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IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981 PULSED HIGH CURRENT OPTICS FOR \overline{p} PRODUCTION AT 5.4 GeV/c

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Summary

To minimize the \overline{p} collection time for $\overline{p}p$ storage ring, the phase space density of antiprotons must be maximized within the acceptance of the antiproton cooler/accumulator. This is achieved by optimization of target geometry, target material, proton beam focusing, and antiproton collection optics. The target-station design is described for the Fermilab antiproton source. The principal difficulties arise from the need for a very intenses small proton beam on the target and for a collection device with very strong focusing to handle a wide range of angles and momenta for the antiprotons diverging from the target. Special high gradient focusing devices have been developed to meet these needs.

Introduction

The antiproton source for the Fermilab Tevatron Phase I¹ project collects antiprotons of 5.4 GeV/c from a target bombarded by protons of about 80 GeV from the Main Ring. The choice of secondary momentum is determined primarily by what is known of the momentum dependence of the forward production cross section,² but is also reasonably matched to available beam cooling techniques. For efficient collection of \vec{p} 's, one wants simultaneously angular acceptance of the same order as the rms production angle $\theta_p = \langle p_1^2 \rangle^{1/2} / p \approx 0.325$ GeV/c / 5.4 GeV/c = 60 mrad and momentum acceptance of several percent. The precooler, the first stage in the Tevatron I accumulator system, has been designed to accommodate a range of combinations of angle and momentum bite depending on the filling scheme employed and whether any transverse phase space cooling is used.

This paper discusses devices and targeting arrangements generally appropriate to this range as well as specific features of the current design. Particular emphasis is given to the description of the focusing devices called lithium lenses which appear highly advantageous as the first optical element for antiproton collection in any of the schemes which have been studied and have possible application to proton beam focusing as well.

Such devices have been used at the Institute of Nuclear Physics (INP) since 1975 for focusing electron beams in the 120-430 MeV energy range to achieve high efficiency in positron production.³ We will describe stronger lenses which have been developed by INP⁴ for the Fermilab and UNK antiproton sources. We also describe briefly a 50 kG dipole being built at INP used for rapidly moving the \bar{p} beam upwards so that the return beam of \bar{p} 's to the main ring can bypass the target train using the same transport elements upstream of the target.

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Lithium Lenses

Basically, a lithium lens is a cylindrical conductor carrying a high pulsed current. For uniform current density j_z there exists an azimuthal field with radial gradient

$$dB_{\theta}/dr = \mu_0 j_z/2\pi a, \qquad (1)$$

where a is the radius of the conductor which is taken as concentric with the z-axis of a cylindrical coordinate system. Such monopole lenses were proposed by Panofsky⁵; unlike quadrupoles, they have the same focusing for all azimuth. Lithium is particularly suitable for a metallic lens because it has low resistivity ($\rho = 10^{-7} \ \Omega m$) and the least nuclear absorption ($\lambda = 120 \ cm$) of any metal.

To obtain the highest possible field strength, the lens is excited with a pulsed current. Because the current distribution should be uniform, the minimum pulse period must be chosen to make the skin depth δ comparable to the conductor radius, 6

$$a = 0.7\delta = 0.7 \sqrt{\rho \tau / \pi \mu},$$
 (2)

where the unipolar current pulse is taken to be half of the sine wave with period τ . The fact that the current pulse may be shortened as the lens radius is reduced means that the heating does not depend on the current density. The limiting excitation is most usefully expressed as a maximum magnetic field at the surface of the conductor. The joule energy/unit volume/pulse is

$$\Delta q = j_m^2 \int_0^{\pi/2} \rho \sin^2(2\pi t/\tau) dt \sim \frac{1}{4} j_m^2 \rho \tau, \quad (3)$$

where j_{m} is the peak current density and the temperature variation of the resitivity ρ is neglected. The field on the surface of the conductor is

$$B_{a} = \mu_{0} I / (2\pi a) = \mu_{0} a j / 2.$$
 (4)

Substituting into Eq. (3) for τ from Eq. (2) and for j from Eq. (4) one obtains, independent of current density and resistivity,

$$\Delta q = \frac{\pi}{0.49\mu} (B_a^2)_{max} \propto c_p \Delta T, \qquad (5)$$

where c_p is the heat capacity. Because lithium has a substantial volume change at melting (1.5%), it is mechanically difficult to make a lens in which the lithium melts during the pulse. Therefore B_a is limited according to Eq. (4) by the temperature



inner titanium cylinder 7 steel sleeve 1 12 ceramic ring 17 lead washer 2 lithium current contact 13 lead washer 18 Ti flange 3 water circuit 8 separating cylinder 14 fill port 19 Ti end cap 4 outer titanium cylinder 9 water circuit 15 beryllium beam window 20 BeO ceramic ring 5 lithium current feed 10 threaded rods 16 Ti foil 21 lead washers weld 11 ceramic ring

Fig. 1. Longitudinal cross section of lithium lens.

difference $\Delta T = T_{mp} - T_{av}$ between the melting point and the average temperature at which the lithium can be maintained. Both by calculation⁶ with the correct temperature dependences for ρ and c_p and by measurement, it has been found that the limiting field on the surface of a lithium lens is 170 kG corresponding to heating between 20°C and the melting temperature 186°C during each pulse. For lenses which are cycled rapidly the practical limitations on heat transfer may require a substantially higher average temperature and therefore much lower maximum field. Note that for lens aperatures of a few mm, the lithium lens can provide gradients of several times 10⁴ kG/m. Such gradients make it possible to use lengths of 10 cm or less in our applications thereby keeping nuclear absorption to less than 10% and scattering of the beam to a barely significant level.

In Fig. 1 we show a cross sectional view of a lens which produces $B_a = 100$ kG at the surface of a conductor of radius a = 2.5 mm on a 13 Hz cycle. The current excitation is 125 kA on a 50 µs pulse. The lithium is contained by a double-walled titanium water jacket.

The titanium jacket must withstand the mechanical stresses caused by the magnetic field as well as those caused by thermal expansion of the lithium. However, the titanium wall must be made thin enough so that most of the current flows in the lithium instead of the titanium. Titanium also has a rather low thermal conductivity, necessitating as thin a wall as is practicable.

Since the lithium is in a closed container, the inner (1) and outer (4) titanium cylinders are the structural elements which are elastically deformed due to volume expansion of lithium. It is assumed here that under the pressure of a few hundred atmospheres, lithium behaves as a liquid. At the ends of the inner cylinder, the walls are enlarged to withstand the concentration of stresses at the joint of the inner and outer cylinders. The welding of the inner and outer cylinders is performed over their outer perimeter (6) in order to increase the welding area. Two methods of welding were tested: electron-beam vacuum welding and electric-arc welding in an argon atmosphere. The latter way is a simpler one and gives satisfactory results in an oxygenless atmosphere. In order to remove stresses after welding, annealing is done by heating the entire internal titanium part together with the ceramic insulators (11,12) to 900°C in vacuum.

A water circuit (3,9) to provide uniform water flow throughout the inner cylinder is formed by placing additional separating cylinders (8) and an internal ceramic insert (12) between the titanium cylinders (1,4). These additional cylinders and ceramic are cut in half lengthwise to allow them to be put on the internal cylinder before welding.

A ceramic ring (11) serves as an insulator dividing the parts of the lens at different potentials. An annealed copper foil compressed before welding, is used to seal the joint between the ceramic and the titanium.

The current feed to the operating part of the lens is through the peripheral lithium (5) which is contained by steel sleeves (7). The outside of these sleeves are the current contacts which are tightly clamped to the secondary turn of the airinsulated transformer.

At each end of the lens assembly is an oxide coated titanium end cap (19) with a beryllium beam window (15). The end cap is insulated electrically from the current contacts by a BeO ceramic ring (20) which is protected against cracking by thin lead washers (21) on either side of it. The window and ceramic insulator are fit into a titanium flange (18). The inside surface of the window and this flange are covered with titanium foil (16) to seal the joint between them. The seal between the current contact (7) and the end-cap assembly and the flanges of the outer titanium cylinders is provided by narrow lead washers (13, 17).

The structure is held together with six longitudinal threaded rods (10). The rods carry no current because the end caps are oxide-coated and the rods are glass-coated or wrapped with polyamide film.

The lens must be filled in such a manner that it is free of voids and weak spots. The filling mechanism is diagrammed in Fig. 2. For the filling process, the complete lens assembly is heated to 250° C. The lens is flushed with argon via the exit port tube and argon pressure is maintained a little above atmosphere during the filling process to keep air out. Molten lithium from a heated bellows installed in a hydraulic chamber is injected into the lens via the fill port (14). The injection pressure is ~ 100 atm. to minimize the possibility of bubbles.



Fig. 2. Lens filling scheme.

When the molten lithium closes a circuit in the exit tube, water is circulated through the exit port cooling jacket to form a solid plug in the exit port and the oven is turned off. The details of the cooling process are also important to avoid bubbles.

In multi-Hertz operation, a major problem is the removal of the heat generated in the lens. At 100 kG field and 0.5 cm diameter, the heat released during each pulse in lithium amounts to $Q \approx 7$ cal per cm of length or 35 cal/cm³. This heat must flow through the inner titanium cylinder wall to be removed by the circulating cooling water. The temperature drop may be evaluated as

$$\Delta T_{\lambda} = \frac{Q_{p} \Delta}{\lambda \tau 2 \pi (Q + \Delta/2)},$$

where Δ is the wall thickness, a the conductor radius, and λ the thermal conductivity. At 10 Hz repetition rate ($\tau = 0.1$ sec), a wall thickness Δ = 0.7 mm was chosen resulting in a drop $\Delta T_{\lambda} = 150^{\circ}$. With water velocities about 6 m/sec, the titanium to water drop, ΔT_{w} , can be $\approx 20^{\circ}$ C. Thus, this cooling can result in an average lithium temperature T_{avg} = $\Delta T_{\lambda} + \Delta T_{w} + T_{ow} = 180^{\circ}$ C. The lithium does not melt. At 10 Hz operation, the specific heat of fusion of lithium, 83 cal/cm³, is higher than the heat released per pulse, 35 cal/cm³. Even if the lithium were to melt, the lens could function, but for mechanical stress considerations, we prefer to design so that the lithium remains solid. Experiments at 13 Hz and 100 kG field have resulted in a temperature in the lithium lens center of $T_{avg} = 170^{\circ}$ C as measured by thermocouple.

Target Station

The target station (Fig. 3) consists of the proton lithium lens (shown in Fig. 1), a heavy metal target, an antiproton collecting lens (shown in Fig. 4), and a pulsed vertical dipole ('C' magnet, shown in Figs. 7 and 8). The proton lens can focus the 80-GeV protons to a 10 micron spot on the target at 50 cm, thus providing a very bright \bar{p} source. The collecting lens is larger in diameter and located close to the target (20 cm). This lens captures diverging beam from the target and directs it into the acceptance of the \bar{p} transport system to the precoder.

The target station is located at the entrance to the target vault. After bombardment with 80-GeV protons, the target and downstream proton dump area will be a very high radiation area. Because of this, the elements such as lithium lenses and target are designed to allow fast remote disassembly and replacement (see Fig. 5). In the event of a failure of a major component, such as a transformer, the whole station may be disconnected remotely and withdrawn for repair.

This target station design depends critically on some trick to preserve the target from destruction by the beam within a single fast spill. One possibility is to place a fast kicker upstream in the proton beam to sweep across the target faster than thermal shock propagates in the target material, viz. ~3 mm/µs. A synchronized kicker downstream is needed to keep the production steered into the secondary beam acceptance. Although there is no fundamental objection to such a scheme, the present choice is to divide the Main-Ring beam into 13 fast spills of 2×10^{12} each separated by 100-200 ms and to increase the beam spot size sufficiently to preserve the target. In this circumstance, the proton beam lens is not really necessary because the focusing required is easily obtained by ordinary transport line quadrupoles. However, the collection lens must now run at as high as 10 Hz which is higher than the design value of the 1 cm radius lens. Because the initially required acceptance is only 5×10^{-6} m, however, the proton beam lens, which is adaptable to 10 Hz operation, can be used as a collector.

Power Supply

The power supply pulser system for the lithium lens must store sufficient energy to provide a long enough pulse to assure a uniform current distribution in the lens. A pulse of 50 μ s is sufficiently long that the skin depth in lithium is nearly equal to the conductor radius.

The pulsers will be located in a normal environment about 50 meters from the lens. The \bar{p} target station, which includes the lenses, will be in a very high radiation zone. Connections from the pulsers to the lenses are via balanced coax. In order to minimize failures, the current step-up transformers, located near the target, are insulated with concrete, ceramic, and air. This pulser is diagrammed in Fig. 6. Energy is stored in a capacitor bank of 24 to 100 µf. This capacitance, when charged to about 7 kV is switched to the primary of the balanced coax feed transformer using either



Fig. 3. Target station.



Fig. 4. Antiproton collecting lens.

thyristors or an ignitron. Current is stepped-up at the target station to the required 250 to 500 kA. The final transformer is air insulated for quick easy remote disassembly. The lens is incorporated in the secondary so as to minimize inductance.

The initial turn-on of the thyristor pulser is accomplished by charging the capacitor through the half-wave rectifier shown at the lower left. Switch $\rm T_3$ is fired prior to beam arrival time to allow



Fig. 5. Lithium lens disconnected from the transformer.



Fig. 6. Lithium lens solid state pulser schematic.

uniform current distribution in the lithium. Switch T_2 allows a path for charge recovery to the inductor and switch T_1 is turned on to replenish the charge from the three-phase full wave rectifier.

50 kG Dipole

In the Tevatron I scheme, 8-GeV antiprotons from the accumulator are reinjected into the Main Ring through the same beam transport and septum that carried 80-GeV protons to the target. To separate the 4.5 GeV production from the 8-GeV \bar{p} line, a 50kG dipole 8-cm long is pulsed during the spill giving the antiprotons an upward bend of 20 mrad.

A prototype of the magnet has been tested at INP. A cross-sectional view of the magnet appears in Fig. 7. A single-turn copper coil is framed by two semicircular cores of stacked laminations. The coil conductors are keyed directly to the cores by iron keys. There are two cooling channels in the conductor. The electrical insulation is provided by placing three sheets of annodized aluminum foil between the half-cores, three sheets over each half core separately, and three additional sheets around the whole circumference. This insulation is good for about 500 V, whereas the excitation is less than 100 V. The whole structure is contained in a shrink-fitted iron sleeve.

The laminations have a cutout to provide a channel for the return \overline{p} beam to pass through the magnet core. The magnet is drawn in Fig. 8 mounted on its pulse transformer. In this prototype form,



Fig. 7. 50 kG Dipole cross section.

the current contacts have not been designed to clear the return beam.

Figure 7 shows a shaping of the conductors for the purpose of field correction. This shaping has not been done on the prototype; in fact, field measurements to determine the correct shimming was one of the major goals of the prototype project. As constructed with flat conductor surfaces, the 1% good-field width is about 1/3 the conductor width of 3 cm. The gap is 2 cm high by 3 cm wide. The magnet has been pulsed many millions of ~ 1 ms pulses at 15 Hz with no problem.

Periodic Target Channel

One of the major problems in the optimization of the beam optics for high luminosity production is



Fig. 8. 50 kG Dipole and pulse transformer.

the loss of acceptance because of the limited depth of field of the collecting lens. This limitation favors the choice of a dense, high-Z target to localize the production. However, such targets limit the acceptable primary intensity far more strongly than light targets. Beryllium has the best combination of mechanical properties, low target scattering, low energy deposition from the electromagnetic cascade, etc. One way to combine the advantages of beryllium targets with very short focal length optics is to place a series of short targets at the foci of a series of lenses as sketched in Fig. 9.⁸ In order to keep the proton



Fig. 9. Periodic target channel concept.

beam focused on these targets, the targets themselves are powered as cylindrical lenses defocusing for antiprotons. By applying accelerator lattice techniques to this FODO channel, it is possible to determine reasonable excitations which render both the proton beam and antiproton beam motions stable and give the correct proton and antiproton β functions to produce the desired proton beam spot and antiproton angular acceptances simultaneously.⁹ A series of three 6-cm long, 2-mm diameter beryllium targets pulsed at 30 kA separated 15 cm center-to-center by the type of lithium lens shown in Fig. 1 pulsed at 90 kA, is 25% more efficient than an optimum tungsten target under the currently-proposed targeting parameters for Tevatron I. Furthermore, because of the properties of bery1lium, such a target should tolerate four times as much beam as a tungsten target. The yield has been calculated in a rather realistic Monte Carlo simulation, but it is not certain that the arrangement quoted is really optimum. The relative advantage of multiple targets vs. standard targetry is strongly dependent on the secondary acceptance. The results above are quoted for $5\pi \times 10^{-6}$ m antiproton acceptance with an rms proton beam spot of 0.22 mm. For larger acceptance or smaller beam spot, the multiple target channel should be more advantageous.

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