SPS COMMISSIONING REPORT No. 12

Acceleration to 400 GeV and Status Report on the Commissioning of the SPS

by

the SPS Division

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1. **Introduction**

On June 17th 1976, at 15 h 35, the SPS accelerated for the first time a beam of protons to its design energy of 400 GeV. During the subsequent hours, while the first measurements on the 400 GeV accelerating cycle were being made, the average number of protons accelerated to 400 GeV was about $10^{12}$ protons per pulse.

The present report describes the measurements made on June 17th but since the latter date was a milestone in the commissioning of the SPS it seems appropriate to give also a brief general survey of the most relevant results obtained up to now during the SPS commissioning. For completeness we shall start with a summary of some important dates.

**5th April 1976**: First beam injected into the 800 m long injection transfer line TT10 and transported to a temporary dump near the SPS.

**8th April, 1976**: First beam passed through the SPS injection system, with the injection kicker not excited.

**3rd May 1976**: First injection tests into the SPS, resulting in a circulating beam with a beam loss of 5% in $10^4$ turns, on the same day.

**26th May 1976**: First passage through transition and acceleration to 80 GeV.

**4th June 1976**: Acceleration to 200 GeV.

**17th June 1976**: Acceleration to 300 GeV at noon and acceleration to 400 GeV a few hours later.

2. **General comments on Q-measurements**

The magnet system of the SPS consists of 744 dipole magnets, each 6.26 m long and 216 quadrupole magnets, each 3.045 m long. The latter are subdivided into two groups of 108 horizontally focussing quadrupoles and 108 vertically focussing quadrupoles. The dipole magnets deflect the proton beam so that it travels along a roughly circular orbit in the
centre of the vacuum chamber, which is called the central orbit. Protons whose trajectory deviates from the central orbit, for instance due to injection errors or the unavoidable small errors in the magnets, are focussed towards the central orbit by the quadrupoles. As a result, the protons oscillate around the central orbit while they travel along the circumference of the SPS. These oscillations are called betatron oscillations and the number of horizontal and vertical betatron oscillations made by each proton when it travels once around the SPS are called \( Q_H \) and \( Q_V \). In the SPS both \( Q_H \) and \( Q_V \) have been chosen to be about 27.6.

As is well known, the betatron oscillations are unstable when \( Q_H \) or \( Q_V \) is an integer, say 28. In fact, if a proton is slightly deflected by a small field error in a given magnet and \( Q_H \) or \( Q_V \) has an integral value, the resulting betatron oscillation will always return with the same phase at the "bad" magnet. Therefore the effects of all small deflections add up and the amplitude of the oscillation increases until the proton hits the wall of the vacuum chamber. The same effect occurs when \( Q \) is sufficiently close to an integral value and in the SPS the entire beam is lost when \( Q > 27.9 \).

A more detailed consideration of the orbits shows that the unavoidable small alignment errors of the quadrupoles and magnet to magnet fluctuations of the small inhomogeneities of the magnetic fields can lead to resonances of the betatron oscillations when the proton orbits close onto themselves after one, two, three or four revolutions i.e. particle loss can occur not only when \( Q = 27 \) or 28 but also when \( Q = 27\frac{1}{2} \); \( Q = 27\frac{2}{3} \) and \( Q = 27\frac{3}{4} \) or when \( Q \) is in the vicinity of these values. The importance of the resonance is less severe when it takes several resolutions before the orbit closes onto itself. In the SPS the beam is lost when \( Q < 27.55 \), while a reasonable fraction of the beam still survives even when \( Q \) crosses the value \( 27\frac{2}{3} \) or \( 27\frac{3}{4} \).

During each accelerating cycle the magnetic field in the SPS dipoles increases in a few seconds from the injection value of 0.045 T to the maximum value of 1.8 T and at the same time the RF system accelerates the protons in such a way that the energy of the protons is always matched to the magnetic field in the dipoles, so that the proton beam remains...
in the centre of the vacuum chamber. For the reasons explained above, the Q-value should remain during the entire acceleration cycle within the limits $27.55 < Q < 27.65$ if beam losses are to be avoided. Consequently the magnetic fields in the two groups of quadrupoles, each of which has its own power supply, must accurately track the field in the dipole magnets.

Q-measurements can be made at any time during the acceleration cycle by kicking the beam with a small fast kicker magnet so that the entire beam makes coherent betatron oscillations with an amplitude of a few mm. The Q-value can then be found by measuring how the beam position in one of the SPS pick-up electrodes varies during a number of revolutions after the beam has been kicked.

3. **Q-measurements on 200 GeV, 300 GeV and 400 GeV cycles**

Figure 1 shows a measurement of $Q_H$ and $Q_V$, as a function of time, made with a 200 GeV cycle on 4th June. The rise time for this cycle was the same as for a 400 GeV cycle but since only 6 of the 12 rectifier stations for the dipoles were used, the maximum dipole field was only 0.9T, corresponding to 200 GeV. Instead of being constant, the Q-values show a strong variation with time and a pronounced bump at about 550 msec after injection. Beam losses occurred when $Q_H$ and $Q_V$ crossed the value $27^{2/3}$ in both directions and for $Q_V = 27.81$, due to the integral resonance $Q_V = 28$. Figure 1 also shows that the mean radial position of the beam during the entire cycle coincided with the central orbit to within a few mm. Such small changes in mean radial position have very little influence on the Q-values and therefore we conclude that the average value of the field in the quadrupoles does not track the field in the dipoles. The most likely explanation is given at the end of this chapter.

The real time computer program which calculates the voltage program $V = V(t)$ on each cycle for the dipole and quadrupole power supplies has the facility to make a correction to the curves $Q_H(t)$ and $Q_V(t)$. By means of this program the curves $Q(t)$ were corrected empirically to remain always within the limits $27.55 < Q < 27.65$. Thereafter no beam losses occurred during the entire acceleration cycle apart from the
losses at the start of acceleration and about 70% of the injected protons were accelerated to 200 GeV.

On 17th June, after some preliminary trials during which the beam was lost after about 500 msec, a magnet cycle with 12 rectifier stations was established in which the bump of the Q(t) curves had been partially corrected. As a result some beam was indeed accelerated to 300 GeV around noon and Q could be measured along the entire cycle. The result is given in Fig. 2 which shows that there was still a large bump in the curves. Therefore an attempt was made to correct the Q-changes and at 13h another measurement of the Q-values was made. The result is given in Fig. 3 and shows that the applied correction had been too large. Therefore $Q_H$ came very close to $Q_H = 27.5$ and about one-third of the beam was lost at 350 msec after injection.

Since we wanted to reach 400 GeV during the same afternoon, while the CERN Council was in session, no further attempt was made to correct the 300 GeV cycle. Instead the magnetic field cycle was changed to a 400 GeV cycle and an approximate correction of the Q-curves was applied immediately. As a result, when the beam was injected again at 15 h 35 about 30% was accelerated to 400 GeV. The measured Q-curves for these first 400 GeV acceleration cycles are shown in Fig. 4, which shows still a moderate bump for $Q_H$ and also some rapid variations with time since the correction of Q was made in a rather approximative way.

Fig. 5 shows the Q-values measured at 18.00 h. after an attempt had been made to improve the Q(t) curves. As can be seen the bumps have disappeared, but the Q(t) curves still show quite rapid variations with time and important beam losses occurred at the beginning of the cycle, probably caused by the resonance $Q_H = 27^{2/3}$. With this cycle about 40% of the injected beam was accelerated to 400 GeV. Due to the festivities resulting from the fact that 400 GeV had been reached, no further attempt was made to improve the magnetic field cycle and the beam survival.

In order to obtain accurate field measurements which can be used to ensure the correct tracking of the dipole and quadrupole fields two reference dipoles (one of type MBA and one of type MBB) have been included
in the dipole circuit and a reference quadrupole has been included in each of the quadrupole circuits. The voltage induced in long search coils placed in each magnet is integrated by an integrator and converted into a series of pulses, (the B-train and Q-trains) each pulse corresponding to a well-defined increment in field, which is e.g. 0.02 gauss for the B-train of the dipoles.

Measurements show that the power supplies accurately track the B-train and Q-trains. Therefore we conclude that when the bumps in the Q(t) curves occur, either the field in the reference quadrupoles is weaker than the average field of the quadrupoles in the SPS ring or that there is an error in the measurement of the field in the reference quadrupoles. The same deformation of the curves Q(t) would occur if the field in the reference dipole is stronger than the average field of the dipoles in the SPS ring or if there is an error in the measurement of the field in the reference dipole.

Figure 1 also shows the value of \( \frac{1}{B} \frac{dB}{dt} \) as a function of time and it is clear that there is a marked similarity in the time dependence of \( Q_H \), \( Q_V \) and \( \frac{1}{B} \frac{dB}{dt} \). Since eddy currents are proportional to \( \frac{dB}{dt} \) we have considered eddy-currents as a possible cause of the Q-changes but the effect, which is of the order of 1% in quadrupole field is too large to be explained by eddy currents. The most likely explanation is, that the measurement of the field in the quadrupoles is wrong. In fact, measurements show that the measuring coils in the quadrupoles have a resistance of \( 10^5 \) ohms and a large interturn capacity because of the way in which they have been wound. The circuit of the measuring coils in the reference quadrupoles therefore behaves as if it includes an RC filter with a time constant of a few msec and this is of the correct magnitude to explain the bumps in the Q(t) curves. The corresponding time constant for the measuring coils in the reference dipoles is much smaller. In future runs an attempt will be made to suppress this delay by adding a suitable correcting network to the quadrupole measuring circuit and eventually the measuring coils may be changed.
4. **Closed orbit measurements**

In the presence of unavoidable small quadrupole misalignments, small dipole field errors and stray fields, the proton orbits are distorted. It can be shown, that under those conditions the proton trajectories can be described as a free betatron oscillation, with the Q-values $Q_H$ and $Q_V$, around a distorted orbit which closes onto itself and is therefore called the closed orbit. The shape of the closed orbit is also a function of $Q_H$ and $Q_V$. The radial and vertical position of the closed orbit at any azimuth around the ring at any time can be found by measuring the average of the radial and vertical beam positions during, for instance, 1 msec which corresponds to about 40 revolutions.

The SPS has 108 radial and 108 vertical beam position monitors which are placed near the horizontally focussing and vertically focussing quadrupoles, respectively. Together with the SPS computer control system these position monitors enable us to make a complete measurement of the horizontal and vertical closed orbit, each at 108 points around the ring on a single acceleration cycle and to display these closed orbits on a TV screen in the main control room.

Figures 6, 7, 8 and 9 show the closed orbits at injection, 200 GeV, 300 GeV and 400 GeV, without any corrections. (The closed orbit at injection can be corrected with orbit correction dipoles installed for this purpose). When a beam position monitor is not operating correctly, the computer sets its measurement to a fixed value of 38.5 mm horizontally and 20 mm vertically.

The numbers listed in Figs. 6 to 9 have the following meaning

- **MOY** = Mean radial position of the closed orbit in mm
- **SIG** = RMS value in mm of the beam displacements in all 108 position monitors
- **MIN** = Largest displacement inward, in mm
- **MAX** = Largest displacement outward, in mm.
The peak to peak (ptp) deformations of the closed orbit are given by MAX-MIN and are listed in the following table. The Q-values were around 27.6 when these measurements were made:

<table>
<thead>
<tr>
<th>Proton energy</th>
<th>horizontal closed orbit, peak to peak</th>
<th>vertical closed orbit, peak to peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV (injection)</td>
<td>20 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>200 GeV</td>
<td>15 mm</td>
<td>16 mm</td>
</tr>
<tr>
<td>300 GeV</td>
<td>13 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>400 GeV</td>
<td>12 mm</td>
<td>16 mm</td>
</tr>
</tbody>
</table>

The ptp deformations of the vertical closed orbit are independent of energy in the range 200 GeV to 400 GeV, but increase to 25 mm at injection, presumably due to stray fields which have not yet been investigated. The ptp deformations of the horizontal closed orbit in the range 200 GeV to 400 GeV are slightly smaller than those of the vertical closed orbit but in a first approximations it can be said that the combined effects of misalignments and construction errors of the quadrupoles is roughly the same in both planes and well within the value specified in the SPS design.

In principle the horizontal closed orbit deformations should be smallest at 200 GeV since all dipoles have been adjusted with end shims to have the same bending power at 200 GeV when \( B = 0.9 \) T and the permeability is largest, so that the main contribution to closed orbit deformations at 200 GeV are the alignment errors of the quadrupoles.

Equality of the dipoles at low field has been obtained by an extensive program of magnetic measurements of the steel laminations followed by controlled mixing of the laminations from different batches with different coercive force so that the average remanent field of all dipoles is the same. The dipole field errors at 400 GeV due to saturation have been corrected partially by means of saturable end shims and the resulting closed orbit deformations have been kept small by combining the dipoles.
in groups of 4 in such a way that their field errors inside each group of 4 cancel each other.

As can be seen from the table, the ptp closed orbit deformations at injection are only a bit worse than at 200 GeV, and at 400 GeV are the smallest of all. This shows that the mixing of the laminations has been very good and the saturation correction excellent.

For comparison it should be noted that the full apertures of the SPS are 125 mm horizontally and 50 mm vertically.

In order to demonstrate the high precision of the magnets and their alignment it can be mentioned, that for an r.m.s. misalignment error of 0.15 mm of the quadrupoles and an otherwise perfect magnet system or an r.m.s. variation $\frac{\Delta B}{B} = 5 \times 10^{-4}$ in the bending power from dipole to dipole and perfectly aligned quadrupoles the peak to peak closed orbit deformation has a 37% probability to exceed 14 mm (11 mm) and a 2% probability to exceed 28 mm (21 mm) for $Q = 27.75$ (27.60). Of course, if both errors mentioned above occur at the same time, their effects must be added quadratically so that the orbit deformations given above must be multiplied by a factor $\sqrt{2}$.

5. **Measurements of chromaticity and stopbands**

When the momentum of a proton is larger than the momentum which corresponds to the central orbit it will circulate on the outside of the central orbit. The average radial displacement is about 1.9 mm for $\Delta p/p = 10^3$. The focussing effect of the quadrupoles on an off-momentum particle is inversely proportional to its momentum deviation and therefore one would expect that the relative change in $Q$ is roughly proportional to $(\frac{\Delta p}{p})^{-1}$. More detailed calculations show that for an SPS with perfect magnets the proportionality factor which is usually called the natural chromaticity, is -1.3, that is

$$\xi_H = \xi_V = \frac{\Delta Q/Q}{\Delta p/p} = -1.3.$$  

Measurements at 200 GeV have given $\xi_H = -1.2$ and $\xi_V = -1.4$ in good
agreement with calculations.

At low fields and especially at the transition energy of 22 GeV the momentum spread in the beam is rather large and this leads to a Q-spread in the beam. Consequently, the Q-value of some protons can be sufficiently close to a resonance value so that these protons are lost. Therefore it is necessary to make the Q-value roughly independent of the proton momentum with the help of sextupoles. In the median plane of a quadrupole we have

$$B_z = c_1 x$$

and

$$\frac{\partial B_z}{\partial x} = c_1$$

where x and z are the horizontal and vertical coordinates in the transverse to the particle motion.

In the median plane of a sextupole

$$B_z = c_2 x^2$$

and

$$\frac{\partial B_z}{\partial x} = 2c_2 x$$

Therefore an off-momentum particle which circulates outside the central orbit at a distance from it which is proportional to \(\frac{\Delta p}{p}\) will encounter in the sextupoles an additional gradient i.e. an additional focussing force which is proportional to its momentum deviation. By a suitable choice of the strength of the two sets of 36 sextupoles one can make \(Q_H\) and \(Q_V\) roughly independent of momentum, that is

$$\xi_H = \xi_V = 0.$$  

Eddy currents in the vacuum chamber walls produce a sextupole component in the magnetic field of the dipoles which changes the chromaticity of the machine, especially in the range from 10 GeV to 50 GeV, where
1 dB
B
\frac{dB}{dt}
is largest. Therefore the currents in the sextupoles must be pulsed according to a curve \( I = I(t) \) which takes into account the different effects discussed above. Up to now the sextupoles have only been pulsed according to the calculated curve \( I = I(t) \) but the absence of beam losses at transition, when the energy spread in the beam is largest, shows that the correction of the chromaticity must be quite good.

As has been mentioned in chapter 2, fluctuations in the dipole fields, quadrupole fields and nonlinear fields around the ring cause beam losses at \( Q = 27^{2/3}, 27^{3/4} \) and 28 or in the vicinity of these \( Q \)-values. The worst beam losses can be expected to occur when both \( Q_H \) and \( Q_V \) are close to the same dangerous \( Q \)-value. Measurements of the importance of these resonances with \( Q_H = Q_V \) have been made at injection and Fig. 10 shows the fraction of the beam which then survives after 200 msec without RF. As could be expected, the vicinity of the integral and half integral resonances \( Q = 28 \) and \( Q = 27.5 \) must be avoided. However, the third order and fourth order resonances \( Q = 27^{2/3} \) and \( Q = 27^{3/4} \) are quite benign and it is expected that in due time it will be possible to suppress these higher order resonances almost entirely with the harmonic correction sextupoles and octupoles which have been installed in the SPS for this purpose.  

6. Measurements with the RF accelerating system

As has been discussed in the previous chapters, most of the commissioning time up to now has been spent in establishing acceptable conditions for the betatron oscillations, by correcting the \( Q(t) \) curves, the chromaticity etc. The task of the RF system then was to accelerate the protons until the beam was lost due to transverse resonances. Therefore little time has been available up to now to study the accelerating system with "clean" transverse conditions. Nevertheless, a number of important measurements have been made which confirm that the RF system performs entirely according to its design specifications.

The accelerating systems in the CPS and SPS operate at 9.5 MHz and 200 MHz respectively. The SPS beam position monitors are only sensitive to the 200 MHz component in the beam. Therefore a short 200 MHz cavity
has been installed in the CPS to premodulate the 9.5 MHz bunches with a
200 MHz structure so that beam observations in the SPS can be made already on
the first turn. The 200 MHz modulation of the bunches in the CPS is close
to 100%. During the first runs it was therefore tried to turn on the power
of the SPS accelerating cavities already before injection and to lock the
SPS accelerating system to the CPS accelerating system by means of an
existing cable link, so that the premodulated 200 MHz bunches coming
from the CPS could be captured immediately in the stationary buckets of
the SPS accelerating system. In this way a capture efficiency in the
SPS of about 75% was obtained. However, such a transfer scheme required a care-
ful adjustment of the CPS magnetic field and radial beam position at extraction.
Moreover, it preserves the 9.5 MHz structure in the SPS, which is undesir-
able.

During the later runs it was therefore preferred to use the method
of adiabatic capture which was, in fact, the method foreseen in the SPS
design study. The SPS accelerating voltage is turned off before the
beam is injected into the SPS. The momentum spread in the beam then
causes a spread in revolution frequency so that after about 100 msec the
9.5 MHz structure in the beam has entirely disappeared. At that time the
RF voltage is turned on slowly (in about 5 msec) and the protons are
captured adiabatically by the RF system. This gives a capture efficiency
of practically 100%. The latter figure was measured by adding a
perturbation to the radial control loop so that the captured beam is dri-
ven into the wall of the vacuum chamber. After the captured beam has
been lost, the fraction which was not captured continues to circulate and
can be measured with a current transformer.

Measurements at the CPS and at FNAL indicate that at high beam
intensities a microwave instability can develop during this long debunch-
ing time. At the intensities used up to now, i.e. a maximum injected
current of about 3 x 10^{12} ppp this instability has not been seen.

From the measured debunching time it can be calculated that the momen-
tum spread of the CPS beam is about

\[ \frac{\Delta p}{p} = \pm 0.6 \times 10^{-4} \]
During the 300 msec flat bottom of the magnetic field cycle and the beginning of the acceleration cycle we usually lose at least 25% of the beam. Since up to now all efforts have been concentrated on reaching 400 GeV there has been no time to investigate the reasons for this beam loss. Therefore it is not clear at this stage if this is a transverse or a longitudinal effect and this matter will now be investigated, for instance, by accelerating with reduced RF voltage.

Once the beam has reached 15 GeV there is in most cases no further loss. The phase control loop and the radial control loop work well, the beam passes transition without any loss and is kept in the centre of the vacuum chamber during the entire cycle.

The effective accelerating voltage seen by the beam in the SPS travelling wave accelerating structure has been calculated, using the known $\frac{dB}{dt}$, from a measurement of the phase angle $\phi_s$ between the proton bunches and the RF voltage. The observed value $\phi_s = 43^0$ measured on the 400 GeV cycle is close to the predicted value, and corresponds to an accelerating voltage of 3.7 MV per turn with 330 kW in cavity 1 and 430 kW in cavity 2.

7. **Survey of other interesting results obtained during the SPS commissioning**

In this chapter we shall make a variety of comments concerning other measurements made with the beam and the performance of SPS systems, which may be of general interest.

The continuous transfer extraction system of the CPS works well but the variations in extracted current during the 10 turn extraction are about $\pm 30\%$. The emittance of the beam is $E_H = E_V = 1.3 \pi \text{ mm x mrad}$ at an intensity of $2 \times 10^{12}$ ppp. This corresponds to a maximum beam diameter in the SPS, with $\beta_{\text{max}} = 109$ m, of about 25 mm which is one half of the vertical SPS aperture.

The injection beam transfer line TT10 works well and takes little time for setting up. At the downstream end of TT10 the beam emittance and matching can be measured with a set of 3 grids of secondary emission
foils. A similar set of 3 grids is located in LSS5. The SPS computer control system permits to display histograms of the cross-sections and calculates the emittances and transverse phase space parameters within a few seconds after each pulse.

The injection system consists of a pair of septum magnets, a pair of kicker magnets and a dump downstream of the kickers, on the inside of the SPS aperture. When the kickers are not pulsed, the protons hit the injection dump and with the help of beam monitors just after the injection septum magnets and in front of the injection dump, the injection trajectory can be adjusted. When the kickers are pulsed the beam goes around the ring once until it hits the first turn stopper just upstream of the injection system.

The beam position monitors are sensitive enough to give an accurate display of the beam position on a single turn. This is a very powerful method to optimize the injection conditions and also to correct the closed orbit at injection since it is much easier to interpret the measurements on a single turn than those on a circulating beam. When the injection system is deliberately mistuned the first turn orbit displays a large coherent oscillation. A Fourier analysis of the beam position around the ring then allows already a measurement of the Q-value on a single turn with an accuracy of ± 0.1.

When the chromaticity has been corrected as described in chapter 5, all protons have practically the same Q-value. This makes the beam very sensitive to the resistive wall instability in which the entire beam develops a coherent vertical instability which is caused by the attractive effect of image charges in the vacuum chamber walls. This effect was stabilized with octupoles which make the betatron oscillation frequency dependent on amplitude. However, since octupoles can lead to transverse resonances we shall install in the near future an active feedback system to damp the resistive wall effect. In such a system the beam displacement in a pick-up electrode is amplified and applied to a suitably located electrostatic deflector.
The SPS controls system with its computer network has proved to be flexible and very powerful in executing complex tasks and in analysing and displaying large amounts of information. Since one can collect so much information on a single pulse a repetition time of 6 seconds has proved entirely satisfactory for commissioning.

All major components, such as magnet system, power supplies and cooling have worked well at the maximum power level on the 400 GeV cycle. The system of reactive power compensation and voltage stabilisation works well. The voltage drop on that part of the SPS mains to which all pulsed power supplies are connected is 0.5% at the end of the field rise, when the reactive power is a maximum and shows a transient of 1.3% at the end of the flat top when the voltage across the magnet is reversed. These results are within the specified values.
Fig. 1  QH, QV and mean radial position on 200 GeV cycle
showing also \( \frac{1}{E} \frac{d\eta}{dt} \)
Fig. 2  QH and QV on 300 GeV cycle.
17 June, 12 h.
Fig. 3  QH and QV on 300 GeV cycle, with over-correction of the bump.
17 June, 13 h.
Fig. 5  QH, QV and beam current on 400 GeV cycle,
after further correction.
17 June, 18 h.
Fig. 6, horizontal and vertical closed orbits at injection without correction (14.5.76, 20.46h)
FIG. 7, HORIZONTAL AND VERTICAL CLOSED ORBITS AT 200 GeV (4.6.76, 21.37h)
FIG. 9, HORIZONTAL AND VERTICAL CLOSED ORBITS AT 400 GeV (17.6.76, 15.50h)
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