Operational History of the SPS Collider 1981 - 1990

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Abstract

In June 1978 approval was given for the construction of an antiproton production and storage facility, the AA complex, and the modification of the SPS to be able to inject, accelerate and store bunches of 270 GeV protons and antiprotons with collisions in the centre of two large experimental detectors.

Two years later, after the construction of the necessary equipment and preparatory excavation of the two underground zones, the SPS fixed target operation was interrupted for nearly 12 months to complete the installations. First collisions of two bunches of protons against one bunch of antiprotons were observed on July the 10, 1981.

Since those early days the Collider performance as measured by the integrated luminosity accumulated per year (directly proportional to the number of W and Z^0 particles produced) has increased by more than two orders of magnitude. Along with the increase in the number of antiprotons produced and stored in the antiproton accumulator the smaller and smaller beam sizes in the region of the experimental detectors, the understanding and control of the collider as a complicated machine physics experiment has gradually increased.

I. MODIFICATION OF THE SPS

The initial scheme for the Collider called for the injection of three proton bunches to collide with three counter-rotating bunches of antiprotons. A new tunnel and beam transfer line, meeting up with one of the existing high energy proton extraction lines, was constructed to bring the antiprotons from the CPS to the SPS.

Particles injected into the SPS in the Fixed Target mode of operation are captured into 4620 stable buckets by the radio frequency system working at 200 MHz..There are four rf cavities through which the bunches pass; they have a travelling wave structure and are located in part of one sextant of the SPS ring; each can provide 2 MV at the nominal power. For collider operation the installation was modified so that two cavities capture and accelerate the protons while the second two units (fed in reverse direction by means of a high power coaxial switch) serve the antiprotons. The exact location of the interaction point in the detectors can be adjusted by phasing the two groups of cavities.

Extra quadrupoles were introduced around the interaction points, where the experimental detectors are located. By powering them independently from the lattice quadrupoles the beta values could be locally reduced during Collider operation only.

The vacuum system was modified to improve the average pressure by two orders of magnitude to 2 x 10^{-9} mbar. New and improved beam instrumentation was introduced. and the software used for equipment control and monitoring was improved.

II. PERFORMANCE OVERVIEW

Luminosity is determined by the energy of the colliding particles, the number of bunches per beam, the number of particles per bunch and their emittance, and by the horizontal and vertical beta values at the interaction points. The design luminosity of the SPS Collider is 10^{30} cm^{-2} s^{-1}. The integrated luminosity depends on the time variation of the above factors during the many hours when the beams are circulating; it is also a measure of the number of interesting events observable during a physics experiment in a given interval of time. An integrated luminosity of one inverse nanobarn, nb^{-1}, equals 10^{33} cm^{-2} or about 1W particle. The evolution of these two parameters over the past ten years is shown in Figure 1 (note the logarithmic scale). There was little Collider operation in 1986 during the upgrade of the antiproton accumulator and detectors.

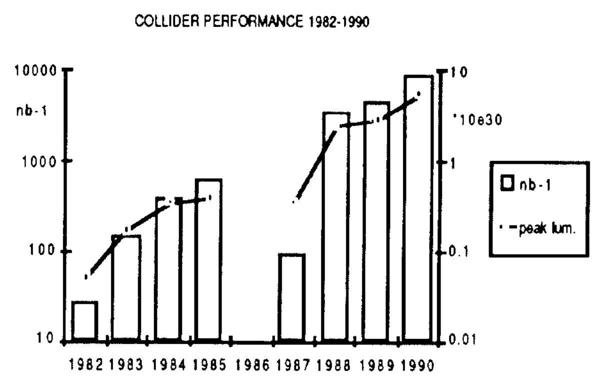

Figure 1. Collider performance from 1982-1990.

The progress from 28 nb^{-1} in the first year of operation for physics to 7240 nb^{-1} in 1990 is remarkable. The production in 1985 was greater than the total production in the four initial years; production in 1990 was close to the combined production in the two previous years with as much produced in three days of 1990 as in the whole of 1985.

The major improvements in performance have come from :

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- an increase from 270 to 315 GeV in particle energies from 1984,
- increased number of antiprotons available per day from the Accumulator Complex, and the change from 3 to 6 bunches
- the reduction of the beam sizes at the interaction regions by means of the low beta insertions at the experimental detectors, and
- the gradual understanding and mastering of the machine physics parameters.

III. MACHINE PERFORMANCE - LUMINOSITY - COLLISION ENERGIES

Initial operation of the Collider was limited in beam energy to 270 GeV by the ability of the water cooling system to cool the ring bending magnets and lattice quadrupoles. During the winter shut-down of early 1984 the flow rate of the cooling water was increased by more than 30% by the addition of one booster pump per SPS sextant. The cooling circuits of the power supplies were also upgraded. These modifications allowed the increase from 270 to 315 GeV during coast, limited by the temperature difference between the inlet and outlet of the dipole magnet coils.

A. Proton Bunch Intensity Limitations

Above a threshold of about 10^{11} protons per bunch there is a fast longitudinal emittance blow-up immediately after injection into the SPS caused by the vacuum chamber discontinuities. It is a microwave instability coming from the coupling of the beam to the high frequency part of the machine impedance. An optimum intensity between 1.2 - 1.5×10^{11} was found.

B. Production and Transfer of Antiprotons

In the first years of operation of the collider complex the antiproton accumulator (AA) produced about 6×10^9 pbars per hour with a maximum stored intensity of 4×10^{11}. The introduction of the Antiproton Collector (AC) in 1987 resulted in an increase in the production rate to 6×10^{10} per hour and a maximum accumulation of 1.2×10^{12} antiprotons.

The efficiency of transfer of antiprotons from the Accumulator to the SPS was low in the early years. Not only were two thirds of the beam lost in the process but the emittance of the antiproton bunches reaching physics energies was also increased. Over the years, careful matching of the beam lines and control of beam blow up in the injector chain and in the SPS resulted in peak transfer efficiencies of 80%. Bunch intensities of around 1.5×10^{10} were achieved.

The steady increase in performance in the AA in the first years of operation resulted in an increase in pbar intensities available at the time of transfer; this was usually done once per day. The operation of this delicate process, when the days production of antiprotons is transferred, is controlled by software that checks the readiness of all the equipment in the chain and synchronizes the transfer from AA to SPS. Protons were ejected from the SPS at 26 GeV and transported back to the PS along the same transfer line that the pbars would pass. Once the energy and injection oscillations of these protons in the PS were optimized the next phase was to transfer pilot pbar bunches of low intensity before finally transfering the intense bunches. Very few intense bunches of antiprotons were ever lost after the commissioning of this software. Precise measurements of the parameters of the beam down the chain were recorded automatically and analyzed after each fill thus allowing the progressive improvement in efficiency from fill to fill.

100 MHz cavities were introduced in the SPS in 1987 to allow the capture of longer bunches reducing the Laslett Q shift and giving more working space in the tune diagram; this helped fight the emittance blow-up during injection and acceleration and resulted in a higher luminosity. In addition it gave better reliability in the transfer efficiency and capture into the SPS at 26 GeV; the operation was made easier.

C. Beam Size at the Detectors

Over the history of the collider one of the major factors in the improvement in performance has been the gradual reduction in the beta values at the experiments by means of independently tuneable quadrupoles in these regions. From 7 m horizontal, 3.5 m vertical in the first year of operation the ß* has been steadily reduced to 0.6 m horizontal, 0.15 m vertical in 1990, Figure 2. The latter represent the limit of improvement since with these values the length of the bunches become comparable to the length over which the beta values are a minimum.

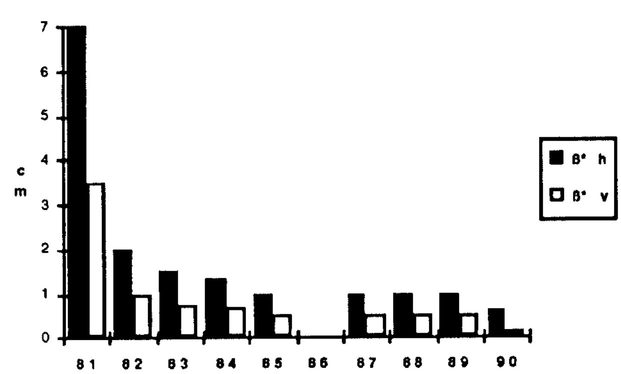

Figure 2. Evolution of beta*.

Reduction in the beta resulted stronger machine chromaticity and introduced coupling. The machine physicists were able to simulate these effects and find suitable parameters for correction using the installed sextupoles and skew quadrupoles.

D. Beam-Beam Effect & Separation

The luminosity lifetime is mainly limited by multiple Coulomb scattering between particles in the same bunch (intra-beam scattering) which increases the emittance and by the effect of the global electromagnetic field of the particles in the opposing beam (beam-beam interaction) which causes particle losses.

The effect of one beam on the other, the so-called 'beam-beam effect', occurs when one bunch of particles passes through the other. This occurs six times around the SPS circumference when 3 proton bunches are injected with 3 antiproton bunches, and twelve times when 6 and 6 are injected. Only two of these crossings are needed for the physics programme. With the increase in particles per bunch and the number of bunches (made possible by the increase in number of antiprotons produced by the AC after 1987), it was necessary to separate the bunches at the unwanted crossing points to reduce the effect of the beam-beam interaction. A system of electrostatic separators kept the proton and antiproton bunches on different horizontal orbits during the injection and acceleration stages, and for the data-taking colliding stage keep the bunches apart except in the adjacent experimental zones and one unwanted collision point between. For the final years of operation 6 proton bunches colliding with 6 antiproton bunches was the standard operation.

E. Beam Monitoring

The introduction of new methods of beam monitoring and the development of the sensitivity of the existing systems were a vital factor in the improvement of machine performance. The introduction of the wire scanners gave an accurate means of monitoring the beam growth during a fill. The sensitive measurement of the tune of both types of particle was made possible with the Schottky pick-ups without disturbing the beam.

F. Machine Alignment

The SPS tunnel is bored out of a shale-like rock called Molasse which is intrinsically stable. When the excavation for the experimental area for UA1, ECX5, was started during normal fixed target operation we were not surprised to find a vertical displacement of the ring elements in this region especially the lattice quadrupoles. As the zone was progressively excavated, from the surface, the symmetry of forces on the tunnel was broken and the quadrupoles on each side of the ECX5 were found to move vertically upwards by over 3 mm (a tolerance of 0.15 mm was specified during the SPS construction period) Over the intervening ten years, and the introduction of the UA1 detector weighing 2000 tonnes and a non-negligible amount of concrete and steel shielding the quadrupoles have gradually returned to and past their original settings. The experimental area for UA2, ECX4, is nearly 60 metres below the surface and tunneling was the only solution. Being completely symmetric there were no movements of the quadrupoles.

IV. MACHINE PERFORMANCE-INTEGRATED LUMINOSITY

A. The Length of the Coast

The length of coast was determined by the lifetime of the beams in the SPS and the intensity of antiprotons stacked and ready to be transferred from the AA.

The design vacuum pressure for the SPS as a fixed target accelerator of 2×10^{-7} mbar. was improved by more than two orders of magnitude to avoid blow up of the beams stored for many hours. At this level the growth of the beam size due to beam-gas scattering was small and proton lifetimes of several 100 hours have been recorded.

Reduction of the noise in the low level radio-frequency system contributed significantly to the improvement of lifetime of the beams to better than 50 hours. The reduction over the years of power supply ripple and noise reduced the diffusion from the buckets induced by the beam-beam.

With such a complex operation, equipment failures resulting in the loss of coasts were inevitable. The constant efforts on the part of the engineers and technicians in the equipment groups resulted in a gradual reduction in lost coasts from 40% to less than 10% in the final year of operation, Figure 3.

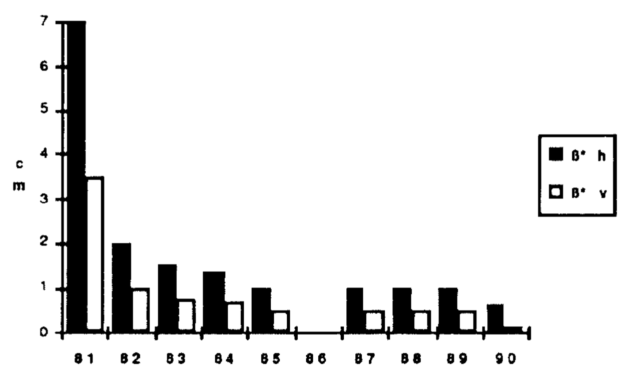

Figure 3. Number of coasts per year and percentage lost.

With the advent of the AC the number of bunches injected was doubled to 6 and the frequency of transfer changed so that by 1990 two coasts per day became routine operation.

V. ACKNOWLEDGEMENTS

The SPS Collider project was the work of large numbers of people in many Divisions of CERN, too many to mention all by name.

I would however like to thank the operations teams of Engineers in charge and Machine co-ordinators, shift leaders and control room technicians, present and past, CPS and SPS, for their enthusiasm and dedication to this project over the past ten years.