SPS COMMISSIONING REPORT NO. 23

Slow extraction tests on 2nd September and 7th September 1976

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1. Summary

Protons were extracted by driving them into the resonance at $Q_H = 27^{2/3}$ excited by four suitably positioned sextupoles. An almost uniform spill of more than 650 ms was achieved, essentially limited by the length of the flat top. A spill modulation was observed with a main frequency at about 150 Hz. Some 5 to 10% of the protons survived the extraction process and were dumped at the end of the flat top.

Measurements done with R.F. off are in good agreement with theoretical predictions.

Extraction seems to work equally well with R.F. on except for an emittance blow-up of the slowly extracted beam.

2. Short reminder of the extraction process

The extraction process is illustrated in Fig. 1. Protons in the beam are represented by their 'emittance' $\epsilon = \frac{(\hat{x})^2}{\beta n}$ and by their horizontal $Q$-value. $\hat{x}$ is the horizontal maximum betatron amplitude of the particles at $\beta = 109$ m. The unstable region around $Q_H = 27^{2/3}$ is created by exciting suitably distributed sextupoles. The boundaries of the unstable region were calculated for the total normalized sextupole strength $K_s$ of 16 m$^{-1}$ used during the measurements.
The beam is extracted by driving it into the unstable region with a speed $\dot{Q}$. A proton which has crossed the left-hand boundary starts increasing its betatron amplitude, that means in Fig. 1 it starts moving towards higher $\epsilon$. Particles survive the extraction process if they reach the stable area to the right before their betatron amplitude has sufficiently increased to throw them into the electrostatic septum.

Figure 2 shows the phase plane situation at the entrance of this septum. Particles within their corresponding triangles are stable, whereas particles on the outward going branches are unstable and gradually move along the branches towards the vacuum chamber walls. A particle that just grazes the wire array of the electrostatic septum at about 24.5 mm distance from its closed orbit will emerge at a distance of 37.5 mm after three more revolutions in the machine. It will have made a 'jump' of 13 mm at the septum, thus avoiding the wires and being extracted.

The speed $\dot{Q}$ with which the protons are driven into the resonance may be modulated due to ripple on the magnets involved in the process, for instance by a ripple on the main quadrupole current. Such a ripple on $\dot{Q}$ leads to a corresponding spill modulation.

If the R.F. is left on during extraction synchrotron oscillations are superimposed to $\dot{Q}$ and a proton may return several times from the unstable area to the stable area before being definitely extracted.

3. **Parameters of slow extraction during the tests**

Figure 3 shows the circulating beam and the extracted beam in the region of the extraction channel for slow extraction at $Q_H = 27^{2/3}$ (trajectories calculated for a circulating beam emittance of $0.3\pi$ mm mrad). After horizontal closed orbit correction the circulating beam was brought close to the foreseen positions of the extraction septa by suitable currents in the horizontal bumpers. The beam positions measured in pick-up stations 6160 and 6180 were 36.2 mm and 28.4 mm respectively. The vertical closed orbit was roughly corrected to be close to zero along the extraction channel.
The septa were positioned such as to cut into the unstable part of the beam at the theoretical position. The strength of the septa were chosen to make the necessary separation between the circulating and the extracted beam and to meet the position and angle required at the theoretical extraction point in TT60.

The resonance was excited by the four sextupoles LSE 1060, LSE 2260, LSE 4060 and LSE 5260. Two of these sextupoles, LSE 1060 and LSE 5260, had positive polarity, the other two had negative polarity. The normalized strength was 4 m⁻¹ per sextupole.

Figure 4 shows the timing and the shape of the currents in the pulsed elements. The details of these currents and other parameters are given in Table 1.

During the extraction experiments the PS intensity was reduced to provide 5 \times 10^{-11} to 1 \times 10^{12} protons in the SPS at 200 GeV/c.

The strength of the Landau damping octupoles had been reduced to the minimum required for a stable beam on the flat top (25 A per LOD). The chromaticity correction sextupoles were off on the flat top.

Protons were driven into the resonance from below by a positive slope on the horizontal Q-value of the machine using S. van der Meer's Q adjustment program. Fig. 5 shows the function applied to Q_H on the flat top during the first test (there is an offset between Q_H and ν_H).

4. Results of the first test on 2nd September with R.F. on

4.1 Spill length, spill structure, beam survival

Spill length and spill shape are shown in Figs. 6 and 7.

The traces on the photograph of Fig. 6 represent:
- trace 1 : the main magnet cycle
- trace 2 : the circulating beam current. On the flat top a fairly uniform decrease of this current is observed during about 650 ms. At the end a small percentage of surviving protons is dumped.
- trace 3 : the losses on the electrostatic septum integrated during the flat top. Again, an almost uniform increase of the signal during 650 ms is observed.

Figure 7 shows several photos taken in BA6. One trace always shows the signal of the secondary emission monitor BSI 610316 in front of the external beam dump, the other trace shows a signal of a newly developed monitor making use of solar cells. Photos 1 and 2 of figure 7 prove again that apart from a spike in the beginning the spill was fairly uniform and more than 650 ms long.

Photo 3 of figure 7 permits a first analysis of the spill modulation. It seems that the main frequency component is close to 150 Hz. Principle candidates which may create this modulation are:

- ripple on the main quadrupole current
- ripple on the extraction sextupole current
- ripple on the closed orbit position in the extraction sextupoles.

Throughout the evening of 2 September 1976 photos and hard copies were taken which prove the extremely high stability of the extraction conditions:

- start of spill at 3200 ± 40 ms without servo loop throughout the 4 hours
- stop of spill at 3865 ± 35 - 45 ms

As can be seen from figure 5 the horizontal Q-value increased linearly during the spill except for the very beginning and the very end. The total change in $Q_H$ during the spill amounts to $\Delta Q \sim 0.024$. 
The fact that the spill always started within an interval of \( \pm 40 \) ms means the overall stability of \( v_H \) during the 4 hours of the experiment was of the order of \( 10^{-4} \). The short term stability of \( q_H \) was considerably larger as is shown in Fig. 8. During 10 cycles the measured quadrupole fields were stable to \( 5 \times 10^{-6} \). The last but one line of the table in Fig. 8 shows the circulating beam current as a function of time. At 3902 ms, that means after the end of the spill, about \( 10\% \) of the protons have survived. These protons were dumped shortly afterwards (dump trigger at 3910 ms).

Beam survival of somewhat less than \( 10\% \) was typical during the first tests. However, we also observed bursts with a survival of about \( 5\% \) only. These measurements are in fairly good agreement with a beam survival of \( 3.5 \pm 1\% \) given by computer simulations for the conditions (emittance and spill speed) of the experiment.

4.2 Position and profile measurements in the extraction channel

Figure 9 shows the arrangement of secondary emission monitors along the extraction channel. Figures 10 to 18 show measurements of the horizontal beam position and beam profile at different points of the extraction channel * and figures 19 to 21 show the vertical position and profile at the electrostatic septum and at the magnetic septa. A number of comments on these measurements seem indicated:

- The maximum jump at the entrance of the second tank of the ZS lies between 9 and 10 mm (Figures 10 and 11). This is in good agreement with the theoretical calculations yielding a maximum jump of 11 mm at this position.

- The rapid decrease of the proton density in the gap of ZS starting at a distance of 6 to 7 mm from the wire array (figs. 10 and 11) indicates a 'jump spread' of about 3 mm which is in contradiction to the calculated value of about 1 mm. This discrepancy might be due to the fact that extraction was done with R.F. on.

* Nota: In case of horizontal measurements the extracted beam is shown on the left of the septum in Figs. 10 to 18.
At the exit of ZS a certain separation between the circulating and the extracted beam are observed, the density being close to zero at the position of the wires (Fig. 12).

Figure 13 shows the excellent adjustment of the MST in the 'hole' created by the electrostatic septum (adjustment achieved by calculation, no readjustment necessary after the measurements during the experiment).

The horizontal measurements done at MST and MSE on 2nd September yield a beam size considerably larger than had been expected. The measured beam size at position 6 1856, for instance, amounts to about 15 mm (fig. 17) compared to a theoretical value of 4.3 mm only (calculations without RF, measurements with RF). There are two possible explanations for such a discrepancy:

a) the beam drifts during the spill
b) with R.F. on protons 'oscillating' between the stable and the unstable area increase their 'emittance' and are finally extracted along outward going separatrices belonging to their new emittance. An emittance blow-up in the ring of a number of protons to about 1.5 π mm mrad would explain the effect. (The measurements done on 7th September prove that the blow-up was indeed due to R.F.; compare chapters 6 and 7.)

The vertical emittance at 200 GeV/c was of the order of .1 π mm mrad (at 5 to 7 * 10^{11} ppp; compare figures 19 to 21).

4.3 Beam losses along the extraction channel

Figure 22 shows the loss distribution along the extraction channel. As expected the main losses occur at the electrostatic septum. The fact that the losses decrease along this septum seems to indicate the good alignment of the wire array with respect to the beam.

Small losses can be observed at the MST, particularly at its entrance.

* All extraction magnets involved are very stable however. (See Annex 1).
There is another small loss at the machine quadrupole QD 6191. This loss can be explained by the fact that the extractor magnet MSE was somewhat too strong during the first experiment.

5. Extraction with R.F. off on 2nd September 1976

At the end of our first slow extraction experiment the R.F. was switched off and the spill was observed without any change of other parameters. We obtained a uniform spill (Fig. 24) practically identical to the spill with R.F. on (Fig. 23).* No further measurements with R.F. off were done on 2nd September.

6. Results of the test on 7th September with R.F. off

After the first test it had been suspected that the discrepancies between the theoretical calculations, all done without R.F., and the measurements were due to the fact that the R.F. was left on during extraction on 2nd September.

As pointed out under 4.2 the main disagreement concerned the horizontal beam size at the magnetic septa.

At two significant positions (first horizontal beam scanners at MST and at MSE) profile measurements were therefore carefully repeated on 7th September, both with R.F. on (Figs. 25 and 27) and R.F. off (Figs. 26 and 28). A comparison between the obtained beam dimensions shows that the beam width at the magnetic septa is in fact considerably reduced with R.F. off. The full measured beam widths of about 6 mm at MST and about 5.5 mm at MSE are in good agreement with the calculated values of 6.9 mm and 5.4 mm respectively (calculations assumed a circulating beam emittance of .15 π mm mrad).

7. Profile measurements in TT60

The ejected proton beam was sent 100 m downstream TT60 onto the external dumps TED 6103. Along this way it is focussed by 3 quadrupoles.

* Nota: The big losses on the flat bottom are due to an RF bump that had not been switched off.
Beam profiles of both the ejected beam with R.F. on and with R.F. off were measured with the three SEM grid monitors BSG 6100, 6101 and 6103. The result is shown in Fig. 29 where the measured beam widths (about 95 % of particles) are compared to the theoretical beam envelope for an assumed emittance of $\varepsilon_H$, $\varepsilon_V = 0.1 \pi \text{ mm mrad}$. In the vertical plane one finds rather well matched beams, the emittance for both cases being equal and somewhat less than $0.1\pi \text{ mm mrad}$. In the horizontal plane one finds both mismatch and larger emittances. A rough estimate from these data for the horizontal emittance is $0.5 \pi \text{ mm mrad}$ for R.F. on and $0.2 \pi \text{ mm mrad}$ for R.F. off.

8. Conclusion

The results of the first tests of slow extraction are very encouraging. The high speed of data acquisition on instrumentation permitted a detailed analysis of the beam properties.

Measurements with R.F. off are in good agreement with theory. With R.F. on the extracted beam emittance is blown up by a more than a factor of 2.

The agreement between theoretical calculations and measurements indicate that the main magnet linearity is, at 200 GeV/c, well within specified values.

Reported by: K.H. Kissler
W. Scandale
E. Weisse
### TABLE 1

**Horizontal Dipoles**

<table>
<thead>
<tr>
<th>Name</th>
<th>Main Pulse (A)</th>
<th>Demagnetisation Pulse (A)</th>
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<tr>
<td>MPSH 6120</td>
<td>– 20</td>
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<td>MPLH 6145</td>
<td>72</td>
<td>– 36</td>
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<td>MPBH 6173</td>
<td>270</td>
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<tr>
<td>MPLH 6217</td>
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<td>– 36</td>
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**Vertical Dipoles**

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<td>MPSV 6210</td>
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<td>– 22</td>
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<td>MPSV 6230</td>
<td>– 7</td>
<td>+ 22</td>
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**Magnetic Septa**

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<tr>
<td>MSE</td>
<td>9634</td>
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**Electrostatic Septum**

- Field: 57.8 KV/CM
- H.T.: 115.6 KV
- Gap: 20 MM

**Septa Positions**

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<th>Name</th>
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<td>MSE upstream</td>
<td>– 9.8</td>
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<tr>
<td>MSE downstream</td>
<td>– 9.8</td>
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Schematic description of the extraction process

Fig. 1
Extraction at $Q_H = 27 \frac{2}{3}$

LSE 1060 : $+0.004 \, \text{mm}^{-1}$
LSE 2260 : $-0.004 \, \text{mm}^{-1}$
LSE 4060 : $-0.004 \, \text{mm}^{-1}$
LSE 5260 : $+0.004 \, \text{mm}^{-1}$

Phase plane diagram at the entrance of ZSW

$\varepsilon_H = 0.15 \, \text{mm mrad}$
SPS SLOW EXTRACTION

2/9/76, 20h - 24h

1 - MBA + MEB ref. field

2 - BCT ring SP 3

3 - BL 61 594

(beam loss monitor nr. 6 in extraction channel)

Horizontal sweep: 500 msec/cm

Fig. 6
Intensity of the slowly extracted beam as a function of time

Fig. 7
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<th>MEAN/RMS</th>
<th>TIME</th>
<th>NUMBER OF CYCLES</th>
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Fig. 8
EXTRACTION CHANNEL / BBS+BSG MONITORS

QF ZS ZS ZS ZS TCE QD
I 0 0 0 0 | 0 0 I
BBSH BBSY BBSH BBSH BBSY

QD MST MST MST MST QF
I 0 0 0 0 0 0 0 I
BBSH BSGH BBSH/C BBSH BBSY

QF MSE MSE MSE MSE MSE MSE QD
I 0 0 0 0 0 0 I
BBSH/C BBSH BSGH BBSH BBSH BBSY

Fig. 9

SPS Comm. Rep. No. 23
YMAX = 1.36 V

MEASUREMENT TERMINATED 25.

POSITION
START 0
STOP 14.9

NO OF STEPS 15

TIMING
START 3 \ 3000 MS
STOP 4 \ 3900 MS

NO OF CYCLES/STEP 1
V$_{MAX}$ = 2.58 V

MEASUREMENT TERMINATED

POSITION
START - 9
STOP 24.1

TIMING
START 3 \ 3000 MS
STOP 4 \ 3900 MS

NO OF STEPS 20
NO OF CYCLES/STEP 1

Fig. 14
VMAX = 3.71 V

POSITION
START 8
STOP 24

TIMING
START 3 / 7000 MS
STOP 6 / 7000 MS

NO OF STEPS 20
NO OF CYCLES/STEP 1
POSITION 22.0  NO OF CYCLES  1

TIMING
START 3 \ 3000 MS
STOP 4 \ 3900 MS

AQUISITION TERMINATED

VMAX = 0.34 V

Fig. 17
BBSV 61638

YMAX = 3.73 Y

MEASUREMENT TERMINATED

POSITION
START -3
STOP 2

TOMING
START 3 \ 3000 MS
STOP 4 \ 3900 MS

NO OF STEPS 20

NO OF CYCLES/STEP 1

Fig. 19
V\text{MAX} = 13.78 \, V

\begin{align*}
\text{NO. OF CYCLES/STEP} & : 1 \\
\text{NO. OF STEPS} & : 20
\end{align*}

\text{Fig. 21}
EXTRACTION CHANNEL / LOSS DISTRIBUTION

ACQ/JS. 3000/3960

MAX. SIGNAL 3.41 V

Fig. 22
**BSH 61758**

**VMAX = 2.27 V**

**MEASUREMENT TERMINATED**

**BSI POSITION OUT NOT REACHED**

**POSITION**

- START 0
- STOP 18

**TIMING**

- START 1 \ 3000 MS
- STOP 4 \ 3910 MS

**NO OF STEPS** 18

**NO OF CYCLES/STEP** 1

---

Fig. 25
YMAX = 3.90 V

BSI POSITION OUT NOT REACHED

MEASUREMENT TERMINATED

POSITION
START 3
STOP 10

NO OF STEPS 20

TIMING
START 1 \ 3000 MS
STOP 4 \ 3910 MS

NO OF CYCLES/STEP 1

Fig. 26
\( \text{BBSH 61851} \)

\( \text{YMAX = 2.45 V} \)

\( \text{MEASUREMENT TERMINATED} \)

\( \text{BSI POSITION OUT NOT REACHED} \)

\[ \text{POSITION} \]

START 7.0
STOP 22.0

\[ \text{TIMING} \]

START 1 \( \times \) 3000 MS
STOP 4 \( \times \) 3910 MS

\[ \text{NO OF STEPS 15} \]

\[ \text{NO OF CYCLES/STEP 1} \]

Fig. 27
VMAX = 6.94 V

BSI POSITION NOT REACHED

POSITION
START 16.0
STOP 17.0

TIMING
START 1 / 3000 MS
STOP 4 / 3910 MS

NO OF STEPS 23
NO OF CYCLES/STEP 1

Fig. 28
Slow ejected beam in TRG: Comparison of calculated beam envelope for E_e = 0.15 m and measured beam width.
ANNEX

Bumpers, extraction sextupoles, septum power supplies stability during slow extraction on the 7th September 1976

1. General (see table)

Each supply was measured at 12 or 20 different instants, either on one cycle or ten cycles from 6 h 10 to 14 h 25 owing to fast acquisition by the digital voltmeter.

Besides, all currents were observed on scopes during a certain time.

If anomalies are left out (once in 20 or 40 pulses), the stability on the flat top from pulse to pulse in comparison with the actual current is about $10^{-3}$ on all supplies used to-day; it is some $10^{-4}$ if the maximum current is taken into account.

2. Particular cases

2.1 Maximum spread

Maximum spreads were observed for MPSH 6120, MPSV 6130, MPLH 6199, MPLH 6217 and MPSV 6230 ($\Delta I/I_{SE} = 22$ to $42 \times 10^{-3}$); MST 6175 and MSE 6183 stay at $\Delta I/I_{SE} = 13$ and $15 \times 10^{-3}$ with mean slopes on flat top smaller than $0.5 \times 10^{-3}$. In comparison with $I_{max}$, only MPSV 6130 ($4.4 \times 10^{-3}$), MPLH 6199 ($4.3 \times 10^{-3}$) and MSE 6183 ($6 \times 10^{-3}$) are important.

2.2 Standard deviations

Maximum for MPSH 6120 (1 %), MPSV 6130 (0.9 %) and MPLH 6217 (0.6 %) with respect to $I_{max}$, these three values become $4 \times 10^{-4}$, $13 \times 10^{-4}$ and $0.6 \times 10^{-4}$, in the specifications.

2.3 Differences with expected values of currents

Maximum differences (3 to $6 \times 10^{-3}$) were observed for 9 supplies, but in comparison with maximum currents, all the differences were smaller or equal to $2 \times 10^{-4}$, except for MSE 6183 at $1.6 \times 10^{-3}$. 
2.4 **Particular anomalies**

- **LSE** Twice, a long fall time (~1 sec. instead of 0.3 sec) were observed for the four LSE together (the cause doesn't necessarily come from the supplies).

- **LSE 2260** On 8 h., bad stabilisation and deformation on middle and at end of flat top.

- **MSE 6183** Three times, a large round off before the end of flat top was observed.

- **MPLH 6199** A short spike was observed before rise.

- **MPSV 6150** Overshoot after fall time (whole day).

3. **Conclusion**

For these values of currents for first slow extractions, the characteristics of these power supplies are largely in accordance with the specifications. Nevertheless, it would be desirable to adjust the calibration of MSE 6183 (for $1.6 \times 10^{-3}$).

Other systematic measurements will be necessary to study the anomalies and spikes to understand their origin.

J. Dupin
### Table 1

<table>
<thead>
<tr>
<th>Power supply</th>
<th>1) I&lt;sub&gt;SE&lt;/sub&gt; amp.</th>
<th>I&lt;sub&gt;max&lt;/sub&gt; amp.</th>
<th>Mean slope on flat top x 10&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>Mean stability pulse to pulse on 8 hours x 10&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>Maximum spread x 10&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>Standard deviation x 10&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>Mean value expected value x 10&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>ΔI/I&lt;sub&gt;max&lt;/sub&gt; specified by E&lt;sub&gt;Bt&lt;/sub&gt;/SE</th>
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<td>LSE 1060</td>
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1) I<sub>SE</sub> - I<sub>SLOW EXTRACTION</ref>