LONGITUDINAL PHENOMENA IN THE CERN SPS

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Summary

After almost one year of operation two kinds of problems dominate the longitudinal behaviour of the SPS beam. At high energy longitudinal coupled bunch instabilities occur. They are driven by the RF cavity impedance both on its fundamental and high-order passbands. Present cures include damping the high-order modes of the cavities, Landau damping techniques and feedback systems. At the injection energy a debunching-rebunching procedure is performed in order to change from the 9.5 MHz RF frequency of the injector to the 200 MHz of the SPS. Debunched beam instabilities driven by the cavity and vacuum chamber impedances (up to the GHz region) at present limit the RF capture efficiency.

Introduction

Certainly one of the most novel features of the SPS is its RF system. Unlike other proton machines, the RF frequency is quite high (200 MHz) which permits the use of untuned travelling wave structures as accelerating cavities^{1,2}. Major advantages of this solution are certainly the reliability (absence of tuning system, a matched load presented to the surface level power transmitters, no active element in the tunnel) and a better efficiency at high beam currents. On the other hand, the relatively low stored energy in the structure has given us some fears about transient beam loading and other possible effects. Having already reached an intensity of more than $1.2 \cdot 10^{13}$ particles per pulse, and even higher local currents, it is comforting to see that the only troublesome phenomena due to the RF cavities are the rather well-known coupled bunch instabilities.

The other unusual feature of the SPS is that its injector (the CPS) is working at a completely different RF frequency (9.5 MHz), and therefore a debunching-rebunching procedure is necessary at the transfer energy. This problem has received considerable experimental effort in the CPS over the last few years. At present the debunching-rebunching process is done in the SPS itself, mainly because the beam intensity is ten times lower, for a single-pulse injection. Nevertheless, instabilities cannot be completely avoided and this results in a capture beam loss of about 10-20% at intensities of $7 \cdot 10^{12}$ particles per pulse.

Brief Description of the RF System

Cavities and power amplifiers

At present, two identical travelling wave structures are used in the SPS RF system. Each of them is a piece of circular waveguide (length 20.57 m, diameter 750 mm) loaded by 55 horizontal bars supporting drift tubes³. At the transition frequency (200.22 MHz) there is exact synchronism between the RF wave in the structure and the beam ($\pi/2$ mode precisely). At different frequencies, especially at injection (199.5 MHz), the total phase slip τ between wave and particle along a cavity is about 180° which gives a reduction in effective accelerating voltage by the factor: $\sin(0.5 \tau)/(0.5 \tau) = 0.64$. The filling time of the cavity is 700 ns (group velocity is 0.095 c) which is much smaller than the revolution period (23 μ secs). Power is fed into and extracted from the cavities

through matched couplers. One is connected to the terminating load which sits on top of the cavity in the machine tunnel, the other one to the feeder line coming from the surface where the power amplifiers are located. Each cavity is fed by a power amplifier which can deliver 500 kW CW power at 200 MHz. The amplifier itself consists of four 125 kW tetrodes (RS 2004 J. Siemens) coupled in parallel through coaxial hybrid junctions. The overall 3 db bandwidth of the power amplifier is 1 MHz and it can provide 1.8 MV peak accelerating voltage to each cavity.

Low level system

The amplitude of the accelerating voltage is controlled via AVC loops working on the RF drive of the power amplifiers. However, very low levels of RF power (< 100 kW) must be avoided because of possible multipactor effects in the couplers and therefore out-phasing the two cavities is used to reduce the voltage, in particular during adiabatic capture at 10 GeV. As usual a phase loop suppresses the possible coherent dipole oscillations. Its bandwidth (~ 10 kHz) is smaller than the revolution frequency as it corrects only the average beam phase. In addition, a radial loop, using electrostatic pick-up electrodes placed where x_p is maximum, keeps the beam on the desired radial orbit. It is interesting to mention that all the RF signals are converted to a fixed 10.7 MHz IF frequency. This allows easy filtering through narrow-band crystal filters, and permits the use of circuits having a very large dynamic range. In fact the whole system can work over a 1000:1 range without sensitivity switching. Several wide-band detectors are used to analyze the beam signals. The resistive gap detector has a sensitivity of 12 Ω (defined as the ratio of output voltage on a 50 Ω line to the beam current) and a bandwidth of 4 GHz.

High Energy Instabilities

These instabilities appear essentially on the intermediate 200 GeV flat-top where the beam is kept bunched for subsequent acceleration. They are dipole ($m = 1$) coupled bunch oscillations. As a result the longitudinal emittance of the beam blows up in an uncontrolled way (of the order of 3 to 4 times) and it is necessary to lower the rate of rise of the magnetic field after the intermediate flat-top. Two kinds of modes of oscillation are present: the mode $n = 1$ and modes around $n = 640$ (n is defined by the phase shift per bunch: $2\pi n/h$; h : harmonic number).

Instability on mode $n = 1$

It is very likely that this instability is driven by the impedance of the cavities around the RF frequency. As the structure is wideband the cavity impedance seen by the beam is still high at a frequency $f_{RF} \pm f_{rev}$. (Z at transition is $2 \times 1.4 M\Omega$; 3 db bandwidth is 1.22 MHz). From the e-folding time measurement (100 ms at 4×10^{12} p.p.p) one can estimate the impedance from Sacherer's formula⁴):

$$\text{Im} \left(\frac{\Delta \omega}{\omega_s} \right) = \frac{1}{2\pi} \frac{\text{Re}(Z) I}{V \cos \phi_s} \frac{M}{Bh} D F_m(\Delta \phi) \quad (1)$$

See (4) for the notations.

One finds $Z = 2.5 \text{ M}\Omega$ which corresponds rather well to the cavity impedance around the RF frequency. It is obvious that this impedance cannot be reduced and therefore other cures have been tested.

Decoupling the bunches by making their synchrotron frequencies slightly different is an old technique⁵. The required spread is of the order of the shift due to the instability ($\Delta\omega/\omega \approx 10^{-2}$). A moderate RF voltage modulation at the revolution frequency (few percent) indeed stops the instability. Modulation with different waveforms and at several times the revolution frequency does not give different results.

As one characteristic frequency of the instability ($f_{RF} \approx f_{rev}$) falls inside the bandwidth of the RF system, it is possible to use a feedback system to damp it. The average and instantaneous bunch phases are compared in a phase discriminator which rejects the effect of missing bunches. The output of the discriminator is filtered to provide the signal at the revolution frequency and this is fed back to the master oscillator of the low-level system. The instability is then completely suppressed.

Instability on modes around $n = 640$

On the intermediate flat top a second instability manifests itself giving clean side band components 27.8 MHz away from the RF harmonics on the beam signal. A cavity signal is picked up simultaneously at 629 MHz (27.8 MHz above the third harmonic of the RF frequency) leading us to suspect a high-order mode of the cavity as being responsible for the instability.

At the fundamental RF frequency, the horizontal bars of the cavities act essentially as $\lambda/2$ resonators. The bar resonances as $3\lambda/2, 5\lambda/2, \dots$ also produce a longitudinal electric field on the cavity axis, and could therefore interact strongly with the beam; but in contrast to the fundamental frequency, these resonances are not damped by the terminating load, because the couplers behave almost as perfect reflectors outside the lower passband.

Measurements of higher modes have shown that in the $3\lambda/2$ passband, the cavity resonance which is closest to perfect synchronism with the beam occurs at 629 MHz. Therefore, damping probes with resistive loads have been designed to be put at the top of a number of cells; they couple as strongly as possible to 629 MHz while being fitted with a 200 MHz rejecting filter.

After installation of the damping probes, each cavity impedance at 629 MHz is expected to drop to 0.9 $\text{M}\Omega$. At present, with only two damping probes installed per cavity, it is estimated to be about 1.8 $\text{M}\Omega$. The magnitude of the parasitic impedance deduced from e-folding time measurements (100 ms) gives $Z \approx 1.2 \text{ M}\Omega$, which is not very different from the above estimate.

Usual Landau damping by RF voltage reduction does not work on a flat-top. Decoupling the bunches by RF voltage modulation at the revolution frequency has been tested. It gives a growth rate reduction of about a factor 2 but unlike the $n = 1$ mode, it does not completely suppress the instability, even with very large modulation depths (50%), which according to theory should be more than sufficient. A possible explanation for this difference might be the influence of the phase lock in the low-level system⁵. Bunch spreading before the instability occurs helps as expected but again does not suppress it. At present, we are considering a feedback system. The probes used to damp the parasitic mode of the cavity can as well be used to feed power

into it at this frequency. Therefore active damping without a dedicated cavity seems possible. A specialized cavity will be necessary for a Landau damping system; this is also being studied. A very efficient spread of synchrotron frequencies inside the bunch is obtained by powering this Landau damping cavity at a multiple of the RF frequency (800 MHz or 1200 MHz).

Instabilities at the Injection Field

Self-bunching around 200 MHz

At transfer the CPS ejects a bunched beam (frequency 9.5 MHz) which is allowed to debunch on the SPS "flat-bottom". Due to the impedance of the accelerating cavities around 200 MHz, self-bunching can occur if a low momentum spread beam is injected into the machine. In the CPS one can produce a very low $\Delta p/p$ beam ($\Delta p/p \approx \pm 0.25 \cdot 10^{-3}$) either by RF gymnastics (bunch rotation in phase space) or by adiabatic reduction of the RF voltage (combined with a 200 MHz Landau damping cavity). Under these conditions one indeed observes self-bunching at high beam currents (e.g. 8×10^{12} particles per pulse ejected over five CPS turns). Modulation at about 200 MHz appears rapidly ($\sim 1 \text{ ms}$) on top of the 9.5 MHz structure which is being debunched. Associated with it a large energy loss is measured (rapid change of the beam revolution frequency) which can be as high as 100 keV/turn. The threshold of the instability, although not very well-defined experimentally, is in good agreement with the stability criterion⁵. At the present intensities this instability is not really dangerous because it can be avoided by ejecting a beam with large $\Delta p/p$ from the CPS.

Microwave instability

It was recognized a few years ago that debunching of a high intensity beam was associated with microwave structure appearing on the beam⁷). This effect can be explained in a very simple way as follows: during debunching the local values of the $(\Delta\gamma)^2/i$ ratio ($\Delta\gamma$: momentum spread and i beam current) become smaller and smaller and the threshold is reached after a time t given by:

$$\frac{Z}{k} t = \frac{0.7}{\pi} U_0 \frac{R}{hc} \frac{A\theta}{I}$$

where eU_0 is the rest energy of the proton, R the machine radius, A the initial emittance (rad), θ the initial half bunch length, I the DC beam current, and Z/k the impedance divided by the mode number.

From this relation and the time at which the instability appears (photo 1), one finds a value of Z/k of the order of 10 Ω . It is interesting to mention that similar measurements made on the CPS and on the Fermilab main ring accelerator have given the same result^{7,8}).

Photo 1

Microwave signal appearing during debunching
Injection trigger
20 ms/cm, 10 db/cm
1300 MHz centre frequency

Assuming a water-bag distribution, one can as well calculate the Z/k value from the folding time measurements (photo 1). Values of about 20-30 Ω have been measured in this way.

The frequency spectrum of the instability is rather flat, extending from a few hundred MHz to 1.6 GHz. Although the situation is less clear at the lower end of the spectrum, presumably due to the impedance of the RF cavities, the upper part of the spectrum is very similar to that obtained by experiments on other machines. It is most likely that impedances in the GHz frequency range are due to discontinuities in the vacuum chamber cross-section, the associated Z/k being a measure of the impedance of the vacuum pipe per unit length. It is therefore not surprising that different machines, although varying considerably in size (PS and ISR, SPS and FNAL machines) have very similar values of $Z/k^{7,8,9}$.

These high-frequency signals, associated with the so-called microwave instability are not only observed during debunching. They also appear in a bunched beam whenever a non-adiabatic process takes place (e.g. filamentation when a high energy coupled bunch instability occurs). Again a possible explanation is that local values of $(\Delta B\gamma)^2/i$ become smaller than threshold^{10,11,12}.

Another interesting fact that can be mentioned in this context is that the same frequency spectrum has been observed at transition in the CPS. We therefore believe that the negative mass instability model which has been used up to now¹³ to explain transition crossing blow-up should be somewhat modified by taking into account the wall properties in the GHz region.

We have made use of the microwave instability as a "white" noise generator in order to analyze the higher modes of the RF cavities which are synchronous with the beam. Apart from the previously mentioned 629 MHz, potentially dangerous modes have been located at 911 and 1185 MHz.

Capture

The debunched beam is captured adiabatically on the 10 GeV "flat bottom". The RF voltage is raised from about 100 kV to 1.5 MV in a few ms. The waveform corresponds to the theoretical adiabatic law, but the capture efficiency does not seem very sensitive to it. If the beam is captured soon after injection, very complicated bunch shapes are observed because the distribution of particles in phase space is not yet uniform. This is quite obvious and one would expect a late capture to be smooth. At high currents this is not the case, and one observes that a microwave structure develops during the rise of the RF voltage (at 1 ms after injection, with a typical growth time of less than one ms). This effect, which seems different from the microwave instability described above (the frequency spectrum is not the same) is still being actively studied. In any case, it imposes another limitation on the capture efficiency at high intensities.

Although injection of two CPS pulses has already been successfully tried (the first CPS batch is debunched and captured twice) we believe that the solution to injection problems at high intensities is a bunch into bucket transfer technique. This, of course, requires the CPS beam to be bunched at 200 MHz at transfer and therefore acceleration at this frequency in the injector is being studied.

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