A Superconducting RF Cavity for Bunch Compression of the High Intensity SPS Proton Beam at Transfer to LHC

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Abstract

The bunch length of the high-intensity proton beam ejected from the CERN SPS into LHC must be reduced to fit into the 400MHz LHC buckets. This will be done using a new 400MHz superconducting RF system in the SPS. Above transition bunch compression is obtained with a cavity tuned slightly below the bunch frequency, thus giving a very high capacitive impedance. Such a system would however be extremely critical and very likely unstable without strong RF feedback. To keep the required RF power at an acceptable level during the ramp, the beam, which occupies only a third of the SPS, is accelerated in a variable harmonic mode to place the beam spectrum substantially above the cavity bandwidth. On the flat top, when the beam spectrum is moved towards the cavity resonance, the phase and amplitude of the reference voltage, including its modulation at the revolution frequency are programmed to keep the required RF power to a minimum. This scheme is described in detail together with the prototype 400MHz superconducting cavity already installed in the SPS. Initial tests with beam will also be reported.

1 INTRODUCTION

The SPS machine, last in the LHC injector chain, will accelerate 243 bunches of 10^{11} protons, spaced at 25ns and contained within 3/11 of the ring circumference, from 26GeV to 450GeV. The existing RF system consisting of 4 untuned wideband travelling wave cavities (TW), with a filling time of 560ns, centre frequency 200.2MHz and providing 8MV accelerating voltage will be used. During acceleration the bunch emittance will be tailored to the 1eVs required in LHC to minimise intra-beam scattering. The 8MV available gives a bunch length of $\sim$ 2ns at 450GeV. With the inevitable phase errors due to the intensity dependent beam loading effects in the TW cavities and the transfer process between machines there is a strong risk of beam loss when capturing in the 400MHz (twice the SPS frequency) receiving buckets in the LHC. At the same time the matching voltage in the LHC would be uncomfortably low. To ease these problems the bunch length must be reduced in the SPS just prior to ejection. Non-adiabatic RF gymnastics using the 200MHz RF system are excluded by the lack of voltage available and the strong beam loading which varies along the batches.

To achieve this bunch length reduction adiabatically, 3 new superconducting RF cavities at 400MHz providing 6MV will be installed in the SPS. This extra voltage in conjunction with the 200MHz voltage will now give 1.7ns long bunches. In principle these cavities could be passive; above transition energy, tuning the cavities just below a multiple of the bunch frequency will produce a focusing beam-induced voltage in the capacitive impedance. However this procedure would be extremely critical, with worries about system stability, the induced voltage depending on intensity, bunch length and distribution. In any case the large impedance would destroy the high intensity beam by inducing coupled bunch instabilities even at 26GeV. To overcome these problems strong RF feedback will be applied. This will reduce the effective impedance and allow external control of the induced cavity voltage.

To test these ideas, a prototype 400MHz cavity, shown in fig.1, has been installed in the SPS and initial tests with a proton beam have been successfully carried out.
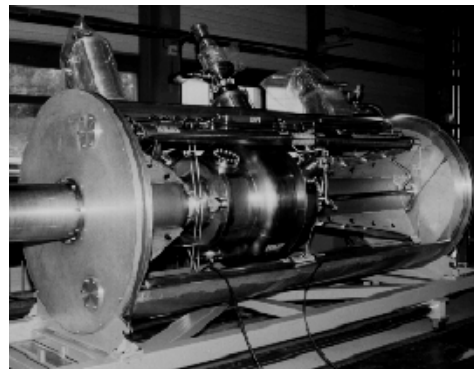

Figure 1: The prototype 400MHz superconducting cavity prior to installation in the SPS.

2 THE SC CAVITY AND AMPLIFIER INSTALLED IN THE SPS

The 400MHz SC cavity installed is a single-cell, wide aperture structure based on the LHC design [1]. The main parameters are given in Table 1. The cavity must remain accurately on tune without active tuning during the acceleration cycle. For the experiment we rely on temperature stabilisation, (long term stability $\pm$50Hz), improved further by using a dummy cycle each supercycle to lock the cavity to a frequency synthesiser using the fast magnetostrictive tuner. The control voltage to this tuner is held constant during the acceleration cycle. The amplifier is a 40kW tetrode ampli-

Table 1: Main Cavity Parameters

Mode	f_0 [MHz]	R/Q[Ω]	Q_{ext} (damped)
Fundamental	400.8	44.2	adjustable
H_{111}	502.6	4.3	12000
E_{110}	538.2	16.0	2500
E_{011}	776.0	1.0	28000

fier based on the 352MHz version [4], already in the SPS.

During normal high-intensity operation the cavity is passively damped.

3 POWER WITH RF FEEDBACK AND NORMAL ACCELERATION

SPS experience shows that the total impedance introduced by the three 400MHz cavities must not exceed 500kΩ to prevent coupled bunch instabilities. This value is achieved by strong RF feedback. Although the loop delay cannot be much below 500ns due to amplifier rise time and cable delay, the phase shift introduced over the cavity bandwidth is small and the loop gain, $G = 6 \cdot 10^{-6}$ A/V, defined at the gap, can be considered real. In this approximation the system acts as a bandpass filter with a 6db/octave slope and a 3dB bandwidth $d_{fb}=\pm52$kHz, filtering the beam spectrum accordingly. The amplifier has to provide a current i_g given by

$$i_g = \frac{i_b - j \cdot G \cdot d_{fc}/d_{fb} \cdot V_{ref}}{1 + j \cdot d_{fc}/d_{fb}}, \qquad (1)$$

where i_b is the beam current, d_{fc} the offset from the cavity centre frequency f_c and V_{ref} the reference voltage to the loop. During acceleration, the beam frequency increases from 200.265MHz to 200.4MHz and will sweep through the cavity centre frequency. The maximum current in this case will be 0.73A for 10^{11} protons /bunch. With 2MV maximum voltage the installed power will then be P=1/2$\times$V$\times i_g$=730kW. This is very large, (tetrode and coupler limitations).

4 POWER WITH VARIABLE HARMONIC NUMBER ACCELERATION

By changing the frequency spectrum of the beam, pushing it far away from the cavity resonance during acceleration and then bringing it back at 450GeV for bunch compression it is possible to reduce this power requirement to an acceptable level [2]. This is possible thanks to the large bandwidth of the TW system and the long beam gap in the ring. Variable harmonic number acceleration is used, providing independent control of the revolution frequency, f_0, and bunch spacing.

This technique has been described in detail elsewhere [3]. Basically the RF waveform is rephased before each beam passage through the TW cavities allowing the instantaneous frequency seen by the beam, f_{beam}, and hence the bunch spacing to be arbitrarily set. The phase change is adjusted so that the mean RF frequency over one turn is hf_0, h being an integer harmonic number. Although the revolution frequency lines are determined by the energy, the envelope of the spectrum is given by f_{beam}. At 26GeV bunches are 4ns long, the beam component at 400MHz is small and therefore the $2 \cdot f_{beam}$ harmonic can be swept through the cavity resonance, f_{beam} increasing from 200.265MHz to 200.56MHz. As the spectrum crosses the cavity resonance the generator current increases by only a small amount. As acceleration proceeds the revolution lines move as usual but the peak of the spectrum remains at 200.56MHz and the generator current is much reduced. It can be reduced even further by placing a notch filter in the loop centred at 2×200.56MHz so that compensation is maximum at f_c but not where the beam current is highest.

The peak current requirement is now 158 mA and the installed power becomes 158kW - more comfortable but nonetheless relying on pulsed operation of the tetrode.
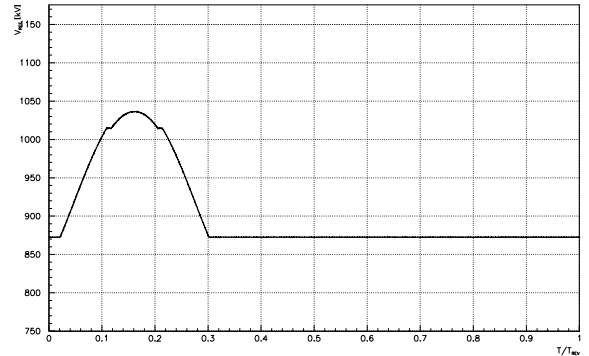

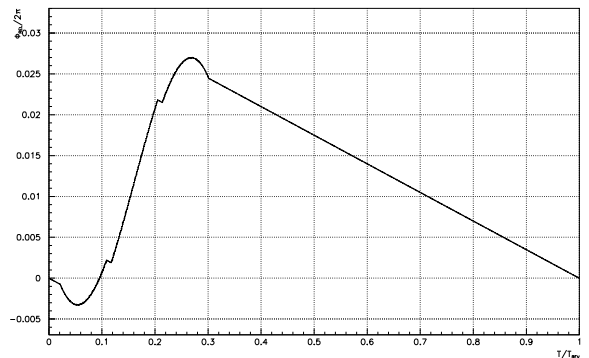Figure 2: V_{ref} amplitude over one turn for Δf_{off}=100kHz

Figure 3: V_{ref} phase over one turn for Δf_{off}=100kHz

5 BUNCH COMPRESSION

At 450GeV, the centre frequency of the cavity is set at

$$f_c = 2hf_0 + \Delta f,$$

where the small offset frequency from the revolution frequency line $\Delta f \sim 950$Hz is chosen to give 2MV induced voltage for the nominal bunch current with the spectrum envelope centred on $2hf_o$. As the peak of the spectrum is brought back from 200.56MHz to 200.4MHz, V_{ref} must be programmed equal to the beam induced voltage so that the two terms in eq.1 almost cancel each other. Indeed the amplifier's job is to compensate the hopefully small errors between reference and beam induced voltage.

The bandwidth of the cavity with RF feedback is comparable to f_0 and this implies that V_{ref} be AM and FM modulated according to the envelope offset,

$$\Delta f_{off} = 2(f_{beam} - hf_0).$$

At the final offset the amplitude is approximately flat as required but a phase modulation is still necessary. Figs.2 and 3 show the theoretical amplitude and phase modulations for Δf_{off}=100kHz. V_{ref} is programmed according to expected machine and beam parameters. Clearly any deviation from these values, e.g. changes in bunch length or intensity, will increase the power required. The aim is to keep them to within $\pm10\%$ of the nominal values and maintain Δf to ±100Hz and Δf_{off} to ±1kHz.
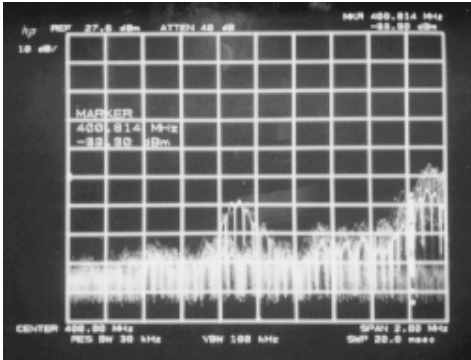

Figure 4: Spectrum envelope shift from injection value to high frequency at 14GeV.

6 TESTS WITH BEAM

With only 40kW available, the coupling to the cavity was adjusted to allow 1MV peak voltage with beam current compensation for $8 \cdot 10^{12}$ protons. This intensity and voltage imply a Δf of 600Hz. The cycle used was from 14GeV to 450GeV, crossing transition. The SPS ring was half filled with an intensity up to $7 \cdot 10^{12}$ protons. The tests used an unmodulated reference voltage programmed as a function of Δf_{off}. An approximation to the fine modulation at f_0 was foreseen - for these beam parameters phase modulation is negligible and the amplitude is triangular along the batch
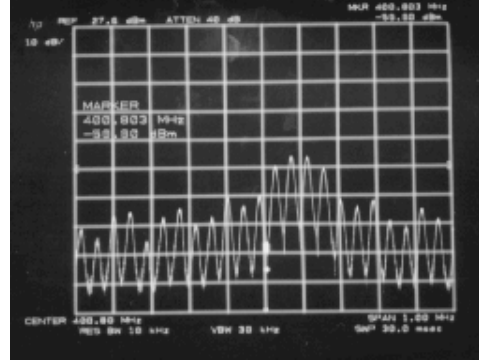

Figure 5: Spectrum at beginning of 450GeV flat top, the cavity resonance is at the centre of the screen.
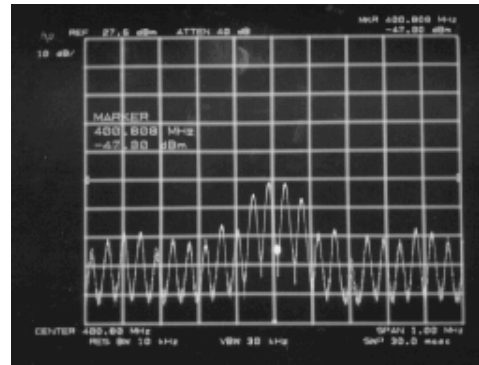

Figure 6: Spectrum for compression.

- but not tried. Figs.4,5 and 6 show the sweep of the frequency spectrum at 14GeV, and the same before and after the shift of the bunch spectrum at 450GeV.

The peak in amplifier power as the bunch frequency was increased at 14GeV was clearly seen - also crossing transition with the very short bunches was visible. At top energy the unmodulated phase and amplitude of V_{ref} were the critical variables for minimising amplifier current as expected.

The final result was 1MV of voltage in the cavity with $7 \cdot 10^{12}$ protons circulating. The tetrode current could be minimised to about 1/2 of the value during acceleration.

7 AKNOWLEDGEMENTS

8 REFERENCES

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