ANTIPROTONS IN THE ISR

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Summary

A brief account is given of the events leading up to antiprotons in the Intersecting Storage Rings (ISR) followed by a synopsis of the characteristics and parameters of the physics runs made to date. Experience gained with critical operations, such as transfer line steering, injection optimization, stacking and phase displacement acceleration is reviewed bearing in mind the extremely low beam intensities. Special reference is made to the various machine improvements, namely the vertical transverse stochastic cooling for proton beams of up to 12 A, the transverse and longitudinal stochastic cooling for the antiprotons, the new antiproton beam position monitoring system in the transfer lines and ring and the use of two high-luminosity insertions. At the end of June 1982, a scheme for reaching higher luminosities by making multiple transfers from the Antiproton Accumulator (AA) and using longitudinal stochastic cooling in the ISR was demonstrated. The absence of any measurable loss rate during long periods of stable beam conditions has been used to set a new lower limit of 1000 h on the antiproton lifetime at rest. Finally, preparations are in progress to collide 3.5 to 6.5 GeV/c antiprotons with a hydrogen gas jet target.

Introduction

The storage of antiprotons in the ISR was discussed as early as 1962[1], before even the ISR were constructed. Several schemes for antiproton production were studied over the following years, but it was not until stochastic cooling had been invented[2,3] and accumulation in a separate ring proposed that useful luminosities could be hoped for. By this time, the emphasis had shifted to having proton-antiproton collisions in the Super Proton Synchrotron (SPS)[4] and in 1977, CERN set up the "Initial Cooling Experiment" (ICE) to test both stochastic and electron cooling. One year later in 1978, the design study was published for the present Antiproton Accumulator (AA)[5], which is now the hub of the CERN antiproton complex[6] and which, via the CERN Proton Synchrotron (PS), feeds antiprotons to the SPS, ISR[7] and Low Energy Antiproton Ring (LEAR) machines. The decision to equip the ISR for antiproton storage and to build a new transfer line was taken in January 1979. On 2 April 1981, the first pulse of antiprotons circulated in the ISR. Over the next three days, further pulses were stacked and finally a stack of 610 μA was collided with 830 mA of protons for the first physics run, which lasted four days.

1. Operation of the ISR Antiproton Collider

By exploiting the excellent vacuum and high reliability of the ISR, antiprotons have been stored for physics runs of up to two weeks. The combination of 80 mm of available aperture, of which 20 mm is used for stacking, and momentum cooling makes it possible to stack the total AA production over several days and the transfers can be made on a very flexible basis. Once the antiproton beam is cooled, it is very small compared to the available aperture and since no collimators are needed to protect physics detectors from background or the superconducting insertion from beam losses, all the aperture is available for the beam. This fact has enabled the antiproton beam to survive on a number of occasions from sudden orbit distortions due to perturbations on the electric grid, typically due to a thunderstorm, or to an equipment failure, whereas the full-aperture proton beam in the other ring has been lost.

The general considerations mentioned above show that the ISR are basically well suited to antiproton operation, but when it is realized that it takes 24 h of accumulation in the AA to store just over 10^{11} antiprotons (equivalent to 5 mA circulating in the ISR), whereas one normal PS pulse is $3\ 10^{12}$ protons, it is clear that antiproton operation demands a more rigorous and frugal attitude[8]. Since the initial set-up in April 1981, the magnet settings have been sufficiently reproducible from run to run to ensure that the first injected pulse has always circulated in the ISR. For a known working condition, a typical transfer will comprise 15 to 20 pulses according to the stack accumulated in the AA, i.e.:

- 1st pulse $\sim 10^9$ measure transfer trajectory from PS and test injection; no RF applied; dumped.
- 2nd pulse $\sim 2\ 10^9$ measure injection error; test RF; dumped.
- 3rd pulse $\sim 2\ 10^9$ check injection correction; check aperture and determine top of stack; this pulse may be kept.
- 4th and 5th pulse $\sim 5\ 10^9$ start stacking.
- 6th pulse onward $\sim 10^{10}$ stacking.

In principle, the AA ejection, transfer to PS and acceleration in the PS are already optimised by reverse injection of protons. In the event of a new ISR working condition or momentum, an extra four or five low intensity pulses may be needed but on the other hand, if the transfer is for adding to an existing stack, only the injection error needs to be corrected. It should be stressed that all optimisation of the ISR transfer lines and machine are done with these low-intensity antiproton pulses since the reverse injection of protons is not possible. Once optimised, the transfer efficiency from the AA stack to the ISR varies between 90 % and 100 % according to the degree of cooling in the AA.

In order to achieve this performance, a number of improvements have been made to the ISR machine and its transfer lines. New pick-up electronics were designed for operating with bunch intensities of $\sim 10^9$ particles with a precision of 0.6 mm r.m.s. and for the new transfer line, new hardware was also designed[9]. Single passage orbits can be measured both in the transfer lines and the ring and the average of multiple passage orbits in the ring. Apart from increased sensitivity, this beam observation system differs from the normal proton system since it is self-triggering from the beam and the beam is in a single bunch rather than a pulse of 20 bunches.

All transfer line magnets were equipped with Hall probes for making accurate relative field changes so as to avoid errors from hysteresis and saturation effects. This is of particular use in reducing the iterations needed to correct the injection error into the ISR. The Hall probes are temperature stabilized to better than 0.1°C for ambient temperatures between 15 and 30°C and give a precision of 10^{-4} of full scale[10]. To guard

* This work is reported on behalf of the now dissolved ISR Division.

against long terms drifts, possibly due to radiation damage, the probe is calibrated at the start of each run with the maximum current in the magnet during the magnet cycling. The rigorous application of a standard cycle to set all magnets is considered to be of prime importance for reproducibility. A much greater use is made of on-line computer checking and logging of all measured data from each antiproton pulse. The computer stores the data for 80 pulses which covers about four transfers. Equipment such as the current transformer for measuring the circulating current[11], the RF system, and the interlock system were modified as were a very large number of computer programs. The very important stochastic cooling systems are described in a later section.

Requirements for the stacking of antiprotons differ from those for proton stacking in that the aim is to avoid any loss of antiprotons rather than to obtain maximum phase-space density. With standard AA rebunching parameters, it is just possible to carry out the normal ISR RF-stacking cycle using suppressed buckets without spill-out - if a low value of sin ϕ_s is used. 25 suppressed buckets are used instead of the normal 10.

An increased signal amplification is used in the RF-phase reference pick-up and a delay is introduced to give the required 180°-shift in the synchronous phase-angle. Because of the low intensity and single bunch injection, the dynamic range of the phaselock system is less than for normal proton operation. The range in injected intensity for stacking is 2 10^9 to 2 10^{10} particles per pulse.

An interlock is used to switch off RF and prevent perturbation of the stack which could result if the injected intensity is less than a lower limit (10^9 particles) or if the phaselock reference is lost due to a low density pulse entering a denser part of the stack.

Stacking is normally continued until the AA is practically empty. Towards the end of the transfer, pulses with larger longitudinal emittance are injected to maintain intensity. These pulses are stacked with correspondingly larger RF final voltages for which suppressed buckets cannot be used and the available aperture is rapidly filled up. Subsequent momentum cooling reduces the momentum spread of the stack and liberates aperture for the next pulses.

Phase displacement from 26.6 GeV/c to 31.4 GeV/c is carried out in exactly the same manner as for proton stacks. However, this is done with the absence of beam in the other ring as beam-beam resonance excitation provokes considerable loss of particles during phase displacement of low intensity stacks.

Tune and beam frequency measurements are carried out using the same hardware as for protons but with inversion and further amplification of the beam pick-up signals.

The existing injection-damping systems[12] were uprated with more powerful output amplifiers and new detection electronics to cope with possible large injection errors. However, with the very high degree of PS and transfer line stability and the use of efficient injection error correction programs, the damping systems have not been required.

2. Synopsis of Physics Runs and Machine Conditions

Table 1 gives a summary of the ISR antiproton physics runs. Apart from these ten runs, two runs at the very beginning were devoted to the setting-up of the transfer from AA to ISR and later in the programme, one more run was devoted to the acceleration of an antiproton beam from 26.6 GeV/c to 31.4 GeV/c in the ISR, but for the most part the development of operational techniques and the introduction of new working conditions has been carried out during the physics runs.

Table 1

Synopsis of ISR $p\bar{p}$ Collider Physics Runs

Starting date	Current* $\bar{p}$ mA	Current* p A	Peak luminosity $10^{26}cm^{-2}s^{-1}$	Momentum GeV/c	Physics data time h
04.04.81	0.61	0.83	0.11	26.6	94
22.05.81	0.19	9.41	0.20	26.6	58
29.05.81	0.48	11.95	0.80	26.6	94
05.10.81	0.10	11.64	0.30	26.6	57
19.10.81	2.00	11.17	9.00	26.6	325
29.03.82	2.04	12.80	5.70	31.4	23
06.04.82	3.49	12.60	12.00	31.4	109
24.05.82	4.18	11.10	16.00	15.4	215
21.06.82	4.32	11.80	78.00**	26.6	149
06.12.82	6.48	21.15	250.00**	26.6	295

* The antiproton beams are frequently the result of accumulating 2 or 3 transfers over several days. In cases where the proton beam has been renewed, the maximum current is quoted.

** Luminosity in the superconducting, high-luminosity insertion.

An experiment on multiplicity was complete in the early runs using the largest streamer chambers yet made. The physics programme then became dominated by proton-antiproton total cross-section measurements, which required a special machine optics known as the Terwilliger scheme[13]. In this scheme, a periodic gradient perturbation is added to the machine to reduce the momentum dispersion to zero at the even numbered crossings, which greatly reduces the beam width and hence the interaction diamond length. Finally, a new machine optics was introduced for the last two runs, which uses the superconducting high-luminosity insertion in I8 (gain x 7)[14] and the normal-magnet high-luminosity insertion in I1 (gain x 2). The increase in luminosity in the last two runs makes it possible to start studying the finer differences between proton-proton and proton-antiproton induced states. The peak luminosity reached was 2.5 10^{28} $cm^{-2}s^{-1}$.

With a disparity in intensity of over three orders of magnitude between the two beams, the signal to noise ratio in the physics counters is critically dependent on the background coming from the halo of the stronger proton beam, since this can easily exceed the low luminosity. For the early runs neither of the high luminosity insertions were used and loss rates were extremely low and stable giving excellent background conditions. With the high-luminosity insertions, there is intrinsically more excitation of machine resonances. The initial conditions that can be obtained are excellent, but the rather more rapid growth of the loss rate makes it necessary to scrape the halo away from the stronger proton beam every few hours in order to restore the background conditions.

3. Stochastic Cooling[15]

Stochastic cooling is used in both the transverse and longitudinal planes on the antiproton beam and in the transverse vertical plane on the proton beam. For the weak antiproton beam, the stochastic cooling systems completely dominate the blow-up mechanisms and during the first 6 to 8 h the beam dimensions are shrunk typically giving a 15 - 20% increase in luminosity. For proton beams of 10 - 12 A, the transverse cooling can only stabilize the beam blow-up. This is achieved with two systems with 6 db bandwidths of 1.65 GHz acting independently on the inner and outer halves of the proton stack.

The momentum cooling was applied in the last two runs in Table 1 to create space within the ISR aperture to stack further AA transfers. Figure 1 shows how an irregular beam with some particles spilled out across the aperture can be cooled into a single narrow peak. The momentum cooling system also cools the horizontal transverse oscillations.

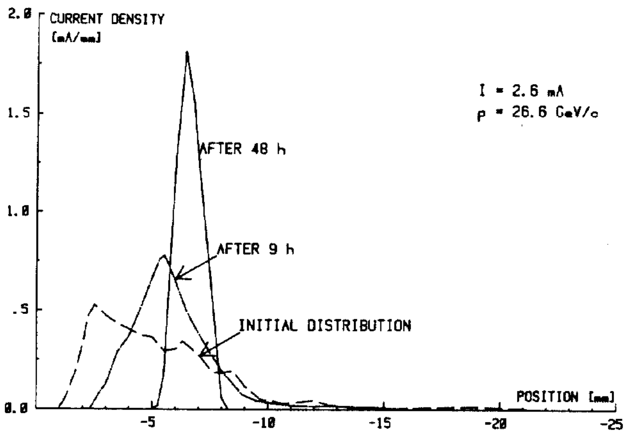

Fig. 1 Evolution of the Longitudinal Density with Momentum Cooling. The Accumulation Orbit Can Be Varied by Means of a Radial Bump in the Cooling Pick-up.

4. Antiproton Lifetime

During the last physics run in 1981, the circulating antiproton current of 1.998 mA had an undetectably small loss rate during the first 55 h of the run (Fig. 2).

A control run with the current monitor showed that readings from this device are reproducible to ± 2.5 μA. With no detectable loss in 55 h, it can be inferred that at 26.6 GeV/c the antiproton mean lifetime is at least 30'000 h and this sets a new lower limit[16] on the mean life at rest of 1000 h (99.9% confidence level).

5. Expectations for the Near Future

The momentum cooling, which has now been used in two runs, makes it possible to go on stacking the AA beams over several days. Based on present AA performance, it should not be difficult to exceed 10^{29} $cm^{-2}s^{-1}$ luminosity.

Finally, preparations have been continuing for some time on the unconventional use of the ISR to collide an antiproton beam of 3.5 GeV/c to 6.5 GeV/c with a hydrogen jet target.

Acknowledgements

The successful exploitation of the ISR as a proton-antiproton collider was the fruit of the work of a very large number of people and much interdivisional cooperation. The author would like to thank his colleagues of the former ISR Division for having entrusted him with the task of reporting their work.

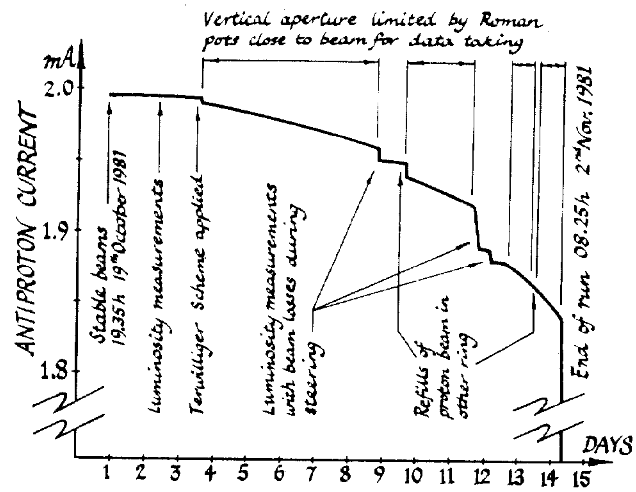

Fig. 2 Evolution of the Antiproton Current during a Two-week Physics Run Devoted to a Total Cross-section Measurement.

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