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THE PRESENT PERFORMANCE OF THE SPS

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Abstract

The CERN SPS has been delivering proton beams at 400 GeV for physics since January 1977 and currently runs with a circulating beam intensity of 2×10^{13} protons per pulse and repetition time of 9.6 seconds. This paper discusses the steps taken to reach this intensity, the limitations at various stages in the development, and the equipment under construction to attain 3×10^{13} ppp. It also reviews the performance and reliability of the SPS during its first two years of operation.

1. Current Operation.

The CERN SPS has now been in successful operation for more than 2 years, and continues to develop rapidly. Over the last year several milestones have been passed, with the opening up of the second experimental physics area in the North, the introduction of double batch injection leading to the attainment of 2×10^{13} protons per pulse, and the acceleration of protons to 500 GeV.

The SPS has been used intensively during 1978, it was run for a total of 5445 hours, of which 4248 were scheduled for physics runs and 945 for machine development, and protons were accelerated for 80% of this scheduled time. The operation was divided into 8 five week periods, each comprising two physics runs of ten days separated by 36 hours of machine development. It is hoped to improve the efficiency of physics runs still further in 1979 by running longer periods, each comprising 3 runs of 10 days.

In order to satisfy the varied physics program best, some 5 different magnet cycles were employed last year. These evolved to reflect the increasing importance of the newly commissioned North experimental area and the introduction of double batch injection. The cycle in use last autumn is shown in fig. 1. It was 9.6 seconds long, and had a 1.5s flat top at 210 GeV for slow extraction to the West experimental area, and a 1.2s flat top at 400 GeV for slow extraction to the North. In addition three fast extractions delivered beam to bubble chamber experiments in the West. Each of the slow extracted beams is split into 3 parts, so in all some 8 targets are served.

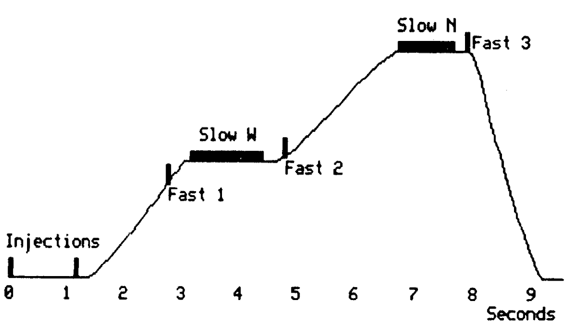

Fig 1. Main Magnet Cycle Showing Extraction Timings

With the great interest in long extraction spill times for counter experiments the speed of acceleration becomes important. The rate of rise is limited by the RF voltage available, so fast rising cycles were developed by matching the field shape to make full use of the RF buckets. With the introduction of 450 GeV cycles next year, it will be the power dissipation which will limit the repetition rate of the SPS, so that a cycle time of 12.8s must be used to achieve a 1.2s flat top at the top energy.

2. Improvements in Operational Intensity.

Fig. 2 shows how the intensity has risen over the past two years. In autumn 1977 some 8×10^{12} ppp were being accelerated, and this was increased to 2×10^{13} ppp during period 8 of 1978. A total of 6.3×10^{18} protons were accelerated in 1977, and 13.7×10^{18} protons in 1978.

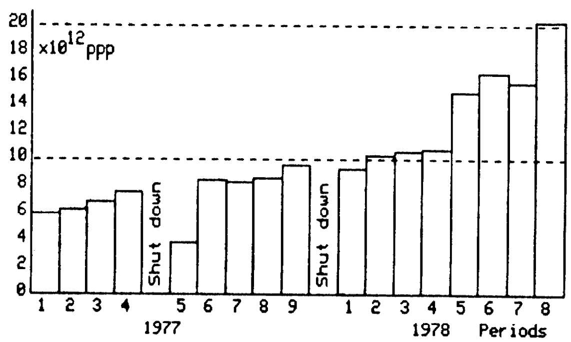

Fig 2. Evolution of Peak Intensity averaged over 15 Minutes

2.1 Single Particle Effects.

The rise in intensity is in part due to hardware improvements, but a significant part has come from better operational control over the single particle behaviour of the beam.

Losses on the first turn after injection have been eliminated by providing an automatic program to steer the injection trajectory so as to minimise the betatron oscillations on the first few turns. This program uses the betatron signal from a single pickup as provided by the Q measurement system, and from this the position and angle error at the injection point are deduced, and hence corrected.

Losses on the 10 GeV coast before acceleration have been eliminated by reducing the closed orbit deviations at 10 GeV to less than 2 mm peak. The closed orbit is corrected by inserting appropriate beam bumps at every quadrupole around the machine. This technique has been sufficiently successful that harmonic correction has not been necessary.

Losses on the front porch are especially sensitive to the detailed tuning of Q, and the accurate compensation of the chromaticity and coupling. It has been established that the working points with QH and QV lying around 27.6, 27.4, 26.6 or 26.4 are equally good, and even points near 20.6 and 15.6 are satisfactory. However at each of these, resonant losses are provoked

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if QH or QV approach the half or third integer closer than 0.04, and coupling losses are provoked if the QH-QV split is less than .04.

Overcoming the problem of maintaining the required Q values with adequate precision has been responsible for much of the improved intensity. A serious problem was the jitter of Q due to small departures in the tracking between the main dipole and quadrupole supplies at low field. Difficulties were experienced with providing an adequately precise measurement of the reference field, and it was not until the field measurement was replaced by current measurement in period 5 of 1978 that the Q became very stable.

Further improvements have come from the precise compensation of the chromaticity and coupling. These settings are very critical on the front porch where the effect due to $\dot{B}/B$ is large, and substantial effort was made in providing better measurement and more flexible control over these settings, leading to better confidence in precise chromaticity compensation.

2.2 Collective Effects.

At the end of 1977 collective effects first started troubling operation. The most dramatic was excited by the first transverse bar mode of the RF cavity at 460 MHz. By adjusting the cavity temperature it was found possible to move the sharply tuned resonance between high harmonics $(N-Q)f_r$ to a point which suppressed the instability. However this proved operationally troublesome to adjust, so by inserting couplers to damp this cavity mode, the threshold was increased by a factor of 2, but it is again starting to give trouble at the high intensities in current use.

The second bar mode of the cavity, a longitudinal mode at 628 MHz causes a large blow up at the approach to the 210 GeV flat top and a subsequent loss at the start of the second ramp. This blowup is now performed in a controlled way by exciting the beam at twice the synchrotron frequency, a technique which also improves the extraction spill.

The transverse resistive wall modes, whose threshold is around 4×10^{12} ppp, occasionally disturbs operation, but improvements in power and bandwidth of the active dampers have normally been sufficient to keep the threshold ahead of the operational intensity.

3. Intensity Improvement Program.

During 1977 it was decided to launch a program involving substantial capital expenditure to upgrade the SPS to provide an accelerated intensity of 3×10^{13}.

The extra intensity was foreseen to be made available by multiple injection from the CPS, injecting up to 5 batches at 10 GeV before acceleration. For this a new inflector has been designed, with 12 kicker modules to give faster rise times.

To satisfy the extra power required to compensate for beam loading, which currently accounts for 240 KW of the 1 MW RF power used, rising to 400 KW for 3×10^{13} ppp, the available RF power is being augmented, in 3 stages. A third 200 MHz cavity was installed in January 1978, and a fourth one is being commissioned. A second set of transmitters is under construction to double the power available to 4 MW.

To overcome the fundamental limit to intensity it is necessary to provide mechanisms for overcoming specific collective effects. In the transverse plane, the power of the beam damper is being increased by an order of magnitude to supress the lower modes of the resistive wall instability, and a new set of 18 D and 12 F octupoles are being installed to supress the high resistive wall modes and the 460 MHz transverse cavity mode instability. These will provide both horizontal and vertical damping, and their larger number has the additional effect of reducing their harmonic component which can give rise to significant third integer resonances. A set of more powerful sextupoles has been installed to allow full chromaticity compensation at high energies, and even to provide positive values to prevent head-tail instabilities.

To combat high cavity mode longitudinal instabilities, such as the 628 MHz mentioned, an additional 800 MHz cavity system is being installed. The introduction of the fourth harmonic into the RF buckets will increase the synchrotron frequency spread, and hence reduce the threshold of the instabilities. For the dipole modes a feedback system is being built as reported elsewhere.

3.1 Double Batch Injection

By the end of 1977 the SPS was able to accept the full intensity from the CPS and there was pressure to provide extra beam to satisfy the demand from the newly commissioned North experimental area. Adequate operational control had been obtained over the single particle properties of the beam, and in development sessions over the problems of synchronising the SPS and CPS machines for the first stage of the intensity improvement program, double batch injection, to be put in operation in period 5 of 1978.

Double injection is achieved by ejecting protons over 12 microseconds from 5 turns of the CPS to fill one half of the circumpherence of the SPS. The beam is left coasting for the 1.2 second repetition time of the CPS, and then the process is repeated to fill the second half of the SPS ring. While this technique doubles the number of injected protons available for the SPS, the repetition rate had to be increased from 8.4 seconds to 9.6 seconds, and consequently the gain of the total number of particles accelerated during a six week period was somewhat less than doubled.

4. Operational Reliability.

The reliability of the SPS has gradually increased over the last two years as the specialists have put right recurrent faults and the operations crew have become more familiar with equipment. The contributions to down-time is spread evenly amongst the various subsystems as can be seen from table 1.

Table 1. Contributions of Subsystems to Down-time in 1978.

Subsystem	% down
Magnet power supplies	2
Control system	1
Radio-frequency	2
Extraction	0.5
Kicker magnets	0.5
Electricity, water, vacuum	2
Thunderstorms	1
Operation	1
Other	4
Total SPS down	14
CPS down	4
Requested off time	2
Total off time	20

Fig 3. shows how the down-time has evolved over the last two years, and reflects the stabilisation of operation. The particularly large figure for period 5 of 1977 occured at a time when the region suffers from a succession of thunderstorms, and immediately after a 2 month shut-down during which a number of major changes had been made.

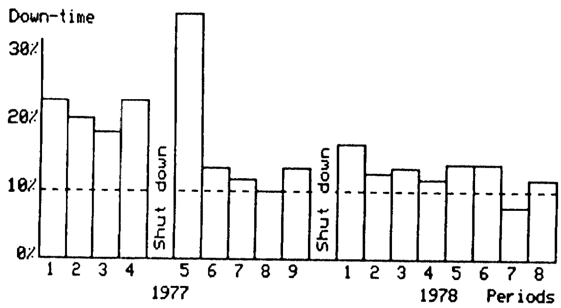

Fig 3. Evolution of Accelerator Down-time over Two Years

Fig 3. shows that even in 1978 the improvement in reliability was halted during the thunderstorm period. The effect of the storm is to induce a large transient on the main 380 KV supply from the French grid, lowering the voltage to as little as 50% of the nominal value over a period of upto 100 msec, with a subsequent overshoot which can cause substantial damage. The computers and other sensitive equipment are now powered from protected battery-inverter supplies which allow the control system to continue unaffected. In spite of this many protective interlocks trip out. Nearly every equipment setting needs to be reloaded, a process which takes about 15 minutes, or upto several hours if any major damage has been sustained.

4.1 Setting-up Procedures.

Since the difficulties in Period 5 of 1977 very much more attention has been devoted to checking equipment thoroughly before each start up. Though this means closing the ring earlier, more time can be devoted to operational problems rather than equipment, and as a result the setting up phase is more reliable, taking 9 hours or less, rather than 24 hours previously. The best intensities are still not reached until several days later.

The large size of the accelerator encourages all equipment to be checked from the control centre. The equipment specialist groups provide their own sets of diagnostic programs, written in NODAL, which are attached to a branch of the program tree so that they may be run from touch buttons at any one of the 4 consoles. These programs are relatively stable since they do not need to follow the constantly evolving operational modes of the accelerator. It appears most efficient to commission new equipment or change system software during a physics run when all else is quiet and faults show up immediately, rather than letting latent faults appear after changes made during a shut down.

The procedures for setting up the machine are largely determined by the need for quick restarts after a major power failure. Most programs are written by operators, and unlike the equipment test programs, are subject to constant evolution as troublesome procedures are improved or operational conditions change. Should these programs fail it is a simple matter for the operator to check that the basic equipment is satisfactory, and then if necessary to correct the fault in the program.

4.2 Maintaining Optimum Conditions.

Once the beam is set up satisfactorily it is necessary to optimise the conditions of the circulating beam. A set of sophisticated control programs have been established using algorithms based on careful investigations and allow technicians to tune complicated parameters of the beam with very little effort. Thus we have programs to match the RF phase and frequency between the SPS and CPS, and other examples were given in section 2.1. These programs try to take into account the fundamental parameters of the machine in the correct way, so that for instance the orbit correction program and the injection steering program work equally well with the machine set for a Q of 15.4 or 20.6 as for the normal Q of 26.6. Fig. 4 shows the closed orbit display as an example.

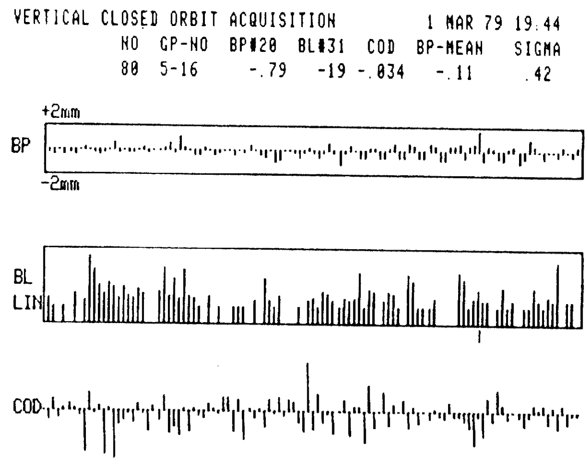

Fig 4.
Closed Orbit Correction Program Showing Beam Position, Beam Loss, and Correction Dipole Currents around Ring.

One of the consequences of distributing the beam to a large number of targets is the problem of maintaining well steered beam on each, with splitting ratios satisfying all users. In spite of difficulties early on, a good reload facility, combined with occasional trimmiming of the final two steering dipoles leads to stable and repeatable beam conditions.

4.3 Equipment Surveillance.

During normal operation when conditions are quiet the most important diagnostic tool is the alarm screen. Equipment fault messages are generated by a large number of autonomous surveillance programs running in the satellite computers. These run at intervals of typically 5 minutes, though summary status bits are scanned every 3 seconds and trigger the relevant program automatically. This usually gives sufficient warning for faulty equipment to be replaced before beam is lost.

Although in the past rather too many alarm messages were reported, sufficient logic has now been introduced in the surveillance programs themselves to take account of the state of the machine, and only to report the most important fault. In this way a flood of consequential alarms is avoided.

5. Acknowledgement.

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