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THE START UP OF THE EUROPEAN 400 GeV PROTON SYNCHROTRON

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Introduction

The design of the European 400 GeV Proton Synchrotron, or SPS as it is called, is based on the well known theory of this class of accelerators, which was first demonstrated by such machines as the CPS at CERN and the AGS at Brookhaven, and was further refined during the 1960s and 1970s. In this respect it does not break new ground.

The main challenge of this machine lay in its size - 2.2 km diameter, or eleven times the diameter of the CPS. The only other comparable accelerator in the world is the FNAL 400 GeV Proton Synchrotron. This feature of the SPS called for considerable development of the technologies used in previous machines of this type. Some of these developments were pioneered at FNAL for their machine, which was started in 1967, about 5 years before the SPS. Others were initiated especially for the SPS, either because of the local conditions presented by the site, or because certain technical or economic advantages were foreseen.

Our main endeavour was to find and exploit all possible ways of reducing the cost per GeV of the SPS. This meant pushing technologies to the limit of what could be reliably manufactured by industry, since such a huge machine presented considerable problems in the mass production of a very large number of components to precise specifications. The technical solutions adopted for the SPS are in several cases different from those adopted for the FNAL machine, but these differences are often in detail, and to the casual observer the two machines look remarkably similar. Even the amount of money made available for the two projects was almost the same.

Authorization for the SPS project was granted by the CERN Council in February 1971, and a maximum sum of 1150 MSF (280 million dollars at the exchange rate of 1971) was guaranteed by the Member States of CERN for the construction of the machine and its experimental areas, including primary and secondary beam line equipment. The SPS reached 400 GeV energy for the first time in June 1976. It is interesting to note that it took longer to get approval for this project than it did to build the machine and reach full energy.

The most obvious design differences between the FNAL and CERN 400 GeV machines are the following. In the FNAL machine a special fast cycling booster synchrotron and linac injector supply protons to the main ring, whereas the CERN machine uses the 28 GeV CPS machine, already in service at CERN since 1960, to feed its main ring. The frequency of the accelerating system of the FNAL machine main ring is 53 MHz, whereas that of the CERN machine is 200 MHz. Also, the FNAL machine tunnel is built by the cut and fill method near the surface of a flat site, whereas the CERN machine is installed deep underground in a tunnel bored in the rock underlying a hilly site. As a consequence, there are many horizontal entries to the main ring tunnel at FNAL but only six to the CERN main ring tunnel, and these are vertical shafts whose depth varies between 25 m and 60 m. Lastly the SPS is controlled through a computer system, and there are none of the racks of electronic equipment that one normally sees in a control room but only three consols, with computer graphics and touch panels, from any one of which the entire machine can be operated. Two of these differences are due to local conditions of the sites and the other two, the RF frequency and the computer system, were free choices.

Preliminaries to the start up of the SPS

One of the precepts of the SPS project, as for the other major accelerators at CERN, was that each component of the machine should be designed and constructed for maximum reliability. The principal was not, however, reliability at any cost, but reliability at a fixed cost. In the case of the SPS project, the total budget granted was much less than had originally been proposed, so the money allocated for each component was the bare minimum.

In general, the design and construction of the components followed the time scales laid down for them. The most serious incident during construction was caused by accidental damage to the coils of the bending magnets of the main ring. This happened about half-way through the assembly of these magnets, but the time lost in taking apart and rebuilding the 280 magnets damaged by this accident was absorbed in the planning so that the last magnet was still installed in the main tunnel on schedule. We have now run the complete magnet system of the SPS for over a year and during that time no magnets have been replaced due to electrical breakdowns.

One implication of the reliability precept was that each machine subsystem, after installation, should be thoroughly tested and proved before it was accepted into the commissioning sequence. This was done in order to avoid tedious delays during commissioning due to component failure. Not all the machine subsystems lived up to this high expectation, but the vast majority did, and this greatly facilitated the commissioning of the machine, and accounted for the short time it took to reach 400 GeV energy. The other reason for the short commissioning time was the smooth operation of the computer control system of the SPS. This control system was fully operational before the commissionning started and proved to be an extremely efficient and rapid man-machine interface enabling adjustments and measurements to be made on the SPS in a fraction of the time it took on the other CERN accelerators.

The Commissioning of the SPS and the West Experimental Area

The first stage of the commissioning, which started on April 5, 1976, was to extract a proton beam from the CPS machine at 10 GeV energy using the continuous extraction scheme, and transport it down the injection transfer line to the injection straight section of the SPS machine, a distance of about 800 m. All the beam elements of this transfer system were set up to their calculated values and the beam arrived at a temporary beam dump placed near the SPS within a few millimeters of the required position. Once the temporary dump was removed, the beam continued through the injection system of the SPS and onto the orbit of the machine.

The second stage of commissioning was to allow the beam to go once round the SPS. This stage began and finished on May 3, about a month after commissioning started. The beam went all round the 7 kilometre circumference of the machine and arrived on a first turn beam stopper only a few millimetres off target. Using the closed orbit correcting dipoles, some minor adjustments were made to the transverse position of the beam at a few places around the circumference of the machine, and then the first turn beam stopper was removed to allow the beam to circulate freely round and round the machine. Much to the delight of the accelerator builders, the beam circulated with very little loss of intensity for over 10.000 turns, after which it was dumped onto an internal beam dump.

These tests confirmed that there were no obstructions in the vacuum system of the SPS and that the 1000 or more elements of the magnet system had been made within the prescribed tolerances and were correctly aligned in the machine tunnel. In many ways this was the most important test of all, since any errors in these respects would have taken months to rectify.

The third stage of commissioning began on May 6 and concerned the acceleration of the circulating beam. During three runs up to May 10, the trapping of the circulating beam in the RF buckets of the SPS was achieved, and the phase and radial loops were closed and operated. The protons were only accelerated a few GeV during these tests; just sufficient to check the trapping efficiency, which turned out to be better than 60%. During these tests it became apparent that more work had to be done on understanding and controlling the movement of the working point of the machine in the Q plane before the acceleration tests could sensibly continue.

Consequently, the runs on May 12 and 14 concentrated on this problem with very encouraging results. The measurements showed that the SPS is a very clean machine in the sense that higher order resonances, due to unintentional sextupole and octupole fields around the 7 km circumference of the machine are only weakly present, and that the magnet fields are nearly pure dipole and quadrupole as one would wish. During these measurements the chromaticity of the machine at injection was measured and then adjusted using the sextupole correcting magnets installed for this purpose all around the machine. The octupole correcting magnets, which are also incorporated in the SPS, were used to suppress a resistive wall instability which became noticeable at moderate intensities. Later on an active feedback system was used to suppress this instability.

The acceleration tests were continued again on May 25 and 26, and this time, after checking the beam trapping and control system, the beam was accelerated through the transition energy, first up to 50 GeV and then to 80 GeV. The reason acceleration was stopped at 80 GeV, was that only 2 of the 12 magnet power supplies were ready at that time.

Tests were resumed on June 3 and 4, by which time 6 power supplies were available and operating under control from the Main Control Room. After removing a transient shift in Q early on during the acceleration cycle, it was found possible to accelerate a proton beam with an intensity of $2.2.10^{12}$ protons per pulse up to 200 GeV without any measurable loss. The beam intensity injected into the SPS was 3.10^{12} protons per pulse so the trapping efficiency was over 70%. Thus in a matter of 2 months from the beginning of commissioning the SPS had reached 200 GeV energy. Four more power supplies were available for the runs on June 10 and 11, but it was found that at a magnet cycle corresponding to an energy of about 240 GeV, instabilities set in in the power supply system and all attention was focused on this problem to clear the way to higher energies. A circulating proton beam of 400 GeV energy was first achieved in the SPS on June 17. 1976, 10½ weeks after the start of commissioning, and 5 years and 4 months after project authorization.

Having reached an energy of 400 GeV, the next step was to extract the circulating proton beam from the machine. The simplest method is to extract all the beam in one revolution, which takes 23 microseconds, and this was successfully achieved for the first time on July 9. During the rest of July and August the circulating beam intensity was increased from 10^{12} to 5.10^{12} protons per pulse. In September, the slow extraction system was brought into operation and all the circulating beam extracted from the machine over a period of 700 milliseconds. On November 3 a circulating beam intensity of 10^{13} protons per pulse at 400 GeV energy was achieve for the first time. Early in December, 4.10^{12} protons per pulse were extracted from the SPS at 400 GeV energy.

In parallel with the commissioning of the SPS machine the primary and secondary beams in the West Experimental Area were installed and tested, and the experiments themselves brought into operation.

The extracted proton beam from the SPS machine was first brough to the primary proton targets, T_1, T_3 and T_5 which feed the secondary beams in the West Hall, on October 22. During the rest of November and December all the secondary beams in the West Hall were powered and used to transport particles to the experiments. Finally, in the middle of December, the narrow band neutrino beam was tested successfully and experiment WA 1 started to collect data on neutrino events.

By the end of 1976, therefore, the SPS machine had been commissioned and was supplying beams of particles to all the experiments installed in the West Experimental Area. Furthermore, the experiments themselves had been commissioned and had been checked out with particle beams. Some of them had even managed to start collecting data. It was decided, therefore, to start scheduled running of the SPS on January 7, 1977.

First Scheduled Operation of the SPS

The machine cycle for the first operating period of the SPS was chosen to provide secondary beams for the West Area, generated by a primary beam of 200 GeV energy feeding targets T_1, T_3 and T_5, and a narrow band neutrino beam generated by a primary beam of 400 GeV energy feeding target T_{11}.

The machine cycle used was therefore a combined one with an intermediate flat top at 200 GeV energy of 1 second duration during which a slow extracted beam of about 700 millisecond duration was fed to targets T_1, T_3 and T_5. The cycle then continued to 400 GeV energy and the beam fast extracted in 20 μsec onto the neutrino target T_{11}. The total cycle time was 8.4 seconds. Of the 4.10^{12} protons per pulse extracted from the SPS, approximately 3.10^{12} protons per pulse were fed to the neutrino target and the rest divided between targets T_1, T_3 and T_5. During the course of this operating period the extracted beam intensity was raised to 5.10^{12} protons per pulse. Recently the SPS has been running with an extracted beam intensity of 7.10^{12} protons per pulse.

The time scheduled for experimental physics during the first 4 weeks of operation was 444 hours and of these, 311 hours were actually achieved, i.e. 70% of those schedules. This operational efficiency is, of course, lower than those currently achieved by the other major accelerators of CERN, which habitually run at over 90% operational efficiency, but it compares favorably with the other machines at the start of their scheduled operation. Furthermore, the SPS operational efficiency cannot be better than that of the CPS which is the injector machine for the SPS. Indeed, of the 133 hours lost to experimental physics during these first 4 weeks of operation, 47 hours were due to a breakdown of the CPS. The operational efficiency of the SPS machine alone was therefore 80%.

Part of the SPS operation time in recent months has been used to study the intensity limitations of the machine, and to examine those beam instabilities which may prevent higher intensities being reached in the future.

One such instability occurs during the capture process in the SPS, and causes losses of about 20% of the injected protons. Since the CPS RF frequency is 9 MHz and that of the SPS is 200 MHz it is necessary to debunch the injected beam in the SPS. During this process instabilities occur in the debunched beam due to interactions between the beam and various resonant structures round the vacuum system, which is 7 km in circumference. The obvious cure is to use bunch to bucket transfer between the CPS and the SPS but this means changing the RF accelerating frequency of the CPS to 200 MHz which will take some time to do.

After capture up to 200 GeV there are negligible beam losses but on the intermediate flat top at 200 GeV energy longitudinal coupled bunch instabilities are observed. The lowest mode is at the RF frequency $\pm$ the revolution frequency, which is within the passband of the RF cavities. This mode can be suppressed by modulating the RF voltage at the revolution frequency which gives different synchrotron frequencies in the different bunches. A higher mode at 3 times the RF frequency $\pm$ the revolution frequency has also been observed, caused by a third harmonic parasitic resonance in the cavities. This resonance will be damped by coupling loops and resistors installed along the length of the cavities.

Finally, during acceleration from 200 GeV to 400 GeV, it becomes impossible to suppress completely a head-tail bunch instability with the sextupoles installed in the SPS. These sextupoles were designed to correct the chromaticity of the machine up to about 100 GeV and they are not powerful enough to suppress the head-tail instability above about 300 GeV. The onset of the instability can, however, be delayed by bunch spreading which decreases the space charge density in the bunches and lengthens them.

All these studies indicate that the SPS as it is now equipped is limited to an extracted beam intensity of about 10^{13} protons per pulse. More than this will be needed by the experiments in the future, and a series of modifications are now underway to increase the beam intensity progressively to 3.10^{13} protons per pulse during the next two or three years. These modifications include more RF power to compensate for beam loading in the cavities and to give bigger buckets, more powerful sextupole and octupole correcting magnets, bunch to bucket transfer between CPS and SPS machines, and multipulse injection from the CPS.

Conclusion

The experience gained during the commissioning of the SPS machine has shown, at least to its builders, that the importance given to reliability, and the thorough testing of the components of the machine, was fully justified by the speed with which it was commissioned and its performance during the first months of scheduled operation. Furthermore, all the effort that was put into getting the experimental areas and the experiments ready in time for the first beams from the machine, has enabled data-taking to start as soon as the machine could be put on scheduled operation. The combination of these two policies, and the devoted efforts of all the staff of CERN whose work I am reporting to you today, has enabled a very good start to be made in experimental physics at the 400 GeV energy level at CERN.