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ANTIPROTON PRODUCTION AND COLLECTION
FOR THE CERN ANTIPROTON ACCUMULATOR

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Summary

Antiprotons are produced for the CERN Antiproton Accumulator (AA) by focusing 26 GeV/c protons onto a 3 mm diameter, 11 cm long copper wire. Negatively charged particles with momenta about 3.5 GeV/c are focused by a short focal length coaxial horn and transported to the AA by a normal quadrupole focusing channel. The yield of antiprotons was found to be considerably less than anticipated (factor about 2) and the reason is presumed to be the assumption of too large a production cross-section in the original machine design proposal. Studies involving new horn design, introduction of an axial current ($\approx$ 150 kA) along the target and use of lithium lenses as an alternative to the magnetic horn are under way. Some preliminary measurements involving some of these techniques have been made, both to confirm the validity of calculations and to test the feasibility of building targets and focusing systems to withstand the mechanical forces and heat load due to the proton beam and the high pulsed currents.

Introduction

At the last Particle Accelerator Conference (Washington, 1981), the measured antiproton yield at the CERN accumulator (AA) was reported as down by a factor of $\sim$ 4 from the value of 2.5×10^{-6} ($\bar{p}/p$) projected in the AA design study[1]. Since that time a modest improvement ($\sim 7 \times 10^{-5}$ $\bar{p}/p$) has been obtained but it is now thought that this is near the maximum value possible with the AA and target station in their present states. Before giving reasons for this belief, the target station and transfer line as well as the techniques for measuring yields will be described.

Target Station and Injection Beam Line

The layout of the target area is shown in figure 1.

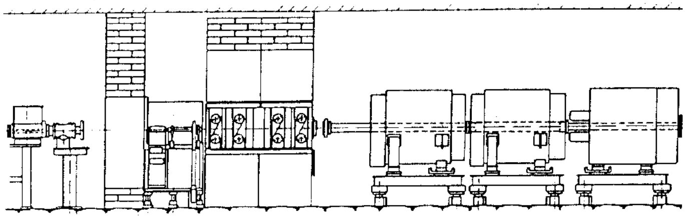

Figure 1. AA Target Area.

From the left there is the last proton focusing magnet, beam transformer, "hot cell" with target and horn, collimator and the first two lens and deflecting magnet before the proton dump. Details of the target and focusing horn are shown in figure 2.

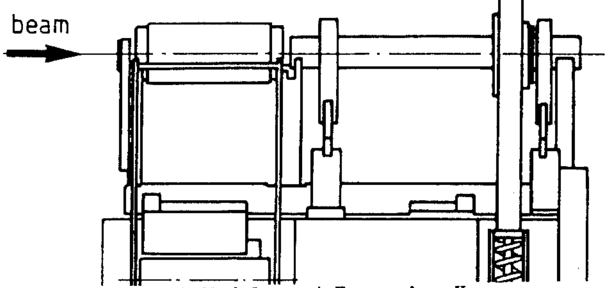

Figure 2. Target Module and Focussing Horn.

The target module and horn are mounted on seperate V-blocks which have been prealigned to the axis of the injection beam transport line. Transverse positioning tolerances are 0.1 mm. The transfer lines around the AA have been described[3]. The main difference between the installed system and that of the design study is that copper has replaced tungsten as the target material. Together with small changes in geometry, this results is a slightly higher optimum horn current ($\sim$ 165 kA). Also, for mechanical reasons, the inner conductor of the horn assembly has been thickened from 0.5 to 1.0 mm giving an increase in the scattering of the antiprotons. Figure 4 gives a comparison of measured and calculated antiproton yields for different horn currents.

Operating Experience

Horn

Since start-up there have been two horn failures. The first was thought to have been due to an accidental mis-steering of the proton beam, while the second appeared to be due to mechanical failure after 1.7×10^{6} pulses. (It had previously been tested for 0.1×10^{6} pulses without beam.)

Target Assembly

The initial target material used was tungsten and was found to suffer only superficial damage[2]. Since then, copper targets of 3 mm and 6 mm diameter have been used. The proton beam is focussed onto a scintillation screen mounted on the front of the target assembly. There is a 2 mm diameter hole pierced in the center of this screen. Under normal operating conditions more than 95% of the beam passes through this hole with a dim halo extending out to $\sim$ 3 mm diameter visible via the TV viewing system. Best yields have been obtained with 3 mm diameter copper targets. Proton intensities of up to 1.3×10^{13} protons/pulse have been used with no apparent target damage.

Methods for Yield Measurements

Yields are defined as the number of $\bar{p}$ injected into the AA ring normalized to the primary proton beam intensity and are measured on a single-shot basis. Different methods have been developed to measure the circulating antiproton beam.

A. Yield with Spectrum Analyzer.

The only absolute method available for measuring the current of $\bar{p}$s in the AA is the direct current transformer[4]. However, this is not sensitive enough to measure the antiprotons injected in one pulse. Instead, the signal from the loops on the ferrite cores which are used for the pre-cooling momentum system acts as a secondary monitor. The 100th harmonic of the revolution frequency is selected for maximum sensitivity and the Schottky signal scanned over a frequency range corresponding to the spread of momentum of the antiprotons injected. The signal is digitized by a Hewlett-Packard 8566A Spectrum Analyzer; a pre-stored background signal is subtracted and the result is integrated numerically to derive an

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antiproton intensity signal. A calibration against the direct current transformer must be made using more intense proton or stacked antiproton beams.

B. Electron Yield

The previous method is slow (∿ 30 sec) compared with the proton beam repetition rate (2.4 sec), a faster technique which is valuable for yield optimization makes use of elections that are injected along with the antiprotons. Electrons injected into the AA lose 1.8 MeV per turn and spiral into the closed shutters seperating the injection from the stack orbit. The radiation downstream from a shutter is measured with a shower detector and the signal is fed into an integrator gated from 5 to 20 µs after injection. During this period, the signal is dominated by the electron showers. Under stable machine conditions, the integrated signal is proportional to the yield measured by the spectrum analyzer method.

To obtain best yields requires that the antiproton beam is steered through the injection line with maximum efficiency. Again, the injected beam cannot be used directly. Instead, use is made of the possibility available of injecting protons from the proton synchrotron at the AA momentum (∿ 3.5 GeV/c). These are transported through the normal antiproton ejection channel. This proton beam, circulating on the injection orbit (but in the opposite direction taken by antiprotons) is then ejected by the antiproton injection system used in reverse and is sent down the injection line towards the target and is clearly visible as a well defined beam-spot on the scintillation screens mounted in the line and on the front of the target module. Steering can then be adjusted as required. Later, when antiproton injection is attempted, a further fine adjustment is possible using the electron signal mentioned above. This signal is modulated by coherent oscillations of the injected electrons. When these oscillations are minimized by resteering the beam, it is usually found that the best yield is obtained.

Comparison Between Measured and Calculated Yields

Calculation of yield have been performed using Monte Carlo techniques. These calculations do not fully represent all the processes involved in antiproton production but are believed to include the most important ones. For the design study, the finite width of the proton beam and target, absorbtion of protons and antiprotons in the target, scattering of the antiprotons by the aluminum inner conductor, and the exit face of the horn and the angular dependence in the antiproton production were modelled. Scattering in the target was ignored as was the development of the hadron cascade and the presence of non-axial trajectories from the target. The calculation of particle trajectories in the azimuthal field between the inner and outer horn conductors (1/r dependence) used integrations made possible by dropping high-order terms[5]. The early predictions are larger than the highest measured yields by a factor ∿ 3.5. This discrepancy has led to a review of the basis nuclear collision parameters. Re-examinations[6,7] of the available experimental data for antiproton production indicated that the value of differential cross-section for antiproton production per interacting proton at zero degrees should be reduced by a factor between 1.9 and 2.2. A further reason for the low yields can be found by examining the measured transverse acceptances of the AA ring. The largest values so far obtained amount to 80 to 85 π mm mr instead of the designed values of 100 π mm mr in both the horizontal and vertical planes. Furthermore, as reported elsewhere at this conference[8], there is incomplete filling of the available aperture by particles with large betatron oscillation amplitudes. This is a property of the AA ring itself and does not depend on the availability of antiprotons in the injection channel.

Yields have been recalculated (Table I) using a modified version of the Monte Carlo program (eg., off-axis trajectories from the target are now included) but otherwise the main features named above are maintained. These calculations have been made for the geometry of the installed target and horn using the parameter listed in Table II.

Table I

	Material	Yield × 10^7 $\bar{p}$/p Copper	Tungsten
Diameter			
3mm	Meas	7.0*	6.1
	Calc	9.8	9.4
6 mm	Meas	6.7	5.2
	Calc	9.0	8.2

*Measured values normalized to this value.

Table II

Parameter List for Monte Carlo Calculations

Proton beam radius (1 s.d. for Gaussian Distribution	0.4 mm
AA transverse acceptance	82π mm mr
Matched radius at Horn exit	19 mm
Differential cross-section for antiproton production at 0° /interacting proton	.0123(st.GeV/c)$^{-1}$
Target length	11 cm
Absorption lengths[9]*:	
protons in copper(26 GeV/c)	14.7 cm
protons in tungsten	9.4 cm
antiprotons in copper(3.5 GeV/c)	12.1 cm
antiprotons in tungsten	7.6 cm

*The absorption length data was obtained by interpolation and for antiprotons at 3.5 GeV/c by extrapolation from the measured values at 6.65 GeV/c, assuming the same variation with momentum as the p-$\bar{p}$ data[10].

The calculations do not include the incomplete filling of the aperture for the large amplitude particle. It can be concluded that to achieve any significant gain in yield some innovations are required.

Prospects for Increased Yields

It is of great importance to the CERN collider project that yields are increased at least to the level given in the design study. If, in the future, ways are found to increase the rate at which antiprotons can be stacked and cooled, then even higher yields would be demanded. Studies and initial experiments have commenced with this aim. The present CERN situation is that we have a primary proton beam with momentum limited to 26 GeV/c and an intensity of 1.2×10^{13} protons each 2.4 sec. It is hoped to be able to reach about 2×10^{13} protons/pulse. The acceptance of the AA ring, both transversely and in momentum is more or less fixed. We hope to understand why the available aperture is not completely filled and remedy this.

Another avenue for improved yield is to have a brighter antiproton source. Various schemes have been proposed involving one or more of three concepts[11-14].

1. Reduce the radius of the primary beam.

2. Decrease the focal length of the lens following the target so as to be able to collect antiprotons at larger production angles. The lithium lens[12] is a promising possibility. Alternatively one may use a non-linear lens that selectively collects some particles at higher angles.

3. Increase the density in phase space of the particles leaving the target. This can be achieved by passing a high current along the target, creating an azimuthal field in and around it.

At CERN some initial steps have been taken, or are planned, to investigate these possibilities and explore some of the formidable technical problems involved.

Conducting Target Tests

Yield improvements are expected if the target is pulsed with currents above ∿ 100 kA. For a 3 mm diameter copper target pulsed to 170 kA with a half-sinusoidal wave of duration 16 μs, the surface magnetic induction is ∿20 T, the magnetic pressure, ∿ 2×10^8 N/m^2, approaches the yield strength while the temperature rises to ∿ 1000°C.

The field inside the target at different times during the pulse has been calculated[15].

Laboratory test have been performed at CERN with the target wire embedded in a graphite cylinder with longitudinal channel to allow gas cooling with nitrogen Currents up to 190 kA are possible without the destruction of the target. Such an assembly has also been tested with the normal proton beam (although not at the maximum repetition rate). Because only one current pulse supply is available in the target area, the target was joined to the horn as shown in Fig. 3.

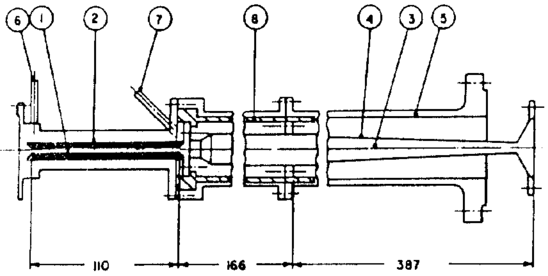

Figure 3. Horn and Target Conducting Target Tests

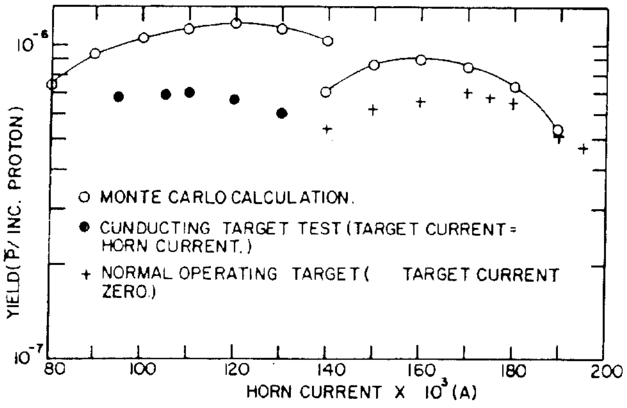

Figure 4. Measured and Calculated Yields

It was not the purpose of these tests to achieve much higher yields but rather to see if target can be made that will support the mechanical and thermal stresses imposed by the high currents and the proton beam both acting on the target. Further development towards higher currents and smaller target diameter is planned. Optimum yields will probably require that seperate current sources for the target and the collecting lens will be needed. For the tests so far concluded, no attempt has been made to prefocus the protons to compensate for the action of the internal field which defocuses the proton beam causing ∿ 20% reduction in the number of protons interacting in the target.

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