

G. Biallas, G. Dugan, J. Hangst, R. Hanson,
C. Hojvat, F. Lange, A.J. Lennox, J. McCarthyFermi National Accelerator Laboratory*
P.O. Box 500, Batavia, Illinois 60510, U.S.A.

Abstract

A prototype Lithium Lens to be used for the collection of antiprotons in the Fermilab Tevatron I project has been constructed. Some of the fabrication details, the procedure for lithium filling and the results of the initial operation are discussed.

Introduction

Lithium lenses have been under development for some time at the Institute for Nuclear Physics, Novosibirsk, U.S.S.R. Academy of Science.¹ The first prototype of the Fermilab lens² has now been constructed and is undergoing power tests. The procedures for assembling the lens and filling it with lithium are discussed in the first part of this article. The results of the initial power tests are discussed in the second part.

Lens Fabrication

Assembly Procedure

The lens cooling jacket assembly required eight separate electron-beam titanium welds. Extensive tests were performed prior to each weld to determine the electron beam parameters for full penetration. Subsequently the assembly was subjected to x-ray analysis to assure satisfactory weld quality. Finally, the titanium tubes for the cooling water inlet and outlet were attached to the cooling jacket assembly using a TIG welding process. (A drawing of the lens can be found in ref. 2.)

After fabrication of the cooling jacket, the lens assembly was completed by mounting the steel outer bodies over the cooling jacket, installing the beryllium end windows in the bodies and capping the assembly with the end flanges. The volume to be filled with lithium was sealed during assembly by compressing annealed nickel rings between the appropriate surfaces. To complete the assembly, the eight high-strength steel retaining bolts were torqued to a ΔL of $\sim 11 \times 10^{-3}$ in per bolt, which imposed a total preload of $\sim 30,000$ lbs on the end flanges. This preload, which is greater than the axial force generated during operation, guarantees that the lens will remain in axial compression at all times.

Lens Filling Procedure

Liquid lithium must be introduced into the lens in such a way that when it later solidifies the solid lithium is completely free of voids and is under a hydrostatic compressive stress of ~ 150 Atm. The reason for this preload is discussed in ref. 2.

Once assembled, the lens is connected to the filling system shown in Fig. 1. All parts of the liquid lithium circuit in the filler and connecting lines are sealed using annealed flat nickel gaskets.

*Operated by the Universities Research Association Inc., under contract with the U.S. Department of Energy.

The lens and filler are evacuated and outgassed at $\sim 200^\circ\text{C}$. After the apparatus has cooled a slug of solid lithium is placed in the bellows in an argon atmosphere. The system is then re-evacuated and heated to $\sim 200^\circ\text{C}$ to assure that all parts are above the lithium melting point. Lithium liquefaction in vacuum inhibits the development of nitrogen impurities in the lithium.

Liquid lithium is injected into the lens by hydraulically compressing the bellows. The initial liquid lithium pressure is established at roughly the required lithium preload pressure. This pressure is monitored by a piezoresistive pressure transducer³ in direct contact in the lithium volume in the lens, and by a hoop strain gauge⁴ mounted externally on the lens steel body. The lens is then cooled by argon gas flowing through the cooling jacket, while the filler and fill lines are maintained near 180°C . As the lithium in the lens cools and shrinks, the hydraulic pressure in the fill system is increased to force more lithium into the lens, thus maintaining the required lens preload. Fig. 2 illustrates the changes in temperature and pressure during the process. When the lithium in the lens reaches room temperature, two stopcocks are turned to seal the lens volume and the completed lens is disconnected from the filler.

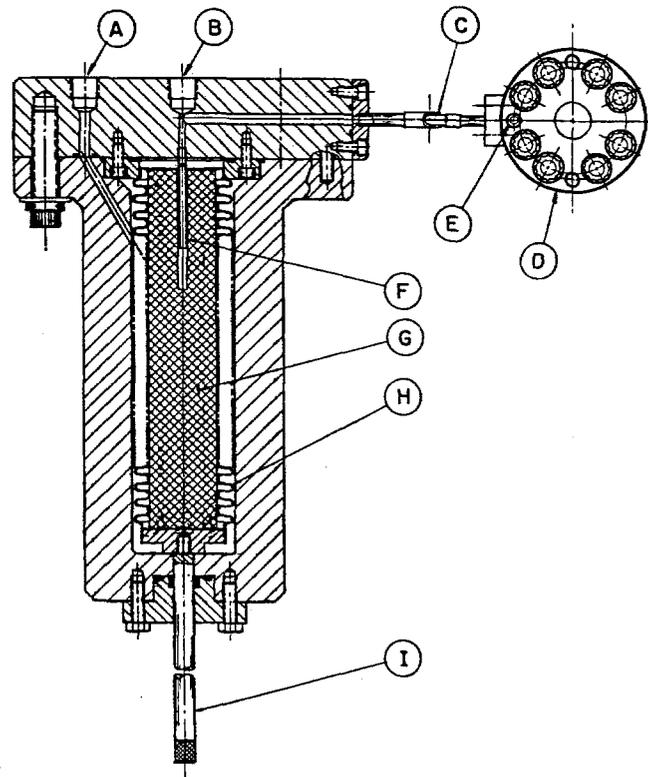


Fig. 1 High Pressure Lithium Filler. A) Hydraulic oil inlet; B) Vacuum port with all metal valve; C) Connecting lines; D) Lithium lens; E) Stopcock access port; F) Tube to bypass top layer of liquid lithium during fill; G) Lithium slug; H) Bellows; I) Rod to monitor compression of bellows.

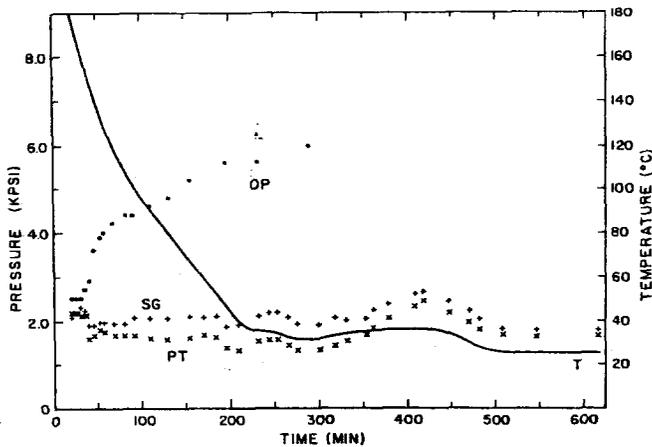


Fig. 2 Temperature and pressure vs time during the filling operation. T) Lens temperature; OP) Hydraulic oil pressure in the filler; SG) Lithium pressure obtained from the strain gauge and (PT) from the pressure transducer.

Power Tests

Operating Parameters

The optimization of the operating parameters of the Fermilab lens has been discussed previously.² A peak current of 670 kA, with a pulse length of 330 μ sec, will result in a field gradient of ~ 1100 T/m at $\phi = 120^\circ$, the phase at which the field has maximum linearity. The Fermilab lithium lens has been designed for operation at these parameters. However, the power tests described here have been limited to peak currents of ~ 425 kA (with a 320 μ sec pulse width) which corresponds to a field gradient at $\phi = 120^\circ$ of ~ 700 T/m. This gradient is expected to be sufficient for operation as an antiproton collector at the CERN antiproton source. The mechanical stresses at this current are roughly 40% of the design values.

Single Pulse Operation

(i) Current and voltage waveforms

The lithium lens completes the one-turn secondary of a toroidal pulse transformer with eight primary turns. The transformer is linked to a capacitive-discharge power supply by a 2 m strip transmission line fed by coaxial cables. Pulsing is performed by discharging the power supply capacitors, initially at a voltage $V_c(0)$, into the transformer primary. The voltage across the primary, V_T , is measured with a frequency compensated voltage divider; the primary and secondary currents are monitored using bifilar Rogowski coils. The secondary Rogowski coil is mounted on the steel body and encircles the lens.

Fig. 3 reproduces the oscilloscope traces of the primary and secondary integrated Rogowski coil voltages, as well as the primary transformer voltage. The power supply capacitance was $C = 2970$ μ F.

(ii) Electric circuit parameters

For the pulse conditions exhibited in Fig. 3, the voltage directly across the capacitor bank was also measured. At the start of the pulse, $V_c(0) = 2400$ V, and at the end $V_c(\pi) = 1350$ V. Then the energy dissipated due to Joule heating in the system is:

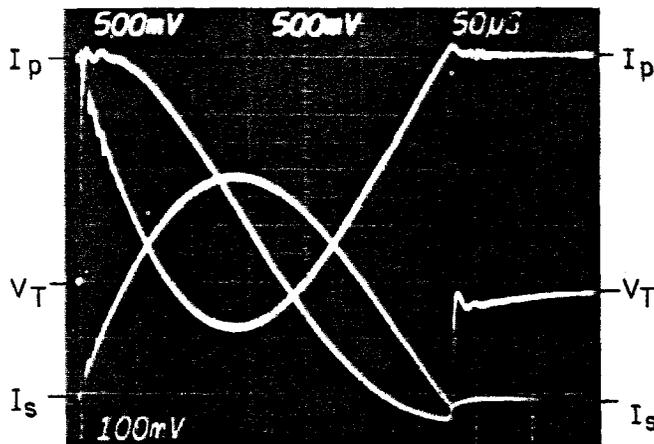


Fig. 3. Oscilloscope traces of: I_s) secondary current through the lens (112 kA/div); V_T) primary voltage across transformer (454.5 V/div); I_p) primary current (12.2 kA/div.)

$$\Delta E = \frac{1}{2}C(V_c^2(0) - V_c^2(\pi)) = 5850 \text{ Joules}$$

The effective resistance of the system is then given by:

$$\Delta E = R \int_0^{T_p} I_p^2(t) dt$$

where $T_p = 320$ μ sec is the pulse length, and $I_p(t)$ is the primary current waveform shown in Fig. 3. Direct integration gives a value for R of:

$$R = 11.3 \pm 1 \text{ m}\Omega$$

where the error arises from systematics on the primary Rogowski coil calibration. If we approximate the primary circuit as an underdamped RLC circuit, then we can write

$$I(\phi) = I_0 e^{-\beta\phi} \sin\phi$$

where $\phi = \omega t$; $\omega = \pi/T_p$; and $\beta = \alpha/\omega = R/2L\omega$. In this approximation the total system inductance is

$$L = \frac{1}{(\omega^2 + \alpha^2)C}$$

The data in Fig. 3 and the value of R above lead to $L = 3.3$ μ H and $\alpha = 1700$ Hz.

The lens-transformer inductance L_T is related to the total system inductance L by $L_T/L = V_T(0)/V_c(0)$. Using $V_T(0) = 1800$ V (from Fig. 3) gives $L_T = 2.5$ μ H. Almost all of the system resistance R is in the lens-transformer system, so $R_T \sim R$. These values of R_T and L_T are within 10% of the calculated values for the lens-transformer system.

The validity of the damped RLC circuit approximation is indicated by Fig. 4, in which the damping factor $F = \ln [I_s(t)/\sin\omega t]$ is plotted vs t. For a simple RLC circuit, this will be a straight line with slope α . The illustrated deviations from a straight line are probably due to current penetration effects during the pulse.

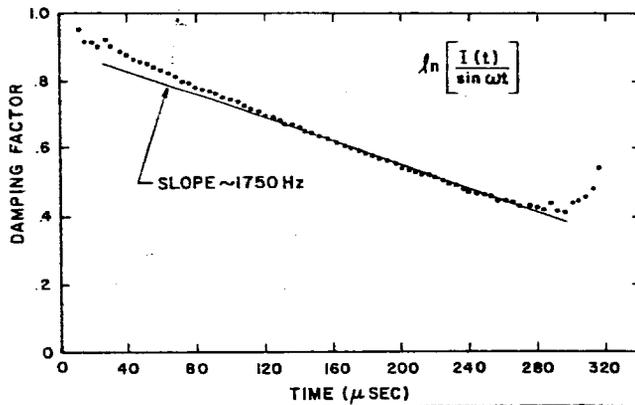


Fig. 4. Current damping factor vs time during a single current pulse. A straight line with slope 1750 Hz is shown.

(iii) Repetitive pulse operation

The lens-transformer system has been pulsed repetitively at rates up to 0.37 Hz for several thousand pulses. No evidence of deterioration of the lens, or long-term change in the internal lithium preload, was observed during this time.

During repetitive operation, the power removed by water flow in the cooling jacket was ~ 2 kW. Typical flow rates to achieve turbulent flow are in the range of 10 gal/min. The pulsed heating of the lithium and the approach to thermal equilibrium were monitored by a miniature thermocouple in the steel body, located within ~ 0.060" of the lithium volume. Fig. 5 shows the response of the thermocouple vs time at the start of repetitive pulsing, together with the prediction from a thermal model of the lens calculated with the program HEATINGS.⁵ The agreement is satisfactory, giving confidence that the predictions of the thermal model for the temperatures throughout the lens are reliable.

Acknowledgements

We thank our colleagues at the I.N.P., Novosibirsk, for many fruitful discussions.

References

1. "The Investigation and Design Development of Lithium lenses with Large Operating Lithium Volume". B.F. Bayanov, T.A. Vsevolozhskaya, Yu. N. Petrov and G.I. Silvestrov, this conference and references therein.
2. "Mechanical and Electrical Design of the Fermilab Lithium Lens and Transformer System". G. Dugan, C. Hojvat, A.J. Lennox, G. Biallas, F. Cilyo, M. Leininger, J. McCarthy, W. Sax and S. Snowdon. IEEE, NS-30, p. 3660, 1983.
3. Entran Device Inc., 10 Washington Ave, Fairfield, N.J. 06-Model EPX-10W-5000A.
4. Eaton Corp., 5340 Alla Rd., Los Angeles, 90066-Model Ailtech SG125-01F(1.5)-10-6S.
5. "HEATINGS", W.D. Turner, D.C. Elrod and I.I. Siman-Tov. ORNL/CSD/TM-15. Oak Ridge.

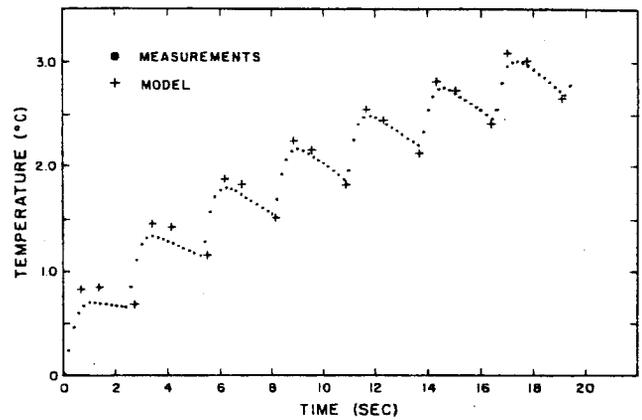


Fig. 5. Temperature near the lithium volume, as observed with a fast response thermocouple, for the first seven pulses at 0.37 Hz. Comparison is made with a computer model of the lens.