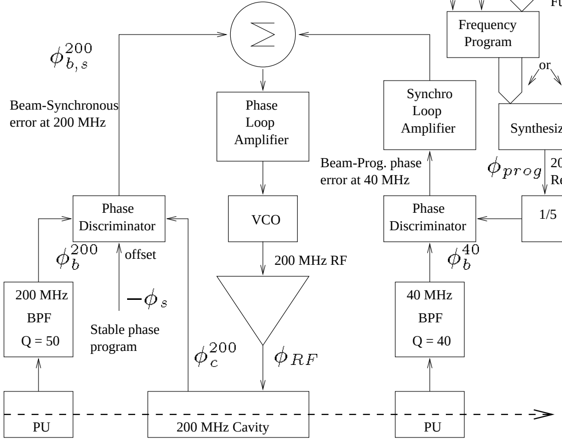

Figure 3: Low Level RF.

6 SYNCHRONIZATION LOOP

The *synchronization loop* is meant to keep the beam locked in phase on either the frequency program or the programmed frequency function during acceleration. Since it must move the beam (accelerate or decelerate it) this loop will be slower than the synchrotron frequency to remain adiabatic. To achieve an acceptable loop response the synchro loop amplifier is a phase advance network:

$$K_{sync}(s) = K_{sync} \frac{1 + a\tau s}{1 + \tau s} \qquad (11)$$

where

$$a = 10, \tau = \frac{0.36}{\omega_s} \qquad (12)$$

and ω_s is the synchrotron frequency in rad/s. Figure 4 shows the step response (beam phase $\phi_b^{200}(t)$ for a step in the phase of the frequency program reference $\phi_{prog}(t)$) for $\omega_s = 2\pi \times 200$ (rad/s), with the loop parameters optimized for that value of ω_s. During acceleration the synchrotron frequency varies between 100 Hz and 400 Hz [4]. Although the loop parameters could be programmed accord-

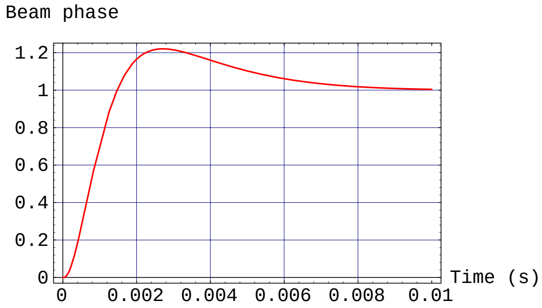

Figure 4: Beam phase for a step in the phase of the frequency program reference.

in the full frequency range.

7 BEAM TESTS IN THE SPS

The method was successfully tested in November 97: The CPS provided a low intensity LHC type beam consisting of 84 bunches spaced by 25 ns (2.2×10^9 p per bunch, 0.09 eVs emittance). After injection in the SPS at 26 GeV, the beam was accelerated to 450 GeV with the new system. (The frequency program was driven by the dipole field). The loops behaved as calculated. The measured longitudinal position at top energy was fluctuating by ± 55 ns ($\pm\frac{1}{400}$ SPS turn) from cycle to cycle (figure 5), consistent with the expected bounds (equation 9).

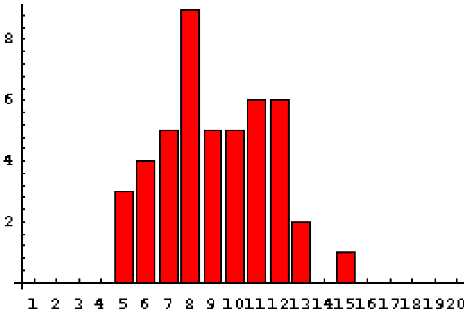

Figure 5: Dispersion of the measured position of the beam on flat top (46 successive SPS cycles). Horizontal axis is time. Each bin is 10 ns wide.

8 CONCLUSION

We have presented a beam control that limits the rephasing of the LHC beam in the SPS. If the frequency program is derived from the main dipole field, rephasing can be completed in 26 ms on the flat top. Alternatively no rephasing is needed if the frequency is driven directly by a programmed function, but the jitter of the magnetic field affects the radial position by ± 0.3 mm at the beginning of the ramp. A beam control system that can implement both methods has been designed.

9 REFERENCES

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