EXTRACTION FROM THE CERN SPS

by

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Extraction from the CERN SPS
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Summary
The experimental programme requires three different modes of extraction from the SPS: fast extraction (burst duration from 3 ms to 23 ms), slow resonant extraction (spill duration 0.5 s to 2 s) and fast resonant extraction (spill duration shorter than 3 ms). All three modes have been successfully tested and brought into operation. Fast extraction of the full beam is 100% efficient. By fast beam shaving, fractions as low as 12% of the circulating beam can be extracted in a fairly stable way. Third-integer extraction is used to produce slow spills of 700 ms or more. The efficiency of resonant extraction is currently some 97%. The spill duty factor at present amounts to about 40%. Fast resonant spills of less than 2 ms were achieved with both integer and half-integer extraction. The different modes of extraction are consecutively performed during each accelerator cycle. At present, a 1 s third-integer spill at 200 GeV/c is followed by a fast shaving extraction at 210 GeV/c and by a fast or fast resonant extraction of the remaining protons at 400 GeV/c.

Extraction channel
The beam is extracted in the horizontal plane. The layout of the extraction channel is shown in Fig. 1 together with the mechanical aperture in the extraction region and beam envelopes for third-integer extraction.

Fig. 1 Layout of the SPS extraction channel

During extraction the closed orbit position and direction of each septum of the extraction channel are accurately controlled by a set of 5 horizontal and 4 vertical dipoles.

As indicated in Fig. 1 a number of beam monitors have been installed along the extraction channel which permit detailed studies of the extraction process. Particularly, miniscanners give precise measurements of parameters like jump size and divergence of the resonant proton beam at the electrostatic septum or beam separation at the copper septa. These scanners consist of thin metallic flags that can be moved in steps through the beam. The positive charge on the flag created by the traversing protons yields a measure of the proton flux at the scanner position. The range of the scan, step size and number of steps, as well as the timing of the acquisition can be varied by a computer program over a wide range.

A total of 14 ionization chambers installed at crucial positions in the extraction channel allow to analyze the losses at the septa and to optimize the adjustment.

Fast extraction
Once the extraction channel has been adjusted, fast extraction is obtained by a rapid deflection of the beam with a pair of fast kickers located one quarter wavelength upstream of the electrostatic septum. Protons which are not sufficiently deflected to jump the septum start a coherent betatron oscillation which is cancelled by another pair of kickers about one wavelength downstream of the first pair. In order to cope with different tunes of the machine, a fifth kicker is used for an optimal compensation of the kick and is located in between the two pairs. All five kickers have rise and fall times of about 900 ns. They can give up to three kicks per machine cycle, each independently adjustable in amplitude and duration. The maximum deflection at the 2S entrance is 24 mm at 400 GeV/c.

Two modes of fast extraction are used in operation:

1. Fast extraction of the full beam, obtained with a kick duration of 23.2 μs. The extraction efficiency is 100% when the rise of the kickers is correctly synchronized with the 2 μs hole in the circulating beam which results from injection.

2. Fast extraction of part of the beam, which is obtained by reducing the kick duration. Usually the kick amplitude is reduced in addition so that only a fraction of the beam cross section jumps the electrostatic septum ("shaving"). In this way it is possible to extract very small percentages of the circulating beam. With a kick duration of about 5 μs and with 60% of the nominal deflection, fractions as low as 1% have been extracted. The extracted intensity fluctuated in this case by about 40% from cycle to cycle as only the edge of the beam profile was shaved off. For 2.5% extracted, the fluctuations are reduced to about 10% of the extracted intensity. Fig. 2 which was obtained with a fast digitizing technique shows the circulating beam and the shaving of a fraction of 3%.

Recently a "learning programme" has been implemented which averages over a few cycles the extracted intensity and then acts on the kicker settings in order to keep the extracted percentage constant.
Fig. 2 Fast shaving extraction of 3% of the circulating beam

Slow resonant extraction

Slow resonant extraction has been successfully tested at the following horizontal tunes: 27 1/3, 27 2/3 and 28. These tests confirmed the prediction that integer and half-integer extractions are more sensitive to ripple on the various magnet currents than third-integer extraction. Moreover, in the SPS νH = 27.4 was found to be a better working point than νH = 27.6. (There is evidence for a 5th order structure resonance at νH = 27.6, linked to the 6-fold symmetry of the accelerator.) For these reasons slow resonant extraction is done at νH = 27 1/3 in present operation and the results reported below refer to this resonance.

Extraction procedure

The third-integer resonance at νH = 27 1/3 is excited by 4 sextupoles, which are located in such a way that they create a field perturbation containing a strong 82nd harmonic with a suitable phase at the electrostatic septum. Protons are gradually brought into resonance by changing the current in the main machine quadrupoles to lower the radial tune.

Slow extraction is currently made on an intermediate 200 GeV/c flat top, keeping the radio frequency (RF) on in order to allow for subsequent acceleration of the non extracted protons to top energy. To achieve a uniform spill a real time feedback system is used. The spill signal from a secondary emission monitor is compared with a reference signal. The difference between the two signals is amplified and acts on the radial position loop of the RF, changing the momentum and therefore the ν-value of the beam.

Extraction losses and efficiency

If the extraction channel is correctly adjusted, noticeable losses are only observed at the electrostatic septum. Figure 3 shows a typical density distribution at this septum (extracted protons are on the left of the wire plane indicated at position "0"). The density at the wires is some 12% per mm. This, together with an effective geometrical septum thickness of 0.2 to 0.25 mm (after careful adjustment of the 4 anodes) permits to deduce that present extraction losses are approximately 3%. No absolute measurement of the losses has been performed to date.

Fig. 3 Density distribution at the electrostatic septum ZS for slow resonant extraction.

Spill duration, spill structure, beam survival

A typical spill is shown in Fig.4. Longer spills up to 2.7 s duration have been achieved with a similar time structure. At present the duty factor for the slow spill is limited to about 60%. This limitation is mainly due to some residual magnet ripple, to an instability of the real time feedback system and to a high frequency time structure (frequencies greater than or equal to the SPS revolution frequency).

Fig. 4 Slow third-integer spill, controlled by a real time feedback system.
Upper trace: Spill signal from a secondary emission monitor.
Lower trace: Integrated losses at ZS.

Whereas our initial effort was concentrated on the investigation of different resonant extraction schemes and their relative merits, the main work is now directed towards an improvement of the spill duty factor.

It is typical for third-integer extraction that part of the protons survive the extraction process and emerge on the other side of the resonance. Beam survival of somewhat less than 10% is usually observed during operation with RF on (the surviving protons are subsequently fast or fast resonant extracted during the same accelerator cycle).
Transverse beam properties

At 200 GeV/c the following emittances of the slow extracted beam are usually measured:

$\epsilon_H = 0.15 \pm \text{mm mrad}$, $\epsilon_V = 0.08 \pm \text{mm mrad}$.

The horizontal emittance strongly depends on the RF voltage which is kept on during the flat top. At full voltage the emittance increases up to a factor of 10 compared to low RF voltage.

The extracted beam properties also strongly depend on the current in the Landau damping octupoles powered at higher intensities mainly to damp the head to tail instability in the SPS.

Fast resonant extraction

Fast spills of less than 2 ms were successfully achieved with both integer and half-integer extraction. After excitation of suitable extraction lenses - one quadrupole and two sextupoles for integer extraction, one quadrupole and 4 octupoles for half-integer - the proton beam was rapidly brought into resonance by one of the following methods:

For half-integer extraction the current in the machine quadrupoles was simply changed at the maximum possible rate and this resulted in the desired short spill.

For integer extraction two different ways were used to spill out the protons rapidly: The first method consists in displacing the beam in the extraction quadrupole by switching the RF off and changing the main magnet field. The resulting deflection in the extraction quadrupole strongly displaces the beam in the sextupoles which then yield the necessary $v_0$ shift. In the second method the required deflection at the position of the extraction quadrupole is made by a pulsed dipole field close to it. With this second method resonant spills as short as 700 μs were obtained.

For a 2 ms integer spill the properties of the extracted beam are not noticeably different from those of a beam extracted within several 100 ms. For half-integer extraction the divergence at the electrostatic septum for a 2 ms spill is twice as large as for a long spill.

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