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

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March 1983

* Presented at the 1983 Particle Accelerator Conference, Santa Fe
New Mexico, March 21-24.
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 5×10⁴ A, 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.

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. Using a capacitor discharge power supply, the lens can be excited by a damped half sine wave of the form

$$I(t) = I_0 e^{-\beta t} \sin \phi, \quad 0 < \phi < \pi$$

where $\phi$ is the phase at time $t$, $I_0$ would be the peak current without damping, and $\beta$ is the damping coefficient.

The phase at which the beam passes through the lens, $\phi$, and the operating parameters of the lens, $(I_0, \omega, \phi_0, \phi)$, are optimized by minimizing the current $I_0$, and the Joule heating, while maintaining the necessary optical properties for the lens as an antiproton collector.

The phase $\phi_0$ and the time characteristics of the current pulse determine the dependence of the magnetic field with radius. 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 ($\beta = 0$).

Figure 1. Normalized antiproton yields vs. lens current $I_0$ (MA) for various values of $\delta$ (cm) and $\phi$ (rad). Curves are labelled by corresponding value of $\delta$.

Figure 2. Optimization curves: Lens current $I_0$ (MA) and Joule heat per pulse Q (kilojoules) vs. $\delta$ (cm). Lens operation at $\phi = \phi_{opt}$.

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Summary

The purpose of the Fermilab Tevatron I Project is to achieve proton-antiproton (p̅) collisions at the highest energies in the Tevatron superconducting accelerator. Fundamental elements of the project are the production, collection, cooling and accumulation of p̅. 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. Many of the ideas utilized in the Fermilab design are the result of their experience with these devices.

Operating Parameters

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Figure 1. Normalized antiproton yields vs. lens current $I_0$ (MA) for various values of $\delta$ (cm) and $\phi$ (rad). Curves are labelled by corresponding value of $\delta$.

Figure 2. Optimization curves: Lens current $I_0$ (MA) and Joule heat per pulse Q (kilojoules) vs. $\delta$ (cm). Lens operation at $\phi = \phi_{opt}$.
The $\sigma$ yield, normalized to the case of a linear field
and $I=0.5$ MA, versus $I$, is shown for 4 values of the standard
skin depth $\delta$. For each we show two curves, one for $\phi_0=J_\delta$ and one for $\phi_0=\phi_{opt}(\delta)$ where $\phi_{opt}$ is
the phase at which the field is "linear". The
optimum phase is strongly preferred; for $\delta>0.4$ cm the
normalized yield can be maintained $\approx 95\%$ with a proper
choice of $I$. The value of $I^*$ from Fig. 1, for the
peak yield, $\phi_{opt}$ is also shown. The resulting
Joule heating is given in Fig. 2 versus $\delta$. $I_0$ has
been corrected taking into account the damping due to
the expected value of $\alpha=1300$Hz (see below) An
operating point with $\delta=0.45$ cm and $I_0=0.83$ 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
forces 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
foiling 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
transfomer 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 $\sim 3Jm$; the
lithium cylinder contributes $\sim 7n$. 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-5Al-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
quadradically from zero to $\sim 16$ 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 $\sim 84$ kpsi to $\sim 20$ kpsi. This corresponds to
roughly 80% of the fatigue limit in this alloy for $\sim 1$
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 ($\sim 10$ kpsi) generated by radially flowing
currents in the end regions, together with Poisson
effect loads ($\sim 14$ 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 of
the beryllium alloy (S200-8) to be used. The windows are
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 modeled using the finite element program
ANSYS.

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

![Equilibrium Radial temperature profiles in lithium and cooling jacket. Curve A: just before a pulse. Curve B: just after a pulse.](image)

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

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 \( I_0 \), \( \alpha \) and \( \omega \) 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:

\[
I_0 = \frac{V}{\omega L}; \quad \alpha = \frac{\omega}{\omega L}; \quad \omega^2 = \frac{1}{LC} - \alpha^2
\]

A 24-turn prototype transformer has been constructed as shown in Fig. 5. The tape wound core, with an area of 145 cm², 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 \( T \sim 1.2 \text{ msec} \). The core requires \( \sim 10 \text{ A} \) of reverse DC bias to prevent saturation.

The measured total load inductance \( (L) \) has been reduced from \( \sim 38 \mu \text{H} \) to \( \sim 21 \mu \text{H} \) 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 \( \beta \) has been made; the peak secondary current achieved in this configuration is 0.52 MA, with \( T=0.4 \text{ msec} \).

With the lithium lens described above as the secondary load, and with an 8-turn primary, the expected circuit parameters are \( L \sim 2.7 \mu \text{H} \) and \( R \sim 6.9 \Omega \). To achieve \( T=0.33 \text{ msec} \), a power supply capacitance of \( C=800 \mu \text{F} \) is required. For \( I=0.83 \text{ MA} \), the necessary voltage is \( V \sim 2.7 \text{ kV} \). A damping factor \( \alpha=1300 \text{ Hz} (\beta=136) \) is expected.

**Pulse Transformer**

**References**

4. Timet Corporation, "Preparation and Processing", Ti 6Al-4V.