The CERN SPS Proton-Antiproton Collider
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Summary

The SPS now operates for about 40% of the time as a proton-antiproton collider at a centre of mass energy of 630 GeV. Towards the end of 1984 the SPS achieved a peak luminosity of 3.6x10^29 cm^-2 s^-1, with a luminosity lifetime of 20 hours and an average integrated luminosity of 5 nb^-1 per day. This report reviews the operational experience and limitations of the collider and describes the improvements which will be implemented to increase its luminosity by an order of magnitude.

Introduction

The CERN proton-antiproton complex consists of three machines, i.e.

1) The 26 GeV/c proton synchrotron (CPS)
2) The 3.5 GeV/c antiproton accumulator (AA)
3) The SPS collider which now operates at a momentum of 315 GeV/c.

Every 2.4 s an intense beam of protons is accelerated in the CPS to 26 GeV/c and extracted onto a target near the AA. The antiprotons collected from the target are accumulated in the AA, where their phase space density is increased by a factor 4x10^8 by means of stochastic cooling. About once per day 3 bunches of antiprotons are extracted from the AA stack, accelerated to 26 GeV/c in the CPS and then injected into the SPS after the prior injection of 3 bunches of protons. All bunches are then accelerated to 315 GeV/c and are kept colliding during a storage time of up to one day.

The first proton-antiproton collisions in the SPS were recorded in the summer of 1981. Table 1 shows the progress of the integrated luminosity per year for each of the two experiments UA1 and UA2 since then.

<table>
<thead>
<tr>
<th>Year</th>
<th>Integrated luminosity (nb^-1)</th>
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<tbody>
<tr>
<td>1981</td>
<td>0.2</td>
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<tr>
<td>1982</td>
<td>28</td>
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<tr>
<td>1983</td>
<td>153</td>
</tr>
<tr>
<td>1984</td>
<td>395</td>
</tr>
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</table>

Until 1983 the momentum of each beam was 273 GeV/c, corresponding to the rms power dissipation for which the magnet system and power supplies of the pulsed 400 GeV CPS accelerator had been designed. After an upgrading of the respective cooling systems the SPS collider has operated reliably during the 1984 run at a momentum of 315 GeV/c per beam.

Operational aspects of the SPS Collider

The operational procedures of the SPS collider are entirely determined by the scarcity of antiprotons.

This has required a continuous effort to improve the reliability of all subsystems of the collider to a level which is much higher than that of a normal proton accelerator where short interruptions of the pulsed operation are of no importance. The result has been that out of the 17 coasts in the 1984 run, only 25 were terminated prematurely due to technical faults. For the rest the average store duration was 17 hours and the longest coast lasted 31 hours.

The SPS is particularly vulnerable to voltage dips on the mains supply and therefore collider runs are never scheduled during the summer months. Evening thunderstorms after the hot summer days are common in July and August and cause serious perturbations even for fixed target operation.

The layout of the proton-antiproton complex has been designed such that all antiproton transfer schemes can be set up with protons in the reverse direction. This permits to optimize the settings of all parameters of the accelerators, transfer lines etc. with protons in repetitive pulsed operation. Thereafter a few antiproton pilot pulses of low intensity are transferred to verify that everything has been adjusted correctly and if necessary, to make some last corrections. Finally, the dense antiproton shot is transferred, with an overall transfer efficiency from AA to coasting beam momentum in the SPS of up to 75%.

The transfer sequence is heavily dependent on software in order to make it as safe as possible. The nucleus is a high-level job manager called the sequencer. This controls the complex sequence of operations needed to prepare the SPS and its transfer lines and to control the antiproton injection process. It is able to abort the transfer up to the last moment if a fault condition is detected.

Present performance of the SPS collider

Extensive machine development studies have led to a good understanding of the SPS collider and have enabled practically all parameters to be pushed to their physical limits with the machine in its present condition, operating with 3 proton bunches and 3 antiproton bunches.

<table>
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<th>Best collider performance in 1984</th>
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<tr>
<td>Momentum (GeV/c)</td>
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<tr>
<td>Proton intensity</td>
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<tr>
<td>Antiproton intensity</td>
</tr>
<tr>
<td>E_p E_\bar{p} of protons (\pi mm x mrad)</td>
</tr>
<tr>
<td>E_p E_\bar{p} of antiprotons (\pi mm x mrad)</td>
</tr>
<tr>
<td>Low beta B_H x B_\bar{p} (m x m)</td>
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<tr>
<td>Initial luminosity (cm^-2 s^-1)</td>
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<tr>
<td>Luminosity lifetime (h)</td>
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<td>Beam-beam tune shift per crossing point</td>
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</table>

Present limitations of the SPS collider

For a discussion of the present limitations and the planned improvements it is convenient to refer to Fig. 1 which shows the tune diagram at injection and storage.
The Laslett $Q$-shift is proportional to $1/\gamma^2$ and therefore is negligible at 315 GeV/c. However, the beam-beam $Q$-shift remains the same, since the effects of increasing particle energy and decreasing beam cross section compete against each other.

During a long coast the beams are sensitive to higher order resonances up to and including the 10th order. Fig. 1 shows that in storage it is just possible with the present parameters to fit the beams in the $Q$ diagram with the protons slightly above the 3rd order resonance and the antiprotons just below the 10th order resonance. However, the $Q$-values are critical within 0.002 and are therefore continuously measured during a coast by means of Schottky beam diagnostics and adjusted whenever necessary.

The transverse emittances of the protons and antiprotons are determined by the characteristics of the AA and CPS and there seems little one can do to decrease their values. In fact, to achieve the values quoted in Table 2 a very careful adjustment of all transfer schemes is necessary to avoid beam blow-up.

The low beta values $\beta_x \times \beta_y = 1 \times 0.5$ m are about as low as feasible with the present insertions. The low beta quadrupoles operate near saturation, while the chromaticity corrections can just be managed with the existing 4 families of sextupoles of the SPS.

The luminosity lifetime $\tau$ during storage is determined by the p and $\bar{p}$ intensity lifetimes $\tau_p$ and $\tau_{\bar{p}}$ and the e-folding time for the growth of the transverse p and $\bar{p}$ emittances $\tau_{ep}$ and $\tau_{\bar{ep}}$.

Initially $\tau_L$ was determined by noise in the RF system and therefore the entire low level electronics of the RF system has been rebuilt with the utmost care to reduce the RF noise. In late 1984 it was found that very small spikes caused by the thyristor firings of the main power supplies led to the loss of energy at the same time near the dense core of the proton beam and increases with increasing amplitude. At injection the $Q$-values of the protons therefore occupy the entire diamond shaped region from $Q_0$ to $Q_o$ in Fig. 1.

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The SPS vacuum system cannot be baked, except over about 50 m on either side of the two colliding beam experiments. Originally, the SPS had 550 sputter ion pumps of 250 l/s and 200 sputter ion pumps of 400 l/s for the larger tanks of the RF systems, extraction systems etc. By doubling the number of 258/s sputter ion pumps and adding 1300 sublimation pumps, the average nitrogen equivalent pressure for multiple scattering around the SPS ring has been brought down to $2.6 \times 10^{-9}$ mbar. This corresponds to an emittance growth rate of about $3 \times 10^{-4} \text{mm mrad per hour at 315 GeV/c}$ and therefore is of little importance for the luminosity lifetime.

The dominant effect now appears to be intrabeam scattering i.e. multiple Coulomb scattering of particles in the same proton bunch. During the early part of a coast this leads to an increase of the horizontal emittance with $\tau_{ep} = 20h$. Furthermore, it causes a gradual increase of the length of the proton bunch which later during the coast starts to fill almost the entire RF bucket so that protons are lost out of the RF bucket by intrabeam scattering, leading to $\tau_p = 50h$.

The value $\tau_L = 28h$ quoted in Table 2 is a representative average value achieved towards the end of the 1984 run for a one day long coast.
The proton-antiproton improvement program

At present the antiprotons emerging from the production target are collected, accumulated and cooled in the same AA ring. To increase the antiproton accumulation rate, a special antiproton collecting and pre-cooling ring ACOL 6 is under construction so that the AA only needs to perform the accumulation and cooling of the antiprotons. Each of the two machines can then be optimized for its specific task.

This arrangement should improve the accumulation rate of antiprotons by an order of magnitude to about $10^{12}$ antiprotons per day. To translate this into the same increase of luminosity in the SPS collider, the number of antiprotons per SPS fill must be increased by the same factor.

The largest stack in the AA until now has been about $3 \times 10^{11}$ antiprotons. The maximum stack intensity which can be accumulated in the AA is limited by intrabeam scattering and is $\leq 10^{12}$ antiprotons i.e. about 3 times the present operational maximum.

The momentum spread of a full AA stack corresponds to a longitudinal acceptance of 6 eVs, whereas the longitudinal acceptance of the beam transfer system and of the SPS collider is only 0.5 eVs. In the present operation with 3 antiproton bunches we can therefore withdraw 1.5 eVs i.e. about 25% of the full stack per SPS fill.

At present this is not a serious limitation since it takes several days to build up a full stack in the AA and the SPS needs one fill per day if there are no technical faults. To make full use of ACOL we must withdraw each day almost 100% (i.e. 4 x 25%) of a stack which has about 3 times the present intensity. We can gain this factor 4 by

1) 6 bunch operation

ii) Doubling the longitudinal acceptance at constant $\Delta p/p = 3 \times 10^{-3}$ of the SPS collider at injection by doubling the bucket length by the installation of a modest 100 MHz RF system.

With 6 pbar bunches the collider must also have 6 p bunches. This gives 12 crossing points so that with the same proton bunch intensity and the same transverse emittances the small amplitude antiproton Q-shift per revolution becomes $\Delta Q = 12 \times 0.004 \times 0.048$. It is clear from Fig. 1 that during storage the antiproton bunches then straddle the 10th order resonance and experiments have shown that this reduces the antiproton lifetime by at least a factor 4. Therefore it is necessary to separate the beams at the unwanted crossing points by a system of electrostatic deflectors. A 3-bunch separation scheme has been tried out successfully during the 1984 collider run and additional separators for 6-bunch separation are under construction.

The 100 MHz RF voltage which is needed to capture the 1 eVs bunches is rather modest, namely 2 MV. For acceleration higher voltages are needed. To avoid this requirement at 100 MHz, the injected bunches will be adiabatically split into two 200 MHz bunches which will be accelerated with the existing 200 MHz RF system while at $315 \text{ GeV/c}$ the two 200 MHz bunches will again be recombined into one bunch. During storage this bunch can be held by the 100 MHz system, with the important advantage that the intrabeam scattering in the two times longer proton bunches is reduced. However, the length of the 100 MHz bunches could be inconvenient for the physics detectors. It may therefore be necessary to find experimentally the best compromise between intrabeam scattering and detector acceptance by a suitable adjustment of the ratio of the 200 MHz and 100 MHz RF voltages during storage.

At injection the Laslett Q-spread of the two times longer proton bunches is halved, whereas the Q-spread of the antiproton bunches is doubled in 6 bunch operation. Inspection of Fig. 1 shows that under these conditions the space occupied by the protons and antiprotons in the Q-diagram still fits comfortably between the third order and fourth order resonances. On the other hand, since the microwave threshold is also doubled when operating with 100 MHz, it becomes attractive to aim for a further increase in luminosity by injecting more intense proton bunches until the Laslett Q-spread of the protons and the beam-beam induced Q-spread of the antiprotons together use up again all the space in between the third and fourth order resonances.

To circumvent the latter limitation we plan to intensify in the near future our program of machine development studies to correct the third and fourth order stopbands at injection with sextupoles and octupoles which are already installed in the SPS. Furthermore, the possibility of separating the beams also at injection is being studied.

Conclusion

The beam dynamics and present limitations of the SPS collider are now well understood and give us confidence about the luminosity improvement program. It should be possible to increase the initial luminosity to the vicinity of $4.4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ corresponding on average to exactly one proton-antiproton event per bunch crossing with 6 x 6 bunch operation.

References

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