II. Antiproton Production

A. Main Injector's role

Antiprotons (or pbars) are produced by bombarding a production target with a high energy proton beam. The pbar production rate is dependent on the incident proton beam energy, the desired pbar energy, the type and length of target material and, to a much lesser extent, momentum spread. The collection efficiency is dependent on the beam spot size on the target, the gradient of the Lithium Lens and the acceptance of the beamline. The beam spot size affects the apparent size of the area from which the secondaries emanate from the target. A smaller proton beam spot results in the cone of pbars being more densely packed together.

An increase in the proton beam energy will result in an increase in yield, but by a diminishing amount after a certain energy threshold is passed. The Antiproton Source was designed for a pbar beam kinetic energy of 8 GeV, since that is the peak Booster energy and was the injection energy for the old Main Ring. Also, the peak in pbar production from a 120 GeV proton beam is close to 8 GeV. A higher energy proton beam will increase pbar yield, but a beam energy of 120 GeV is the best compromise between targeting efficiency, cycle time and design constraints for the transport line. Prior to its decommissioning, the Main Ring was capable of delivering 120 GeV protons with up to a 2 second cycle time. The Main Injector was built, in part, to reduce the cycle time. Unfortunately, stochastic cooling limitations kept the Antiproton Source from taking advantage of the shorter cycle times. The Main Injector Design Report called for an intensity of 5 x 10^{12} protons per stacking cycle with a 1.5 second cycle time. With the implementation of "slip stacking", Main Injector has been able to deliver 8E12 or more protons per stacking cycle. Running the Main Injector in "mixed-mode", where beam to NuMI and Pbar are accelerated together, now limits the cycle time to no shorter than 2.2 seconds.

A single Booster batch comprised of 84 53 MHz bunches (there are actually fewer bunches due to the Booster extraction process) is accelerated in the Main Injector on stacking cycles. Two Booster batches are slipped in time in the Main Injector to effectively double the number of injected protons. Radio Frequency (RF) manipulations are performed on the beam at 120 GeV, just prior to extraction from the Main Injector, in a procedure known as bunch rotation. This process, described below and shown in figure

2.1, narrows the bunches in time at the expense of increasing the momentum spread (Δp/p). The Δp/p of the antiprotons is minimally affected by the Δp/p of the protons hitting the target. By narrowing the bunches prior to extracting them from the Main Injector, the phase space density of the antiprotons is maximized, resulting in a smaller Δp/p in the Debuncher ring after bunch rotation and momentum cooling.

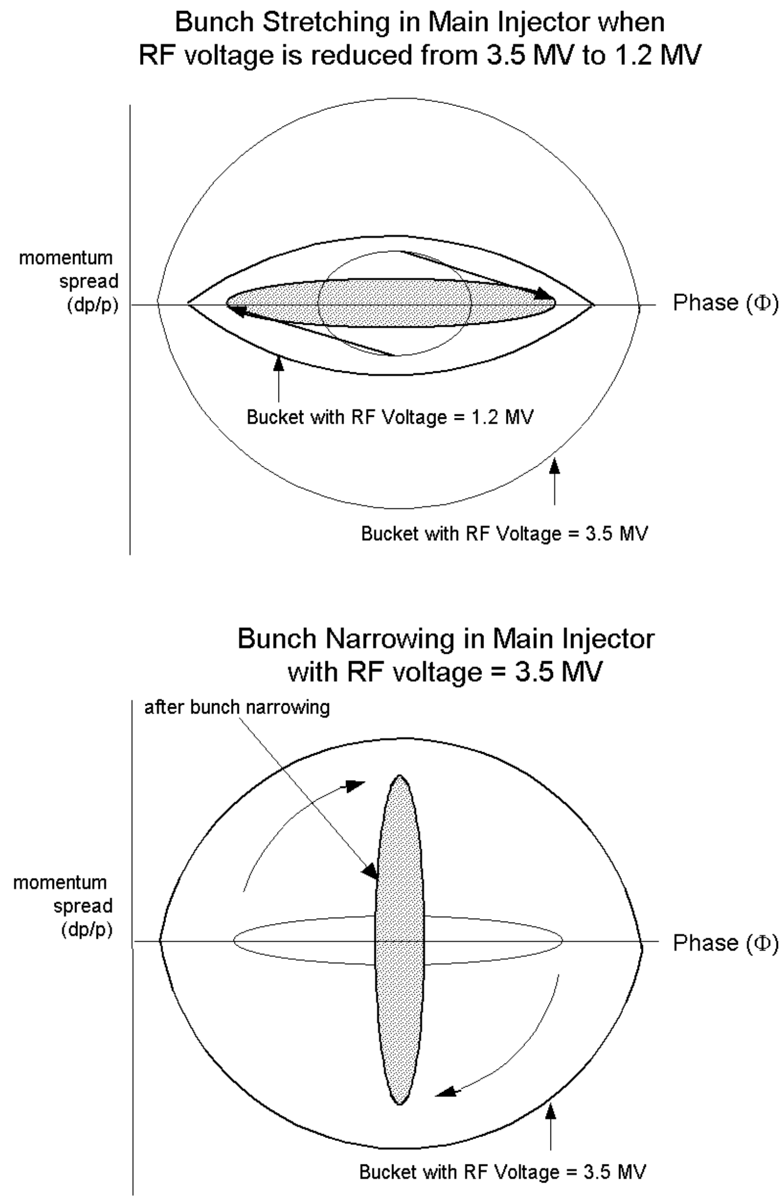

Figure 2.1 Main Injector Bunch Rotation

Once the beam reaches flattop in the Main Injector, the RF voltage is quickly lowered to 1.2 MV from its normal value of 3.5 MV by turning off 12 of the 18 RF stations. The RF is left at 1.2 MV for about 1.9 milliseconds while each bunch stretches in time, occupying a large time spread and small momentum spread. The RF is then quickly increased back to 3.5 MV. One quarter of a synchrotron oscillation or approximately 1.2 milliseconds later, the bunch has rotated 90° in phase space, reversing the time and momentum spread.

After bunch rotation, the beam is extracted from the Main Injector towards the pbar production target. The proton bunches have a small time spread and a large momentum spread. The extraction process is completed in a single turn by a fast rise time kicker located at MI-52, which kicks beam into the field region of a set of three Lambertson magnets. The extracted beam travels down the P1 line, continuing into the P2 line in the Tevatron enclosure at F0, then follows the path of the decommissioned Main Ring to F17. At F17 a B3 magnet and a pair of C-magnets bends the beam upward into the AP-1 line. The AP-1 line exits the Tevatron enclosure at F18 and continues through the Pre-Target and Pre-Vault enclosures before reaching the production target in the Target Vault. A pair of "Sweeping Magnets" are located in AP-1 at the end of the Pre-Vault enclosure and are used to minimize peak heating in the production target. A toroid, M:TOR109, is located in the AP-1 line in the narrow space between the Sweeping Magnets and the Target Vault wall to provide a measure of beam intensity at the production target.

B. Target Station

The actual production and collection of antiprotons occur in a specially designed vault located 17 feet below the floor of the AP0 service building. The Target Station components are hung from 6-foot high steel modules that are suspended into the Vault. This arrangement allows easy removal and replacement of faulty components and the steel provides radiation shielding. The major components as seen by the incoming proton beam are:

Upstream sweep magnets – This system is actually located just upstream of the Target Vault, in the Pre-Vault enclosure. It was included here because it is functionally part of the Target Station and was designed to have components in the Vault itself. The Sweeping System has magnets that produce a rotating dipole field that deflects the proton beam in a roughly circular pattern on the target to minimize local heating. Antiproton yield increases with a smaller spot size down to a beam σ of about 0.13 mm, but increases the peak heating on the target. A proton beam intensity of 5E12 or more causes the loss of target material around the outside circumference of the target. The Sweeping System only moves the beam a few σ's, enough to reduce the local heating by about a factor of 2-3. Use of the Sweeping System only slows the rate of target deterioration, which is caused by a complex combination of oxidation, thermal and mechanical effects. The original Sweeping System design included a downstream Sweeping Magnet to create a closed orbit bump through the target vault. It was to be located immediately downstream of the Lithium Lens. The downstream Sweeping Magnet has not been used operationally because of the complexity and reliability related to running the two systems synchronously. Use of the upstream system alone was found to have a minimal negative impact on the stacking rate.

Target SEM grid – The Target SEM (Secondary Emission Monitor) is used to measure the beam position and size near the target. Central wires in the SEM are only 0.125 mm apart to provide good resolution measurements of the spot size. The SEM has motion control to move the wires out of the beam path during normal operation. Beam intensity of more than about 4×10^{12} could melt the SEM wires. Even when the target SEM is in the "out" position, the beam is only about 5mm from the wires, so grossly mis-steered, high intensity beam could still damage the wires. The SEM is under vacuum with a small, dedicated ion pump providing the pumping.

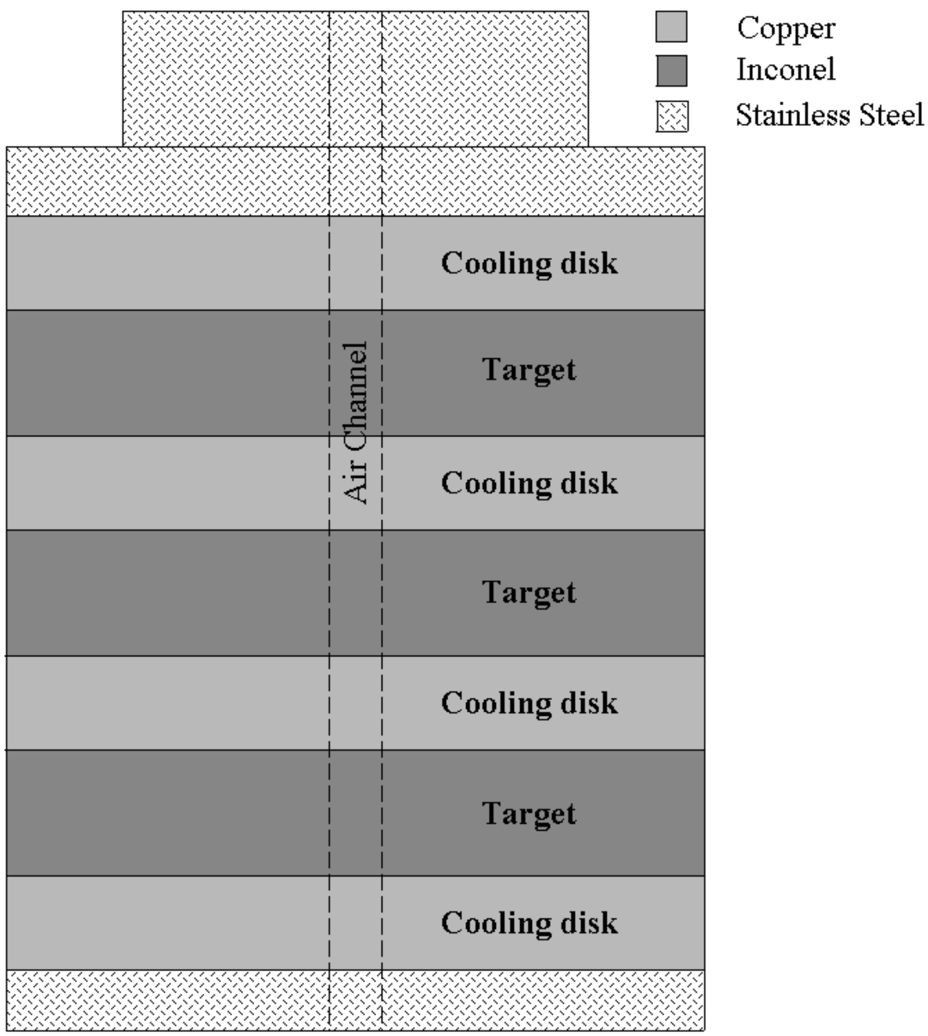

Figure 2.2 Pbar production target

Target assembly – The Target design has had a number of improvements over the years and has recently gone through another revision. The old design was made up of a stack of metal target disks, separated by copper cooling disks that had air blowing through them to provide heat removal from the targets. In the past, the target has almost always incorporated alternating target and cooling disks. Tungsten targets were used in the early years of pbar operation, followed by targets of copper, nickel and eventually Inconel (a nickel-iron alloy). Inconel was chosen as the best choice of target material because it can withstand higher stresses caused by the rapid beam heating. Figure 2.2 shows the cross section of the old target assembly used after 2006, but prior to the new design. The new target design is made of a single cylinder of Inconel, with air blowing through a heat exchanger incorporated into the center shaft. A shell of beryllium provides a cover for the Inconel target, to reduce target oxidation and damage. Since the target design is still evolving, an illustration won't be available until the design is finalized.

The horizontal target position is adjustable (D:TRX) so that the amount of target material the beam passes through can be varied. This distance, known as the target length, is one of the parameters that determine the antiproton yield. The target assembly is rotated so that target damage is minimized – depletion of the material is distributed more uniformly through the entire target. The rotation rate can be varied, but typically takes less than a minute to complete a revolution. Vertical motion control (D:TRY) makes it possible to adjust where beam hits the target or change the target disk in use. The position of the target in the z axis (D:TRZ), the distance between the target and lens, can be adjusted to match the diverging cone of secondary particles to the focal length of the Lithium Lens.

Lithium Lens - immediately downstream of the target module is the Lithium Lens module. The lens is designed to focus a portion of the 8 Gev pbars coming off of the target, greatly reducing their angular component (as illustrated in figure 2.3). Electric current passing through the cylindrical lithium conductor produces a magnetic field that has strength approximately linear with radius that focuses the 8 GeV pbars. The Lithium Lens has the advantage over conventional quadrupoles in that it focuses in both transverse

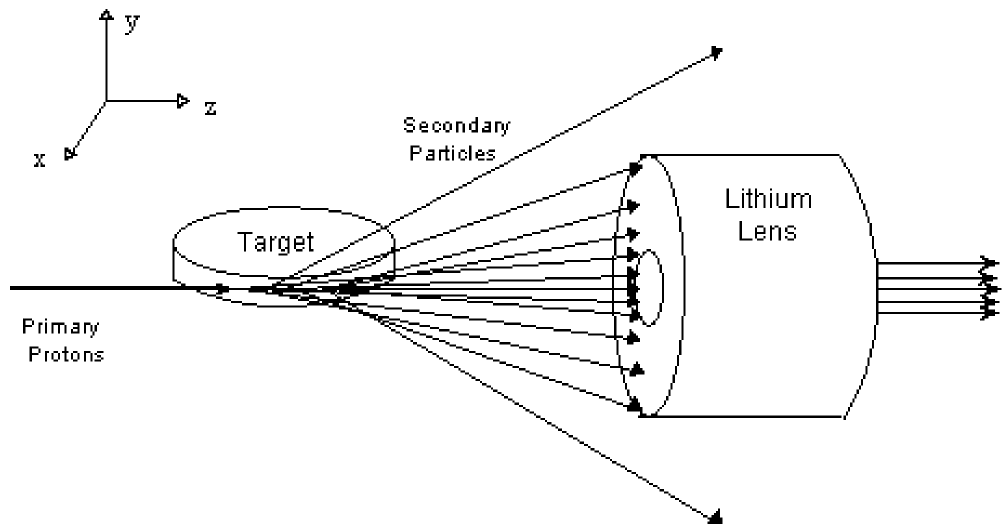

Figure 2.3 Pbar Lithium Lens

planes and produces an extremely strong magnetic field. The main disadvantage of the lens is that beam passes through the beryllium end windows and lithium conductor, resulting in about 18% of the antiprotons being absorbed. The beryllium and lithium also cause some scattering of the pbar beam, increasing the beam size. Lithium was chosen because it is the least-dense solid conductor, which in turn minimizes the scattering and absorption.

The lens is contained within a toroidal transformer and is designed to operate at a peak current of 650,000A for a gradient of 1,000 Tesla/meter (operationally lenses are run at a lower gradient to prolong their life). The transformer is used to step up the current received from the power supply (D:LNV) by a factor of 8 in order to achieve the current required. The lithium conductor is 15 cm long and 2 cm in diameter. The lens and transformer are cooled with a closed loop cooling system. Low Conductivity Water (LCW) from the closed system is heat exchanged with chilled water. Horizontal motion control is provided by a pair of eccentric shafts, which can be used to vary the position and angle of the Lithium Lens. The entire lens assembly can also be moved vertically.

Collimator – This device is used to reduce heating and radiation damage to the Pulsed Magnet, which is located immediately downstream of the Collimator. The Collimator is cylindrical in shape and made of copper, with a hole in the middle for the beam to pass through. Water cooling lines are located on the outside of the Collimator to remove heat and are connected to the Pulsed Magnet water system. Use of the Collimator, designed and implemented during Run II, was in response to reduced Pulsed Magnet survival rate as the intensity of the primary beam increased.

Pulsed Magnet – The Pulsed Magnet is a 3-degree pulsed dipole that is located downstream of the Collimator. Its purpose is to select 8 GeV negatively-charged secondaries and bend them into the AP-2 line. The dipole was designed specifically for the Target Vault and is a single-turn, radiation-hardened, water-cooled, 1.07 m long magnet with an aperture measuring 5.1 cm horizontally by 3.5 cm vertically. Radiation hardening is achieved by using ceramic insulation between the magnet steel and the single conductor bars as well as using Torlon as the insulating material on the bolts which hold the magnet together. The pulsed magnet achieves a field of 1.5 Tesla. Figure 2.4 shows the location of the Pulsed Magnet and other devices located in the Target Vault.

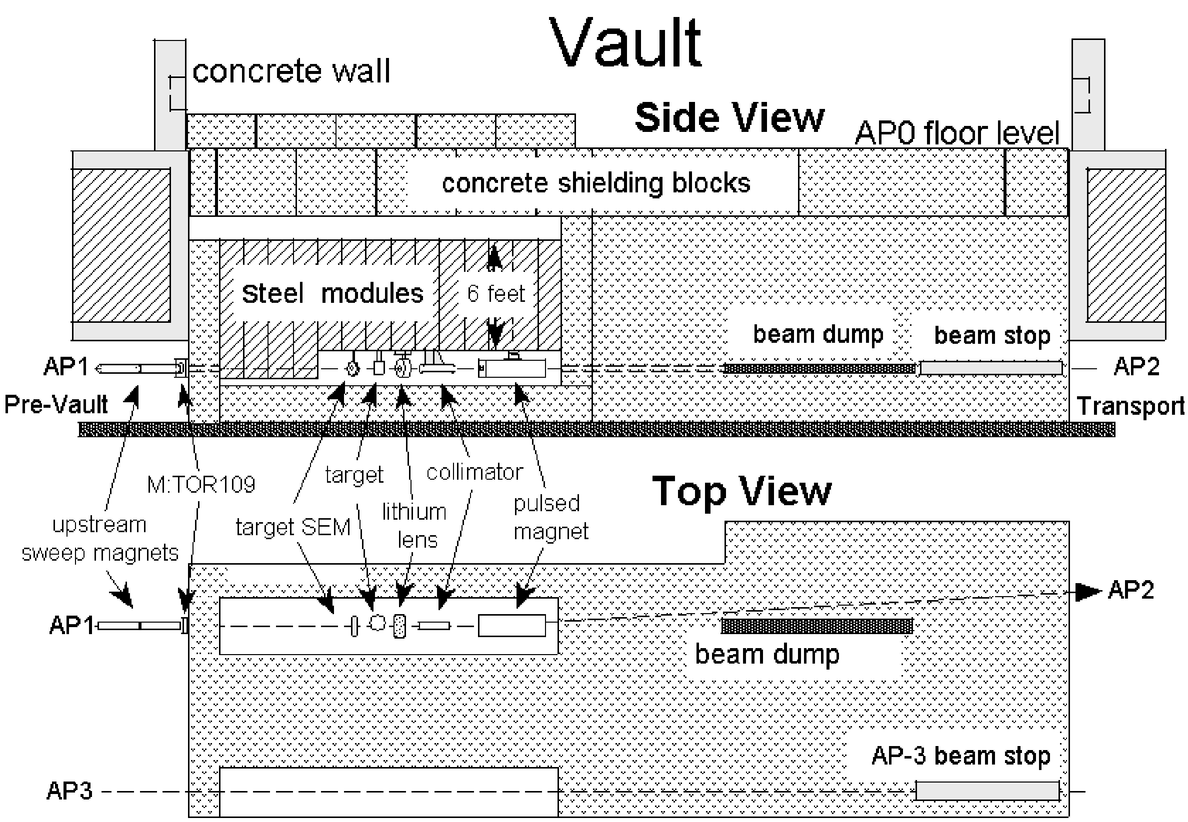

Figure 2.4 Target Vault Layout

Beam dump – Most of the particles not momentum and charge-selected by the Pulsed Magnet are absorbed in the Beam Dump. The dump is modeled after the Tevatron abort dump, with stacked steel and concrete and a water-cooled dump core in the beam path. The graphite core is encased in an aluminum shell that contains water cooling passages. A channel through the steel shield provides an exit for the 8 GeV negative beam and allows it to pass into the AP-2 line. The downstream end of the dump also contains a beam stop for the AP-3 line (D:BSC925) which is a safety system critical devices and is remotely operable. The AP-2 beam stop (D:BSC700) was originally located in the dump, but was relocated to the Transport enclosure to improve aperture in the channel through the dump steel.