BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

INTERSECTING STORAGE ACCELERATOR NOTES

Antiproton Intensities at ISA

H. Foelsche and H. Hahn

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ANTIPROTON INTENSITIES AT THE ISA

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Summary

In the ISA an antiproton beam with an intensity of approximately 3×10^9 antiprotons appears feasible without resort to electron cooling.

1. Methods of Obtaining Antiproton Beams

Various methods of accumulating large antiproton intensities in storage rings have been considered in the past.¹ Budker² has proposed to damp the phase space distribution of antiprotons by electron cooling. For the ISA this method does not appear to be practical.³ It has also been proposed to produce antiprotons from antilambda decay near the target.⁴ The antilambda travels a finite distance before producing the antiproton. This separates the phase space occupied by antiprotons from the target phase space, and in principle, one can then stack antiprotons indefinitely.

In this note we wish to show what can be done realistically by straightforward matching of target phase space into the accelerator. A target is placed into a proton beam of 200 GeV taken from one of the storage rings. Antiprotons of about 30 GeV are produced and captured in the second ring and accelerated to 200 GeV. The first ring is refilled with protons in the opposite direction, and antiproton-proton collision are induced. The full acceptances of the rings are filled in both cases at 30 GeV, and due to adiabatic damping the beams attain the same small size as in conventional use at 200 GeV.

Assuming for the moment that the bunch structure of the proton beam has not been appreciably altered prior to targeting, the antiproton bunches fit naturally into the RF buckets of the second accelerator. That is to say, at this point of the argument we simply fail to exploit the slight advantage gained from the fact that the bunch length of the 200 GeV

proton is smaller by $(200/30)^{1/2} = 1.6$ than the phase acceptance for antiprotons at 30 GeV. For maximum brightness, we assume that the target is placed in a low-beta region with the same properties as a high luminosity straight section. In principle, one can obtain an ideal transverse match of antiprotons filling all the available phase space of the second ring (30 GeV). Nothing is gained then by repeating this process because either the target or the injection apparatus would knock out the antiprotons already stored.

One may, however, improve the instantaneous source brightness; i.e., the longitudinal match into the antiproton ring, by rebunching the primary proton beam prior to targeting. The longitudinal phase space of the proton beam ($\Delta E/E$, Δt) has been damped adiabatically by a factor of 200/30 during acceleration from 30 to 200 GeV/c. Assuming that one is permitted to use the same large fractional energy spread at 200 GeV that one has at injection, the bunch structure can in effect be shortened by a factor of 6.7 prior to targeting. Thus, one may stack six times more antiprotons in the longitudinal phase space of ring #2. In practice this might be done as follows: The protons in the ISA are first debunched and then rebunched with a triangular sawtooth on the fifth harmonic of the revolution frequency. One obtains five (instead of 30) proton bunches of the original length, but with a six times wider energy spread. One injects antiprotons into every sixth bucket in the ring #2, and one may repeat this process six times.

One has then reached the limit imposed by Liouville's theorem for injection at 30 GeV. To gain more one must circumvent this theorem by using one of the two methods mentioned in the introductory remarks above.

The choice of targeting energy is flexible, in principle. If one chose a 30 GeV targeting energy, one could accelerate 6-GeV antiprotons in the ISA. As the antiproton beam would damp down much more sharply upon acceleration to 200 GeV, one can stack more antiproton bursts in transverse phase space at 200 GeV. On the other hand, the gain is offset by a sharp decrease in antiproton yield per interacting proton of 30 GeV. We discuss this in more detail below.

However, this second approach entails several technical complications. The antiprotons would have to be accelerated through the phase transition

(~ 16 GeV) requiring a more complex RF system. Due to remanent fields in superconducting magnets, injection at higher field is preferable. Furthermore multiturn injection of antiprotons adds substantial complications.

2. Yields

Measurements of negative particle yields from pp collision at the CERN ISR⁴ provide new information in the equivalent laboratory energy region of 200 - 1500 GeV. On the one hand, it is established that negative pion yields scale in a straightforward manner in the regions from about 12 to 1500 GeV equivalent primary lab energy. The invariant cross section for pion production, $E \times \left(\frac{d^3\sigma}{d^3p} \right)$, where E and p are the energy and momentum of the secondary, does not depend on the total center of mass energy of the reaction, and depends only on the transverse momenta p_t and the longitudinal momentum fraction $X = (p_L/p_{\max})$. On the other hand, antiproton yields increase much more rapidly than this scaling law would predict in the range from 24 to 200 GeV. The ratio of antiprotons to pions ranges from 4 to 7% in the 500 to 1500 GeV energy region, but is less than 1% at 24 GeV primary energy.

For 30 GeV negative pions generated by a 200 GeV proton in hydrogen in the laboratory ($X = 0.15$), one has from the CERN results

$$\left(E \frac{d^3\sigma}{d^3p} \right) = \frac{E}{p_L} \frac{d^2\sigma}{d\Omega dp_L} \approx 1.5 \left[\text{mb}/(\text{GeV}^2/c^3) \right]$$

at a transverse momentum of $p_t = 200 \text{ MeV}/c$. The antiproton ratio is published for a transverse momentum of 400 MeV/c and $\geq 500 \text{ GeV}$ equivalent lab energy, but we just assume that it is the same for $p_t = 200 \text{ MeV}/c$ at 200 GeV energy: $(\bar{p}/\pi) \approx (4 \pm 2) \%$.

Per interacting proton, assuming about 45mb total interaction cross section one obtains

$$\frac{d^2 N_{\bar{p}}}{d\Omega dp_L} \approx 0.4 \left[\frac{\text{antiprotons at 30 GeV, per interacting proton}}{\text{sr GeV}/c} \right]$$

with $p_t = 200 \text{ GeV}/c$ and 200 GeV primary protons on hydrogen.

One will certainly use targets of higher density than Hydrogen. Experience at low energies shows that the secondary particle yield per interacting proton rarely decreases significantly compared to hydrogen.

We assume this to be so at high energies as well. Furthermore, we think that yields at zero transverse momentum are not less than at 200 MeV/c, thus on heavy targets at forward angles ($\sim 0^\circ$) we also expect

$$\frac{d^2 N_p^-}{d\Omega dp_\perp} \approx 0.4 \left[\begin{array}{l} \text{antiprotons at 30 GeV per interacting 200 GeV} \\ \text{proton / sr. GeV/c} \end{array} \right]$$

This number is uncertain to about a factor of 3.

3. Intensity

The acceptance volume of the ISA⁶ is, at 30 GeV

$$A_{2v} \times A_{2h} = 0.5\pi \times 3.75\pi \times 10^{-6} \left[\text{mm}^2 \text{sr} \right]$$

with

$$\Delta p_\perp = 0.15 \text{ GeV/c total.}$$

The target cross section in a low beta straight section will be $\pi \times 7.22 \times 0.7 \text{ mm}^2$ which then results in a matched solid angle of

$$\Delta \Omega = 38 \times 10^{-6} \text{ sr.}$$

Thus the ISA accepts

$$\frac{N_p^-}{N_p} \approx 2.3 \times 10^{-6} \quad \begin{array}{l} \text{antiprotons at 30 GeV per interacting 200 GeV} \\ \text{proton} \end{array}$$

The target efficiency on single traversal will not exceed 1/3. With a full charge of 6×10^{14} protons at 200 GeV incident on the target; i.e., 2×10^{14} protons interacting, one obtains

$$4.6 \times 10^8 \text{ antiprotons (without rebunching)}$$

or repeating the process six times by rebunching as described above

$$\sim 3 \times 10^9 \text{ antiprotons (with rebunching).}$$

In principal, disregarding the technical complications mentioned above, one can obtain the same intensity starting with 6-GeV antiprotons produced by 30 GeV protons from the AGS. The production cross section is down by a factor of 25.⁷ The momentum acceptance at 6 GeV is five times lower, and this must be regained by longitudinal stacking at higher energy. The transverse phase space after acceleration, on the other hand, will be $(30/6)^2 = 25$ times smaller at 200 GeV for a single burst. One can stack transversely twenty-five times more bursts, thus cancelling the disadvantage in production cross section. There is, in principle, no gain or loss.

In conclusion, there appears to be a realistic prospect of accumulating 0.5×10^9 to 3×10^9 antiprotons in one ring of the ISA.

4. Luminosity

In a high luminosity straight section at Isabelle with quasi-zero crossing angle (configuration 1b in Ref. 6, pages 74-78), one has a luminosity for unbunched beams:

$$L \approx 2\beta_0 L'(0)$$

and

$$L'(0) = \frac{2c}{(2a)(2b)} \frac{N_p N_{\bar{p}}}{C_{ISA}^2}$$

where β_0 = betatron function at the straight section center

c = velocity of light

$(2a)(2b)$ = vertical and horizontal diameter of beams

$N_p; N_{\bar{p}}$ = number of particles stored

C_{ISA} = circumference of ISA

We shall use $C_{ISA} = 3 \times C_{AGS} = 2420$ m rather than the somewhat smaller circumference ($2.5 \times AGS$) used in Ref. 6 prior to the summer study. Otherwise we assume parameters identical to the ones in Ref. 6 (page 78)

$$\beta_0 \approx 70 \text{ cm}$$

$$(2a)(2b) = 6 \times 10^{-3} \text{ cm}^2$$

$$N_p = 6 \times 10^{14} \text{ proton}$$

$$N_{\bar{p}} = 0.5 \text{ to } 3 \times 10^9$$

Thus, one obtains

$$L(\bar{p}p) \approx 0.7 \text{ to } 4.2 \times 10^{28} \text{ cm}^{-2} \text{ sec}^{-1} \text{ for unbunched beams.}$$

The antiproton yields underlying these estimates are uncertain to a factor of 3.

If there were 6×10^{14} protons in both rings, the corresponding luminosity would be $0.86 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ for unbunched beams. The proton-proton luminosity probably cannot be improved by keeping the colliding beams bunched due to longitudinal instabilities and the beam-beam interaction. In order to keep the betatron-tune shift within bounds, the bunching would have to be compensated by a shortening of the interaction region. This restriction also applies for the much lower anti-proton intensity

because of the betatron tune shift induced in the antiproton ring. Thus, generally we expect the $\bar{p}p$ luminosity will be

$$L(\bar{p}p) \approx (0.8 - 5 \times 10^{-6}) L(pp).$$

5. A Few Practical Remarks

A target as small as proposed here will explode when it is exposed to 6×10^{14} incident protons in a single pass. It seems best to locate the target in the emergency beam dump line bypassing the machine vacuum. This will also keep the attendant secondary radiation away from the main rings. Then one needs a single-turn extraction system to realize the intensities we have computed.

The technical ramifications of running the ISA asymmetrically as proposed have not been studied in any detail. This seems to be the major complication in design which is required for reaching the computed antiproton yields. On first sight, the remaining technical complications introduced by the antiproton option do not appear to be major.

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