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FAST RESONANT EXTRACTION FROM THE CERN SPS

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Summary

Two different modes of fast resonant extraction are used at the SPS: non-coherent half-integer extraction with a spill duration from 1 ms to 3 ms and coherent half-integer extraction with a spill duration from about 70 μs (two 23 μs bursts separated by a 23 μs interval) to 1 ms. A special requirement is to stop a 2 ms spill after extraction of part of the beam. The remaining beam is then accelerated to higher energies and can be extracted by any of the other extraction modes in operation at the SPS. The duration of a coherent spill is generally adjusted by choosing a suitable strength of the fast ferrite kicker which kicks the beam into the unstable region in phase space after it has been brought close to the resonance. The shortest coherent spill was studied in some detail. Excellent agreement was found between theoretical predictions and measurements.

Introduction

During the construction of the SPS, provision was made for a 2 ms spill-out of the full beam by installing a fast half-integer scheme. This scheme was successfully run during the year 1977 for wide band neutrino physics. An entirely new requirement had to be met at the beginning of 1978 when it became necessary to stop the 2 ms spill after extraction of part of the beam and to re-accelerate the remaining protons for later use in the machine cycle. Two different methods to stop a fast spill were developed and are described in this paper.

In the first year of SPS operation fast extraction using ferrite kickers was run for narrow band neutrino physics. This extraction allows a maximum burst duration of 23 μs. While the intensity of the accelerator increased gradually up to 2 x 10^{13} ppp during 1978, the need was felt for longer bursts of a duration of some 100 μs. The only practicable way to produce such a burst in the SPS is coherent resonant extraction. This mode of extraction was first reported by FNAL[1]. Careful tests of both, coherent integer and half-integer extraction were made at CERN before the second scheme was successfully brought into operation.

Fast non-coherent half-integer extraction of the full beam

Method

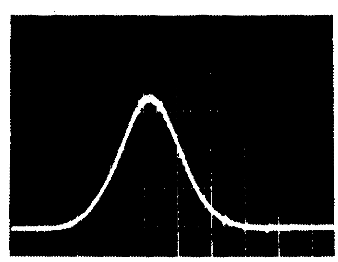
Fast half-integer extraction is done as follows: First the current in the main accelerator quadrupoles is adjusted to bring the radial tune ν_H sufficiently close to the half-integer, in general to $\nu_H = 26.55$. Then a capacitor bank is discharged through an extraction quadrupole. This quadrupole together with four suitably distributed octupoles defines a stable area in radial phase space in which betatron oscillations are stable, whereas they are unstable outside the limits of this area. The quadrupole current follows a semi-sinusoidal curve, reaching its maximum after 8 ms. With the rising current the stable area in phase space rapidly shrinks below the circulating beam emittance. Protons start unstable betatron oscillations with fast growing amplitudes and with a phase locked to that of the extraction quadrupole. A proton whose amplitude has grown sufficiently will enter the first deflecting device of the extraction channel[2], an electrostatic septum. The two-turn amplitude growth at this septum is largely determined by the strength of the extraction octupoles and is normally set to some 13 to 15 mm, the distance of the stable fixed point from the septum being about 25 mm.

The octupoles are installed in such positions that they find themselves slightly upstream of the maxima of the two-turn closed trajectory of the unstable fixed points. This results in a good straightness of the outward going separatrices, the trajectories in radial phase space along which protons move towards the eletrostatic septum after having been spilled out of the stable area. Usually, the extraction octupoles are powered to give a total strength K of about 300 m^{-2} ($\bar{x}' = K\,\bar{x}^3$ with all units normalized to β_{max}).

With the above procedure spill-out starts between 2 and 3.5 ms after the trigger of the fast pulsed quadrupole, depending on the capacitor charging voltage (maximum 3 kV) and on the radial chromaticity $(\Delta\nu/\nu)/(\Delta p/p)$ of the SPS at extraction time. The spill duration can be adjusted in the range from 1 to 3 ms. This is most effectively done by varying the chromaticity between 0 and -1, if necessary assisted by a modification of the capacitor charging voltage.

Performance

A typical Gaussian shaped spill is shown in Fig. 1.



500 μs/div

Fig. 1 - Fast non-coherent half-integer spill

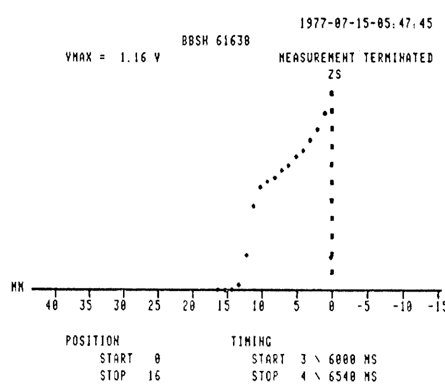


Fig. 2 - Distribution of protons measured in the gap of the electrostatic septum (ZS) for fast non-coherent half-integer extraction

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The time jitter of the spill does, in general, not exceed ± 200 μs. Fig. 2 shows a density distribution of the extracted protons at the electrostatic septum (the beam splitting plane which consists of a row of vertical tungsten-rhenium wires is indicated at position "0"). The proton density at the wires is some 12% per mm. This, together with an effective geometrical septum thickness of 0.2 mm results in extraction losses of less than 3%.

Fast non-coherent half-integer extraction of part of the beam

Method

Two different methods were developed to stop a fast non-coherent half-integer spill after extraction of part of the beam:

1. After having initiated a fast spill by exciting a first extraction quadrupole as described above, a second quadrupole is triggered to counteract the effect of the first one with a certain delay. Both quadrupoles have equal current waveforms but opposite polarities. The amount by which the second quadrupole is delayed determines the fraction of protons remaining in the SPS after the fast spill. A detailed analysis shows that the betatron phase-shift Θ between the two quadrupoles is very critical. With ν_H being equal to 26.55 and the strengths of the quadrupoles changing at about equal rate, Θ must fall into one of the intervals:

$$0^o + n\pi \leq \Theta \leq 18^o + n\pi; \; n = 1, 2, \ldots 53$$

2. Just one extraction quadrupole is used. It is connected to a new generator developed during the second half of 1978. Fast high power thyristors allow a change of the quadrupole current within a minimum time interval of 300 μs from a positive rate of rise of up to 60 A/ms to a negative one of equal value. This effectively stops the fast spill after extraction of a given amount of protons.

The stopping device (the second quadrupole or the fast turn-off thyristors) can either be triggered at a fixed time or by an external signal derived from an intensity detector. The second trigger method guarantees good cycle to cycle stability of the amount of residual or extracted protons depending on the detector which is used. It suffers, however, from the 600 μs delay between the time at which a proton becomes unstable in the resonant process and the time at which it leaves the accelerator. With this trigger method the residual intensity is therefore limited to a maximum of about 50% of that of the initial beam.

Performance

The properties of both, the fast resonant extracted beam and the residual beam, were carefully investigated with sharing ratios in the range from 5 to 95%. If only a small fraction of protons is extracted the shape of the fast spill becomes slightly unsymmetrical. All other properties of the extracted beam remain unchanged. Similarly, the properties of the circulating beam do not notably suffer from a partial fast resonant extraction even if only a small percentage of protons remains in the machine. The residual beam is usually accelerated to top momentum and either fast or slow extracted. The properties of both extractions are entirely independent from the preceding fast half-integer spill.

During the first months of 1978 a residual beam of some 3 to 5 $\times 10^{11}$ protons was required with the SPS running close to 1×10^{13} ppp. This small residual intensity was, in general, stable within $\pm 1 \times 10^{11}$ protons.

As it economizes a quadrupole with its pulse generator, only the second method to stop a fast half-integer spill will be used in future SPS operation.

Coherent half-integer extraction

Both coherent integer and half-integer extraction were carefully tested in the SPS. Coherent integer extraction has the advantage that protons are spilled out on every turn and not on every second turn as for coherent half-integer extraction. However, the integer scheme installed in the SPS turned out to be less suited for coherent extraction. The achieved spill duration, corresponding to four or five SPS revolutions, could practically not be varied and the angular spread of the extracted beam at the electrostatic septum was rather large. It was therefore decided to only use the half-integer scheme in regular operation.

Method

Coherent half-integer extraction is done as follows: First a non-coherent spill is set up as described earlier in this paper. The radial chromaticity of the accelerator is corrected to be zero around extraction time. This guarantees the same shrinkage of the stable area in phase space for protons of different momenta. When the beam is close to the limit of stability, it is kicked into the unstable region by a fast ferrite kicker installed a quarter wavelength upstream of the electrostatic septum. The protons start coherent betatron oscillations with rapidly increasing amplitudes. After two or more turns in the SPS they begin to enter the extraction channel and proceed to spill on every second turn until they have all left the machine.

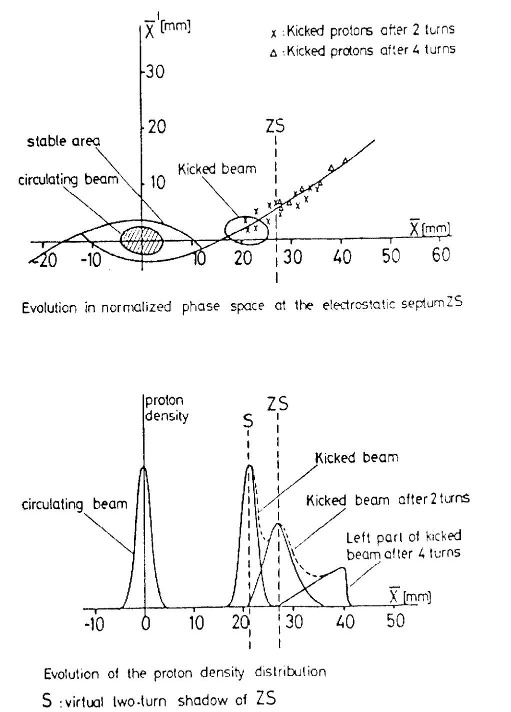


Fig. 3 - Schematic description of two-burst coherent half-integer extraction. Protons to be tracked were chosen on the envelope of the kicked beam

The spill duration is essentially determined by the strength of the fast kicker. Larger kicks will throw the beam deeper into the unstable region, leading to a smaller number of turns of the unstable protons in the SPS and to a shorter spill. The kicker is usually fired about 500 μs before normal non-coherent spill-out would start. Extraction of all protons within two 23 μs bursts of equal intensity (separated by a 23 μs interval) is then achieved by a kick which displaces the beam by about 21 mm in normalized phase space (normalization to β_{max}). Two turns after the kick half the beam is extracted, the other half leaving the accelerator after two more turns. This extraction is schematically illustrated in Fig. 3. The trajectories of the protons after the kick were computed with a tracking program. Obviously the protons are strongly "attracted" by the outward going separatrix. In order to avoid at the electrostatic septum too big a difference in angle between the two 23 μs bursts, the beam must be kicked close to this separatrix as is the case in the SPS.

Performance

Coherent half-integer extraction was studied for spill durations reaching from 70 μs to nearly 1 ms. The desired duration is easily adjusted by choosing an adequate kicker strength. Fig. 4 which was obtained with a fast digitizing technique shows a two-burst spill together with the fast kick.

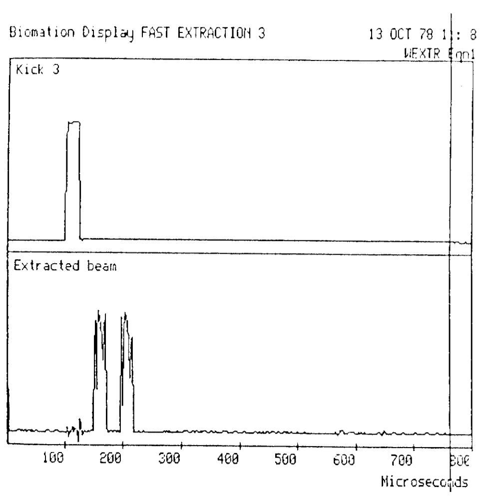
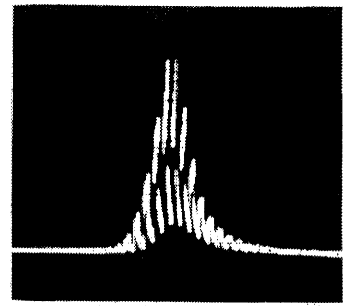


Fig. 4 - Two-burst coherent half-integer spill

Note that the spill starts indeed two turns after the beam was kicked into the unstable region. When the kicker strength is lowered, the delay between the kick and the start of extraction increases as well as the spill duration. For example, a kick which displaces the beam by about 11 mm in normalized phase space, results in a 500 μs spill starting after 8 SPS revolutions.

The intensity distribution within a spill of more than 200 μs duration is roughly Gaussian, but somewhat unsymmetrical as shown in Fig. 5. For spills consisting of more than three 23 μs bursts, the density distribution of the extracted protons at the electrostatic septum and therefore the extraction losses are similar to those observed for non-coherent extraction. For shorter spills the proton density at the septum is slightly different, resulting in a moderate increase of losses. A characteristic distribution measured for two-burst coherent extraction is shown in Fig. 6.



200 μs/div

Fig. 5 - Coherent half-integer spill of 600 μs duration

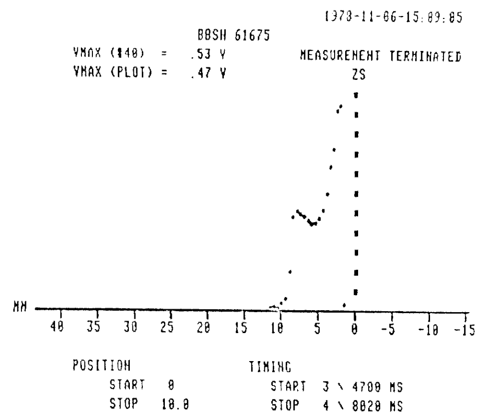


Fig. 6 - Distribution of extracted protons measured in the gap of the electrostatic septum for two-burst coherent half-integer extraction

It corresponds to the predictions of Fig. 3. Profiles of the extracted beam measured 90° downstream of the electrostatic septum are also in excellent agreement with theory. Two-burst spills and five-burst spills were successfully used in SPS operation through the second half of 1978.

Acknowledgements

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