Pbar Target Energy Deposition and Beam Sweeping

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Motivation

Antiprotons are produced from the interaction of a 120 GeV proton beam from the Main Injector with a Nickel alloy target. Quadrupole magnets focus the incident beam on the target. The smaller beam spot increases the antiproton collection efficiency but also increases the peak energy deposition in the target. The target material has evolved from Tungsten to Copper to Nickel and Nickel alloys over the past two decades as the combination of increased beam intensity and reduced spot size has greatly increased peak energy deposition. It is anticipated that the target presently used will experience local melting and damage from shock waves with intensities expected when slip stacking is introduced in the Main Injector. If the beam spot size is increased to reduce the peak energy deposition, antiproton yield will suffer.

The switch from Copper to Nickel targets occurred during the latter part of Collider Run I. Nickel is similar in atomic structure to Copper, so the optimum target length and yield characteristics of the two materials are nearly identical. Nickel has the advantage that the onset of melting requires nearly twice the energy deposition as

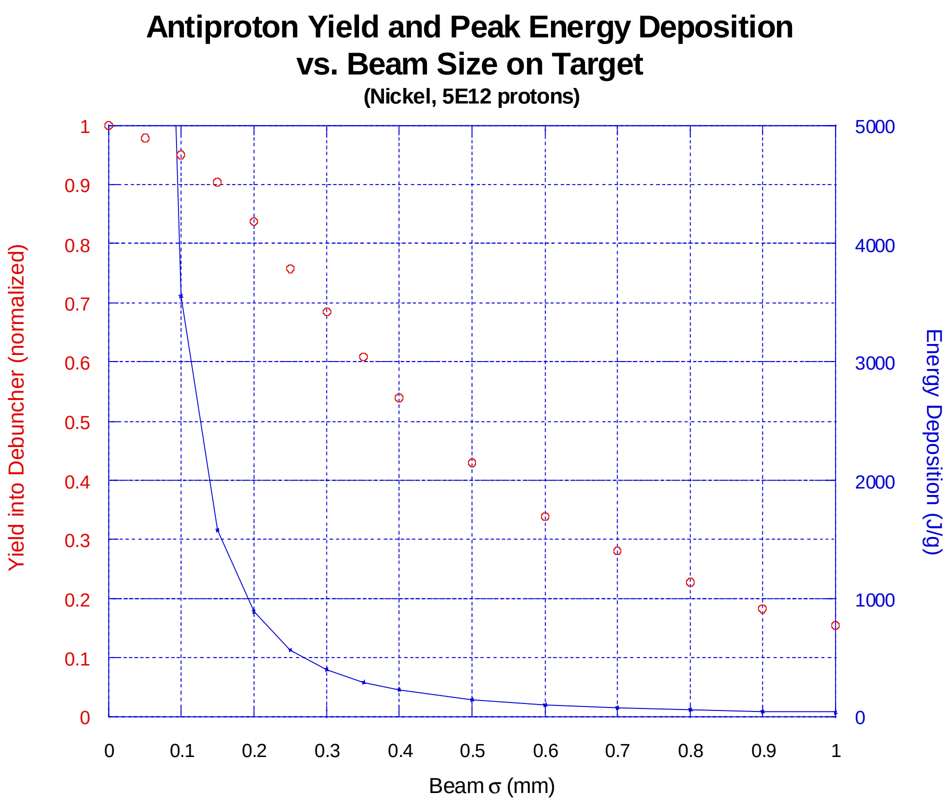

Figure 1: Antiproton yield (open circles) and peak energy deposition (solid line) vs. beam spot size on target

Copper. In addition, Nickel is more tolerant of the shock waves that develop during the beam pulse. Without a beam sweeping mechanism in place, the spot size on the target would be increased to prevent damage. The increased spot size would reduce antiproton yield 2-3% at 5E12 protons per pulse (ppp) (Main Injector design intensity) and 5-10% at ~9E12 ppp (slip stacking).

The Nickel and Inconel® targets have performed better than originally anticipated. Beam intensity on target in Run II has been as high as 5.0E12 ppp with an RMS spot size of σ_x = 0.15, mm σ_y = 0.16 mm. Although the targets sustain long term damage that results in yield reduction, the process takes place over days when beam is repeatedly targeted to the same location. Normal target rotation distributes the damage over the entire circumference of the target, extending the service life of a target to months. Target yield reduction studies suggested that damage did not increase significantly when the RMS spot size was reduced from σ_x = 0.22, mm σ_y = 0.16 mm to σ_x = 0.15, mm σ_y = 0.16 mm. Future studies will continue efforts to improve yield with smaller RMS spot sizes and to assess the resulting target damage.

An investigation into alternative target materials has again been initiated. Candidate materials are required to have similar yield characteristics and material properties that are superior to the present Nickel target. Inconel® alloys appear to be the most promising of the materials considered. Inconel® is a family of Nickel alloys containing Chromium, Iron and other metals that have excellent high temperature tensile strength. Yield characteristics of the Inconel® targets are expected to be similar to the Nickel 200 target due to the high percentage of Nickel present. The energy required to begin the onset of melting in the Inconel® targets is also similar to that of Nickel.

Peak energy deposition in the target (and stresses) can be reduced by changing the position of the beam during a pulse. The idea of sweeping the proton beam across the target to reduce peak heating was introduced in the "Tevatron I Design Report" (1984). The design phase of the sweeping project began in 1993 and included several years of research and development. Early sweeping designs made use of kicker style magnets similar to those used to transfer beam between accelerators. In the final design, the sweeping magnets have conductors rotated about the beam axis to generate a rotating dipole field. The power supply required to provide the bipolar magnet current pulse involves two-stage compression with saturated reactors.

The targeted beam needs to be moved about 0.3 mm during the 1.6 μs beam pulse to adequately distribute the beam energy. Sweeping magnets are required both upstream and downstream of the target to preserve the proper trajectory of the antiprotons entering the AP-2 line. There is a pair of upstream sweep magnets and a single downstream sweep magnet. The magnets are of the same design, but only one magnet is required in the downstream location because the proton beam energy is 120 GeV and the antiproton beam energy is only 8 GeV. There are differences in the striplines and other external details of the downstream magnet in the vault as compared to the upstream magnets located in the AP-1 line.

Goals

Beam models and measurements suggest that antiproton yield does not increase significantly when the spot size is reduced below σ = 0.15mm. Under these conditions, peak energy deposition also increases rapidly. A beam spot size of σ = 0.10mm will be defined as the lower operational limit. The goal is for the operational pbar target to withstand beam intensities of 1.0E13 ppp with a beam spot size of σ = 0.10mm while maintaining the present antiproton yield. To be successful, the following areas of effort have been defined:

- Identify alternative target materials based on high temperature tensile strength, ductility and predicted yield characteristics. Test targets with beam to compare longevity and yield characteristics with Nickel targets.
- Slip-stacking may lead to beam on target having larger transverse emittances. Develop beamline lattice changes that will reduce the beta functions at the target so that σ = 0.10mm in both planes when the proton emittance is 25 pi-mm-mr. The new optics may be required so that antiproton yield won't be lost due to a larger spot size during slip-stacking.
- Finish electrical testing and install the beam sweeping system in the beamline. Commission the sweeping system with beam.

Status

Alternative target materials

A variety of alternative target materials were considered, but nickel alloys appear to be the most suitable. In particular, Inconel® alloys were attractive because of their mechanical attributes and widespread availability. These alloys are used in high temperature applications, such as jet engine assemblies, and due to their high nickel content are expected to have acceptable yield characteristics. The Inconel® family of

	Tungsten	Copper OFHC	Nickel 200	Inconel® 600	Inconel® 625	Inconel® 686	Inconel® 718	Inconel® X-750
Weight %								
Tungsten	100					3-4.4		
Chromium				14-17	20-23	19-23	17-21	14-17
Copper		100	<0.25	<0.5			<0.3	<0.5
Iron			<0.4	6-10	<5.0	<5.0	17	5-9
Manganese			<0.35	<1.0	<0.5	<0.75	<0.35	<1.0
Nickel			>99.0	>72	>58	>58	50-55	>70
Silicon				<0.5	<0.5	<0.15	<0.02	<0.5
Aluminum			<0.01		<0.4	<0.5	<0.35	0.4-1.0
Cobalt					<1.0		<1.0	<1.0
Molybdenum			<0.35		8-10		2.8-3.3	
Titanium					<0.4		0.7-1.2	2.3-2.8
Niobium					3.2-4.2		4.8-5.5	0.7-1.2
Density (g/cc)	19.3	8.94	8.89	8.47	8.44	8.72	8.19	8.28
Spec. Heat (J/g-C)	0.134	0.385	0.456	0.444	0.410	0.373	0.435	0.431
Tensile ult. (psi)	142,000	50,000	67,000	95,000	128,000	105,000	199,000	181,000
Tensile yield (psi)	109,000	45,000	21,000	43,000	67,000	53,000	160,000	123,000
Elongation %	<1	9	45	45	50	71	25	30
Melting point (°c)	3,370	1,083	1,441	1,384	1,320	1,359	1,298	1,410

Table 1: Composition and mechanical properties of various target materials

alloys has nearly two-dozen common variants, of which five were chosen to be representative of the different varieties. See table 1 for a comparison of composition, tensile strength and other physical characteristics for various target materials.

Inconel® 600, 625, 686 and X-750 have been tested with beam and compared with nickel 200 (a relatively pure variety of nickel used to make the targets). Results from the beam studies indicate that most of the Inconel® alloys have increased tolerance to stresses as predicted. The alloys generally showed a reduced rate of yield reduction as compared with the nickel 200 target during studies where thousands of beam pulses were delivered to the same location on the target. Table 2 summarizes the relative yield characteristics of the materials during the beam studies. There were several surprising results from these studies. First, although Inconel® 600 had virtually the same antiproton yield as Nickel 200 for most spot sizes, there was a small decline in yield for the smallest spot sizes. Inconel® 625 had a small reduction in yield for all spot sizes, but had better tolerance to

Material	Spot size	Starting Yield	Ending Yield	Protons on target	Yield reduction scaled to 10^{18} protons
Nickel 200	σ_{xy} = 0.15, 0.16	1.000	0.970	5.7×10^{17}	5.3%
Nickel 200	σ_{xy} = 0.22, 0.16	0.990	0.935	6.6×10^{17}	8.3%
Inconel® 600	σ_{xy} = 0.15, 0.16	0.995	0.970	10.6×10^{17}	2.4%
Inconel® 600	σ_{xy} = 0.22, 0.16	0.990	0.960	10.7×10^{17}	2.8%
Inconel® 625	σ_{xy} = 0.22, 0.16	0.980	0.970	6.6×10^{17}	1.5%
Inconel® X-750	σ_{xy} = 0.15, 0.16	0.985	0.965	5.7×10^{17}	3.5%
Inconel® 686	σ_{xy} = 0.15, 0.16	0.970	0.935	1.0×10^{17}	38.2%
Stainless 304	σ_{xy} = 0.15, 0.16	1.000			

Table 2: Target reduction yield studies, results are normalized to Nickel 200 with a spot size of σ_{xy} = 0.15, 0.16

stresses than Inconel® 600. For both the Nickel 200 and Inconel® 600 target, yield reduction was actually less with reduced spot size. It was expected that the large increase in peak energy deposition with the smaller spot size would cause damage to occur faster, not more slowly. From studies to date, Nickel 200 still gets the greatest antiproton yield, but will probably not be able to tolerate increased stresses expected as the energy deposition is increased. Inconel® 600 shows only a modest reduction in yield with

Material	Starting Yield	Average yield after 10^{18} protons
Nickel 200	1.000	0.974
Inconel® 600	0.995	0.986
Inconel® 625	0.985	0.973
Inconel® 686	0.970	0.785
Inconel® X-750	0.985	0.968
Stainless 304	1.000	

Table 3: Target yield and depletion summary, spot size is σ_{xy} = 0.15, 0.16, results are normalized to Nickel 200

improved tolerance to stresses, while Inconel® 625 provides the smallest yield reduction at the cost of somewhat reduced initial yield. Inconel® 686 was the most disappointing target material tested with beam. The high tensile strength, ductility and elevated Nickel content made the alloy appear to be an excellent candidate material. However, beam studies showed that the baseline yield was down 3% as compared with Nickel, and the target suffered a rapid loss of yield during the depletion study.

Smaller beta functions at the target

Beamline optics improvements implemented during 2002 have already zeroed dispersion at the target. With the new zero-dispersion optics, the spot size was maintained at $\sigma_x = 0.22$, $\sigma_x = 0.16$ with transverse emittances of about 19 pi-mm-mr. Another optics change was implemented during the fourth quarter of 2002, further reducing the spot size to $\sigma_x = 0.15$, $\sigma_x = 0.16$. To meet the goal of a spot size of $\sigma_x = \sigma_y = 0.10$ with a 25 pi-mm-mr beam, the beta functions at the target will need to be reduced an additional factor of three. Beta functions in the final-focus quadrupoles at the end of the AP-1 beamline are already very large, and will get significantly larger when the betas are reduced at the target. A pair of small aperture trim magnets in this region may need to be replaced to accommodate the larger beam anticipated. New optics solutions will be modeled and tested with beam during the first half of 2003 to identify possible aperture problems.

Beam sweeping system

The beam sweeping project was initiated in 1993 and was scheduled to be operational at the start of Run II. The expectation was that the combination of RMS spot sizes experienced in Run I and the increased beam intensity anticipated in Run II would cause serious damage to the target. The sweeping system would spread the “hot spot” around so that the RMS beam size on target could be maintained at Run I levels or even reduced.

Early sweeping designs incorporated kicker style magnets that were 90° opposed to provide the desired beam movement on the target. The final design evolved into magnets with four two-phase conductor windings rotated about the beam axis. This arrangement can produce a circular beam trajectory on the target while reducing much of the local non-linearities in the magnetic field. Sweeping magnets are required both upstream and downstream of the target and collection lens to maintain the proper trajectory into the AP-2 line. The sweeping radius on the target will be about 0.3 mm, enough to reduce the peak energy deposition of a 0.1 mm RMS beam by a factor of five.

The beam sweeping system is nearly ready to test with beam. The upstream magnets have been installed in the tunnel and testing is expected to begin during the first quarter of 2003. The downstream sweeping magnet is being completed and has not yet been installed. Because the downstream magnet will become extremely radioactive after it is installed, the plan is to complete testing on the upstream system first to identify problems.

Fortunately, pbar yield in Run II has not been compromised by the delays in completing the project. Targets have proved to be more robust than predicted. Optics improvements have more than offset the increase in emittances in the targeted beam. The present RMS spot sizes are comparable to the smallest ever observed in the pbar source and the smallest used at operational intensities. At intensities of 5E12 ppp or less, the beam sweeping system would only bring a minimal improvement to pbar yield if increased target damage or local melting is observed when the RMS spot size is reduced to $\sigma_x = \sigma_y = 0.10$ mm. In any case, the increase in intensity to 8-10E12 ppp expected with slip stacking is expected to necessitate the use of beam sweeping to preserve maximum pbar yield.

Plan

Beam testing and data analysis will be completed for the Inconel® alloys during the second quarter of 2003. Special care will be taken to characterize antiproton yield for the smallest attainable spot sizes. After comparing yield and yield reduction characteristics of the various alloys, a new operational target material will be chosen. A target assembly will be put together that includes several disks of the new material plus a Nickel 200 disk for reference. The new target assembly will be installed during the latter part of 2003.

Beam optics studies will continue during 2003 to further reduce the beta functions at the target. The highest priority will be put on identifying (and improving) limiting apertures in the final-focus region of the AP-1 line. Beamline models suggest that the desired beta functions at the target can be achieved with existing magnets in their present locations.

The upstream beam sweeping magnets were installed in the AP-1 line during January 2003. The power supplies have been extensively tested prior to the magnet installation. The system will be tested with beam after interlock electronics are completed during the second quarter of 2003. The downstream sweeping magnet will be installed after beam tests with the upstream magnets are completed. It is expected that the beam sweeping system will not be required until beam intensity on target is significantly increased above 5E12 ppp. Further reductions in spot size in the near future may also make it desirable to use the sweeping system prior to the increase in beam intensity.

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