THE RESULTS OF PROTOTYPE TESTS AND TEMPERATURE AND FIELD COMPUTATIONS OF THE CERN LITHIUM LENS

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Summary

For the ACOL-Project at CERN, aiming at an increased antiproton yield, the development of lithium lenses was launched. A design, alternative to that originally developed at the INP at Novosibirsk/USSR has been elaborated. The mechanical assembly, the filling procedure and the electrical parameters of the lens are reviewed. The successful life tests in the laboratory of the first two lenses, pulsed at peak currents of 450 kA are described. Some results, selected from in-depth computations of the temperatures and transient fields are reported.

Introduction

Within the frame of the CERN ACOL-project aiming at improving the antiproton yield, lithium lenses will be used to focus the proton beam onto the production target as well as to collect the antiprotons at the downstream side. There a large lens with a diameter of 36 mm is foreseen. In the immediate future, however, a small lens with a diameter of 20 mm will be used with current pulses of 450 kA peak. A design, considerably different from that developed elsewhere[1,2] has been chosen and extensive prototype tests have been made. The experience, gained during the manufacture, filling and pulsing of several small lenses of this new type and some results of further computations of the temperature rises and magnetic fields are reported in the following.

Discussion of the Design

The principle lay-out of the lens, described in detail in Ref.3, is shown in Fig.1. The central Li-cylinder (16) is contained in the tube (10) of a martensitic stainless steel (Cr 16%, Ni 4%, Mo 1%, C 0.06%) with a thickness of 2.5 mm. This material was chosen for its good mechanical characteristics, weldability and compatibility with liquid lithium as well as for its corrosion resistance to demineralised water. Due to its elevated electrical resistivity, the current passing through this relatively thick walled tube is only about 7% of the total current. This container is further supported radially via ceramic spheres (9) (hot pressed silicon-nitride) by the outer housing (18) made from the same steel as the container (10). To test the numerous electron beam welds and the overall mechanical resistance, all lenses are He-leak checked and pressure tested up to 24 kN/cm^2. Failures have been observed at pressures above 35 kN/cm^2.

Due to the rigidity of the container, which allows only small thermal expansions of the lithium, the only substantial "elasticity" inherent in the structure is provided by the compressibility k of the lithium which leads to average pressure rises P in the central lithium rod according to $P=3\alpha\ T/k$ (α: coefficient of linear thermal expansion, T : average temperature rise). This pressure is, however, reduced by the additional buffer volume of lithium (15) (1.5 times the central Li-volume) which is located in the

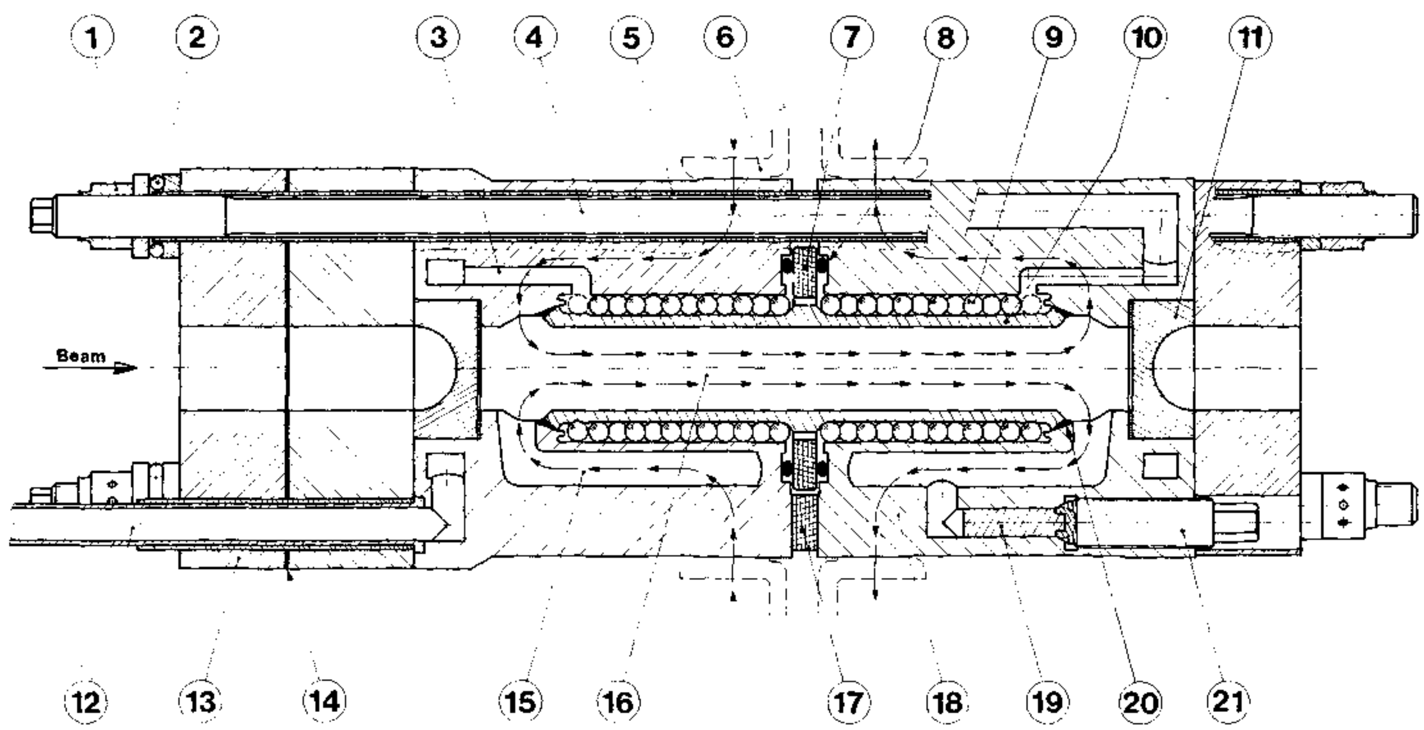

Fig. 1. Cross-Section of the Lens.
1:Titanium nut, 2:Silicon nitride spheres, 3:Cooling inlet channels, 4:Titanium tie bolts, 5:Alumina insulation, 6:Current contacts, 7:Silicon nitride ring, 8:Metal gaskets, 9:Silicon nitride spheres, 10:Stainless steel container, 11:Titanium window, 12:Cooling inlet pipe, 13:Insulated auxiliary flange, 14:Insulating mica disk, 15:Lithium channels, 16:Central lithium rod, 17:Ceramic spacers, 18:Steel housing, 19:Pressure piston, 20:Final weld after assembly, 21:Sealing plug.

outer steel housing where hardly any heating occurs and which absorbs partially the thermal volume increase of the central Li-rod.

For the end caps (11) titanium has been selected, to keep the absorption and scattering of the traversing particles to a minimum. The uniform hydraulic pressure on these windows from the lithium at 450 kA is at most 10 kN/cm^2. Under this assumption, the stresses in the windows have been calculated with a commercially available finite element programme. The stresses depend in detail on the applied boundary conditions at the rim of the window and are between 10 daN/mm^2 and 20 daN/mm^2. For comparison, different window shapes and in particular flat windows with the same average thickness have been considered. Two examples are shown in Fig.2. Although the stress patterns in these windows depend on their particular shapes, the absolute maximum stresses anywhere in the windows are within ±10% the same.

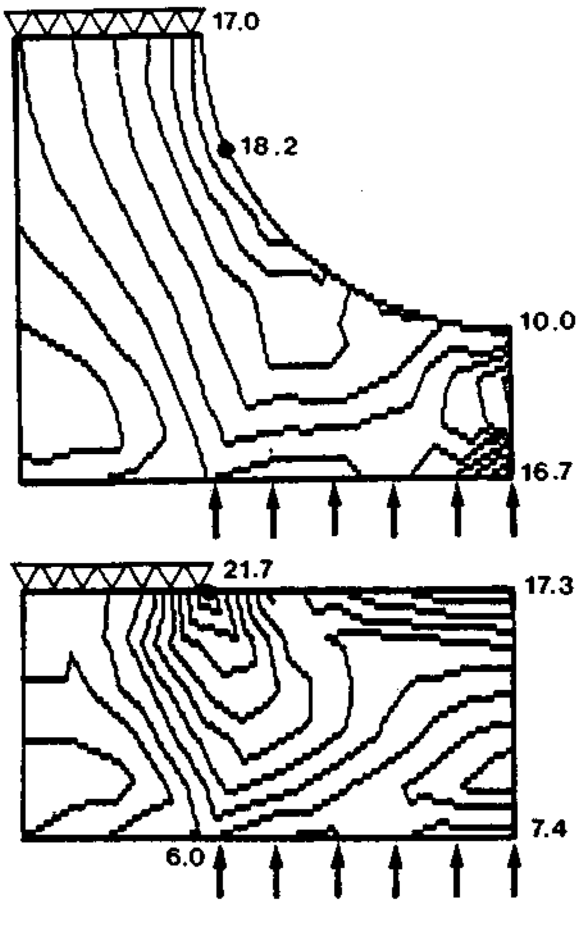

Fig.2. Iso-stress lines in Ti-windows of different shapes, but of the same average thickness. Some characteristic values are given in daN/mm^2. The triangles indicate the fixed boundary and the arrows the hydraulic pressure of 10kN/cm^2 from the lithium.

In addition to the hydraulic pressure from the lithium, the windows are also submitted to thermal stresses which are induced by the beam heating. In order to minimise the deposited energy the window thickness should be as thin as possible at least in its centre where most of the beam passes. From this point of view, the selected shape (11) (thickness in the centre 5. mm, average thickness 8.3 mm) is more favourable than a flat disk of 8.3 mm (average) thickness. Still, the deposited beam energy and the resulting average steady state temperature may rise considerably in the titanium due to its poor thermal conductivity. Therefore, provisions have been made to mount beryllium windows which absorb much less beam energy at the same thickness and which have a much better thermal conductivity. Beryllium is, however, less resistant to cyclic thermal stresses than titanium.

To attempt to increase further the mechanical resistance and the electrical conductivity of the outer steel housing of the lens, a high strength maraging steel (Ni 18.5%, Co 9%, Mo 5.3%, Ti 0.6%, Al 0.1%, C>0.03%) was used for a prototype. This material had been checked for its compatibility with liquid lithium for several weeks. The lens which had been pressurized to 20 kN/cm^2 and then heated to 240°C without pressure, failed at 80 N/cm^2 when it was filled with liquid lithium at 220°C. Cracks were found in this steel housing (18) starting from the marks imprinted by the ceramic spheres (9). Further metallurgic investigations did not lead to any conclusive results. They suggest, however, that the mechanical resistance of this maraging steel is reduced by liquid lithium at elevated temperatures in the presence of micro-cracks and possibly residual stresses.

Filling of the Lens

The filling procedure, as described in Ref.3, has been simplified and improved. As shown in Fig.3, the reservoir (5) and the entire station are evacuated now via a channel through the solid lithium in the reservoir. After melting this lithium during which the channel collapses, an argon pressure of 100 N/cm^2 is applied through the valve (2) into the reservoir which drives the lithium into the pre-heated system. Then, the reservoir and its junction (6) are cooled down, disconnected and the system closed with a high pressure plug. Thereafter, the pressure in the system is raised by the compressor (12) to 4 kN/cm^2 and cool down of the lens starts while the compressor and the pipes remain at 220°C. Fig.4 shows as a function of the temperature of the lens, the applied pressure and the relative volume loss of the lithium in the lens, as deduced from the height of the bellows (13) in the compressor (12). The expected volume loss of 1.5% at the transition from liquid to solid lithium at about 175°C is clearly observed. At about 150°C the pressure is raised to 10 kN/cm^2 at which a further volume transfer of about 1.3% occurs. This is consumed by the additional compression of the total amount of lithium contained in the system and possibly also by voids which have persisted or which appeared in the lens

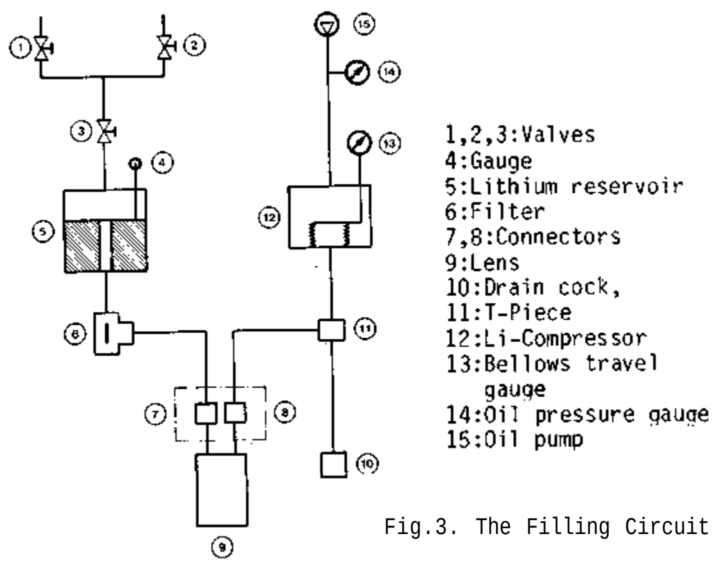

Fig.3. The Filling Circuit

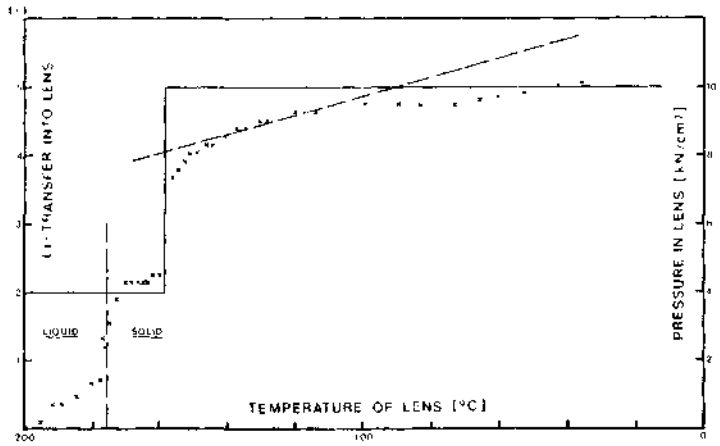

Fig. 4. The relative Li-volume V/V (indicated by the crosses, V:Li-volume contained in the lens) transferred into the lens and the applied pressure (solid line) during the cool-down. The dashed line indicates the relative volume transfer expected according to 3α T (α is corrected for the shrinkage of the steel).

during its cool-down. Thereafter, a more steady volume transfer occurs which seems, however, to be smaller than one would expect from the thermal shrinkage 3α T.

Then the lens is disconnected and transferred into the argon glove box. There, an additional lithium volume of about 1% is forced into the lens by the pressure piston (19), enough to produce a significant signal in the strain gauge which is mounted onto the steel housing. The lens is left at this pressure for at least 12 hours to allow the lithium to settle down and to fill up all voids which might have persisted. Thereafter the pressure pistons are removed and the lens left open for further 6 hours, during which some lithium must necessarily flow back plastically into the open channels. After this "pressure releaving" procedure a final lithium volume of 0.3% is added which should create a preload of at most 3 kN/cm^2. Thereafter the lens is sealed. Finally, to test its pressure resistance at elevated temperatures, it is heated to 60°C which is well above the expected average operating temperature.

Laboratory Tests

The lens is connected to the capacitor pulse generator via a high current transformer with a turns ratio of 23:1, similar to the design described in Ref.1 and 2, where the lens forms part of the single secondary turn. From the analysis of the damped half-sine current pulse

$$I(t) = I_0 \exp(-\delta t) \sin \omega t$$

with 6=1470 Hz and ω=π/580 μs and the parameters of the power supply and the transformer proper, a resistance and inductance of the lens of 100 μΩ and 31 nH respectively were found. These values are very similar to those obtained in lenses described in Ref.2.

No measurements have been made of the temperature rises in the lithium. The average temperature rises in the housing of the lens were measured inside a channel drilled into the steel, close to the current contacts (6) (see Fig.1), where the highest steady state temperatures are expected. In fact, the temperatures recorded on the Ti-windows (11) were always about 10% lower. As shown in Fig.5, the temperature rises

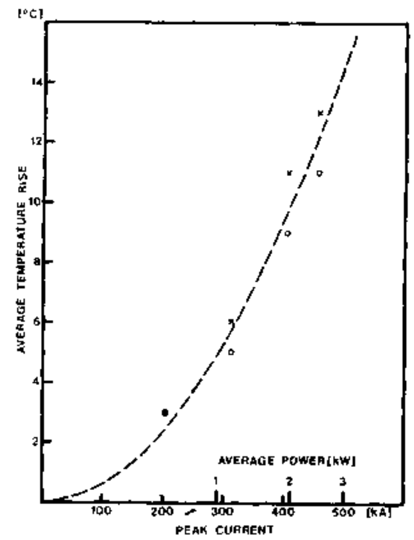

Fig.5 The temperature rise during the steady state in the housing of the lens (o:upstream, x:downstream) as a function of the peak current and the average power dissipated in the lens.

increase about quadratically with the peak current. At 450 kA, which represents an average power of 2.4 kW dissipated in the lens it reaches the very moderate value of 13°C. The applied water flow was 1.8 m^3/h at which the pressure drop across the lens was about 50 N/cm^2. Due to the high efficiency of the cooling jacket, the performance of the lens is thus not limited by the average power but, more likely by the thermal and magnetic shock effects induced in the lithium.

To be prepared to use air cooling of the lens, whenever this should become necessary, some results have been obtained under the following conditions:

Pressure at the air in-let	:	70 N/cm^2
Pressure at the air out-let	:	10 N/cm^2
Mass flow of the air	:	200 kg/h
Peak current	:	320 kA
Average dissipated power	:	1.3 kW
Average temperature rise at		
"upstream" steel housing	:	20°C
"downstream" steel housing	:	30°C

This shows that even for the design current of 450 kA, air-cooling, with somewhat increased air-flow is feasible.

Today, the first two lenses have undergone extensive life tests in the laboratory which included several million pulses at peak currents of 320 kA and 400 kA and for the final acceptance test 2 mio pulses at the design value of 450 kA. The lenses and their electrical characteristics have regularly been checked during the runs, however, no degradation nor variation was found. Two newly manufactured lenses have successfully been filled and are ready for pulsing. Tests with beams are scheduled for the beginning of 1987.

Results of Temperature and Field Computations

One may expect that the most critical part of the lens is located at the ends of the central steel container (20) where it is welded to the outer steel housing and where the highest current densities and stress concentrations might occur. Since it is important to investigate this further and since measurements at this location are hardly possible, detailed computations of the time and space dependent current densities in this area and the resulting temperature rises have been made with a specially designed programme[4], however, under somewhat simplified assumptions. These computations revealed that in spite of the sharp bend of the current conductor at the considered location (20), the current is rapidly driven from the steel due to its high electrical resistance into the lithium (ρ st.steel/ ρ Li $\approx$ 7). It results that at a peak current of 450 kA the maximum temperature rise per pulse in the steel is about 27°C, which is about 4.5 times higher than in the central straight section of the steel container. In spite of the low thermal stresses resulting from this moderate temperature rise, failures may still occur at this location due to the pressure from the lithium or even due to imperfections in the weld which are difficult to verify and which may lead to crack propagation, spark erosion or stress corrosion, in particular at the side which is in contact with the cooling water.

The computer programme described in Ref.4., also permits the study of the magnetic field development everywhere in the lens. Fig.6 shows the equi-field lines of the circumferential magnetic field B_ϕ, which rise radially in the central core in steps of ΔB_ϕ=1 Tesla. The picture shows the field lines at the working point, i.e. at the moment during the current pulse when the field gradient in the central core is most uniform. This is illustrated by the nearly uniform line density in the centre. Fig. 6 clearly indicates the depth of the inhomogeneous end fields which occupy at most 20% of the total depth of the lithium. These computations can be carried further to study in greater detail the magnetic properties of the lens for collecting antiprotons.

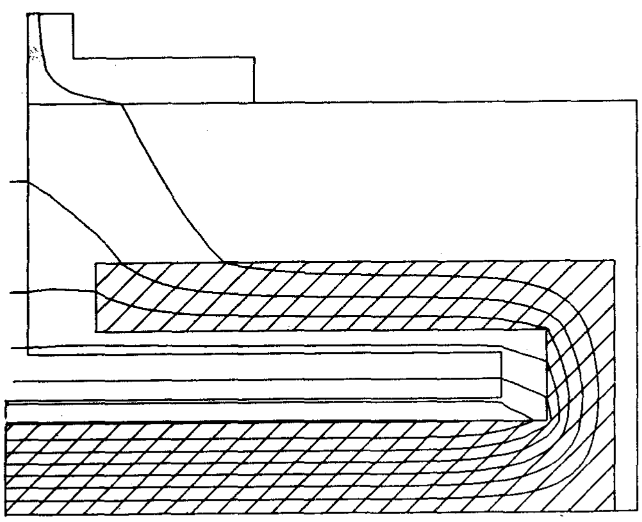

Fig.6. Iso-field lines of the circumferential magnetic field in the lens at the working point. Only one of the symmetric quarters of the cross section of the lens is shown. The step size ΔB_ϕ between two lines is 1 Tesla.

Conclusions

Four lenses of a novel design with a diameter of 20 mm have been constructed and successfully filled. Two of them have undergone extensive life tests in the laboratory, including more than 2 million pulses at peak currents of 450 kA and a repetition time of 2.4 s. Owing to the excellent efficiency of the cooling jacket of the lens, very moderate average temperatures are attained in the steel container with water cooling as well as with air-cooling. Therefore, the performance of the lens does not seem to be limited by the average power deposited in the lens but more likely, by the adiabatic temperature rise in the central Li-core and by shock and fatigue effects. However, during the tests no failures have occured, neither in the container, the housing and the tie-bolts nor in the central water gasket which initially was of great concern, and the windows. Therefore, the adopted design seems to be sufficiently healthy to expect safe operation at 450 kA also in the beam. Although the additional beam energy deposited in the lens should easily be absorbed by its cooling system, the beam heating of the Ti-windows and possibly also of the Ti-bolts which are in poor thermal contact with the cooled housing, may cause problems. Therefore, some minor design modifications may be necessary in the light of the experience gained during forthcoming tests in the proton beam.

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Discussion

В.П.Джелепов. Какова причина увеличения диаметра линзы?

P.Sievers. A small lens was not quite optimal since the target had to be very close to the lens a larger lens allows a larger target /lens distance and larger angles of the $\bar{p}$'s to be accepted.