# High Gradient Lithium Lens

April 10, 2003
J. Morgan

## *Motivation*

The antiproton source incorporates a lithium lens to greatly improve the transmission efficiency of antiprotons into the Debuncher ring. A lithium lens is ideally suited for capturing the highly divergent antiproton beam emanating from the target into a phase space that can be transported through a beamline with magnets of conventional dimensions. The lens has a large axial current passing through a solid lithium cylinder that produces a strong magnet field approximately proportional to the radius. The lens also has the advantage that it focuses in both transverse planes. The design gradient of the 1 cm. radius lithium lens was 1,000 T/m (10 Tesla surface field). However, operational

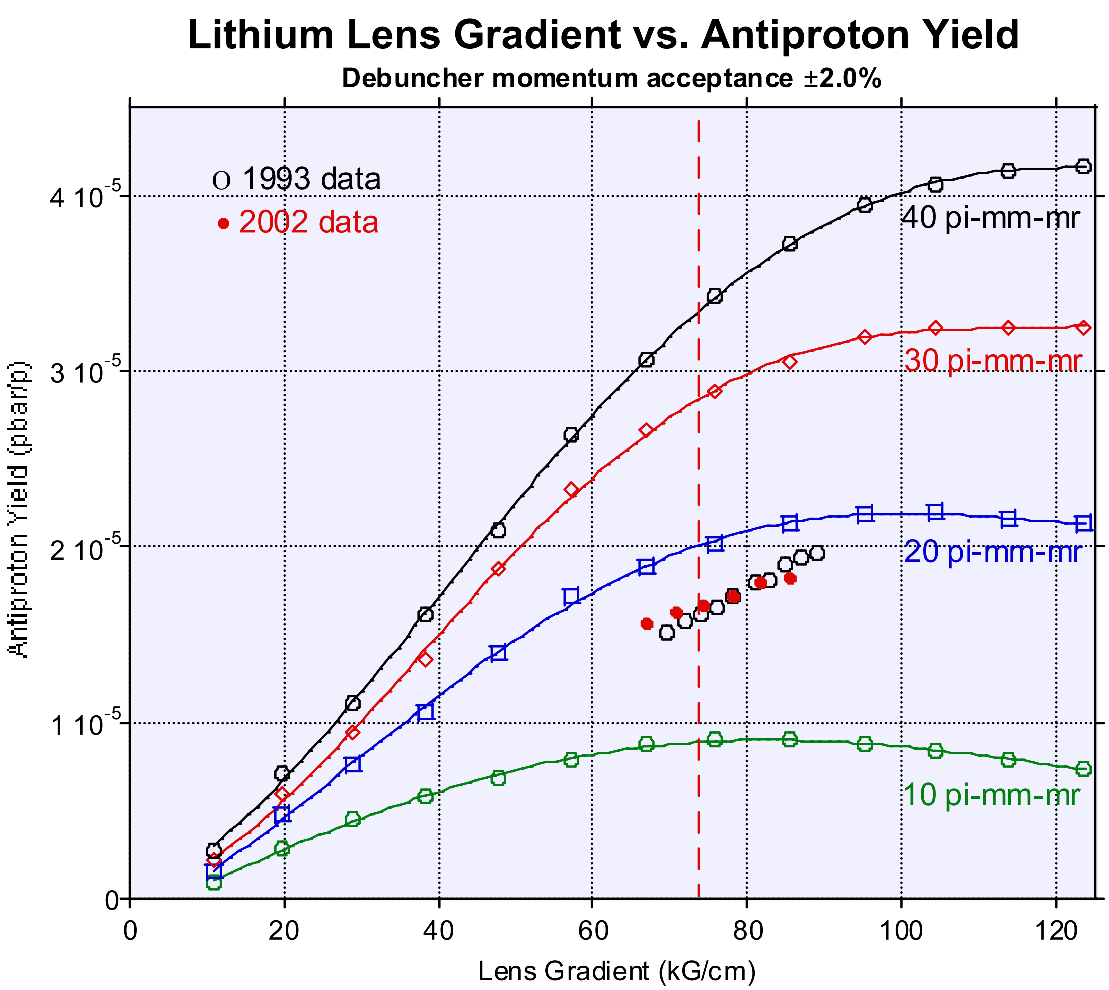


Figure 1, Lens gradient vs. Antiproton yield (predicted and measured) for various transverse acceptances.

lenses have not been able to sustain the design gradient for enough pulses to be practical. Lenses at the design gradient have failed within days or weeks due to mechanical failures of the titanium tube that contains the lithium. Peak stresses in the titanium rise rapidly as the electrical current and Ohmic heating are increased. Running lenses at reduced gradient has allowed them to survive for an acceptable length of time, millions of pulses and an operational life of greater than 6 months. The penalty for lowering the gradient is less antiproton yield due to the reduction in focusing strength. The operational gradient of the lithium lens is 745 T/m, which is a compromise between service life and performance.

Beam models and measurements indicate that the antiproton yield can be increased by running the lithium lens at an increased gradient. Figure 1 shows the predicted relationship between antiproton yield and lithium lens gradient as a function of transverse acceptance. Two sets of measurements are also included that are in reasonably good agreement with the model. The ideal gradient is dependent on the optics and acceptance of the AP-2 line, but in most cases is around the design of 1,000 T/m. Operating at 1,000 T/m instead of 745 T/m is expected to increase the antiproton yield by about 10% with the present AP-2 and Debuncher acceptance, and up to 17% after the acceptance is doubled.

## *Goals*

The manufacturing process for a lithium lens is sufficiently complex and lengthy so that the rate of production has roughly equaled the rate of failure, even operating well below the design gradient. Table 1 provides the observed relationship between lens gradient and the expected lifetime. The number of pulses to failure is based on subjective estimates due to the small number of lenses that have been used and assumes no manufacturing flaws. Depending on running conditions, the operational lithium lens presently accumulates 5-10 million pulses in a year.

| Lens Gradient (T/m) | Average pulses to failure |
|---|---|
| 1,000 | <500,000 |
| 900 | 1,000,000 |
| 800 | 3,500,000 |
| 745 | 8,500,000 |
| 700 | >10,000,000 |

Table 1: Expected lifetime as a function of lens gradient

The high gradient lithium lens project was undertaken in order to increase the operational gradient to 1,000 T/m with a 1 cm. radius lens and achieve a lifetime of 10,000,000 pulses. Even if this goal is not completely achieved, any increase in gradient from the 745 T/m level presently used will produce a partial increase in antiproton yield. To achieve this goal, there have been three main categories of effort.

- A collaboration between Fermilab and BINP in Novosibirsk was initiated in 1997 to develop a liquid lithium lens. The perceived advantage of a liquid lithium lens is that the mechanical stresses are reduced due to the fluid characteristics of the liquid lithium and the use of buffer volumes. Cooling water would no longer be necessary, as heat deposited in the lithium conductor would help keep the lithium in the liquid state. The support systems for a liquid lithium lens are technically difficult to design and operate reliably.

●Design enhancements to the existing lithium lens to improve the longevity of the lenses. To be successful, research is required into the material properties of lithium and titanium, autopsies are to be performed on lenses that failed during operation and more sophisticated mechanical modeling needs to be developed. Quality control issues must also be examined with an emphasis on the handling and acid etching of the inner septum tube and the lithium fill process.

●Research and development of a new design solid lithium lens utilizing diffusion bonding, eliminating the electron beam welds on the present lens. Alternative titanium alloys can be considered because good welding characteristics would not be required. The new lens body would be made entirely of titanium and requires major changes in the geometry of the lens. The diffusion bonding technique achieves more complete bonding with more uniform microstructure. A lens of this design also has the advantage that the fabrication of the lens body assembly can be made quickly and less expensively by an outside vendor.

## *Status*

### *Liquid lithium lens*

The liquid lithium lens project was effectively terminated during 2002. The challenges in producing a reliable liquid lithium lens appeared to be too great to overcome within the time scale of Collider run II. Pulse tests on the prototype liquid lithium lenses were not promising, with septum failures occurring at low gradients and small numbers of pulses.

### *Solid lithium lens improvements*

Past lens failures have been analyzed with a combination of a Finite Element Analysis (FEA) of the lithium lens and autopsies of the failed lenses. Results of the FEA analysis to date suggest that peak stresses in the operational lens should be significantly below the fatigue strength of the Ti 6Al 4V septum. If the model is accurate, this would suggest that cracks are initiated by another mechanism. Possible sources of crack initiation would be liquid metal embrittlement during the lens fill, acid etching during lens fabrication and hydrogen embrittlement.

Five lenses that failed in service have had their lithium removed and are in various stages of analysis. One of the lenses, #16, did not have a septum failure and was instead removed from service due to a water leak. The other lenses, #17, 18, 20 and 21, developed fractures in the septum that separates the lithium conductor from the cooling water. The analysis process involves sectioning of the lenses, and examination with both an optical and a scanning electron microscope. The septum is examined at various points near the failure area as well as in the “good” material. Lens #16 is being examined to find whether cracks had begun to develop in this lens after several million pulses. Preliminary results of the autopsies show that there are signs of small cracks developing in the septum away from the main fracture area, suggesting that cracking had been initiated prior to pulsing the lens.

Due to concerns about cracks developing during the fabrication of the lens, quality control has been improved in the solid lens fabrication. Two new lenses, #27 and #28, were completed during the year and included most of these improvements. Oxidation to the inner septum during the welding process was greatly reduced by developing protective shields. The acid etching of the inner septum was performed more uniformly and with a weaker acid to reduce the risk of crack development. The lithium filling process was completely revamped to greatly reduce the error in measured pre-load and reduce the length of time that lithium is molten during the fill process. Lens #27 incorporated low-ELI titanium, which is considered superior in this application.

Measurements have been made to better understand the mechanical properties of lithium and titanium. Endurance tests with Ti 6Al 4V have been made with several geometries and joining techniques to duplicate conditions in the existing solid lens as well as the diffusion bonded lens. Tests have been made to investigate possible liquid metal corrosion during the filling process by dipping stressed titanium samples into liquid lithium. An instrumented titanium tube has been filled with lithium to measure rates of mechanical creep. Several fundamental measurements of the mechanical properties of lithium have been required due to the lack of available experimental data.

Mechanical models of the lens suggest that increasing the wall thickness of the inner septum can reduce stresses. The present design has a 1 mm. septum wall thickness, which provides some flexibility and good heat transfer to the cooling water. Models suggest that increasing the thickness by approximately 50% will significantly reduce peak stresses while maintaining acceptable heat transfer rates. The reduced flexibility of the thicker tube will require additional pre-load to be applied during the filling process to ensue good lithium to titanium contact during the current pulse. Another geometry change being contemplated is a longer septum, 18 cm. instead of 15 cm., to increase the integrated field by 20%. Ideally, the lens would be as strong and short as possible to minimize absorption in the lithium and reduce focusing aberrations. A longer lens would only be built if the planned improvements failed to produce a reliable high gradient lens. Both the thicker lens and longer length lens can be made by making relatively minor design modifications to the existing lens design.

*New design solid lithium lens*

The first prototype diffusion bonded lithium lens is in the process of being completed. The titanium body was successfully bonded, and machining is being completed so the lens can be filled. The lens will require a larger lithium preload pressure due to the thicker inner septum that is less flexible. Prototype lens #1 has a smaller diameter conductor, and is in large part a "proof of principal" for a diffusion bonded lens. During the testing process, the current will be gradually increased until a surface field of 10 Tesla is achieved. If the lens is able to sustain prolonged pulsing at the elevated gradient, fabrication of the second prototype lens will proceed. Prototype lens #1 will be tested to failure and analyzed for the failure mechanism.

Prototype lens #2 has gone through much of the design phase and has incorporated significant changes from the first prototype. The lithium conductor radius is increased to 1 cm, which is the radius of the operational lens. The titanium septum will most likely incorporate a coating and may be made from the alloy Ti 10-2-3 instead of Ti 6-4. Changes have also been made to the water passages to accommodate the larger lithium conductor. Fabrication of the second lens will be delayed until testing of the first prototype has been completed to ensure there are no unexpected design flaws.

## *Plan*

One more lens, #22, is scheduled for lithium removal and autopsy in FY 2003. The lens had a septum breach in September 2001 and was removed from service. The lens is very radioactive but has cooled significantly over the last 17+ months. This lens is particularly interesting because it accumulated the most pulses during its service life (~9.2 million) and did not fail during pulsing. The failure region should be unusually pristine since it would not have experienced the usual arcing caused by cooling water entering the lithium conductor and forming lithium hydroxide. In addition, analysis of the other autopsied lenses will be completed in FY 2003.

The FEA model will continue to be refined and expanded in FY 2003. Models will be developed for the existing operational lens, the prototype lenses and the thicker septum lens. Efforts will continue to develop a model that accurately simulates failure mechanisms in the lithium lenses to facilitate design changes.

The top priority for the first half of FY 2003 is the completion of prototype lens #1 so that it can be tested. The diffusion bonded lens has the longest lead-time of the various design options. The test of prototype lens #1 will be very valuable in evaluating the future of this design and will be used to identify design improvements to prototype lens #2. It is anticipated that fabrication of prototype lens #2 will begin during the first quarter of FY 2004, with testing beginning in the fourth quarter of FY 2004. Prototype lens #2 will probably be tested both on the test stand and with beam in the target vault.

During the third quarter of FY 2003, Lens #27 will be put into service. After about a month of operation at a gradient of 745 T/m, the gradient will be increased to 820 T/m and pulsed to failure. Since lens #27 incorporates all of the quality control improvements identified over the past two years, this should help quantify if they will improve the longevity of lenses. Experience with past lenses suggest that the service life will be greatly shortened (Table 1) by running at 820 T/m if the quality control changes did not improve the durability of the lens.

Construction of two new lenses, #29 and 30, will be initiated in the first or second quarter of FY 2004. These lenses will incorporate a thicker inner septum (in the range of 1.2 - 1.5 mm instead of 1.0 mm) to reduce peak stresses. However, the thicker septum will conduct more current and transmit heat to the cooling water more slowly. These two drawbacks do not appear to be a serious problem and models suggest that the lens could be run at 5-10% higher gradient with the same stresses as the thinner septum presently used. These lenses would be tested in the third quarter of FY 2004 and could be used operationally soon afterward.

Presently, design and fabrication of the longer 18 cm lens is being delayed pending results from the upgrade designs. Models suggest a modest (2-4%) gain in antiproton yield can be expected from this style lens. However, the design is relatively easy to implement and much of the preliminary work has already been done. A lens of this design would provide useful data to compare to the beam models while providing a small boost in antiproton yield. A lens of this design may be produced in FY 2004, depending on progress with the other alternative designs and aperture improvements in AP-2 and the Debuncher.

## *References*

D. McGinnis et al,“Plans for the Tevatron in Run IIb”, 2001
http://www-bdnew.fnal.gov/pbar/run2b/Documents/Default.htm

P. Hurh, Z. Tang, “FEA Analysis of AP-0 Target Hall Collection Lens (Current Design)”, Pbar note 663, 2001
http://www-bdnew.fnal.gov/pbar/documents/pbarnotes/pdf_files/PbarNote663.pdf

V. Lebedev, ” Production and Collection of Antiprotons”, Pbar note 666 , 2001
http://www-bdnew.fnal.gov/pbar/documents/pbarnotes/pdf_files/PB666.pdf