LARGE CYLINDRICAL LENSES WITH SOLID AND LIQUID LITHIUM

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The employment of lithium lenses for antiproton collection has confirmed their high effeciency and the present antiproton target stations at FNAL and CERN are running on the basis of 2-cm-diam lenses working at magnetic fields roughly equal to 100 kOe [1, 2]. The current problem of the progress to the technology of lithium lenses is further extension of the range of their parametres: diameter up to 4—6 cm, frequency of the running cycle and ultimate magnetic field over 100 kOe. The analysis of heat removal regimes [3] and the stresses caused by thermal expansion of lithium [4] shows that when designing large-diameter lenses it is not advisable to merely enlarge the sizes, but it is necessary to search for the basically new designs. In the existing designs the heat is removed from the operating volume of a lens through a thin envelope confining a lithium cylinder and made from a material with low thermal conductivity—titanium or stainless steel, and the water passes over its outer surface. The time of heat removal, as a function of the envelope thickness Δ and its radius r_0, may be estimated as $\tau \simeq \frac{\Delta r_0 (c\gamma)_L}{\lambda_{en}}$ where c and γ are the heat capacity of lithium and its density respectively, and λ_{en} is the thermal conductivity of the envelope. Simultaneously, the full energy released in the lithium volume grows as r_0^4 because in addition to an increase the lithium volume with increasing the radius, the duration of the current supplying the lens must increase also as r_0^2 to conserve the ratio σ/r_0 (σ is the thickness of the skin-layer) determining the degree of homogeneity of the current density; as a result, the lens cooling becomes a serious problem. At the same time, the maximum pressure in the lens, limiting the allowable magnetic field, is defined as

$$P = \frac{\alpha T}{\chi_{Li} \frac{V_0}{V_h} + \frac{2}{E_{en}} \frac{r_0}{\Delta}}$$

where T is the temperature of pulse heating proportional to H^2, α is coefficient of thermal expansion of lithium, χ_{Li} is its compressibility, E_{en} is the modulus of elasticity of the envelope, V_0—the total lithium volume, V_h is its part being heated, which can achieve several hundreds atmospheres already at 100 kOe fields. A considerable reduction of the pressure in the system might be achieved by an increase of the ratio V_0/V_h by means of special buffer volumes of lithium, for example, in the region of current lines where lithium is heated up insignificantly. These buffer volumes have to take over the thermal expansion of its operating volume. The main obstacle to this is a large, in tens of second, time for relaxation of the plastic deformation in solid lithium. At comparatively short cooling time this leads to a reduction of the pressure in the operating part of the lens below the initial level. For the pulse intervals shorter than the relaxation time, this can result to tear away of lithium from the wall and in violating the cooling conditions for the lens.

A cardinal change in the operational mode of the lens is the transition to the designs capable of working with liquid lithium which is pumped through the working volume of the lens and a heat exchanger. In this case, the pulse repetition frequency determined only by the time of lithium exchange in the lens, i. e. it will have no restrictions of principle. The amplitude of the pressure pulses will decrease substantially both due to bigger liquid lithium compressibility by a factor of about 5 and to the possibility to use effectively the large «buffer» volumes at the relaxation times in liquid lithium which are determined only the sound propagation in the system. When advancing the technology of liquid-lithium lenses we developed simultaneously two directions: the creation of small lenses at a pulse repetition frequency in hundreds of Hz for application to positron sources of linear accelerators the major problem for which is to remove the power in several kilowatts released in a volume of about 1 cm^3, and the creating of large ones (4 cm and more in diameter) for an energy release in several tens of kilojoules [5, 6]. The development of the new lenses necessites to eliminate the air-tight joints from the lithium volume for its reliable tightness under high-temperature conditions and to create all-welded constructions. Below we will consider one of the recent designs of a 4-cm-diam lens satisfying the requirements for the operation at high radiation levels.

The lens (Fig. 1) is all-welded and much simpler in design owing to the absence of water cooling. The wall thickness of central tube *4*, determining the cooling time in the former designs, is limited only by a permissible shunting of the current and can be increased, for the sake of reliability, up to several millimetres at the expense of a certain complication of the power supply system.

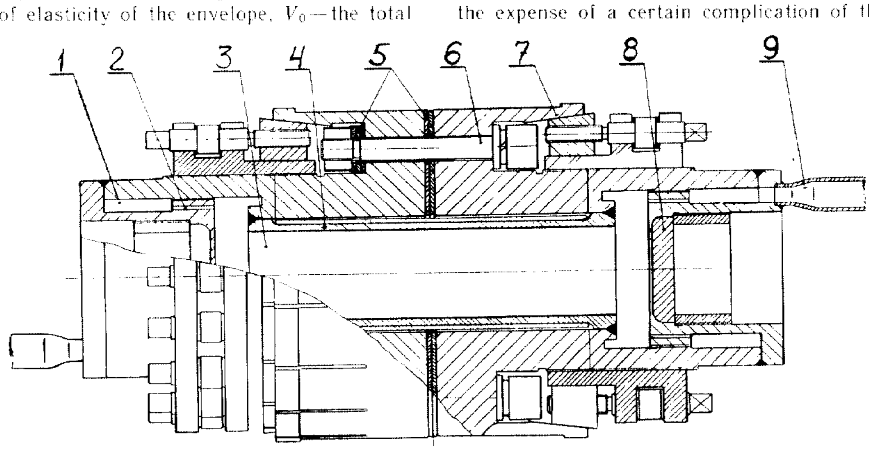

Fig. 1. Longitudinal section of the lens with circulating liquid lithium:
1—buffer volumes; *2*—supply channels; *3*—operating lithium volume; *4*—thin-wall envelope of the operating lithium volume; *5*—oxidized titanium insulators; *6*—retaining bolts; *7*—collet contacts; *8*—beryllium windows; *9*—supply tubes for liquid lithium.

The central tube is welded to the side cups soldered in turn to copper current lines gradually transforming to collet contacts; note that the latter provide a connection of the lens to a transformer. Liquid lithium is supplied owing to that the faces of the lens are connected to the buffer lithium volumes *1* through a large number of holes small in diameter *2* which provides its uniform supply. The buffer volumes are connected, by means of transport tubes *9*, to a system for lithium pumping.

The equipment for lithium pumping comprises an electromagnetic conductive-type pump designed at the INP for this purpose, a heat exchanger, an electromagnetic flowmetter and a system responsible for lithium pressure. The latter device is an important component in the work with liquid lithium in a closed contour because it makes it possible to create and control a preliminary pressure (~50 atm) which guarantees the absence of any hollows: these can appear at lithium melting and hardening. It is a bellows with a welded bottom, which is filled with lithium and connected to the system. The bellows is placed in an air-tight cylinder filled with a gallium-indium alloy and connected in turn by a thin tube with a manometer and a piston pump.

The first experiments with liquid-lithium lenses of large diameter have shown that the basic problem is the shock waves in lithium arising in it at pulse heating and, as consequence, the units of the lithium circulation system should be reinforced additionally. Note that this determines the serviciability of the system as a whole. In this case, the whole lithium system serves as a buffer for lens operation. The holes of small diameter *2* at the lens faces through which lithium flows to its working volume attenuate these shocks partly. However, the cardinal solution is the mounting of locking valves at the exit and entrance of the lens which divide the lens volume from the whole system at the moment of a working pulse. The device is demonstrated in Fig. 2. Its massive central steel core *3* is in lower position between the working cycles thus allowing lithium to flow freely in the contour. Before triggering of the lens, the winding of the valve *2* is powered and the core is lifted to the upper position and switched the circulation of lithium off. After a working cycle the valve winding ceases to be powered and the core sinks on the bottom of the body due to its own weight so that lithium continues to circulate.

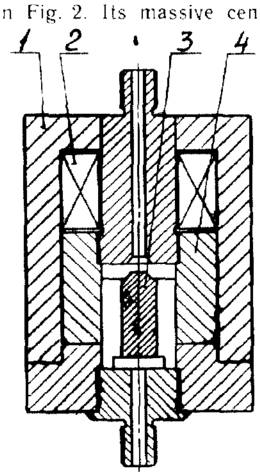

Fig. 2. Locking valve: *1* — magnetic core; *2* — coil; *3* — steel core; *4* — stainless steel cylinder;

As the lens diameter increases (≥4 cm) the current necessary for its powering seems to be roughly equal to 1 MA and more and for the pulse duration increasing proportionally to r_0^2 and equal to >1 ms, the power supply for the lens becomes rather a complicated problem. Note that as far as the power supply is concerned, there is one more advantage of liquid lithium: it offers the possibility of working at considerably shorter current pulses — in the ratio of the resistivity of liquid lithium to that of solid one $\tau_s/\tau_e=\rho_e/\rho_s=3\div 4$ for the same requirements to the field linearity, i. e. to the quantity σ/r_0. At the same energy release in the working section of the lens the ohmic losses in its current lines, transformer and the units of the pulse generator, usually equal to a half of the total energy release, will be correspondingly ρ_e/ρ_s times less.

The lens is a low-inductive load with $L\simeq 40$ nH and $R\sim 5\cdot 10^{-5}\Omega$. It is powered by means of matching transformer, designed such that it has low scattering inductance with ceramic insulators; the latter determines its high radiation resistance. The transformation ratio is taken equal to 10—20, so that the load matches with minimal losses to a current feeder and the voltages in the radiation zone do not exceed 1—1.5 kV. The second transformer of conventional design with the coefficient 2—4 is assumed to be placed behind the radiation shielding for further matching with the pulse generator and for reducing the current being commuted down to several tens of kiloamperes; it is simply achieved by means of thyristor valves.

A radiation-resistant transformer is a thick-wall torus, (Fig. 3) rectangular in cross section and being a secondary turn with a cut on the inner diameter which the lens is connected to. Inside the torus there is a circular magnetic iron core also being of the rectangular cross section. On the inner diameter it is separated from the secondary turn by an air insulation gap. The design of the transformer is based on the principle of a balanced primary winding whose each turn is placed on the holes in thick walls of the secondary turn with symmetrical gaps and does not interact with the neighbouring ones. In addition to the balance of turns, such a design provides a minimal inductance of scattering.

In this design each primary turn is the section of coaxical lines, i. e. the rods passing in the axial direction through cylindrical

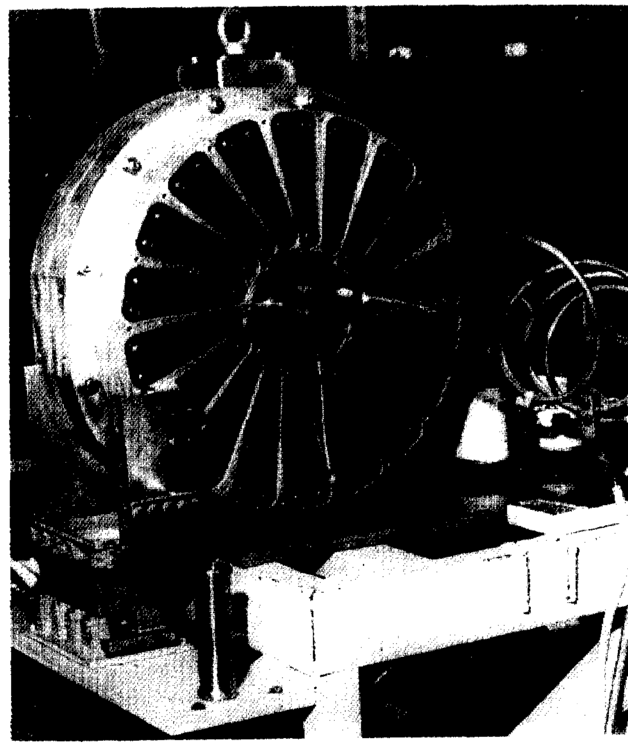

Fig. 3a Photograph of the lens-transformer and liquid lithium system.

holes in the body of the secondary turn; these are placed by one on the inner diameter and by two on the outer. The rods are linked in the radial direction by flat wedge-like connector being in the radial grooves on the faces of the secondary turn. The transformer faces are spanned by circular copper covers so that the equal gaps are formed above the planes of the wedge-like connectors, thus ensuring the equality of the magnetic fields on their surfaces and the complete winding balance. The collet clamps connect the cylindrical sections of the winding to the flat connectors. Each connector rests on ceramic insulators inserted into the cylindrical notches in the bottom of the body of the secondary turn, so that each turn proves to be aligned at several points on the ceramic insulators, the 3 mm air gaps being exactly fixed. Such a transformer (the cross section of iron 180 cm^2) provides a current of 1 MA for a pulse duration of 3 ms. In this case, the induction inside iron core can achieve 3 T by its reversal of magnetization. It is the regime we obtained in our tests of a 3.6-cm-diam lens with solid lithium designed and manufactured in CERN. In service tests this lens carried half a million of pulses at 0.8 MA current. The liquid-lithium lens of 4 cm diameter, manufactured at the INP, was tested a pulse duration of 1 ms.

Since the lens is a load with low Q-factor when its powering by unipolar current pulses from the discharge of a bank of capacitors the back edge of the pulse turns out to be longer than the front one so that the energy is mainly released in the lens after the current reaches a maximum. We have tried to design a generator providing a considerable shortening of the back edge of the pulse because it can be of importance for lenses operating at ultimate regimes with respect to pulse heating. The principle of operation of the generator (Fig. 4) at a maximum current it is switched, by means of switching the thyristor T_2, to the bank C_2 charged up to the working voltage of the bank C_1; as a result, the

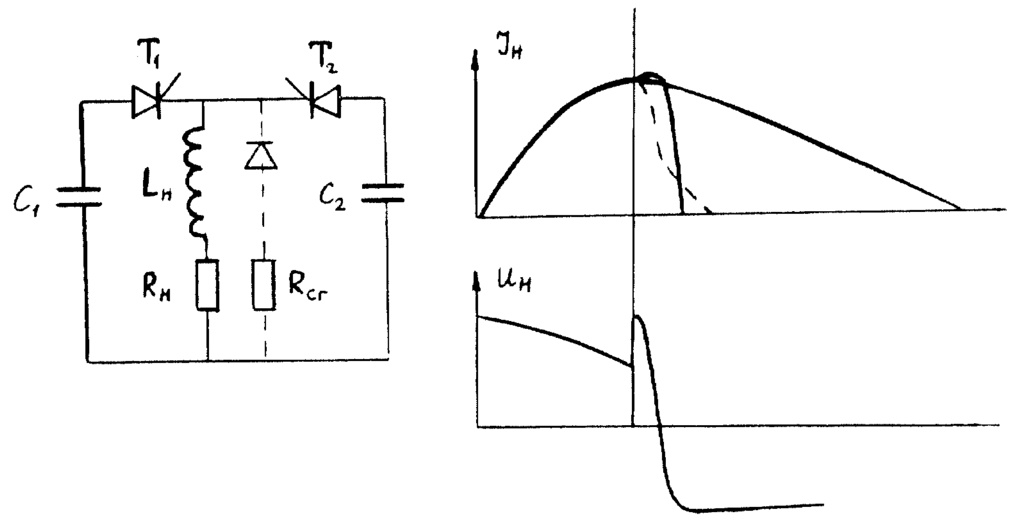

Fig. 4. Principal scheme of the pulse generator.

back front of the pulse becames shorter the ratio $(C_1/C_2)^{1/2}$. This is achieved at the expense of the complication of the generator scheme since the requirements for the commutators T_1 and T_2 become considerably more stringent. T_1 has to provide a minimal time of switching on, which determines the admissible rate of cut the back front of pulse, i. e. the quantity C_2 and the maximum rate of increase of the direct voltage, while T_2 is responsible for the maximum possible value of the derivative of the current increasing to the amplitude one for 10—20 μs determined by the spurious parameters of the scheme. Modern thyristors satisfy these requirements and are capable of providing the formation of the back edge in several hundreds of μs. The dotted line shows a modification of this scheme which is more prefereable from the point of view of the minimization of the energy release if the voltage, at which the capacitance C_2 reverses its polarity, is the same.

Such a scheme was applied to the generator powering the liquid lithium lens at a current up to 0.6 MA.

References

1. G. Dugan. «P-bar Production and Collection of the FNAL Antiproton Source».—XIII Intern. Conf. on High Energy Accelerators. Novosibirsk, 1986, v.2, p.264.
2. R. Bellone. et al. «The Results of Prototype Tests and Temperature and Field Computations of the CERN Lithium Lens».—XIII Intern. Conf. on High Energy Accelerators. Novosibirsk, 1986, v.2, p.272.
3. T.A. Vsevolozhskaya and G.J. Silvestrov. «Thermal Regime of Cylindrical Lenses».—Preprint INP 84-100, Novosibirsk, 1984
4. B.F. Bayanov et al. «The Investigation and Design Development of Lithium Lenses with Large Operating Lithium Volume».—Proc. of 12-th Intern. Conf. on High Energy Accelerators, Fermilab, August 11—16, 1983, p.587.
5. B.F. Bayanov et al. «Multi-Hertz Conic Lenses with Liquid Lithium for the Focusing of Low-Energy Positrons».—Proc. of the 9-th National Accelerator Conf., Dubna, 1984, v.I, p.406.
6. B.F. Bayanov et al. «Cylindrical Large-Diameter Lenses with Liquid Lithium».—Proc. of the 9-th National Accelerator Conf., Dubna, 1984, v.I, p.402.

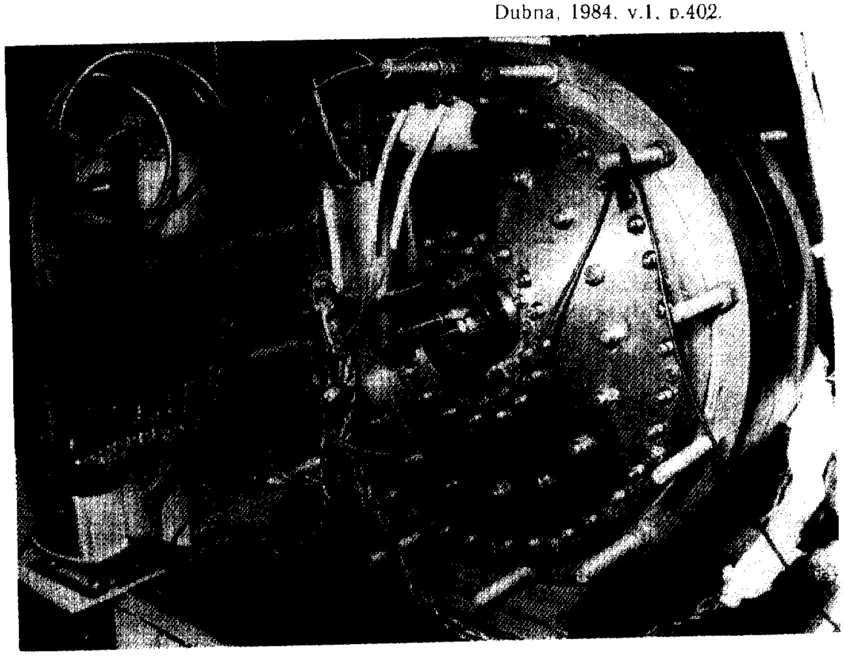

Fig. 3в Photograph of the lens-transformer and liquid lithium system.