# Damping of Phase Errors at Injection in the LHC

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## I. INTRODUCTION

Capture losses must be kept to an extremely small value in the superconducting, very high intensity (0.85 A per beam) LHC machine [1]. Bunches from the injector (the SPS accelerator) are fairly long (51 cm full length compared to the RF wavelength of 75 cm) and phase injection errors may bring the edge of the injected bunch very close to the separatrix. Following the SPS collider experience, it is therefore of prime importance to quickly damp any phase (or energy) error at injection in order to avoid capture losses as much as possible. The main LHC RF system is composed of eight single cell 400 MHz superconducting cavities [2], which are common to both beams and cannot be used to act independently on a newly injected batch. Dedicated cavities (or longitudinal kickers) working on each beam separately will provide damping of phase oscillations just after injection; they may also be used to suppress any coupled bunch longitudinal instability during coast.

## **II. PHASE ERRORS AT INJECTION**

## A. Phase Modulation in the LHC

As explained in ref [3], the equilibrium phase of the LHC bunches is not constant along one machine turn, due to the effect of transient beam loading. The RF waveform will be phase modulated via the reference voltage of the RF feedback circuits; this is in order to keep the required RF power within acceptable limits. When a new batch is injected, the equilibrium phase modulation changes immediately (Fig. 1). This means that the already injected bunches become out of phase with the new RF waveform and start phase oscillations. The maximum phase error  $\delta \phi_{max}$  occurs when the last batch is injected:

$$\delta\phi_{\text{max}} = \frac{1}{2} \frac{R}{Q} \frac{\omega_0}{V} I_B \Delta t_0$$
(1)

where  $\frac{R}{Q} = 8 \times 43.5\Omega$  is the characteristic impedance of the

eight RF cavities,  $\omega_0/2\pi$ =400 MHz the RF frequency, V=8 MV the RF voltage at injection, I<sub>B</sub>=1.25A the RF component of the injected beam current,  $\Delta t_0$ =6.2µs the length of the injected batch and T=1/f\_0=89µs the revolution period. One finds  $\delta \phi_{max} = 0.42$  rad (24° RF phase).

## B. Phase Modulation in the SPS

The SPS RF system is composed of four 200 MHz travelling wave structures [4], each 16 m long (4 sections). The accelerated batch for LHC, which occupies only a small fraction (6.2 $\mu$ s) of one SPS turn (23  $\mu$ s) induces in each accelerating structure a voltage V<sub>b</sub> = 1.40 MV, almost in phase with the beam current. This beam induced voltage must be compensated by an increase of the RF input power in the structure from 560 kW (I<sub>B</sub>=0) to 750 kW (I<sub>B</sub>=1.57A at 200 MHz). A straightforward way to achieve this is with a

feedforward technique: the I<sub>B</sub> signal measured with a beam monitor is added to the cavity drive signal after one turn delay and proper phase and amplitude adjustments. Compensation cannot be perfect, however because of the limited bandwidth of the RF power amplifiers and of the different responses of the cavity to the beam and to the RF drive. For a simplified model of the cavity (transmission line equivalent) the transient beam induced voltage is parabolic with a response time of 560 ns. The correction from the amplifier has a rise time of about 1  $\mu$ s (combination of linear rise of 560 ns in the cavity and amplifier rise time) (Fig. 2). The maximum difference when the amplifier is slightly overpowered (max power 1 MW) can be kept below V<sub>b</sub>/4, which corresponds to a residual phase modulation of  $\pm$  10° at 200 MHz for a 2MV RF voltage per cavity.

In order to compress the bunches prior to ejection the SPS will be equipped with three superconducting single cell 400 MHz cavities providing an additional 6MV RF voltage, but with a negligible contribution to the machine impedance (with RF feedback). These cavities will be essentially beam driven at ejection, when the instantaneous RF frequency of the beam current is brought close to the s.c. cavity resonant frequency [5]. The residual phase modulation due to the travelling wave cavities will be reduced by the factor  $h_1V_1/(h_1V_1+h_2V_2)$  where  $V_1$ ,  $V_2$ ,  $h_1$ ,  $h_2$  are the voltages and harmonic numbers at 200 MHz and 400 MHz respectively. It follows that the residual 400 MHz phase modulation at ejection is  $\pm 8^\circ$ .

Due to the large bandwidth of the travelling wave structures, it is always possible to phase modulate the ejected batch to match the equilibrium phase slope in the LHC.

Finally, errors in the synchronization electronics between the two machines will result in a random (but constant for one batch) error estimated to  $\pm$  15° at 400 MHz.

#### III. SIGNAL PROCESSING

#### A. Phase Detection

A classical double balanced mixer circuit will be used as a phase detector at 400 MHz between a reconstructed RF burst from the beam and the RF reference. A technique similar to that proposed for the SLAC B factory [6], but working at the RF frequency looks adequate. Each bunch will produce a 20 ns long 400 MHz burst (8 periods) at the output of an eight quarter wave couplers comb generator. In order to minimize the total length of the comb generator, the quarter wave couplers need not be spaced by one full wavelength provided the cable lengths to the combiner are properly selected. The output of the mixer is sampled at the bunch frequency (40 MHz) and converted to digital form for subsequent processing.

In order to avoid large offsets ( $\approx 60^{\circ}$ ) which would considerably reduce the useful range of the phase detector, the RF reference applied to the mixer must be phase modulated like the reference applied to the RF cavities [2] [3].

#### B. Filtering

The phase error signal of each bunch should ideally be phase shifted by 90° at the synchrotron frequency and applied

to the same bunch as an additional feedback voltage Vf, after a delay of one or several turns. If the same processing is applied to every bunch, one obtains an overall periodic transfer function which repeats every  $f_0$  [7] [8]. Within a 0 $f_0/2$  interval the filter should exhibit a high gain and phase shift close to 90° at the synchrotron frequency  $f_s$  to get optimum damping with minimum RF power. Outside the range of fs the gain should be low to limit noise power, in particular it must vanish at zero frequency to reject the phase detection offsets. For the particular case of fast damping of injection errors, it is important to quickly reject the injection offset; this takes a time of the order of  $1/f_p$  where  $f_p$  is the frequency of the peak response of the filter ( $0 < f_p < f_0/2$ ). For  $f_p > f_s$  (differentiator case) the offset is rejected in less than one synchrotron period, which allows closing the damping loop very soon after each injection without saturation. Noise induced power outside the fs band is unimportant at injection, as power requirements are completely determined by the initial phase errors.

The selected filter architecture is based on the difference of two recursive digital filters of the form:

$$H(\omega) = \frac{1 - K_1}{1 - K_1 \exp(-j\omega T)} - \frac{1 - K_2}{1 - K_2 \exp(-j\omega T)}$$
(2)

which can be realized with a limited memory capacity (3 times the number of bunches) and simple hardware (Fig. 3), especially if  $K_1$  and  $K_2$  are of the form 1-2<sup>-N</sup>. In this case, only adders and substractors are needed. The cycle time of the filter (two adders, truncation, memory access and latch) amounts to less than 20 ns, smaller than the bunch to bunch distance of 25 ns. Consequently neither multiplexing nor down sampling would be necessary. The same filter could be used in coast where  $f_s=20Hz$  is smaller by changing  $K_1$  and  $K_2$  ( $K_1=7/8$ ,  $K_2=15/16$ ). With  $K_1=3/4$ ,  $K_2=7/8$  and  $K_1=7/8$ ,  $K_2=15/16$  one obtains the curves  $H(\omega)$  of Fig. 4. An additional memory will complement the filter to achieve an overall one turn delay. Fig. 5 shows how quickly the filter separates the useful  $f_s$  signal from the unavoidable offset at injection.

## C. Post Processing

A further signal processing will be needed before applying the signal to the feedback cavities (longitudinal kickers). An equalization circuit is needed to compensate the cavity response at least up to a frequency corresponding to the fastest change of phase errors at injection (a few MHz). The feedback cavities will be equipped with RF feedback in order not to increase the machine impedance. Their closed loop transfer function including the loop delay is very similar to that of a second order system and can be compensated at the digital level by the inverse circuit.

Holes in the LHC bunch trains need special treatment, otherwise the step in the filter output signal at each new bunch following a hole will saturate the power amplifier during the passage of the first bunches of the batch. It is proposed to write in the last memory, instead of the non significant values of the hole, the value of the first following bunch. The step, which now appears at the beginning of the hole will saturate the chain during the hole instead of during the passage of bunches. After digital processing, the feedback signal is translated in frequency by a double balanced mixer (rejected carrier) driven by the (phase modulated) RF.

## IV. HIGH POWER EQUIPMENT

#### A. Feedback Voltage

For a damping time of three synchrotron periods and maximum phase error of 24° RF phase, the peak feedback voltage amounts to  $V_f=360$  kV. It will be provided by three 200 MHz "bar cavities" per beam, similar, but longer to those described in [1]. The total R/Q of the feedback cavities (525 $\Omega$ per beam) is comparable to that of the main cavities (348 $\Omega$  for the two beams), however their effect on transient beam loading can be made negligible with RF feedback (bandwidth ± 400 KHz). Each feedback cavity will be driven by one or several 200 MHz tetrodes. The transformation ratio between accelerating voltage and anode voltage should be approximately constant over the range of the bunch to bunch feedback system i.e ± 20 MHz. This means that the tetrode cavity distance must be as short as possible which is also beneficial for RF feedback.

#### **B.** Power Requirements

The peak power capability of the tube is determined by V<sub>f</sub> (120 kV per cavity) and the maximum tube current I<sub>g</sub> transformed at the cavity gap. During the passage of a batch I<sub>g</sub>  $\approx$ -I<sub>b</sub>=1.25A (RF feedback effect) whereas during the hole preceding the newly injected batch (0.97 µs long) I<sub>g</sub> is needed to change V<sub>f</sub> rapidly. In the worst case  $\delta \phi = 24^{\circ} + 15^{\circ}$ , one finds I<sub>g</sub>=1.82A and finally an installed power of 110 kW per cavity.

In this scenario the very fast rate of change of  $V_f$  induced by the residual SPS phase modulation (8° in 200 ns) will be slow rate limited by the processing electronics, the result being a slower damping for the limited number of bunches concerned.

## V. REFERENCES

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Fig. 1 Phase modulation at injection

Fig. 2 Transient induced voltage in the SPS travelling wave structure



 $z^{-L}$ ; delay of L clock periods (one turn)  $z^{-L}$ ; delay of L' clock periods (one turn minus a fixed delay) N: number of bits

Equation of the branch of the filter with K=15/16: y(n)=y(n-L)+(x(n)-y(n-L))/16 or  $y(n)=15/16^*y(n-L)+x(n)/16$ 

Fig. 3 Architecture of the filter







Fig. 5 Rejection of injection offset top:  $f_s$  oscillation (2 phases a, b) superimposed on unit step offset bottom: filter output