PERFORMANCE AND OPERATIONAL EXPERIENCE WITH CERN-LITHIUM LENSES

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Summary

Lithium lenses were originally developed by the INP at Novosibirsk/USSR for the collection of positrons downstream from the converter target. With the advent of proton-antiproton colliders for which efficient $\bar{p}$ sources are required, Li-lenses serve also as the first matching element [1],[2] which transforms the strongly divergent $\bar{p}$-beam into a parallel one. A novel design of lithium lens has been developed at CERN for the ACOL $\bar{p}$ source. Small lenses with diameters of 2 cm have been extensively tested in the laboratory with peak currents up to 625 kA, yielding a field gradient of up to 1000 T/m. During the commissioning of ACOL in 1987, such a lens was used successfully in the beam at its design current of 420 kA. For future use at ACOL, large lenses with a diameter of 3.6 cm have been built and submitted to current pulses of above 800 kA, providing gradients above 400 T/m. The operational experience with these lenses, their optical parameters and their performance limits are discussed.

Description of the Lenses and their Tests

The design of the large 3.6 cm diameter lens is given in Fig.1. It is essentially a scaled up version of the smaller 2 cm lens [3]. The axial lithium conductor in the centre, inside which the focussing, circumferential magnetic field is produced, is surrounded by water cooled stainless steel containers. These serve as current leads and provide simultaneously sufficient rigidity to retain via the ceramic spheres the radial, thermal pressure from the central lithium rod. In order to lead the current from the outside periphery towards the centre, the two steel shells have to be insulated from each other axially by a specially designed water gasket and they are retained against the axial magnetic forces by electrically insulated tie rods. The lens is powered from a capacitor bank which is discharged into a toroidal transformer of which the load is formed by the lens as part of the single secondary coil. The transformer fitted with the 2 cm lens is shown in Fig.2.

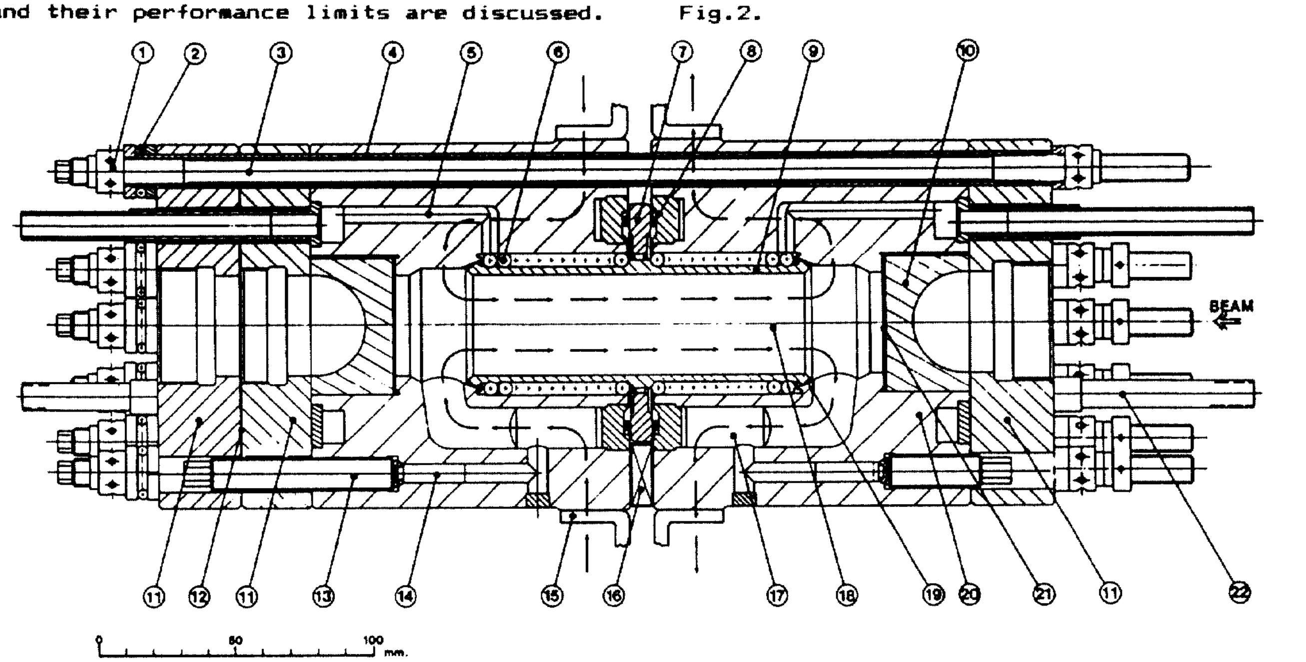

Fig.1: Cut through 3.6 cm diameter lens: 1. Titanium nut- 2. Si-N-Spheres, Ø=3.5 mm - 3. Titanium tie bolt - 4. Alumina insulation - 5. Water inlet channel - 6. Cooling jacket plus Si-N-spheres, Ø=5 mm - 7. Si-N-ring - 8. Metal gasket - 9. Stainless steel container 10. Titanium or Beryllium window - 11. Retaining end flanges - 12. Insulating mica disk - 13. Sealing plug - 14. Piston for pre-loading - 15. Current contacts - 16. Si-N-spacers - 17. Lithium channels - 18. Central lithium rod - 19. Final weld - 20. Steel housing - 21. Titanium foil - 22. Water outlet.

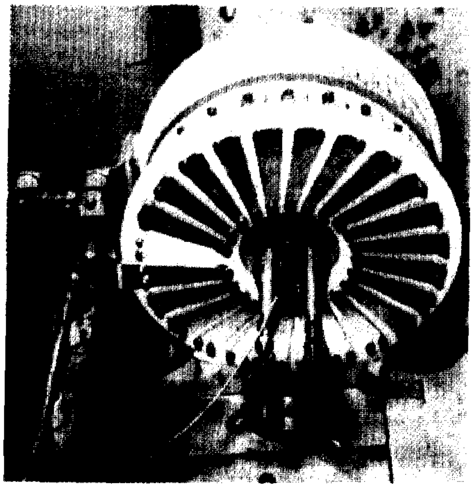

Fig.2: Test stand for the 2 cm diameter Li-lens, located in the centre of its transformer (outside diameter 42 cm). The piping for the water cooling of the lens and part of the 23 ceramic insulated turns of the primary coil are clearly visible.

Laboratory Tests at CERN : The first prototype lens, of which the design and filling procedure has been described in Ref. [3], has been tested up to 10^7 pulses with a peak of 450 kA, a duration of 600 µs and a repetition time of 2.4 s, which equals 278 days of permanent operation of ACOL. Thereafter, the lens was opened and after dissolving the lithium, thoroughly inspected. No signs of degradation, such as corrosion, fatigue cracks or erosion were found. Thus, the adopted design proved to provide excellent reliability and lifetime which is not expected to be considerably reduced during long term operation downstream of the target with beam (See later).

High Current Tests at FERMILAB: To exploit the performance at higher peak currents, one 2 cm diameter lens was shipped to FERMILAB and mounted there into a test stand capable of peak currents up to 650 kA, which at that time could not be achieved with the CERN pulser. However, a relatively short pulse of 345 µs duration, matched to the FERMILAB lens [1] had to be employed. During a long-term test, over 10^4 pulses at peak current of 625 kA were accumulated at a repetition time of 1.5 s. The resistance R and inductance L of this lens, measured during these tests, were 214 µΩ and 20 nH respectively. They are different from the values measured at CERN with a pulse duration of 600 µs (R= 100 µΩ, L= 31 nH). This can be attributed to the incomplete current penetration of the central lithium rod during the shorter pulse due to the skin effect. Detailed computations of the effective gradient, expected to be ≈ 1000 T/m have still to be made. The average power deposited in the lens during the tests at FERMILAB was about 9 kW which is 4 times the power dissipated with the parameters employed for ACOL. As a result, the average temperature rise in the lens was about 28°C as compared to 13°C. From these tests it can be expected that the lenses are capable of providing reliably gradients of at least 1000 T/m at a repetition time of below 2 s.

Operation in Beam for ACOL: During the commissioning of ACOL at the end of 1987, a 2 cm diameter lens was operated for the first time in the beam downstream of the $\bar{p}$-target, being irradiated with 8×10^{12} p^+/pulse at 26 GeV/c and a repetition time of 4.8 s, twice as long as envisaged for final operation. The $\bar{p}$-yield achieved with this lens will be reported in Ref.[2]. Particular measurements of the additional average temperature rise due to the power deposited by the beam in the steel housings and the tie rods were made [4] which are summarized below, for the repetition time of 2.4 s and various proton intensities. It shows that the average temperature in the lens body should not lead to any problems even at 2×10^{13} p^+/pulse. However, for the titanium tie rods, which are electrically and thus also thermally insulated from the surrounding steel, additional air-cooling should be provided at their ends [4].

Peak Current (kA)	Proton Intensity $10^{13}p^+$/pulse	δT (el) (°C)	δT (beam) (°C)	T (max) (°C)
425	0.8	12	22	55
	2.0	12	54	87
625	0.8	27	22	70
	2.0	27	54	102

Test of Large 3.6 cm Diameter Lens: A first prototype of the large 3.6 cm diameter lens, (See Fig.1), was built at CERN. In that lens the total Li-volume is about 430 cm^3 of which only 30% is contained in the central conductor, where most of the electrical power is dissipated. In this way a large amount of the average thermal pressure, originating in the centre, is absorbed by compressing the excess lithium buffer volume. The filling procedure as described in Ref.[3] was somewhat modified, i.e. the evacuated lens was filled with liquid lithium at 220°C but cooled down to room temperature under a rather low pressure of 15 atm. Thus, voids will be created in the lens due to the thermal shrinkage of about 5% (22 cm^3) of the lithium volume. Therefore, additional solid lithium was transferred into the lens at room temperature under inert atmosphere via the pressure pistons (See Fig.1). After injecting about 30 cm^3, the lithium started to be extruded through the opposite filling ports, which indicated that the lens was completely filled. After adding a further 0.3% of lithium to create the required preload the lens was sealed.

Since no transformer nor power supply was available at CERN for this large diameter lens (outside diameter 13.2 cm), the lens was sent to the INP/Novosibirsk where also a programme for the development of large Li-lenses [5] is under way and where the test facility could be made available for the initial performance tests of the CERN lens. The INP transformer fitted with the CERN lens is shown in Fig.3.

Fig.3: Test set-up at the INP/Novosibirsk for the CERN 3.6 cm Li-lens, visible in the centre of its toroidal transformer (outside diameter 60 cm).

The lens equipped with its pair of current contacts is shown in Fig.4. The transformer and the test facility at the INP is described in Ref [5].

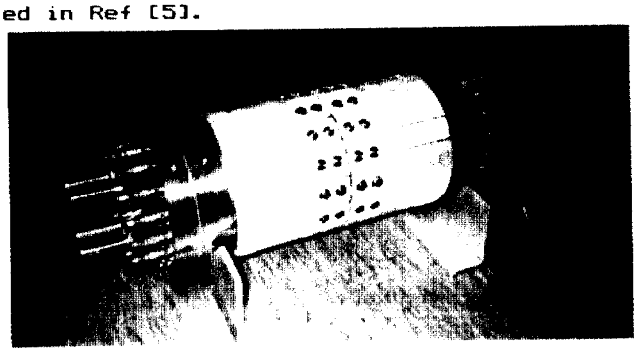

Fig.4: 3.6 cm diameter Li-lens with its water connections and the studs of the 14 axial tie rods, protruding at both ends. Bolted around the lens (diameter 13.2 cm) is a pair of silver coated current contacts.

A long term test was made with a peak current of 800 kA, a time to peak of 1.0 ms, which is adequate for full current penetration, and a repetition time of 2.3 s. The approximate values for the resistance R and inductance L of the lens proper were : $R \approx 38$ $\mu\Omega$, $L \approx 35$ nH. The average power dissipated in the lens was about 13 kW causing an average temperature increase of about 20°C. The tests were successfully terminated after 5 10^5 pulses at 800 kA and some short term tests up to 1000 kA, the maximum design current of the transformer. These tests showed that the developed basic design and in particular its cooling system is also adequate for large lenses with diameters of about 4 cm in which gradients of at least 400 T/m can be achieved.

Optical Parameters and Performance Limits

To qualify the optical performance of the lenses, the following two parameters are considered: the maximum angle α under which 3.5 GeV antiprotons, starting from the target centre and still accepted by the lens, emerge parallel at its end; the focal distances S between the target centre and the front face of the magnetic volume. In Table 1 these parameters are given for various peak currents $\hat{I}$ and magnetic lengths l. In view of the tests described above it may be hoped that with the small lenses angles up to about 90 mrad can be accepted with some re-designing of the lens (shortening of the magnetic length and rearrangement of the entrance window to allow for the reduced focal distance S). Applying similar modifications to the larger lens, angles up to 120-130 mrad may be within reach. Further tests of large lenses with peak currents up to 1500 kA are planned in collaboration with the INP/Novosibirsk in the near future.

Table 1: Principle parameters for 2 cm (top half) and 3.6 cm lenses (bottom half): achieved during the tests (*), at higher peak currents believed to be feasible (**) and at estimated upper current limits (***). $\hat{I}$:peak current;g:magnetic gradient;$\sqrt{k}$:quadrupole strength for p = 3.5 GeV/c; l:magnetic length;α:maximum accepted angle; S:focal distance.

$\hat{I}$ (kA)	g (T/m)	$\sqrt{k}$ (m^{-1})	l (cm)	α (mrad)	S (cm)
420*	700	7.75	13	66	8
625*	1000	9.26	13	86	4
625*	1000	9.26	10	74	8
800***	1300	10.55	8	79	8.5
625*	1000	9.26	11.5	81	6
800**	1300	10.55	9.5	89	6
800*	430	6.07	13	78	16.5
1000**	540	6.80	13	95	12
1500***	800	8.28	9.5	106	12
1500***	800	8.28	10.5	114	10.2
1500***	800	8.28	12	125	8
1500***	800	8.28	13	131	6.5

Acknowledgements

Obviously, without the diligent support of many persons, the extensive construction and test programme of the lenses would have been impossible. Since all cannot be mentioned by name, acknowledgement of their efforts is made by thanking their respective home institutes for their massive support: CERN, FERMILAB and INP/Novosibirsk.

References

[1]G.Dugan, $\bar{p}$-Production and Collection at the FNAL Antiproton Source, in Proc. of the 13th Int.Conf. on High Energy Acc., 264-271, 1986.

[2]F.Pedersen, Performance of the CERN Antiproton Accumulator Complex, Europ. Part. Acc. Conf.1988.

[3]P.Sievers et al., The Results of Prototype Tests and Temperature and Field Computations of the CERN Lithium Lens, in Proc. of the 13th Int.Conf. on High Energy Acc., 272-275, 1986.

[4]P.Conventry, CERN-PS-AR NOTE 88/14,June, 1988, to be published.

[5]B.F.Bayanov et al., Large Lithium Lenses with Solid and Liquid Lithium, Europ. Part. Acc. Conf. 1988.