Electromagnetic, Thermal and Structural Analysis of the Fermilab Antiproton Source Lithium Collection Lens

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A coupled field finite element ANSYS analysis was done on the electromagnetic, thermal and structural aspects of Fermilab Antiproton Source lithium lens operation. The temperature distribution from Joule heating and the radial magnetic pinch forces were used as input for a 2-D structural model with a fine mesh density. The results of this analysis show that the preload on the lithium as it is filled into its titanium container may be reduced by 15 percent. This reduces the radial stress on the Ti can after the pulse when only preload and thermal stresses remain. Further reduction in preload could come from a scheme to pre-pulse the lens at low current. The heating of the lithium before standard operating current is applied would then play the role of preload at fill. The results of this analysis and future implications for lens operation will be discussed.

I. Antiproton Production and Collection

The Fermilab Main Ring delivers 3×10^{12} protons per pulse to the 8 cm long Ni antiproton production target. The transverse spot size of the beam is .5mm (3σ). The beam pulse consists of 80 1 ns bunches spread evenly over 1.6 μs. Beam pulses arrive once every 2.4 seconds. A lithium collection lens sits 20 cm downstream of the target. The lens collects 8.9 GeV/c secondaries produced within a 35 milliradian cone. The lens focuses the beam to an angular spread of 2.6 milliradians and a radius of 1 cm. A pulsed dipole bends the beam 3 degrees into a transport line which leads to a 500 m circumference debuncher ring. After bunch rotation and some transverse cooling, the antiprotons are then kicked into a 500 m circumference storage ring where they are stochastically cooled and stacked. Detailed Fermilab and CERN antiproton source descriptions are given elsewhere[1].

A conventional lithium lens is a cylinder of solid lithium carrying current. A charged particle passing through the lens with some angle with respect to the lens axis will feel a radial Lorentz force. A lens with radius r, length l carrying a current I, will produce an azimuthal magnetic induction $B(r)=\mu_o Ir/2\pi r_o^2$. An ideal lens is in focus when the distance from a point source of particles to the upstream face of the lens is $Z=1/(k\tan(kl))$ where $k=(.3G/p)^{1/2}$,G =lens gradient and p=particle momentum.

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II. Collection Lens Design and Construction

The lithium lens used for antiproton collection at Fermilab has a diameter of 2cm and a length of 15cm. A 640 kAmp 350 μs damped half sine wave current pulse passes through the lithium in this lens. The lens completes the secondary of an 8:1 step up current transformer. A cross section of the lens in the plane of the beam is shown in figure 1. The lithium is encased in a water cooled titanium can. The lens, can and water conduits all reside in a steel cylinder. The steel is divided into two halves separated spatially and electrically by ceramic ring standoffs. The current input is attached to one half and the output to the other. The two halves are bolted together(with electrical isolation). Further electrical and mechanical description is given in other references[2,3].

During the filling process, lithium is pumped under pressure into an evacuated titanium can. The lithium is heated to 200^{o} C, introduced into the lens at 500 psi(for Li, $T_{melt}= 180^{o}$C) and then allowed to cool to 160^{o}C before the fill continues. As the lithium cools to room temperature, more and more pressure is applied. The final fill pressure is 2300 psi when the stopcock is closed.

Fermilab lithium lenses of more recent design have survived up to 7 million pulses at a lens gradient of 750 T/m. The original design lens gradient was 1000T/m. Lenses run at even 800T/m experience a failure of the titanium jacket encasing the lithium. This typically occurs after 1-2 million pulses. As will be shown, small stress increases in the titanium cylinder result in a great reduction in the life of the lens.

III. Electromagnetic Model Results

The 3-D ANSYS[4] electromagnetic package SOLID96 was used to produce a Lorentz force density map (figure 2). This map was used as structural model load input. The Joule heating of the lithium was also calculated as a function of radius thus providing thermal model input data. The magnetic field and current density maps were used to cross check the expected current skin depth and magnetic forces.

One quarter of the lens was divided into 11 radial, 6 azimuthal and 10 longitudinal sections. Azimuthal symmetry, vector potential and electrostatic potential boundary conditions were then applied.

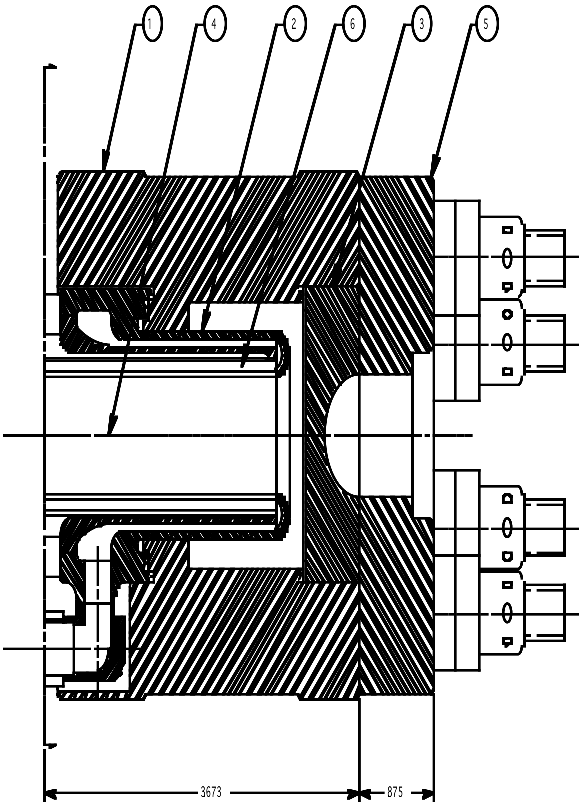

Figure 1: Lithium Collection Lens(half symmetry):1-Electrical Contact;2-Water Septum;3-Be End Cap;4-Li Cylinder Axis;5-End Flange;6-Inner Cooling Jacket.

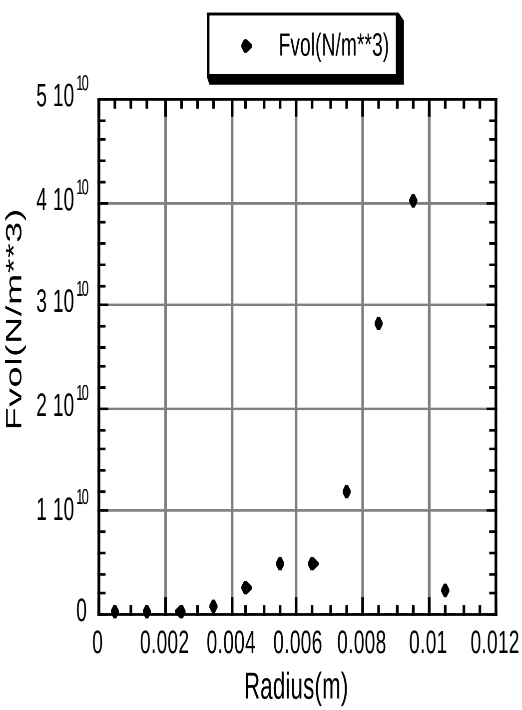

Figure 2: The magnetic force per unit volume as a function of lithium lens radius at mid-pulse.

IV. Thermal and Structural Model Results.

The SOLID96 model described above was coupled to the thermal modeling package SOLID70. The temperature distribution shown in figure 3 was generated from the Joule heating map provided by SOLID96.

The SOLID70 output was coupled to the SOLID45 structural package in a test run, but final results were obtained using a much finer 2-D axisymmetric element mesh(with PLANE42) to improve the accuracy near the lithium-titanium interface. The electromagnetic forces and thermal model temperature predictions were input as loads on individual elements in the PLANE42 model.

The results at mid-pulse are shown in tables 1 and 2. In the tables, the radial and tangential(hoop) stresses are given. The effect of just the lithium preload is shown in row 1. The impact of both the preload and the magnetic pinch together are shown in row 2. Finally in row 3, the effect of thermal stresses is added in.

Two illustrative cases are displayed in the tables. The first case is that of present lens preload at mid-pulse on the first pulse. The second case is done at a reduced pre-load, but at mid-pulse after the system has been pulsed many times and has reached steady state. The design lens gradient of 1000 T/m is assumed in each case.

A negative(compressive) radial stress is indicated by the final row in each table which includes a preload on the lithium, a magnetic pinch from the current pulse and the thermal expansion stress from the subsequent temperature rise of the lithium. The implication here is that the titanium can is acting to compress the lithium. This is equivalent to the statement that there is physical contact between the two materials and that there is enough preload to overcome the magnetic pinch produced by the current pulse.

The excess preload for the first case amounts to 350 psi. A third case was run with only 1950 psi of preload to verify that the radial stress becomes zero at mid-pulse. Removing preload on the lithium is good because it limits the maximum radial and hoop stress which will be placed on the titanium can after the magnetic pinch is gone(between pulses). The case presented in table 2 indicates that if steady state conditions can be maintained at all times, the preload can be dropped much more. The stress from the preload removed is replaced by the thermal stress gained from a higher initial temperature at the beginning of the pulse.

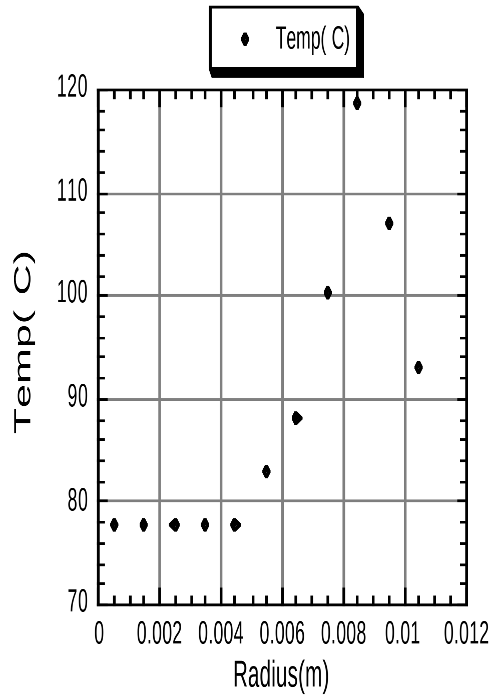

Figure 3: The temperature of the lithium lens at mid-pulse as a function of lithium lens radius.

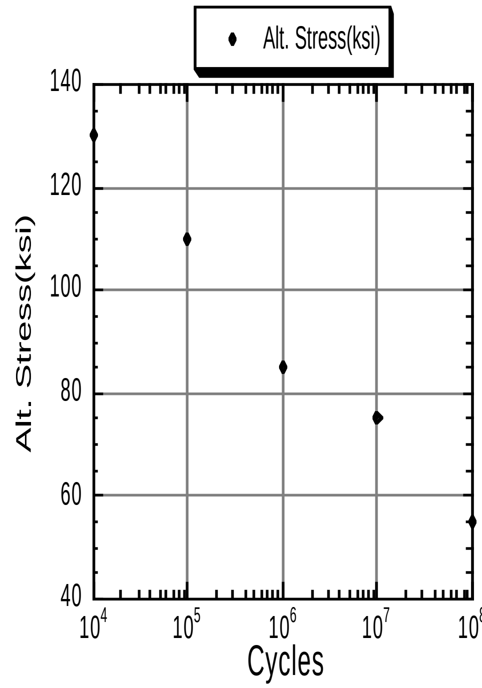

Figure 4: The alternating stress as a function of the number of cycles to fatigue failure.

Table 1: Ti Septum Stress@ 2300 psi Preload during 1st Pulse(T_o=20^o C)

Effects Included	σ_r(Pa)	σ_t(Pa)
Preload Only	-1.528×10^7	$+1.610\times10^8$
Preload+Pinch	$+1.213\times10^7$	-1.584×10^8
Preload,Pinch, Thermal Expansion	-2.405×10^6	-2.346×10^7

Table 2:Ti Septum Stress@ 500 psi Preload during Steady StatePulse(T_{ss}=65^o C)

Effects Included	σ_r(Pa)	σ_t(Pa)
Preload Only	-3.335×10^6	$+3.352\times10^7$
Preload+Pinch	$+2.407\times10^7$	-2.841×10^8
Preload,Pinch, Thermal Expansion	-1.294×10^7	$+8.752\times10^7$

V. Implications for Li Lens Reliability

The S-N curve in figure 5 shows the strength of Ti-6Al-4V [5] as a function of the number of stress reversals. If one assumes(based on 800 T/m lifetime) that the titanium in the can experiences a maximum stress of 85 ksi, then decreasing this by 15%(by decreasing preload) should result in a lifetime increase of up to 9 million cycles under present operating conditions. This curve is not completely suitable for making this prediction since a lithium lens does not undergo complete stress reversal as it is pulsed.

If the current was ramped up to full value over a number of pulses so that a temperature close to steady state could be obtained before the first full current pulse, then a preload much lower than 1950 psi could be considered. At 500 psi preload, one could consider increasing the lens current by 25% while accepting little or no decrease in the number of cycles to titanium can failure.

VI. REFERENCES

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