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# BUNCH COMPRESSION IN THE SPS AS LHC INJECTOR

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For the SPS to work as injector for the LHC it may be necessary to install 400 MHz cavities in order to obtain the necessary bunch length prior to extraction of the beam towards LHC. To reduce the RF power requirements for these superconducting cavities the method of non-integer harmonic number acceleration is proposed. Bunch compression is then achieved by adiabatically displacing the spectrum of the beam.

*Keywords:* SPS; Bunch compression

## 1 INTRODUCTION

The SPS will accelerate 243 bunches each of about $10^{11}$ protons, spaced at 25 ns and occupying 3/11 of the ring circumference using the existing travelling wave cavities. These cavities have a filling time of 600 ns, a centre frequency of 200.2 MHz and provide 8 MV accelerating voltage. With this voltage, the bunch length at top energy (450 GeV) will be 2 ns. However, for reasons of intrabeam scattering, accounting for injection phase errors and allowing an acceptable capture voltage the LHC requires bunches with a longitudinal emittance of 1 eVs and 1.7 ns long. Therefore it is necessary to compress the bunches in the SPS prior to extraction towards the LHC.

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## 2 COMPRESSION SCHEMES

Several compression schemes could be envisaged. Adiabatic bunch compression is excluded because the 8 MV provided by the 200 MHz travelling wave cavities are insufficient. Bunch rotation (non-adiabatic) is excluded because not all bunches will be properly matched due to beam loading effects and non-linearity of voltage. Magnetic bunch compression in the transfer lines towards LHC is also excluded because the necessary compression factor is too large.

However, the required compression can be obtained with an additional voltage at 400 MHz. It is foreseen to use three superconducting cavities[1] providing 6 MV in total.

## 3 400 MHz POWER REQUIREMENTS

The maximum bunch compression voltage and the necessary cavity impedance reduction determine to a large extent the 400 MHz power requirements[2].

Experience with existing superconducting cavities in the SPS has shown that in order to avoid coupled bunch instabilities their impedance at 400 MHz should be smaller than about 500 kΩ in total or 170 kΩ per cavity. The impedance reduction is obtained using RF feedback. The gain $G_0$ is given by the apparent shunt impedance as $1/G_0 = 170\,\mathrm{k\Omega}$. With this value the gain margin is 20 dB and the phase margin 80°. The RF generator current $i_g$ for zero cavity voltage is given by

$$i_g \approx -\frac{1}{1 + j\delta f_c/|\delta f_{FB}|} i_b \qquad (1)$$

with $i_b$ being the beam current, $\delta f_c$ the frequency deviation from the cavity centre frequency $f_c$ and $\delta f_{FB} = \pm(G_0/2)(R/Q)f_c = \pm 51\,\mathrm{kHz}$ the $-3$ dB bandwidth. This equation is the response of a band pass filter (unity gain at the centre frequency $f_c$, bandwidth $\delta f_{FB}$, slope 6 dB/octave away from $f_c$).

For bunch compression at 450 GeV the 400 MHz cavity is tuned a few kHz below twice $f_{RF}$, the frequency of the 200 MHz RF voltage, as a capacitive impedance is needed for bunch compression above transition energy.

During acceleration from 26 to 450 GeV the frequency $f_{RF}$ changes from 200.265 to 200.400 MHz: the second harmonic of $f_{RF}$ coincides with the 400 MHz cavity centre frequency, leading to a maximum generator current $\hat{i}_g$ of 1.2 A. As the gap voltage for bunch compression is 2 MV, the power requirement (using a klystron) is $\hat{P} = V_{cav}\,\hat{i}_g/4 = 600\,\text{kW}$ (as the cavity impedance is nearly purely reactive practically all incident power is reflected). This power exceeds by far the cavity's RF window power limit of about 200 kW.

## 4 NON-INTEGER HARMONIC NUMBER ACCELERATION

The LHC beam in the SPS has a gap of about 17 μs, the filling time of the 200 MHz travelling wave RF system is less than 1.5 μs. Therefore it is possible to apply the method of non-integer harmonic number acceleration[3]. It provides control of the bunch spacing (as given by the frequency $f_{RF}$) independent of the revolution frequency. As a consequence it is not necessary that $f_{RF}$ is an integer multiple of the revolution frequency. At injection energy the frequency $f_{RF}$ can be chosen, within limits given by the bandwidth of the travelling wave cavities, such that the spectrum of the long bunches is shifted above the 400 MHz cavity centre frequency and will stay there fixed even during acceleration. This procedure leads to a reduction of the maximum 400 MHz generator power to $\hat{P} = 200\,\text{kW}$.

## 5 ADIABATIC BUNCH COMPRESSION

Adiabatic bunch compression[2] is obtained by simultaneously programming the reference voltage (amplitude and phase) for the RF feedback, $V_{ref}$, on a revolution period time scale such that $V_{ref} = ZHi_b$, $Z$ being the actual cavity impedance, $H$ being the transfer function of the loop's return path, and shifting the beam spectrum now back towards the cavity centre frequency. As at injection, $f_{RF}$ is varied to shift the beam spectrum while maintaining the revolution frequency constant. As the beam spectrum approaches the cavity centre frequency the beam induced voltage increases and the bunches are compressed. Under ideal conditions, applying the proper $V_{ref}$, practically no 400 MHz RF power is necessary for this compression.

## 6 EXPERIENCE WITH MACHINE DEVELOPMENTS

With the prototype 400 MHz superconducting cavity installed in the SPS[4] and using a 60 kW tetrode amplifier the technique of shifting the beam spectrum and non-integer harmonic number acceleration was applied. Bunch shortening was observed at the flat top energy as well as the power reduction when $V_{ref}$ was programmed for bunch compression. The beam used for the machine developments filled half the SPS circumference and consisted of about 2310 bunches of $3 \times 10^9$ protons. Unexpectedly a coupled bunch longitudinal beam instability causing emittance growth was detected at the beginning of the flat top. This instability will be suppressed in the future either by eliminating the responsible impedance or by longitudinal feedback or a combination of both.

The maximum beam current and the ultimate compression voltage of 2 MV/cavity can only be obtained when the final high power klystron will be available.

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### *References*

[1] D. Boussard and V. Rödel, *Proc. 15th Int. Conf. on High Energy Accelerators*, Hamburg, 1992.
[2] T. Bohl and D. Boussard, 400 MHz Superconducting Cavities in the SPS, CERN SL Note 93-47 (RFS), Geneva, 1993.
[3] D. Boussard, J.M. Brennan and T. Linnecar, CERN SPS/89-49 (ARF), Geneva, 1996.
[4] T. Bohl, D. Boussard, T. Linnecar and V. Rödel, A superconducting RF cavity for bunch compression of the high intensity SPS proton beam at transfer to LHC, *5th European Particle Accelerator Conference* (EPAC 96), 10–14 June 1996, Sitges (Barcelona), Spain.