

Introduction

The idea to use the forward current axially-symmetric magnetic field for focusing charged particle beams seems to be rather attractive. The first attempt to develop a focusing device in the form of a plasma lens on the base of this idea was undertaken in the USA. In a simplified form, this is an insulated pipe filled with a low pressure gas and plugged with current conducting plugs from both ends. The current between electrodes was produced by a discharge of the capacitor battery. The operable device was failed to be done because of instability of plasma channel and damage of end plugs by arc.

The first Li – lens for focusing of high energy electrons has been developed and manufactured at BINP at the end of 1970s and is being operated up to now at VEPP-2. Lithium is a soft chemically active metal that prevents its use as a construction material. In the lithium lens, the natural Li ($\sim 92.5\% \text{ } ^7_3\text{Li}$; $7.5\% \text{ } ^6_3\text{Li}$) is enclosed in a thin-wall pipe made of titanium alloy with high electric resistance, which is transformed into hollow discs covered by beryllium foil at both ends. Current is generated by the capacitor discharge and heat is removed through the power bandage insulated from the titanium pipe.

Further development of the idea to use forward current magnetic field was based on the joint work of FNAL and CERN. Rather large lithium lenses quite reliably operated in some certain range of current pulse repetition frequencies and currents of the order of a few hundreds of kilo amperes were created.

These are technically complex devices with powerful capacitor batteries, charging device, the primary current commutator and matching toroidal transformer at hundreds of kA.

There are a water cooling system, monitoring and control systems of the lithium lens. A solid-body Li – lens has a limitation on the maximum current and current pulse repetition rate. This limitation is related to difficulties in removing heat from the lithium rod in a titanium shell with a low thermal conductivity. Another limitation is the mechanical stress of the Li – lens body and titanium pipe with lithium caused by a thermo-cyclic influence and pressure of the magnetic field due to passing current pulses.

Lithium lens with liquid lithium.

In order to increase the lens magnetic field and pulse repetition rate, we started the work on the development of the Li – lens with liquid lithium. The problem of lens cooling is solved by the use of the actuating fluid (metal Li in its liquid phase) as a heat carrier. Liquid Li heated by current pulses is pumped by the electromagnetic pump through the closed contour being under high static pressure and then it is cooled outside the lens.

From the point of view of the development of the Li – lens, the most important characteristics of lithium are the following: melting temperature, volume variation in the range from $t \sim 20^\circ\text{C}$ to $t \sim 300^\circ\text{C}$, change of electric resistance, compressibility and chemical activity. According to the latest data, the lithium melting temperature is $t_m \approx 180.54^\circ\text{C}$. Heating of lithium in an operating volume of the lens at a 10 T field is $\sim 60^\circ\text{C}$ per pulse. Taking this into account, the lithium temperature in the system should be $250^\circ\text{C} \div 300^\circ\text{C}$. The lower limit guarantees the defrost of the system and an increase in the upper limit is undesirable because of sharp increase in the chemical activity of Li, thermal losses due to an increase in ohmic resistance, and an undesirable redistribution of a current in the titanium shell and lithium rod.

Lithium density is strongly dependent on temperature.

$\rho_s = 533 \cdot (1 - 1.8 \cdot 10^{-4} \cdot t)$ kG/m³ is a density of a solid Li.

$$\rho_l = 540.43 - 0.02729 \cdot (t + 273.2) - 8.0035 \cdot (t + 273.2)^2 \cdot 10^{-5} + 3.799 \cdot (t + 273.2)^3 \cdot 10^{-8} \text{ kG/M}^3$$

– is a density of a liquid Li

During melting, the Li volume is increased by 1.5%. The total increment of Li volume in the range from $t = 20^\circ\text{C}$ to $t = 300^\circ\text{C}$ is $\sim 5.25\%$. The isothermal compressibility of Li at temperature of 300°C is $\sim 1.0 \cdot 10^{-10} \text{ Pa}$.

This fact leads to that with a system Li - lens - pump - contour completely filled with solid lithium at heating up to $250^\circ\text{C} \div 300^\circ\text{C}$ the pressure can rise up to the values determined by the rigidity of the system which might lead to its damage.

In order to avoid the damage of the system, the pressure control system is built-in the lithium contour for maintaining pressure at a given level. After switching the system off, lithium decreases its volume and vacuum cavities occur at places with the lower heat emission.

With the repeated switching on the system, this circumstance should be taken into account and heating of the system should proceed in a certain succession.

Another important parameter of Li is its specific resistance.

$$\rho_s = 8.55 + 38.1 \cdot 10^{-3} \cdot t - \text{for solid lithium, } t \text{ is temperature in } ^\circ\text{C}.$$

$$\rho_l = 27.884 \cdot (1 + 2.7 \cdot 10^{-3} \cdot t) - \text{for liquid lithium.}$$

$$\rho_{(20^\circ)_s} = 9.3 \cdot 10^{-6} \text{ Ohm} \cdot \text{cm} \quad \rho_{(180^\circ)_s} = 15.44 \cdot 10^{-6} \text{ Ohm} \cdot \text{cm}$$

$$\rho_{(180^\circ)_l} = 41.38 \cdot 10^{-6} \text{ Ohm} \cdot \text{cm} \quad \rho_{(300^\circ)_l} = 50.47 \cdot 10^{-6} \text{ Ohm} \cdot \text{cm}$$

With the phase change from solid to liquid state the lithium specific resistance changes by ≈ 2.7 times.

This circumstance has a great influence on the choice of material for the container forming the lithium cylinder. Therefore, taking into account all the mentioned above properties of lithium we have chosen the titanium alloy VT-6 (Ti - 6Al - 4V), USA with a specific resistance of $\sim 160 \cdot 10^{-6} \text{ Ohm} \cdot \text{cm}$ and $\sigma_{s(20^\circ\text{C})} \approx 95 \div 105 \text{ kG/mm}^2$, which at the lithium rod diameter of 20 mm and the container wall thickness of 1 mm provides the current distribution in the pipe and lithium 6.6% and 93.4%, respectively, at 300°C .

Construction material for the lens body.

Prior to the shift to considerations of the lens production technology, let us briefly dwell upon the properties of titanium alloys from the point of view of their compatibility during a long term operation in a melted lithium at temperature $\sim 300^\circ\text{C}$.

The atomic number of Ti is 22, its atomic weight is 47.9.

Titanium is polymorphous metal existed in its two allotropic versions: a low temperature one α , stable up to 882.5°C and having a hexagonal tightly packed grid. The high temperature – titanium modification with a volume centered cubic grid (VC) is stable in the temperature range from 882.5°C to the melting point of 1668°C . For strengthening titanium and giving some other technological properties we use two kinds of doping materials. The first group of elements includes α – stabilizers Al, Ga, In, O₂, N₂, C expanding the area of existence for α - phase. The second group includes β - stabilizers Mo, Cr, V, Mn, Nb, Fe, Cu, Ta reducing the temperature of $\alpha \rightarrow \beta$ transition. According to doping materials used, the titanium alloys are divided to ($\alpha; \alpha'$) ($\alpha + \beta$) ($\beta^1 \beta$) α – alloys and α^1 alloys (with a small adding of β - stabilizers) are of high plasticity and corrosion resistance. They can be stable operated at temperatures $350^\circ \div 500^\circ\text{C}$. They have a small-grain structure with no tendency to the grain growth during heating and insensitive to the heating rate which is important for titanium welding. Mechanical stresses are removed by annealing. The only disadvantage is their low strength.

β -alloys and β^1 alloys are of high strength and capable for thermal strengthening (hardening, ageing). They have a strong tendency to the grain growth and have low thermal stability.

Two-phase $\alpha + \beta$ alloys are of mixed structure. By varying ratios of α and β structures the alloys properties are rather broadly varied. The strengthening is achieved with thermal treatment. The strength drops with an increase in temperature because of the instability of β phase. They have a strong tendency to the grain growth during heating and sensitive to the cooling rate after welding. In comparison with steel, a large-grain structure occurred after overheating cannot be removed by further thermal treatment in all the titanium alloys.

Grains can only be reduced by mechanical deformation.

Chemical resistance of the titanium body and container

In a liquid lithium lens, the lithium rod shell is under action of lithium at temperature up to 300°C, static pressure over 100 atm., and pulse pressure of ~ 500 atm. Therefore, for the shell made of titanium alloy VT-6 (Ti, 6Al, 4V) its chemical resistance is important. In 1970s at BINP, the qualitative experiments have been performed on the applicability of this titanium alloy for the operation in lithium at temperature up to 800°C with the total experimental time of 100 hours. In this case, we have not observed any changes in the weight of the titanium specimen probably because of insufficient accuracy. However, the surface of the polished specimen became slightly mat and dark (probably because of absorption of admixture N_2 and Li_3N). Thorough quantitative measurements of recent years yield the dependence of metal solvability (mole fraction) in lithium as $\ln(x) = (a - b \cdot 10^3/T)$. For titanium $a = 4.68$, $b = 18.39$. Mole fractions of titanium dissolved in lithium correspond to:

1000°C	500°C	250°C
$x = 5.8 \cdot 10^{-5}$	$x = 5 \cdot 10^{-9}$	$x = 5.8 \cdot 10^{-14}$

that for volumetric percents corresponds to $\sim 4 \cdot 10^{-2}$ % at 1000°C and actually absent at 250°C. Therefore, the decrease in chemical resistance of titanium alloy VT-6 seems to be more affected by washing out aluminum from the alloy.

Specific features of treatment and control.

($\alpha + \beta$) titanium alloys are sensitive to cuts, scratches, inner defects i.e. concentrators of mechanical stresses. Therefore, prior to the primary treatment the titanium blanks are objected to annealing and ultrasonic echo spectroscopy for finding heterogeneities in metal.

The ultrasonic generator frequency is $25 \cdot 10^6$ Hz. The characteristic size of found heterogeneities is about 0.1 mm i.e. of the order of the wavelength in titanium. The most stressed part of the lithium lens is a titanium pipe. Its inner surface has a contact with liquid lithium and it is subjected to the thermal and hydrostatic shocks during the passage of a current pulse. In order to avoid stress concentrations, the inner surface was treated with a high accuracy by a special instrument.

Insulation of lens components.

The contact surface of two halves of the lens body and tightening pins should be insulated from each other. The outer surface of a pipe should be insulated from the supporting body by a heat-resistant and radiation resistant insulation.

Gas-kinetic insulation technique.

Al_2O_3 , applied with a gas-kinetic spraying technique was used as insulation. The essence of the technique is that the suspended powder of Al_2O_3 , with a grain size of $10\div 15$ microns is heated with the acetylene-oxygen mixture up the temperature of $3000\div 3200^\circ\text{C}$ and it is thrown in the form of melted drops onto the outer surface of a pipe with a velocity >1500 m/s. The heated drop is alloyed with the pipe surface. Then, the ceramic layer is increased up to the required thickness. In this case, the pipe temperature does not rise higher than 100°C since each single throwing has a store of heat insufficient for heating the pipe and between throwings the pipe is cooled. Prior to coating the pipe outer surface is made rough to enlarge the coupling area. The final machining of the outer surface of ceramics is realized by diamond polishing.

Micro-plasma insulation technique.

Another kind of heat-resistant coating of the lithium lens components is a micro-plasma coating. The essence of the technique is the following, in the so-called valve metals (Al, Ti, Ta, Nb, Zr, Hf, V), oxide films on metal surfaces in electrolytes have valve properties. The component made of such a metal is placed into electrolyte as an anode. The stress on this element is growing with the coating thickness. Upon reaching some certain coating thickness, an electric breakdown is occurred in the oxide film and it is melted at the breakdown point. From this moment, the stress growth is automatically ceased and the oxide coating is melted at the entire surface of the element independently of its configuration by electric breakdowns of high density. In this case, the element is glowing in electrolyte. The optimum coating thickness is determined by the onset of luminescence decrease. Electro-insulation coatings of such a kind have a thickness of ~ 25 μm and withstand voltages of 600-1000 V depending on admixtures in the basic metal. The coating is sufficiently porous. Therefore, with an increase in the electric breakdown voltage the coating if necessary is impregnated with a heat-resistant polyamide compound (mylar) and baked. After such a treatment, elements withstand the breakdown voltages of over 1000 V at a pressure of 750 kG/cm^2 , that in practice, does not change the size of elements since oxidation proceeds into the metal depth.

Insulation tests.

. Preliminary tests of the ceramic insulation for the electric strength have performed for coatings on titanium and stainless steel at temperature 850°C during four hours. The thermal-shock steadiness was tested on flat titanium and stainless steel specimens. The ceramic spot of 24 mm in diameter and 0.5 mm thickness was sprayed on square specimen of $30\times 30\times 1$ mm size. Than the ceramic coating was polished to 0.3 mm thickness and the breakdown voltage was tested. It varied in $25\div 35$ kV/mm limits for various samples probably because of the ceramic purity. The specimen was subjected to the thermal shock. To this end, they are cooled in liquid nitrogen and quickly submerged into boiling water. After twenty cycles, the breakdown voltage was checked again, which was 30-35% reduced for different specimens. After tests, specimens were put into vacuum oven and heated up to 850°C keeping there for 4 hours and cooled together with the oven. After cooling the electric tests were carried again. The tests have shown that electric strength remained the same as that after thermal shocks, i.e. the pre-breakdown leak current remained to be at the same level of voltage. Tests of coatings for the static pressure resistance have also been carried out. A 0.5 mm thick coating was applied to the inner end surface of the lens body. The body of the first lens prototype was made of stainless steel. A 100 mm^2 area punch was loaded through the ceramic coating by the force of $1 \cdot 10^4$ kG. In this case, the punch

was pressed in the metal by 2 mm. The coating along punch outer circumference was cut and merged into metal but under the punch, the ceramics remained monolithic.

By some assumptions, the coating by ceramics of the pipe outer surface produces numerous knots of mechanical tensions thus leading to the loss of strength and finally to destruction. In this connection, we have carried out comparative tensile tests of standard samples made of titanium alloy without coating, with the gas-detonation coating, and with a micro-plasma coating, which was used for insulating some individual components of the lens.

Samples were fabricated of the same material from the same blank for two samples. Test results are presented in Table.

Num.	Coating	σ_t kG/cm ²	$\delta\%$	$\Psi\%$
1	Without coating	52.7	16.8	46
2		53.1	14.3	46.5
3	Gas-detonation coating	55.3	12.5	46.6
4		54.1	13	46.6
5	Micro-plasma coating	52.7	18.9	44.5
6		53.5	20	44.5

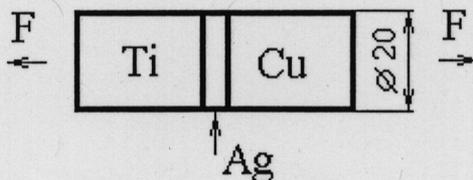
As one can see from experimental results, the micro-plasma coating did not affect the sample strength but the gas-detonation coating somewhat increased the sample strength. The authors of the method explain this effect by the fact that melted drops of aluminum oxide smooth tensile concentrators at the pipe surface. Apprehension that ceramics at a distance of $\sim 2\div 3$ mm from the place of electron-beam welding could affect badly the joint quality was not proved. Preliminary experiments have shown that an Al_2O_3 ceramic was not gassing and the temperature of the near-the joint-area of $800\div 900^\circ C$ did not violate the joint quality. Test of pipe samples of $\varnothing 10 \times 1.0$ in diameter made of technical titanium without coating and those coated with the gas-dynamical and micro-plasma techniques did not reveal a substantial difference in the strength of pipes. Pipes destroyed in the welding area at $P=1400$ kG/cm² independently of the presence of coating.

Contact material.

Electric current is applied to the lens from the toroidal transformer through the collet contact. In the design under development the copper collet is soldered to the lens titanium body. The clamping is provided by conical split rings. The pressure is transmitted to the transformer body. Since the contact is well operated if surfaces are not oxidized and the material of one of contacting pairs is brought to the plastic deformation, the Ag-Ag contact was replaced by the Ag-In contact. This is caused by the fact that the hardness of indium is lower than that of silver, indium is chemically resistant, it allows to lower the load to the transformer body. The collet by its inner thread is put onto the outer thread of the lens titanium body and for the reliable contact the collet and lens contact surfaces should be soldered. Titanium is chemically active and it is hard to be soldered. The solder joint should not be fragile since it feels sharp shocks during the passage of the current pulse.

Brazing of titanium.

We have carried out experiments on brazing the copper samples with titanium by brazes of pure silver, silver-copper and aluminum-indium alloys. During brazing with silver, copper samples of cylindrical form were silver galvanized with the coating thickness of $(5 \div 10) \cdot 10^{-6}$ m and then connected end-to-end with pure titanium samples with the load of $3 \div 5$ kG/cm² and heated in the vacuum oven up to 850°C and cooled together the oven. Then tensile tests were carried out.



$$S \approx 3 \text{ cm}^2, F = 900 \text{ kG}, \sigma = 300 \text{ kG/cm}^2$$

The break was partially on copper and partially on the joint. The joint is fragile. Brazing of the copper sample with titanium through the 70% Ag + 30% Cu alloy foil gave slightly worse results. During brazing through the aluminum foil at the same temperature regime we have obtained the following results for destruction $F = 100$ kG/cm²; $\sigma = 33$ kG/cm² with the extremely fragile joint. The aluminum brazing was checked assuming that aluminum is ultimately solvable in titanium up to 7% of the weight and it is α - stabilizer increasing temperature of phase transition for α titanium into $(\alpha + \beta)$ and β titanium up to 950°C.

The third in the capability of increasing temperature $\alpha \rightarrow (\beta + \alpha) \rightarrow \beta$ after aluminum and gallium is indium. The wetting temperature of titanium by indium is $\sim 650^\circ\text{C}$ and indium with titanium do not produce any intermetallides in this temperature range. Copper and titanium samples with $S = 3 \text{ cm}^2$ were brazed with indium in vacuum at temperature $\sim 700^\circ\text{C}$ and cooled together with the oven with the result of $S = 3 \text{ cm}^2$. $P = 1050 \text{ kG/cm}^2$ $\sigma = 350 \text{ kG/cm}^2$. In this case, the joint was quite fragile because of diffusion of copper from the copper-indium alloy to titanium with the generation of intermetalides. It became obvious that the brazing methods considered do not provide a guarantee of the long term reliable operation of the joint under conditions of shock loads caused by current pulses. Therefore, it was suggested the separate galvanic coating of copper and titanium by indium and after that to proceed to the low-temperature brazing with $t \sim 350^\circ\text{C}$. For coating titanium with indium we selected the electrolyte composition which enabled the applying of a dense indium coating of the required thickness being well soldered. The galvanic coatings on titanium melted in vacuum and air have identical parameters. The collet brazing to the lens titanium body is performed after coating the titanium body and copper collet and their twisting without melting the galvanic indium layer. Then the product is placed into the vacuum oven and heated up to 350°C. At the place of the brazed joint, some metal indium is preliminary placed for filling gaps between threads.

Welding of titanium.

One of the most responsible operations in the lens production is welding of titanium parts with each other. In the first versions of the lens we had many places where its components were connected with the electric-beam welding. With the further improvement of the lens design the only two joints remained, namely the pipe ends are welded to the lens body. At the melting place of titanium in the in the zone of thermal influence, quite complex chemical and structural transitions occur, which affect on the joint properties (strength, hardness, fragility, etc) and the stability of properties in time. For various kinds of titanium alloys this influence is different and

mainly dependent on the temperature, time of being under temperature, and cooling rate. The worsening of joint properties compared to the basic metal is mainly determined by the grain growth and mechanical tensions. The latter are removed or decreased by thermal treatment. As already said, the change in grains can only be achieved with the mechanical deformation. For the welding regime we have tried a great number of samples of flat and cylindrical shape and also tried regimes on the models copying the real shape and size of lens elements. There we selected the beam current and a possibility of annealing zones of thermal influence by defocused beam. For flat samples, the joint quality was determined by the tensile strength and by the bending method. The tensile strength was about 90% of the strength of the basic metal and admitted the bend by 180°C for α alloy. The joint for the alloy VT-6 ($\alpha + \beta$) after annealing had a 90% strength of the basic metal strength but it was more fragile.

After the selection of the most optimum regime, the one pass welding of the pipe with the lens body was performed. In the first versions of the lens, welding joints were annealed by heating the assembled lens in the vacuum oven at $t = 850^\circ\text{C}$ during four hours. In this case, we had an apprehension that the brazing joint between the collet and lens body could become more fragile.

Therefore, in the latest version, we shift to the local annealing. The local annealing temperature was reduced down to $600\div 650^\circ\text{C}$ because of the replacement of the pipe material by α -titanium alloy OT-4-1 (Ti-1.5Al-1.0Mn). In order to eliminate the oxidation of the copper heater, annealing was performed in argon medium.

Input windows.

The melted lithium is kept in the lens body by titanium flanges with inserted beryllium windows. The shape of the beryllium insert is chosen under assumption of minimizing the particle beam losses and cross-section equal-strength against the applied pressure. The insert is made of cylindrical rods produced with the powder metallurgy technique. Mechanical characteristics of the used beryllium are the following:

$$\begin{aligned} \sigma_s &\approx (65\div 70) \text{ kG/mm}^2 & \sigma_{0.2} &\approx (35\div 40) \text{ kG/mm}^2 & \delta &\approx (5\div 10\%) \\ \rho &\approx 5 \cdot 10^{-6} \text{ Ohm}\cdot\text{cm} & & & & \text{at } t = 20^\circ\text{C} \\ \sigma_s &\approx (50\div 55) \text{ kG/mm}^2 & \sigma_{0.2} &\approx (30\div 35) \text{ kG/mm}^2 & \delta &\approx (15\div 20\%) \\ \rho &\approx 1 \cdot 10^{-5} \text{ Ohm}\cdot\text{cm} & & & & \text{at } t = 300^\circ\text{C} \end{aligned}$$

Beryllium is sufficiently resistant in liquid lithium up to the temperature of $\sim 500^\circ\text{C}$ under static conditions and normal pressure. The penetration depth is $\sim L = 0.115 \text{ mm/year}$. At a temperature $\sim 300^\circ\text{C}$ its resistance is much higher. Structurally the beryllium is pressed into the titanium flange and from the side of lithium it is covered by a thin titanium plate. An insulation is put between the titanium plate and beryllium insert, which eliminates the current redistribution and uncertain current contact which might cause the erosion of the beryllium insert. Natural tests of the beryllium insert with a pressure of 1350 kG/cm^2 have been conducted.

In this case, the insert itself and the tightness of the protective titanium plate were not deteriorated. The test was ceased because of the deformation of the high pressure tank (so-called – bomb).

In conclusion one can say that this is a short and far from exhaustion list of works done on the development of the lens. We did not consider the way of lens tightening by pins, a complex system of heating and temperature control, preparatory procedure for melting lithium, the melting process and filling the system under vacuum, problems of resistance, wetting by gallium-indium alloy of the cooling-heating contour. There are some problems at the stages of development and tests.