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Increasing Antiproton Production by Recirculating Proton and Antiproton Beams

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Abstract

Antiproton production with recirculating beams of both protons and antiprotons is investigated.

1 Introduction

Using a recirculating proton beam to produce more antiprotons is examined in [1]: the proton beam creates $\overline{p}$s by repeatedly traversing a *thin* target but further manipulation of the $\overline{p}$s is not considered. Some pluses, compared to the present—single pass—scheme, are that more of the protons in the beam contribute to the $\overline{p}$ yield and that a thin target eliminates the 'depth-of-focus' effect as well as $\overline{p}$ reabsorption, thus increasing $\overline{p}$ yield per proton accelerated. Low-Z targets actually offer superior yields in this scheme and are also preferred for their lower energy deposition and induced radioactivity. But, as pointed out in [1], the overriding disadvantage is that (longitudinal) phase space density at production is much smaller compared to the thick target case and it would require an inordinate amount of cooling to realize any eventual gain in luminosity. But with the commissioning of the Recycler and its impact on the operation of the Antiproton Source, along with the use of electron cooling in both machines, as well as recent concerns about overall *proton* economy at Fermilab, the recirculating beam scenario may be worth another visit.

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2 Recirculating $\overline{p}$s

A possible mitigation of the phase space dilution problem is achieved by recirculating $\overline{p}$s as well as protons. Outside of a short stretch including target, $\overline{p}$-focusing device, and dipoles to merge and separate the two beams, each follows its own path. One could envision the proton beam returning to Main Injector for one or more turns while the $\overline{p}$-beam circulates in the Debuncher (or Recycler)—preferably with some preliminary cooling. At appropriate times the two beams are extracted and transported back to the target hall where they enter a merging dipole with a time separation such that $\overline{p}$s and beam protons arrive at the target position simultaneously. After $\overline{p}$ focusing a second dipole splits the two beams on their way to the next cycle. The optimum number of such cycles is discussed below. An obvious drawback to this scheme is that almost all $\overline{p}$s interacting in the target are lost to the beam and, in the case where the target is larger in area than both p and $\overline{p}$ beams, it winds up resembling a thick target case—though with considerably improved collection efficiency. However, if the area of the target is chosen to be roughly that of the proton beam and if the recirculating $\overline{p}$-beam is only weakly focused at the target, only a fraction of the $\overline{p}$s traverses the target thereby making further gains possible. Some penalty will be paid because beamline and debuncher now must accommodate the recirculating $\overline{p}$s along with the newly created ones. Populating the available $\overline{p}$ transverse phase space as uniformly as possible during the recirculation stage is likely the best strategy. Perhaps correlations between $x-$ and $y-$phase space could be induced and exploited to further limit $\overline{p}$ flux through the target. Eventually, well before the point where the increasingly depleted proton beam makes fewer $\overline{p}$s than are lost from the increasingly intense $\overline{p}$-beam, the production stage is halted. The remaining protons are dumped, the $\overline{p}$s are debunched and cooled while a new Main Injector accelerator cycle gets underway.

3 Example

To make some preliminary estimates of yield gains at the Fermilab $\overline{p}$-Source, an example is presented. It is simplified to the point that it can easily be studied analytically. Let the radius of the proton beam, r, be equal to that of the target and let the recirculating $\overline{p}$-beam have radius R ($> r$). Assume both beams have a disk shape cross section with uniform density within their radii and zero density outside. Thus all protons traverse the target at each recirculation. Let the target have thickness, t, expressed in units of interaction lengths, and let Y $\overline{p}$s be produced—into the acceptance—per interacting proton. A rough measure of when to halt recirculation is when $\overline{p}$ production by the protons equals losses in the target. The net production rate of $\overline{p}$s is expressed by:

$$\frac{d\overline{N}}{ds} = Y\,t\,e^{-t\,s} - \overline{N}\,t\,u \tag{1}$$

where u is the ratio of $\overline{p}$s to protons crossing the target ($u = r^2/R^2$ in this example) and s is the number of turns (in the limit where it is treated as a continuous variable). The number of $\overline{p}$s as a function of s then becomes

$$\overline{N} = \frac{Y}{1-u}\left(e^{-u\,t\,s} - e^{-t\,s}\right). \tag{2}$$

Setting $d\overline{N}/ds$ to zero in Eq. 1 while substituting for $\overline{N}$ from Eq. 2 gives the turn number at which production equals loss:

$$s = \frac{-\ln u}{(1-u)t} \tag{3}$$

independent of Y. Plausible values of the parameters are $r = 0.02cm$, $R = 2cm$, and $t = 0.013$—equivalent to about 1 g/cm^2 for light nuclei. This results in $s \approx 700$ turns. Essentially Y $\overline{p}$s are produced per proton accelerated since, having traversed 700 g/cm^2 or some nine interaction lengths, almost the whole proton beam is spent. One would surely halt recirculation well before this. But—among other things—the example illustrates that, in contrast with the single pass scenario, (a) almost the entire proton beam interacts in the target, (b) at the optimum place defined by beam optics while (c) the number of turns is still very small compared to that of the proton acceleration cycle, and (d) few $\overline{p}$s are re-absorbed (for $u \ll 1$).

The case where the target covers the aperture corresponds to $u = 1$ in Eq. 1. This gives $\overline{N} = Yste^{-t\,s}$ instead of Eq. 2 and the optimum number of turns becomes $s = 1/t$ (about 77 for t as above). At that point $\overline{N} = Y/e = 0.368\,Y$, i.e., the expected $\overline{p}$ yield from an (optimal) one interaction length target. Note, however, that the improved collection efficiency afforded by a thin target results in significant gains over a conventional thick target.

The estimates of the number of useful turns, s, and of $\overline{p}$s produced, $\overline{N}$, are obvious upper limits since they ignore the penalties in delaying acceleration of the next batch of protons, the losses of ps and $\overline{p}$s elsewhere in the recirculation, and increased emittance of the proton beam due to multiple scattering. Some of these issues are addressed in [1]. Eq. 1 assumes that $\overline{p}$ and p have the same total cross section—reasonable at these energies—and does not separate inelastic from elastic and quasi-elastic interactions. A more complete analysis could take these and other extras into account without much difficulty but quantitative studies will require simulations particularly for targetry and $\overline{p}$-collection.

4 Target

Target geometry is evidently a main concern. The above example assumes the target is somehow levitated and centered at the proton beam—or perhaps is supported by a 'stem' through which cooling is provided. More realistically, a band—in rapid motion so as to reduce energy deposition densities and cooled outside the beampipe—might serve as a target. Mechanical and heat transport aspects of moving band targets have been studied in connection with muon production [4]. A (wire-like) band 0.04 cm wide, t interaction lengths thick, has the same $\overline{p}$ yield per proton as above but with increased $\overline{p}$ loss. The parameter u increases from 0.0001 to 0.0127, the optimum number of turns is reduced to 340, and per Eq. 2 now $0.945\,Y$ $\overline{p}s$ are created per proton accelerated. Liquid jet targets [2] or firing pellets across the beam [3] have been considered in connection with ν-factories and other applications. These options come close to a levitating target and offer perhaps superior heat transfer to a band target but may be somewhat restrictive in their choice of materials.

Beryllium and carbon are the most likely candidates because of low Z and good thermal properties. Energy deposition in the target is almost entirely due to ionization losses of the proton beam. Target heating and its dissipation are best studied by simulation but are not likely to pose insurmountable problems. Manipulating the proton recycling scheme could be exploited to mitigate targetry problems, e.g., early on when the beam is most intense one opts to keep the beam in the Main Injector for multiple revolutions allowing a band target to progress and cool further. The small price to pay, (5.5%) for the 0.04 cm wide band target in the example above, suggests wider bands—and/or larger area proton beams—may be considered if target heating problems demand it. The target will not be significantly activated. For beryllium, the only nuclides of interest are tritium and Be^7. For carbon one should add to these Be^{10} and C^{11}. This results in much lower levels of activation than in the present-day thick, mid-Z targets.

5 Focusing $\overline{p}$s

To focus the (newly minted) $\overline{p}$s, a lithium lens—favored for thick targets—presents problems here because of adverse effects on both recirculating beams. A strong, variable field, solenoid such as contemplated for muon collection at a ν-factory is the most likely instrument of choice for this purpose. Acting as a recirculator could be a solenoid based ring-cooler similar to those proposed for a ν-factory [5], wherein the wedge absorbers are replaced by electron cooling. In a solenoid, the higher $p_\perp$ of the uncooled (or minimally cooled) $\overline{p}$s guarantees a larger beam radius vis-a-vis the protons at the target location—as is desired in this scheme. A magnetic horn, a widely used focusing device, is another possibility. Its field free center allows both recirculated beams to pass through unaffected while scattered $\overline{p}$s from the beam get refocused in the field region along with newly created ones. The material present in the horn may be detrimental to a recirculating beam.

Elsewhere in the target hall, problems with energy deposition and radioactivation are expected to be comparable to the present system. A dump—with apertures for p and $\overline{p}$s—must be present downstream to intercept pions, etc., created in the target. The considerable distance between where pions are created and absorbed means energy deposition will be considerably diluted compared with direct dumping.

6 Concluding Remarks

To attempt a crude estimate of $\overline{p}$ yield gains vis-a-vis the present day $\overline{p}$-Source, some of the numbers derived above are now combined with those of Ref. [1]. The best case(s) of Ref. [1] predicts gains in (noncirculating) $\overline{p}$ yield close to an order of magnitude over a single-pass target. This factor, 9.7 if one compares predictions for a thin beryllium with a thick copper target, includes some of the considerations mentioned at the end of Sec. 3. It must now be discounted for the reabsorption of the recirculating $\overline{p}$-beam by the numbers estimated above. A levitating disk target incurs virtually no reabsorption loss while a band target cuts yield gain only slightly (by 5.5%), to 9.2. For a target covering both beams yield would still be up by a factor of 3.5. Collection efficiencies for a variable field solenoid or magnetic horn are expected to differ from a lithium lens. For a horn used with (thick target)

$\overline{p}$ production at CERN a 20–40% penalty [6] is estimated. For a variable solenoid the penalty—if any—is likely to be less but at perhaps considerably higher cost. Even the horn estimate leaves an overall improvement factor of 5.5–7.5 for the levitating disk or band targets and 2–3 for the large area target. Further reductions, such as reduced collection efficiency, are likely to apply so that such gains may well be hard to achieve in any practical scenario. Nonetheless, it might still be interesting to study in more detail how to optimize a recirculating scheme with respect to $\overline{p}$ production and focusing, target heating, p and $\overline{p}$ recirculation optics, cost, etc.

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References

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