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MECHANICAL AND ELECTRICAL DESIGN OF THE FERMILAB LITHIUM LENS AND TRANSFORMER SYSTEM*

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FERMILAB LITHIUM LENS AND TRANSFORMER SYSTEM

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Summary

A lithium lens focusing device will be used for the collection of 8 GeV antiprotons in the Fermilab Tevatron I Project. The details of the mechanical and electrical design of the Fermilab lens and its associated toroidal transformer are discussed. The lens, with a radius of 1 cm and length 15 cm, is expected to achieve gradients of 1000 T/m for a focal distance of 0.225 m. The gradient requires a current on the order of 5×10^5A, resulting in large electromagnetic and thermal stresses. The power supply discharge current and the effect of the inductance of the power leads and connections are minimized by the use of a toroidal matching transformer surrounding the lens itself.

Introduction

The purpose of the Fermilab Tevatron I Project is to achieve proton-antiproton ($\bar{p}$) collisions at the highest energies in the Tevatron superconducting accelerator.[1] Fundamental elements of the project are the production, collection, cooling and accumulation of $\bar{p}$'s. Antiprotons emerging from the production target will be collected by a focusing lithium lens. The required lens should have a radius of 1 cm, be 15 cm in length and have a 1000 T/m gradient.

A lithium lens is essentially a metal rod carrying an axial current, resulting in a collection device with simultaneous focusing in both transverse dimensions. The choice of lithium minimizes the absorption and multiple scattering of the particles to be collected. As very short focal distances can be achieved, large collection angles and low chromatic aberrations are possible. Lithium lenses have been under development and use for some time at the Institute for Nuclear Physics, Novosibirsk, U.S.S.R. Academy of Sciences.[2] Many of the ideas utilized in the Fermilab design are the result of their experience with these devices.

Operating Parameters

To prevent very large energy deposition by Joule heating, the lens will be operated in a pulsed mode. Non-uniform current density, resulting from the skin effect, must be taken into account.[3] Using a capacitor discharge power supply, the lens can be excited by a damped half sine wave of the form

$$I(t)=I_o e^{-\beta\phi} \sin\phi \;, \quad 0 < \phi < \pi \quad (1)$$

where $\phi=\omega t$ is the phase at time t, I_o would be the peak current without damping, and β is the damping coefficient.

The phase at which the beam passes through the lens, ϕ_b, and the operating parameters of the lens, $(I_o, \omega, \beta, \phi_b)$ are optimized by minimizing the current I_o, and the Joule heating, while maintaining the necessary optical properties for the lens as an antiproton collector.

The phase ϕ_b and the time characteristics of the current pulse determine the dependence of the magnetic field with radius.[3] The effect of these non-linearities on the antiproton collection, for a fixed geometry, is shown in Fig. 1, where no damping has been assumed (β=0).

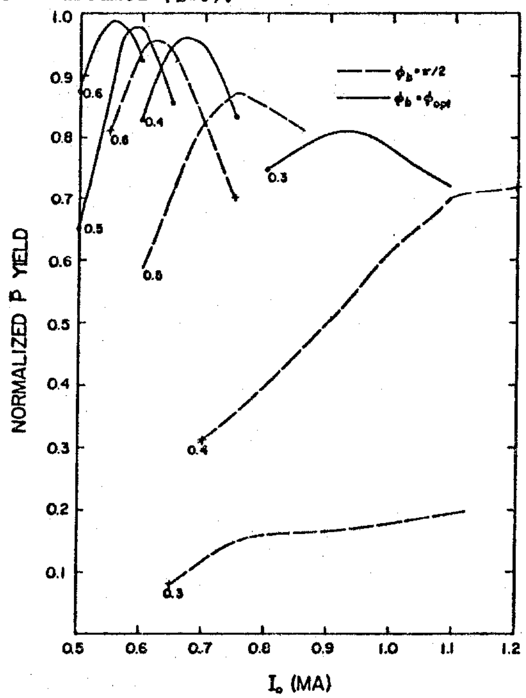
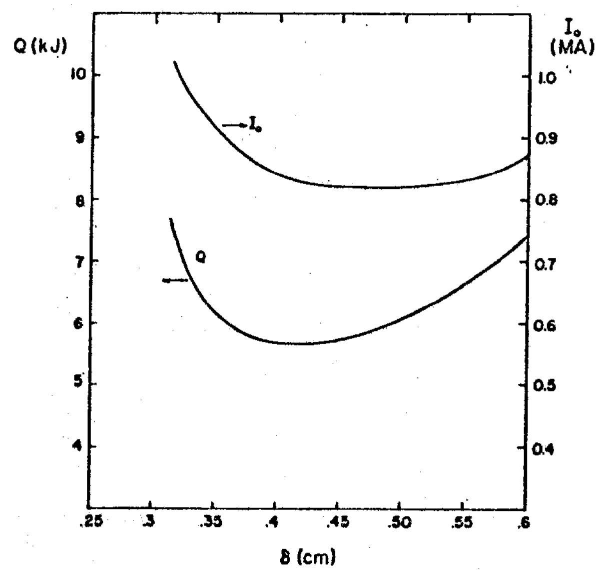


Figure 1. Normalized antiproton yields vs. lens current I_o (MA) for various values of δ (cm) and ϕ_b (rad). Curves are labelled by corresponding value of δ.



--gure 2. Optimization curves: Lens current I_o (MA) and Joule heat per pulse Q (kilojoules) vs. δ (cm). Lens operation at $\phi_b = \phi_{opt}$.

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

The $\bar{p}$ yield, normalized to the case of a linear field and I_o=0.5 MA, versus I_o is shown for 4 values of the standard skin depth δ. For each we show two curves, one for $\phi_b=\pi/2$ and one for $\phi_b=\phi_{opt}(\delta)$ where ϕ_{opt} is the phase at which the field is "most" linear[3]. The optimum phase is strongly preferred; for $\delta>0.4$ cm the normalized yield can be maintained >95% with a proper choice of I_o. The value of I_o, from Fig. 1, for the peak yield at $\phi_b=\phi_{opt}$, together with the resulting Joule heating are shown in Fig. 2 versus δ. I_o has been corrected taking into account the damping due to the expected value of α=1300Hz (see below) An operating point with δ=0.45 cm and I_o=0.83 MA is chosen. The peak current in the lens will be 0.67 MA for a pulse width of $T=\pi/\omega$ = 0.33 msec.

Lithium Lens

The prototype lithium lens design is shown in Fig. 3. The design should provide: i) adequate cooling of the lithium conductor, ii) high transparency beam windows, iii) a structure strong enough to sustain the thermal and magnetic stresses induced during operation, iv) a current flow path mainly in the lithium itself, which minimizes the inductance, v) structural materials in contact with the lithium not subject to corrosion or destructive alloying with the liquid lithium during filling.

The current must be introduced into the lithium cylinder in such a way as to minimize the total resistance and inductance associated with the current feeds. To this end, the current contacts to the transformer have been made as close as possible to one another. The current is delivered to the lithium through low-carbon steel, which has relatively low resistivity and is compatible with liquid lithium. The total inductance of the lens structure excluding the lithium itself is expected to be ~31nh; the lithium cylinder contributes ~ 7nh. The total resistance of the lens structure excluding the central conductor is 42 $\mu\Omega$; the lithium central conductor contributes 56 $\mu\Omega$.

The cooling jacket for the lithium conductor must carry a minimum of current, allow adequate heat exchange between the lithium and the cooling medium (water) and sustain the stresses produced by the pulsed heating of the lithium. The prototype design, which has an inner cooling jacket of Ti-6Al-4V, of thickness 1 mm, resulted from a compromise between these demands. Fig. 4 shows the calculated radial steady-state temperature distribution in the lithium, for a 25 °C average cooling water temperature. The two curves correspond to the temperature just before and just after a pulse. The heat exchange is sufficient to prevent the lithium from reaching its melting point (180.5° C). During the pulse, the magnetic forces produce a radially-inward pressure distribution; the peak radial pressure profile varies roughly quadratically from zero to ~16 kpsi at 1 cm.

The resulting total stresses in the lithium and the inner cooling jacket, due to the thermal and magnetic effects, have been calculated in the plane strain approximation for infinite cylinders. The stresses just before and after the pulse are due to thermal strains; the mid-pulse stress is produced by the magnetic pressure superimposed upon a temperature distribution intermediate between those shown in Fig. 4. The peak stresses occur in the cooling jacket, and are primarily tensile hoop stresses; they are cyclic from ~84 kpsi to ~20 kpsi. This corresponds to roughly 80% of the fatigue limit in this alloy for ~1 yr. of lens operation.[+]

The beryllium end caps should be just strong enough to sustain the axial forces generated by thermal strains and the magnetic field. The design of Fig. 3 produces a beam loss of less than 4% (vs. 11% in the lithium); and an increase in the total multiple scattering of less than 20%. The peak axial pressure load on the end caps is primarily due to the axial pressures (~10 kpsi) generated by radially flowing currents in the end regions, together with Poisson effect loads (~14 kpsi) associated with the radial compression of the central cylinder. The resulting stresses generated in the window are estimated to be substantially less than the endurance limit[5] of the beryllium alloy (S200-E) to be used. The windows are contained by steel end flanges. A ceramic insulator separates the two halves of the lens; a Rogowski coil will be placed outside this ceramic to monitor the lens current. The entire assembly is contained against the axial forces by 8 high-strength steel bolts, preloaded to reduce flexing of the end caps during operation. The design of the lens is presently being modelled using the finite element program ANSYS.[6]

Lithium will be loaded into the lens through two pentrations using a filling device with a bellows. After outgassing the lens and filler, the filler bellows is loaded (in an argon atmosphere) with a

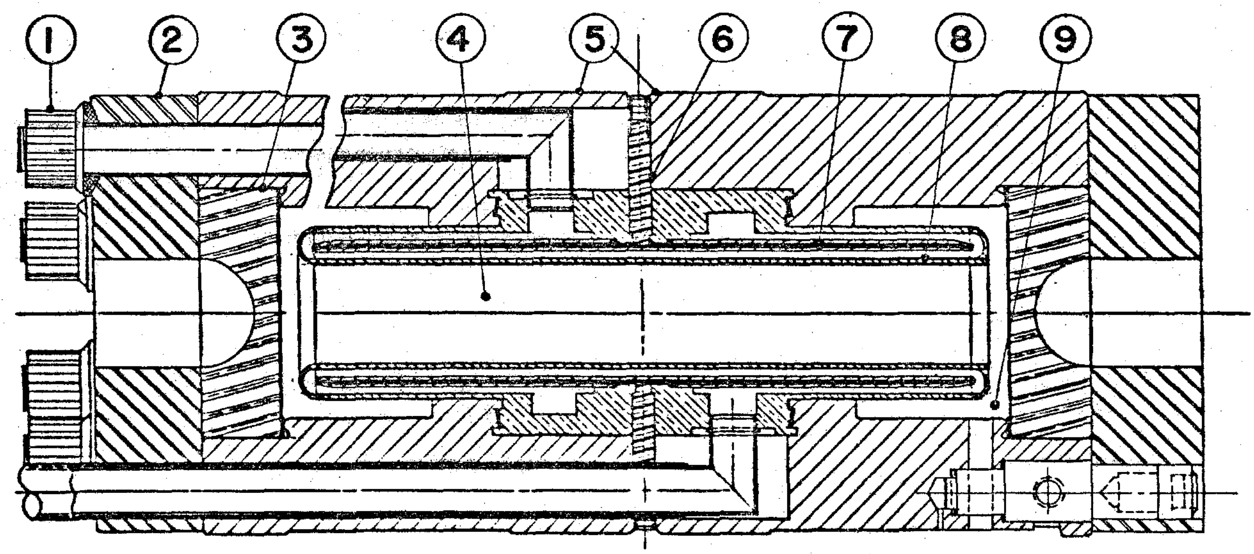


Figure 3.- Lithium lens prototype: 1-Retaining bolt;2-End flange;3-End caps;4-Lithium;5-Current contacts; 6-Ceramic insulator;7-Water septum;8-Inner cooling jacket;9-Fill port.

lithium slug and evacuated. The lens and filler are heated to lithium melting temperature, and the liquid lithium is introduced into the lens under pressure. As the lens is allowed to cool and the lithium shrinks, additional molten lithium is introduced to maintain a pressure in the lithium, continuously monitored by a pressure sensor. By this process a void-free lithium cylinder is cast under a compressive preload to prevent radial separation of the lithium from the cooling jacket under the action of the impulsive pinch stress generated by the field pulse. Estimates of the requied compressive stress to inhibit separation are in the range of 50-100 Atm. This compressive preload promotes good thermal and electrical contact between the lithium and the surrounding materials.

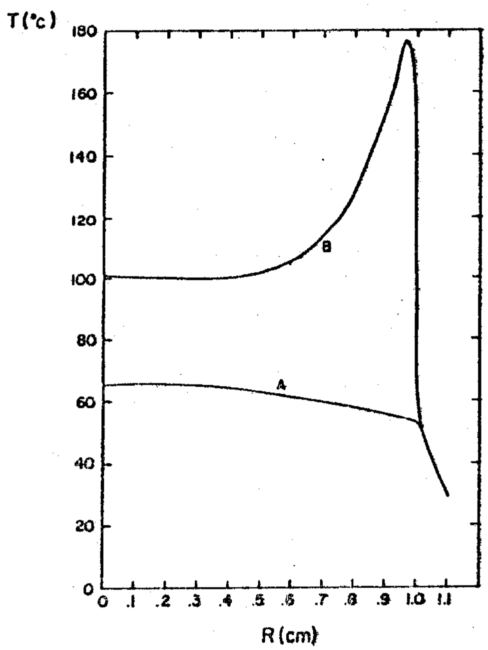


Figure 4. Equilibrium Radial temperature profiles in lithium and cooling jacket. Curve A: just before a pulse. Curve B: just after a pulse.

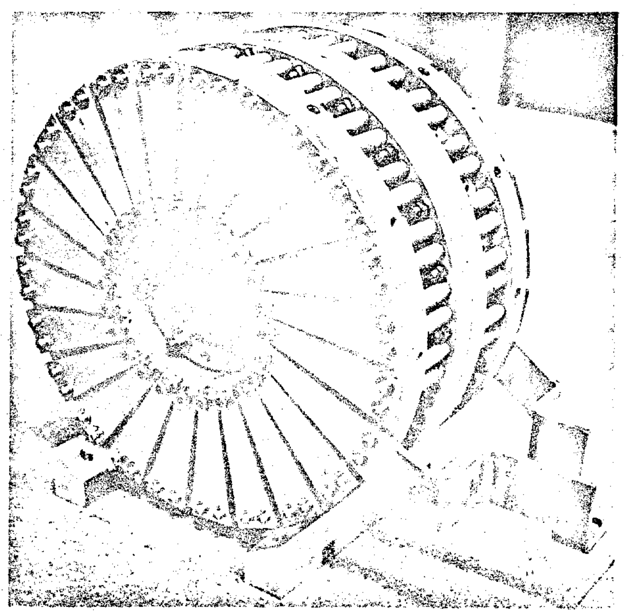


Figure 5. Lithium lens 24-turn prototype pulse transformer. Overall diameter 41 cm.

Pulse Transformer

The lithium lens completes the one-turn secondary of a toroidal pulse transformer. The transformer will be linked to a power supply by a 2 m strip transmission line and coaxial cables. Pulsing occurs by discharging a capacitor, initially at a voltage V, into the primary, resulting in the wave form (1). The parameters I_o, β and ω are related to the power supply parameters (C, V) and the load inductance and resistance (L, R) seen in the primary circuit by the relations:

$$I_o = V/\omega L \; ; \; \beta = \alpha/\omega \; ; \; \alpha = R/2L \; ; \; \omega^2 = 1/LC - \alpha^2$$

A 24-turn prototype transformer has been constructed as shown in Fig. 5. The tape wound core, with an area of 145 cm^2, is enclosed in an aluminum housing which is part of the secondary circuit. The lens is clamped into the center of the housing to complete the secondary circuit.

The transformer has been pulsed with a dummy lens (a 1 cm radius tantalum rod) under a number of different conditions. The peak secondary current achieved , measured with a Rogowski coil, has reached 0.4 MA with T $\sim$ 1.2 msec. The core requies $\sim$ 10 A of reverse DC bias to prevent saturation.

The measured total load inductance (L) has been reduced from $\sim$ 38 μh to $\sim$ 21 μh by a redesign of the current path between the secondary housing and the lens central conductor. A substantial further decrease in the inductance is required in order to keep primary voltages below 3kV with the short pulses wanted for optimum operation. A reduction in the number of primary turns to 8 has been made; the peak secondary current achieved in this configuration is 0.52 MA, with T~0.4 msec.

With the lithium lens described above as the secondary load, and with an 8-turn primary, the expected circuit parameters are L $\sim$ 2.7 μh and R $\sim$ 6.9 mΩ. To achieve T=0.33 msec, a power supply capacitance of C=4000 μf is required. For I_o=0.83 MA, the necessary voltage is V $\sim$ 2.7 kV. A damping factor α=1300 Hz (β=.136) is expected.

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