DEVELOPMENT OF LITHIUM LENSES AT CERN

P. Sievers, K. Bellone, A. Ijpeet, P. Zanasco
European Organization for Nuclear Research CERN
CH-1211 - GENEVA 23, SWITZERLAND

Summary

For the upgrading of the antiproton source as part of the ACOL project, strong lithium lenses with gradients of 500-1000 T/m are required. The characteristics of these lenses, like the current and field distributions and the temperatures and forces have been computed based on these studies, a novel lens design has been developed, including a lithium container of very high pressure resistance. For the proper filling of the lens a special circuit has been built to cast the liquid lithium under vacuum and high pressure into the container. The design and the assembly of a lens with a diameter of 2 cm are described. The tests of the lens in the laboratory have started. Presently, more than 10^4 current pulses have been accumulated at the required repetition rate of 2.4 s and peak currents of 320 kA without causing any failure of the lens.

Introduction

Lithium lenses, powerful tools to collect secondary particles from production targets, have successfully been applied or are being developed at the INP, Novosibirsk, USSR, and FERMILAB, Batavia, USA. In these devices, use is made of the focusing circumferential magnetic field which is created by an axial current pulse inside a lithium cylinder. This metal is chosen for its high electrical conductivity and its transparency for secondary particles. Guided by the experience in the above institutes, also at CERN prototype development was started for lenses with diameters of 2-4 cm for the ACOL-antiproton source. Here we report on the status of this development and in particular on the design and tests of the "small" lens with a diameter of 2 cm.

Design parameters

To achieve with a half-sine current pulse the initially required magnetic gradients of about 500 T/m during the passage of the antiproton burst, a peak current of about 300 kA and a duration of about 600 µs is required. The magnetic length of this lens is about 13 cm. However, to explore its performance also at higher gradients, studies have been made for currents up to about 600 kA.

A computer programme has been written which calculates for a given current pulse the development of the current density with time in the lithium as well as in the stainless steel container around it. Taking into account the effects of eddy currents the magnetic field, the electro-magnetic forces and the temperature rises are computed for a single pulse as well as for steady operation with repetitive pulses, where the temperature dependance of the material properties of lithium are included. The optimum current pulse was found by balancing the optical quality of the lens (uniform field gradient) against the temperatures and thermal pressures in the lithium. The results described in detail in ref. 4, are summarized in Table 1 and the magnetic fields and temperatures are illustrated in Fig. 1.

The design

A vessel had to be developed which resists the elevated pressures from the thermal expansion of the lithium. This led to the design shown in Fig. 2. The central lithium cylinder is surrounded by a martensitic stainless steel pipe (the container) with a wall thickness of 0.25 cm. This material has adequate strength, is weldable and has an electrical resistivity of about 7 times that of lithium so that only about 5% of the peak current passes through the container wall. The radial forces from the lithium are transmitted through the stainless steel to ceramic spheres.

Table 1. Computed maximum forces, pressures, temperatures and magnetic gradients in a lens with a diameter of 2 cm, cooled by water and compressed air with flows of 0.15 kg/s (1) and 0.06 kg/s (2).

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Fig. 1. The radial distribution of the circumferential magnetic field and the temperature during the pulse (time increments 80 µs, steady operation, ambient temperature 20°C, 320 kA peak).
As cooling medium, demineralized water or compressed air is foreseen. It is fed to the circular layer of spheres via two axial pipes which are split inside the housing into a set of eight smaller channels equally spaced around the circumference for good flow distribution. The cooling outlet is arranged similarly. The cooling efficiency has been measured in a model where a known amount of electrical power was dissipated in the central container and the temperature difference was detected between the latter and the cooling medium. At water flow rates of 0.5 kg/s the heat transfer coefficient at this interface was large compared to that of the container wall proper of $0.8 \times 10^4 W/m^2\cdot ^\circ C$. With compressed air at 6 bar and a flow of 0.06 kg/s a heat transfer coefficient of $0.7 \times 10^4 W/m^2\cdot ^\circ C$ was obtained. Values up to $2.3 \times 10^4 W/m^2\cdot ^\circ C$ could be expected with increased flow rates. Table 1 gives the computed results for both cases which shows that air cooling could be used in small lenses up to 400 kA.

To avoid any current by-passing the central lithium rod, the two steel housings have to be insulated from each other. Therefore, the gaskets 8 which are densely packed around the container 10. This unit, in turn, is restrained by hollow cylinders 18 made of electrically low resistive, high strength maraging steel (the housings). Thus, the lithium is rigidly supported radially by an electrically insulating layer which still allows the cooling medium to flow around the container. For the spheres, hot pressed silicon nitride is used which supports static loads up to 20 kN and impact energies from a drop hammer of up to 11 Joules per sphere. Therefore, with a packing density of 4.5 spheres/cm$^2$, static pressures up to 90 kN/cm$^2$ can in principle be supported. This is well above the computed pressures and the resistance of the central steel container. Prototype assemblies were tested up to 40 kN/cm$^2$ when the container showed considerable plastic deformations.

Presently, titanium windows 11 with an average thickness of $t = 0.8 \ cm$ each are mounted. To reduce further multiple scattering and absorption, average thicknesses of 0.6 cm have been tested statically up to pressures of 40 kN/cm$^2$. The expected repetitive pressure pulses of up to 20 kN/cm$^2$ would allow windows with $t \leq 0.5 \ cm$. Also beryllium windows, as mounted in the lenses described in ref. 1 and 2 could be selected.

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The electrical current delivered from a toroidal transformer (identical to the Fermilab design) around the lens is applied to the circumference of the housings in the middle of the lens. From there the current runs inwards and thereafter in axial direction, partly through the steel 18 and partly through eight axial lithium channels 15. Their total cross-section, initially being about twice the central conductor, is gradually reduced and is about equal to the latter at their junction. The heat dissipation in the housing was checked in a water cooled model through which a d.c.
current of 5 kA was passed, which is equivalent to current pulses with peaks of 450 kA, pulse durations of 800 μs and a repetition time of 2.4 s. The maximum temperature rise on the housing during the steady state was only 30°C and is even pessimistic, since during pulsed operation the power is dissipated closer to the heat sink due to the skin effect. Detailed computations of the temperatures and forces inside the housing are in progress. Preliminary estimates indicate that very localised, temperature rises due to current concentrations in the lithium close to the sharp edges may approach the melting point of 183°C. Moreover, thermal and mechanical shocks in the steel at this "hair pin bend" 20 may limit the life time of the lens.

The manufacture, assembly and filling

The radial part of the lithium and water channels could not be machined by current means and had to be spark-eroded. The silicon nitride spheres 9 were glued around the container 10 in their pre-determined positions. After the assembly of the container 10 and the housings 18 the glue was removed with acetone and the above parts were welded together (20). Throughout, all welds were made with an electron beam gun, they were helium leak tested and those in contact with lithium were pressure tested up to 20 kN/cm². After the filling of the end caps 21 and the bellows 5, a load of 30 kN/cm² was applied to expand plasticly the central container 10 in order to suppress the radial play of the ceramic spheres 9.

The circuit, to fill the lens is shown in Fig. 3. First the container 2 was filled with liquid lithium in a glove box under pure argon. After cool down and sealing, it was mounted into the circuit, to which also the lens 1 was connected via high pressure stainless steel pipes. After evacuating and heating the circuit to 220°C, a small argon pressure of below one bar was applied on top of the molten lithium in container 2. This driven the melt through the circuit. Filling the lens 1, the bellows 5 of the compressor and the container 3 where the excess of lithium was recuperated. After cooling and insulating of the low pressure part A of the circuit from its high pressure side B, the bellows in the compressor was submitted to an external hydraulic pressure of 30 kN/cm². Thus additional lithium was pressed into the lens during its cool down in order to compensate the volume loss of about 4% during this phase. After the end caps 21, the piston with the plugs 21, the housings and the bellows 5, were pressure tested the lens was mounted into the circuit, from which the high pressure side of the housing of the lens began to respond only, after the assembly of the container 10 and the housings. Up to now the lens withstood more than 10⁴ pulses without any failure. This life test will continue till several 10⁵ pulses have been accumulated. Further tests will be made with peak currents of above 500 kA. We also foresee to run the lens with air cooling.

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References


