THE DESIGN OF A DIFFUSION BONDED HIGH GRADIENT COLLECTION LENS FOR THE FNAL ANTIPROTON SOURCE*

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Abstract

Advances in metal joining technology have made it possible to manufacture a one piece lithium lens design utilizing diffusion bonding rather than the current multiple piece, electron beam welded lithium lens design. Advantages of the new design include fewer lithium seals, incorporation of heat treatment with the bonding cycle, vastly simpler assembly requirements, and decreased cost and manufacturing time. Fatigue testing results are presented which indicate that the diffusion bonded joints are just as strong as the parent material. Results from a first prototype of this new design are presented as well as the design of a second prototype.

INTRODUCTION

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 beam-line 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 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 joule heating is 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.

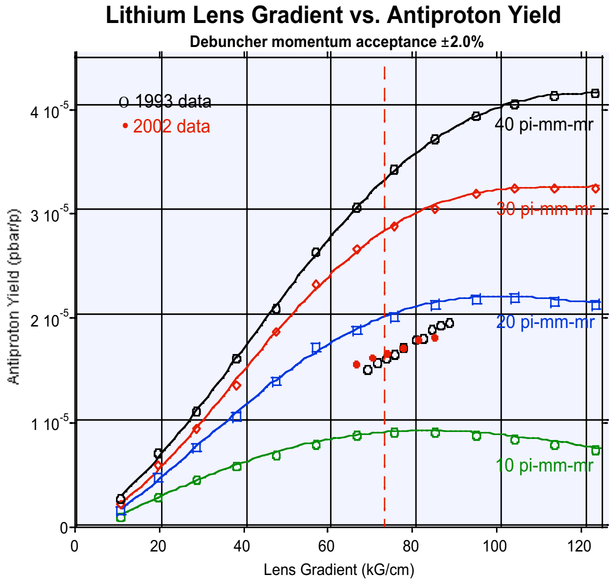

Fig. 1: Lens gradient vs. Antiproton yield (predicted and measured) for various transverse acceptances.

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. 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.

Figure 2 shows a cross-section schematic of the currently operating Lens design. The central lithium conductor volume is bounded by the Ti 6Al-4V cooling jacket (historically called the septum), two beryllium end windows and two steel body halves. The entire assembly is held together by highly pre-loaded Ti 6Al4V bolts which provide sealing force to the critical lithium seals between the end windows, the body halves and the septum. The cylindrically shaped Lens assembly is clamped within an 8 to 1 transformer so that it makes up the single, secondary circuit. Current enters the lens assembly from the transformer contact fingers at the outer diameter of the steel bodies. Current passes through the steel body into the dumbbell shaped lithium buffer regions external to the septum where it is directed into the central lithium conductor by the septum.

The most highly stressed part of the septum is the conductor tube. Stresses arise from several loading sources such as thermal expansion from the current pulse (nearly 500 kA at operating gradient) and the beam pulse, magnetic forces, and structural loading from clamping bolts and lithium filling pre-load. This tube directly contacts the lithium central conductor cylinder on its inner surface (1 cm radius) and directly contacts longitudinally flowing low conductivity water on its outer surface. The conductor tube wall thickness is 1 mm. Failures of past Lenses have generally involved the failure of this septum conductor tube [1]. The septum is constructed through a painstaking electron beam welding process that involves several steps of machining, cleaning, etching, baking, and

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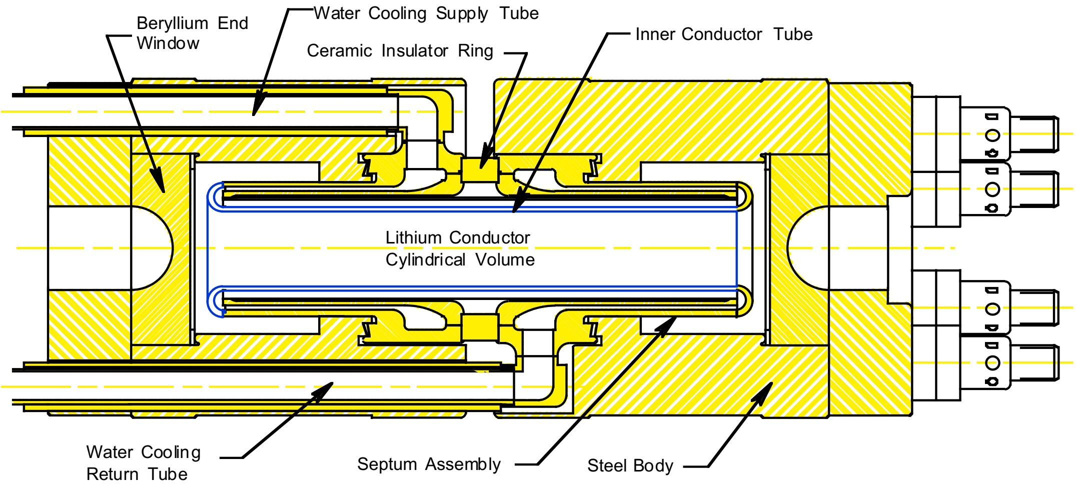

Figure 2: Cross-section diagram of Collection Lens Device. Septum conductor tube is shown in blue.

radiographic NDE for each weld. This, in conjunction with the custom fitting of seal interfaces and the lithium filling process, make the construction of the current Lens design a lengthy (8-10 months at best) process.

The goal of designing an improved Lens is to reliably construct Lenses capable of a 1,000 T/m focusing gradient over a 1 cm radius aperture in a beam environment of 5E12 protons on target per pulse (at 0.5 Hz pulse frequency) without failing in less than 10E6 pulses. Practical considerations also limit the geometrical size of the Lens assembly such that it fits within the existing transformer. It is also desired to increase the ease of manufacture and assembly to improve cost, schedule, quality assurance and reliability.

HIGH GRADIENT LENS FEATURES

At the time of this writing, several design features for a high gradient Collection Lens design are being researched for possible inclusion in a full-scale, operable prototype Lens, hoped to be constructed within the next year.

Diffusion Bonding

Diffusion bonding is a process of joining suitably active metals using pressure and high temperature in a vacuum environment. Figure 3 shows a micrograph of two titanium alloy (Ti 6Al-4V) blocks diffusion bonded together. Away from the edge of the blocks, grain growth across the bond line has been achieved such that material strength in the bond area should be that of the parent material. Advantages of diffusion bonding in a Collection Lens design include ease of construction (one bonding step versus many electron beam welds), elimination of critical lithium seals (body halves and septum can be of one piece construction), and incorporation of water cooling into the body halves themselves. Disadvantages include precision machining requirements (both pre- and post-bond), possibly decreased fatigue strength, and the fact that it is an untried technology for this application.

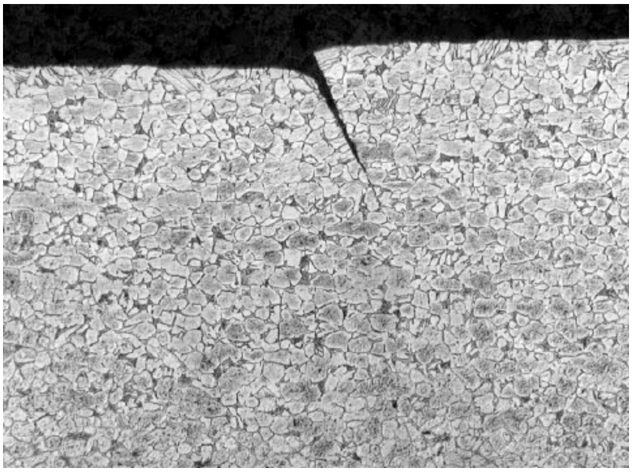

Fig. 3: Diffusion bond joint in Ti 6Al-4V (100x).

In order to explore these advantages and disadvantages two identical proof-of-principle, small prototypes were constructed which utilized diffusion bonding. One was cut open to examine bond quality (Figure 4), while the other is currently being assembled and filled with lithium for test pulsing. In addition, several samples of the central critical joint (in the septum conductor tube) were fatigue tested and compared to un-bonded parent material samples of identical geometry. The diffusion bonded samples were found to exhibit fatigue endurance limits equal to the un-bonded parent samples (approx. 60 ksi, R=0.1, greater than 10E7 cycles). Thus diffusion bonding is deemed to be a highly promising technology to be incorporated in the full-scale prototype.

For one piece diffusion bonding construction, the Lens body halves must be made of titanium alloy rather than carbon steel. Although titanium is significantly more resistive than steel, diffusion bonding allows the easy inclusion of water passages within the body halves for increased cooling. Also, the dumbbell shaped lithium buffer regions are eliminated in a diffusion bonded Lens. This may help constrain the lithium from extruding out of the central conductor volume during the magnet pinch, but may increase pressure upon the end windows. These

Fig. 4: Bonded Lens, before post-bond machining.

issues will be explored by utilizing finite element analysis (FEA) techniques currently being developed [2].

Material Upgrades

A near-beta titanium alloy (Ti 10V-2Fe-3Al) is being investigated as a replacement for the currently used alloy (Ti 6Al-4V). Ti 10-2-3 possibly possesses significant improvements in fatigue endurance limit and fracture toughness over Ti 6-4. Solution and age heat treatment can be easily incorporated with the diffusion bond process to develop optimal properties. Currently fatigue test results confirm that the Ti 10-2-3 endurance limit is at least 105 ksi (R=0.1, greater than 10E7 cycles) after the diffusion bond heat schedule. This can be compared to the 60 ksi value for Ti 6-4 cited earlier. If diffusion bonding of Ti 10-2-3 can be developed to preserve this 175% advantage, then significant gains in Lens lifetime may be achieved.

Also being investigated is replacement of conventional alumina ceramic insulators with yttria partially stabilized zirconia ceramic.(YTZP). In the past, time intensive hand lapping of alumina ceramics was required. Preliminary tests using YTZP (with its increased flexural strength) have shown that these fitting procedures can be entirely eliminated. Some disadvantages of YTZP are decreased resistivity (especially at high temperature, 300 - 500 ˚C) and de-stabilization in humid, moderate temperature environments (200 ˚C). For Lens operations, temperatures will need to be controlled below these limits.

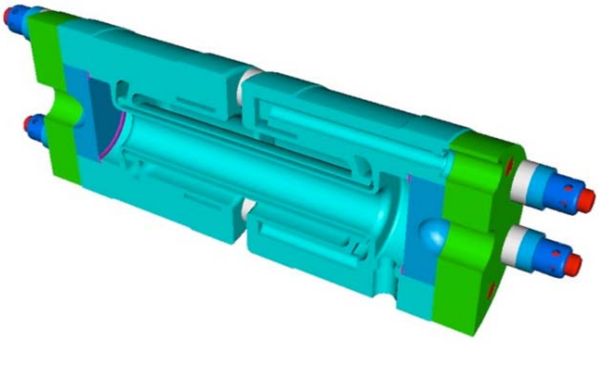

Fig. 5: Conceptual drawing of high gradient Lens prototype.

Protective Coatings

Autopsy results of failed Lenses have indicated that fatigue failure of the septum conductor tube may be aided by some material degradation mechanism such as hydrogen embrittlement or stress corrosion cracking [1]. In order to protect the critical inner surface of the conductor tube from contaminants, an anodizing process is being investigated. It is hoped the anodized surface will provide a barrier to degradation and simplify assembly procedures. Tests are underway to gauge the effect of the coating on fracture toughness and fatigue endurance limit.

Geometrical Changes

Geometrical changes to the structural components are being considered to reduce stresses in critical locations. One obvious structural component is the septum conductor tube. Increasing its thickness may reduce stresses at the expense of higher temperatures in the lithium. Unfortunately, preliminary FEA results [2] indicate that temperatures in the lithium, during high gradient pulsing, near lithium’s melting point (180.6 ˚C). Thus, increasing conductor tube wall thickness is not a viable option. Other changes, such as shape and size of lithium buffer regions are similarly being investigated.

FUTURE STUDIES

Figure 5 shows a conceptual design of a high gradient diffusion bonded Lens that incorporates some of the features described above. Also several improvements are being considered that improve efficiency, lower cost and increase quality (such as seal re-design and improvements to the lithium fill procedure).

Future research includes using FEA methods to tweak Lens geometry, fatigue testing of diffusion bonded and anodized Ti 10-2-3 samples, and diffusion bonding a YTZP insulator ring directly into the Lens assembly (bypassing costly machining steps). The small, proof-of-principle prototype Lens is currently undergoing final preparations for filling with lithium and should be on the test stand during summer ’03. Hopefully lessons learned from building and testing it will provide us with the knowledge and confidence to design and build the full-size high gradient Collection Lens prototype this fall.

REFERENCES

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