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ACCELERATION IN THE CERN SPS
PRESENT STATUS AND FUTURE DEVELOPMENTS

D. Boussard, G. Dôme and T.P.R. Linnecar

SUMMARY

The hardware status of the 200 MHz accelerating system is described together with changes that are foreseen in the near future. The parameters for an 800 MHz Landau damping cavity at present under construction are given. Recent studies on the machine have been in the following areas: beam loading effects in the cavities, coupled bunch instabilities, and acceleration of intense single bunches. The results of these studies are presented.

A) Hardware Status

For the last year the accelerating system in the SPS has comprised three accelerating cavities, each one of 5 sections (total 20.57 m) and fed by an amplifier at a nominal 350 kW [1,2]. The total accelerating voltage (held constant by amplitude loops) has been $\sim$ 5 MV at transition (including beam loading, phase slip $\tau = 0$). During the present shutdown a new cavity of 4 sections (total 16.46 m) is being installed and two of the old cavities are being shortened to 4 sections. This allows operation to much higher beam intensities ($> 5 \times 10^{13}$ p) without serious lessening of voltage due to the beam loading. The total beam-cavity coupling impedance remains approximately the same as before. Four new (nominal 350 kW in the cavity) 200 MHz amplifiers, each amplifier comprising 16 output tetrodes of maximum output power 35 kW, are being constructed. The output from pairs of the resulting 8 amplifiers will be summed in hybrids to double the power to each cavity (700 kW). For the $p\bar{p}$ project three of the four cavities are also being supplied with coaxial switches which allow the power flow to be reversed for acceleration and storage of the anti-proton bunches.

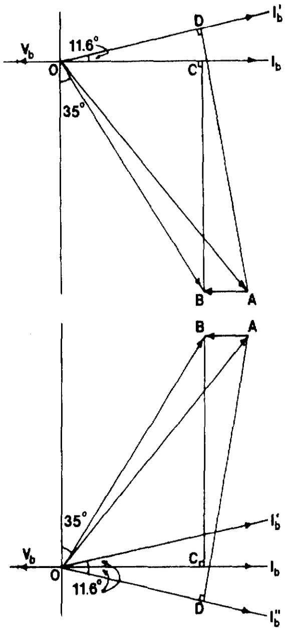
To combat longitudinal instabilities at high intensities (see later) 2 Landau damping cavities are being installed. These cavities are disc-loaded structures, each 3.46 m long (37 cells) operating at 800 MHz. Each of the two power amplifiers, with 4 output klystrons, will deliver 200 kW via waveguide to the cavity, providing a voltage of 1.24 MV/cavity. The 2.48 MV total is approximately one quarter of the main 200 MHz accelerating voltage for 4 cavities with 700 kW.

The beam is captured at 200 MHz in the CPS before transfer. During the present machine stop the number of CPS cavities is being increased from 4 to 8. This will give a total voltage of $\sim$ 320 kV, the acceptance increasing from 100 mrad to 140 mrad.

B) Machine Studies (RF)

(i) Bunch into bucket transfer. For the latter half of the past year the SPS has run with bunch into bucket transfer and double batch injection (2 CPS pulses per SPS pulse). In the CPS on the 10 GeV flat top the beam is blown up from $\sim$ 20 to $\sim$ 60 mrad (preventive blow-up) and then debunched adiabatically (the 9.5 MHz cavities being properly compensated for beam loading)[3]. The beam is then captured adiabatically at 200 MHz with a capture efficiency for 4 cavities of $\sim$ 90%. All beam, captured and uncaptured, is transferred to the SPS. The signal from the 200 MHz frequency synthesizer in the CPS is sent via a high quality cable (frequency ÷ 21, transmission, × 21) to the SPS and provides the reference phase before injection. At injection the beam is phase locked to this signal and held by this frequency until the second batch arrives 1200 msec later when the frequency synchronization loop is switched to the radial loop and the beam is accelerated. In principle the matching voltage in the SPS is $\sim$ 500 kV though in practice higher values are required (see later). The two machines are matched by comparing the revolution frequency of the incoming beam with the transmitted CPS signal. The easiest technique found is to correct for any error by changing the synthesizer frequency in the CPS. The CPS radial position before debunching must then be adjusted to optimize the capture in the CPS, the continuous transfer is optimized and then the radial position in the SPS is measured. If necessary a further iteration is made. A variable delay in the link is then used to correct the phase. For optimum capture in the SPS the mean frequency error between the machines should be < 100 Hz (the jitter is $\sim$ 150 Hz), and the phase error < 5°. In operation, an optimization is made once or twice per day.

(ii) Beam loading effects at transition. Variations in charge distribution from bunch to bunch lead to transient beam loading in the cavity. In particular for double batch injection there are two "holes" in the beam which are longer than the filling time of the cavities (700 nsec). The first bunch after the hole will see a higher voltage than those following, the voltage dropping linearly during 700 nsec to a steady value. To receive the same energy gain per turn these first few bunches must have a stable phase different from the average (average stable phase is 35° from the zero crossing of the voltage). At transition the phase slip is zero and the beam loading is purely resistive. Refer to the phasor diagram, Fig. 1. For the majority of



(i) before transition
OA : voltage applied by the RF
AB : beam-induced voltage ($= V_b = 900$ kV)
OB : voltage seen by beam (5 MV)
OC : energy gain/turn, average bunch
OD : energy gain/turn, 1st bunch (OC = OD)
I_b : beam current, average bunch
I_b': beam current, 1st bunch before and right after transition
I_b'': beam current, 1st bunch at stable phase after transition
(ii) after transition

Fig. 1 - Phasor diagram of the RF voltages and currents showing the effect of phase jump at transition

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CERN, F-01631 CERN CEDEX, France

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particles the phase jump is entirely symmetric but the first bunch should now have a phase offset of the same magnitude but opposite sign to be in equilibrium. It therefore oscillates in the bucket with an amplitude of 2x the initial offset, filaments and produces a hollow bunch; see Fig. 2. For 3 cavities of 5 sections, the beam loading is 900 kV for 1.5×10^{13} particles and the relative offset is 11.6^0. The increase in bunch length after filamentation is therefore $\sim 46.4^0$ i.e. 0.67 nsec. The effect can be cured by lowering the voltage for the first bunches. Theory and experiment both show that a reduction of $\sim$ 25% is required. Fig. 2.

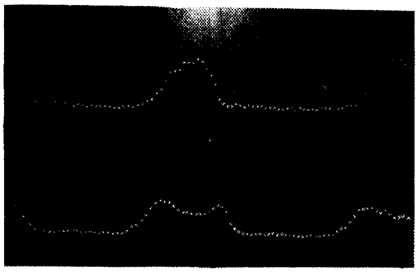

Fig. 2 - Bunch No. 20 (h = 4620) after transition
1 ns/div

This type of effect is expected whenever there is a non-adiabatic change in beam loading conditions. Another instance is at injection where the bunches from the CPS are all equispaced but the effect here is masked by a strong coupled mode instability (see later).

(iii) Coupled bunch instabilities at injection. Dipole instabilities with growth times of 2 to 3 msec have been observed at injection for intensities $> 1.8 \times 10^{13}$ particles, see Fig. 3. The mode number n, freq. ($f_{RF} \pm n f_{rev}$), is typically 12 or 13, but lower numbers are found near threshold. The same effect occurs for each batch injected, particles already in the machine remaining quiet. After 50 msec the batch is again stable, the bunches have a smoother distribution and fill the bucket. The violence of the instability is reduced on raising the SPS capture voltage, but at the same time the mismatch bunch into bucket is increased. An operational optimum is found for a capture voltage approximately twice the matching voltage.

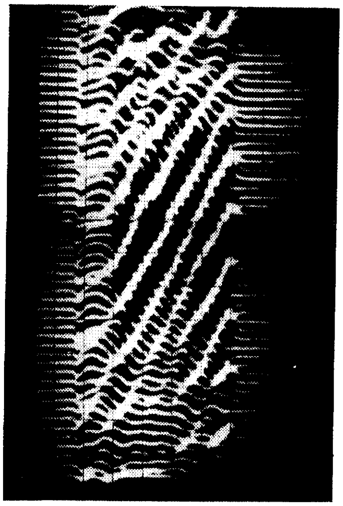

Fig. 3 - Instability at injection.
Each trace shows phase error along one batch.
Traces are separated vertically by
10 revolutions.

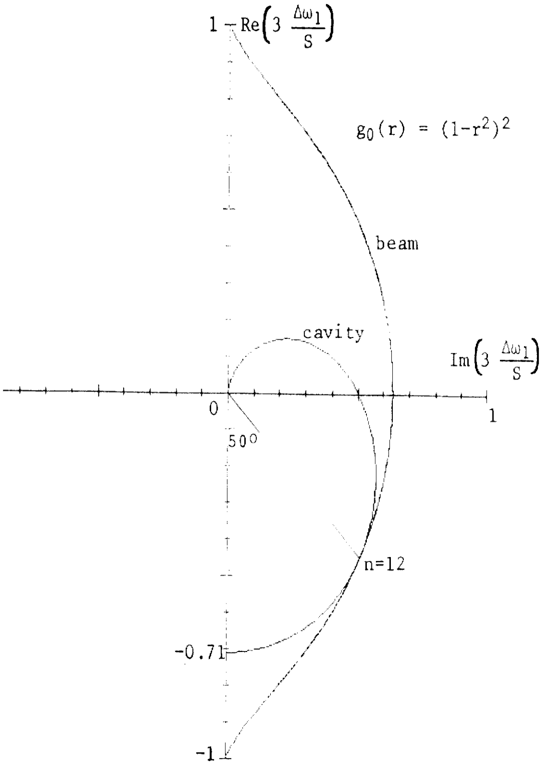

Fig. 4 - Threshold for instability at 10 GeV/c

The coupled bunch mode theory developed by Sacherer[4] has been extended to cover the particular case of the SPS. A plot of the beam and cavity frequency shifts at threshold are given in Fig. 4 for the most stable distribution, $g_0(r) = (1 - r^2)^\nu$, where $g_0(r)$ is the circular distribution in phase space, r is the normalized radius and $\nu = 2$. A threshold intensity of 1.13×10^{13} particles is found for the 4 nsec bunches from the CPS with V_{0B} = 800 kV. Similar plots at the working intensity, 1.9×10^{13} p, show that the growth rate is between 2 and 4 msec according to the distribution chosen. At these higher intensities the mode predicted lies between 13 and 15 for the dipole mode; near threshold the mode number is between 1 and 17 according to ν.

A feedback system operating as follows has successfully damped these dipole modes. The instantaneous phase of the bunches is acquired over one turn and stored for one quarter of a synchrotron period in a serial analog memory (during this time, the phase offset converts to an energy offset). The information is then applied via a loop amplifier to a phase shifter in the cavity drive lines. This damps the oscillation if the gain is sufficient. By gating the feedback at the revolution frequency it is even possible to stabilize part of the batch, the remainder remaining unstable (Fig. 5). The sampling lowers the effective gain and places restrictions on the maximum gain as a function of the total delay. The system, however, operates in real time and damps all modes within its bandwidth (at present $n \leqslant 15$).

It is interesting to note that since such large spreads (almost full buckets) are required to stabilize the beam by adequate Landau damping, even if the dipole modes are suppressed, the quadrupole modes will still blow up the bunch to approximately the same length if their threshold is exceeded. This can be seen from Sacherer's formula

$$S > \frac{4}{\sqrt{m}} |\Delta\omega_m|$$

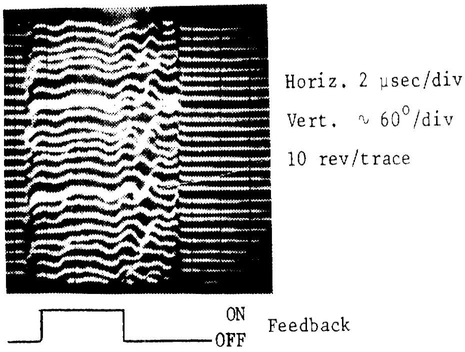

Fig. 5 - Stabilization of part of 1st batch

where S is the spread of synchrotron frequencies in the bunch, m is the oscillation mode and $\Delta\omega_m$ is the coherent frequency shift. For the same resonators (RF cavities) and 5 nsec bunches the form factor F determining $\Delta\omega_m$ is about the same for m = 1 and m = 2. Therefore the required spread will be only $1/\sqrt{2}$ smaller. The Landau damping cavities will act upon all modes to stabilize the bunches. Until they are installed the increased matching voltage in the SPS due to the doubling of cavities in the CPS will help reduce the effect.

(iv) Coupled bunch instabilities at higher energies. A longitudinal and a transverse coupled bunch instability are excited by higher modes in the cavities. The longitudinal mode at 629 MHz has a Q_0 of 19 700 to which corresponds a standing wave impedance of 4.25 MΩ (model measurement). For the transverse mode, $f_{res} = 460$ MHz, $Q_0 = 28000$ and the standing wave impedance for horizontal deflection is 36 MΩ*). (The model measurement has been verified by exciting the beam via a probe in one cavity at 460 MHz and measuring the displacement: 30 MΩ is found.)

To lower the impedance the cavities have been damped for each mode in two separate ways. For the 629 MHz resonance, 2 pairs of resonant probes are inserted in each section of the cavity. The probes in each pair are separated by one cell ($\lambda/4$ at 200 MHz) to minimize reflection at 200 MHz. For the 460 MHz, the cavity is terminated at each end plate by two horizontal balun dipoles; the compensation for reflection at 200 MHz is made by adjusting the main couplers. The symmetric 200 MHz signal is not coupled out by the dipoles unlike the anti-symmetric 460 MHz signal. Thus for the 460 MHz passband the cavity approaches travelling wave operation whereas at 629 MHz the damping is distributed along the cavity. In both cases the result is a reduction in the total impedance by a factor of 20. This reduction appears to be the best obtainable via the hardware unless each individual cell is heavily damped (particularly difficult for the 460 MHz mode).

At the present high intensities ($\sim 2 \times 10^{13}$ p) the longitudinal instability is present on the rise of the magnetic field at high energies (> 150 GeV). The transverse one can be cured by octupoles. Another unexpectedly sensitive parameter for the transverse instability is the coupling between vertical and horizontal tunes. The stronger the coupling the more unstable the beam. The Landau damping cavity should improve the situation in the longitudinal plane and if necessary stronger octupoles can be used for the transverse.

(v) Single bunch operation. For the simulation of the $p\bar{p}$ project single bunches have been transferred from the CPS to the SPS, accelerated and stored at high energy. The bunches in the CPS are placed on the unstable phase and allowed to stretch in phase space. After a certain time, the phase is changed back and the bunches rotated in the bucket. When the bunch length is minimum a single bunch is fast extracted. The various timings are adjusted to match the final bunch as near as possible to the waiting SPS bucket. The link described above is used to define the phase of the bucket relative to the incoming bunch. The phase lock is switched on at injection, followed 2 msec later by the radial loop, and the bunch is immediately accelerated. An unexplained phenomenon leads to emittance reduction of the intense bunch up to transition, at which point with this low emittance a negative mass instability causes large beam loss. For this reason the transition energy was lowered and injection was subsequently made above transition. For a more detailed description of this effect and the effect of RF noise on the stored bunch, see Ref. 5.

Acknowledgements

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*) This value is ½ the transverse (standing wave) shunt impedance as defined for RF separators. In order to convert it into a transverse coupling impedance as used by the ISR group[6], multiply by $\omega/c = 9.64\ \text{m}^{-1}$.